System Operations, Power Flow and Control
Portfolio Overview

MODERNIZATION INITIATIVE
U.S. Department of Energy

Jeff Dagle – System Operations, Power Flow and Control Technical Area Lead

Pacific Northwest National Laboratory

April 18, 2017
Arlington, VA

U.S. DEPARTMENT OF ENERGY

PNNL-SA-125328

System Operations and Control

Advanced control technologies to enhance reliability and resilience, increase asset utilization, and enable greater flexibility of transmission and distribution systems

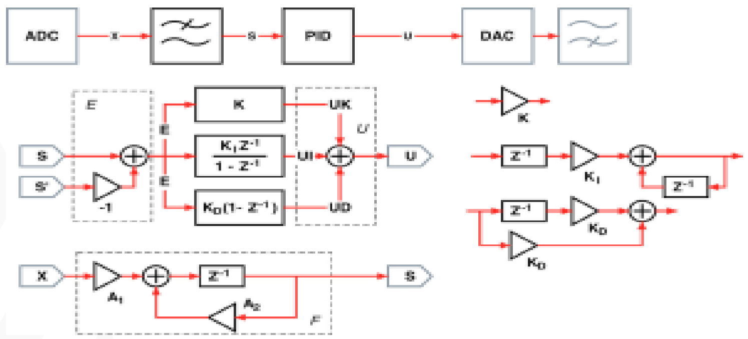
Expected Outcomes

- By 2020 deliver an architecture, framework, and algorithms for controlling a clean, resilient and secure power grid
  - Leveraging advanced concepts, high performance computing, and more real-time data than existing control paradigms
  - Involving distributed energy resources as additional control elements
- Develop software platforms for decision support, predictive operations & real-time adaptive control
- Deploy, through demonstration projects, new classes of power flow control device hardware and concepts
- Advance fundamental knowledge for new control paradigms (e.g., robustness uncompromised by uncertainty)

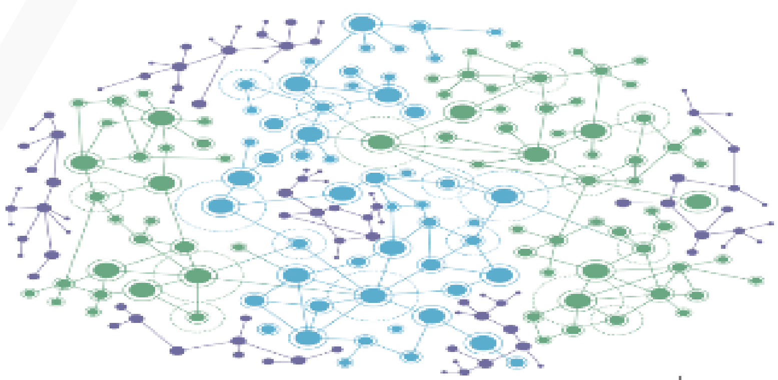
Federal Role

- Convening authority to shape vision of advanced grid architecture, including new control paradigms for emerging grid to support industry transformation
- Deliver system engineering and other supporting capabilities from the National Laboratory System to research & develop integrated faster-than-real-time software platforms and power electronics controls

Conventional Controls



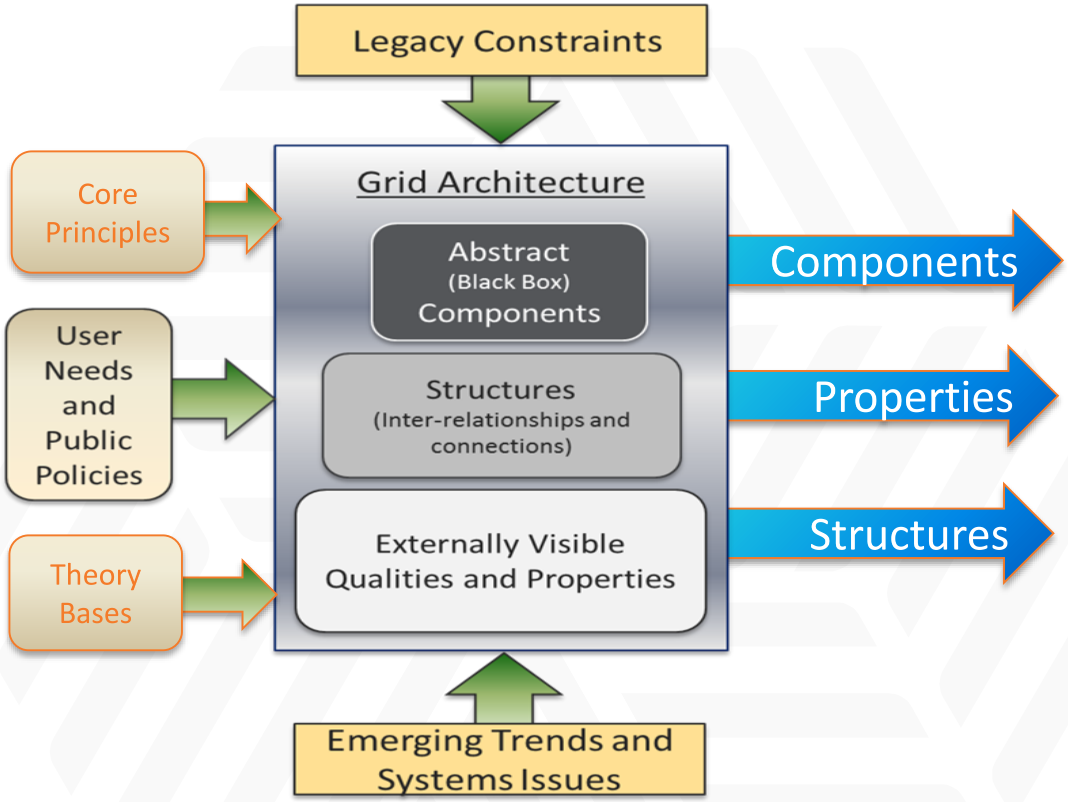
Distributed Controls



Multi-Year Program Plan (MYPP) Activities

Activity	Technical Achievements by 2020
1. Develop Architecture and Control Theory	• Comprehensive architectural model, associated control theory, and control algorithms to support a variety of applications to improve grid flexibility, future adaptability, and resilience while not compromising operational reliability or security. • Wide-area control strategies to improve reliability, resilience, and asset utilization.
2. Develop Coordinated System Controls	• New control grid operating system designs reflecting emerging system control methodologies. • Framework(s) for integrating the next generation energy management system (EMS), distribution management system (DMS), and building management system (BMS) platforms.
3. Improve Analytics and Computation for Grid Operations and Control	• Future and real-time operating conditions with short decision time frames and a high degree of uncertainty in system inputs can be evaluated. • Automation with predictive capabilities, advanced computational solvers, and parallel computing. This includes non-linear optimization of highly stochastic processes. • Decision support to operators in control rooms through pinpoint visualization and cognitive technologies.
4. Develop Enhanced Power Flow Control Device Hardware	• Low-cost, efficient and reliable power flow control devices that enable improved controllability and flexibility of the grid.

1.2.1: Grid Architecture



PoP: FY16/17/18

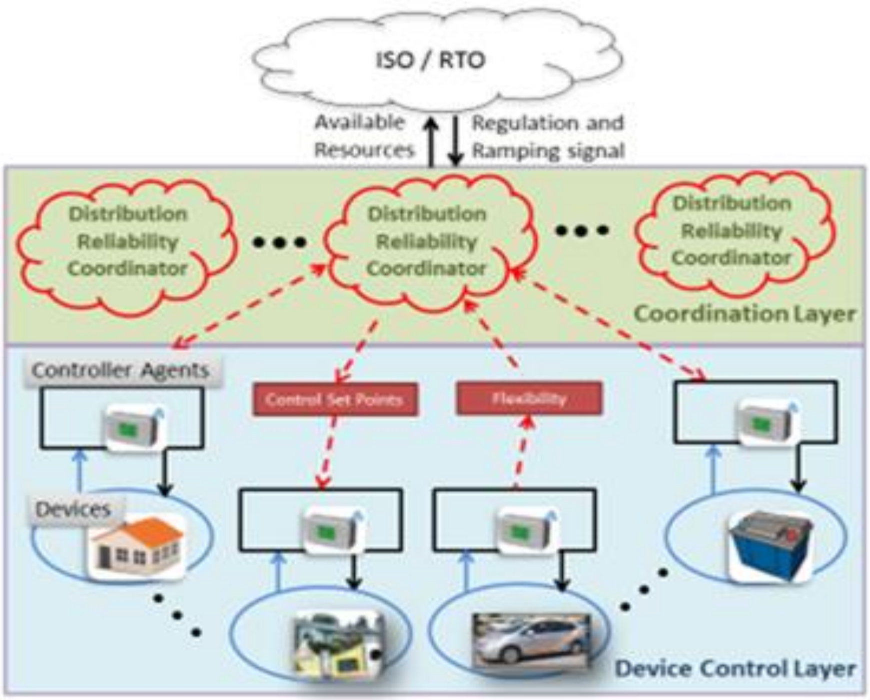
Budget: $3M

Labs: PNNL, ANL, NREL, ORNL, LANL, LBNL, LLNL, SNL

Partners: GE, EPRI, GWU, UTC, SGIP, Omnetric Group, CA ISO

Build a new stakeholder-driven architecture for grid modernization, provide it to the industry along with the tools they need to adapt it to their needs, and use it to inform the playbook for the GMLC program managers. The result will be superior stakeholder decision-making about grid modernization activities of all kinds.

1.4.10: Control Theory



Candidate hierarchical distributed control architecture based on future distribution reliability coordinator model

PoP: FY16/17/18

Budget: $6.5M

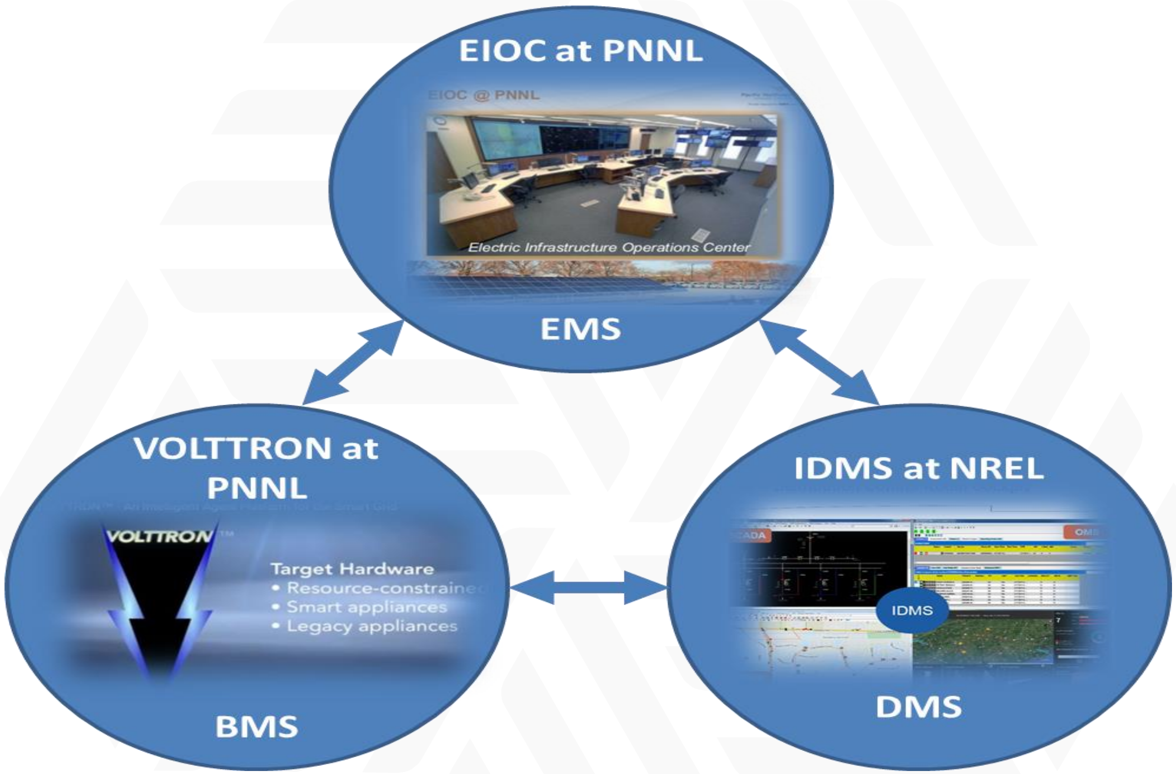
Labs: LANL, PNNL, ANL, INL, NREL, SNL, LLNL, ORNL

Partners: Oncor Electric Delivery, PJM Interconnection LLC, United Technologies Research Center

Develop new control solutions including topologies, algorithms and deployment strategies for transitioning the power grid to a state where a huge number of distributed energy resources are participating in grid control to enable the grid to operate with lean reserve margins. The theoretical aspect of this project will recognize the need to engage legacy control concepts and systems as we transition to more distributed control.

1.4.11: Control Integration

Energy Management System (EMS)



Building Management System (BMS) **Distribution Management System (DMS)**

PoP: FY16/17/18

Budget: $3.5M

Labs: ANL, BNL, LANL, LLNL, NREL, PNNL, SNL

Partners: GE, Duke Energy, PJM Interconnection LLC

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.

Regional Partnership Projects

- **1.3.01 Southeast Regional Consortium: Improving Distribution Resiliency through Reconfiguration in the Presence of Renewable Energy and High Impact Low Frequency Events**
  - Lead organization: Savannah River National Laboratory
  - Other organizations involved: ORNL, EPB, UNCC, Santee Cooper, Duke, Clemson, Southern Company, TVA
- **1.3.09 Smart Reconfiguration of Idaho Falls Power Distribution Network for Enhanced Quality of Service**
  - Lead organization: Idaho National Laboratory
  - Other organizations involved: PNNL, SEL, WSU, Idaho Falls Power
- **1.3.10 Vermont Regional Partnership Enabling the use of DER**
  - Lead organization: Sandia National Laboratories
  - Other organizations involved: NREL, Green Mountain Power, Vermont Electric Coop, Vermont Electric Company, University of Vermont, Vermont Department of Public Service, Vermont Energy Investment Corporation, Spirae
- **1.3.99 Clean Energy and Transactive Campus**
  - Lead organization: Pacific Northwest National Laboratory
  - Other organizations involved: State of Washington, UW, WSU

Program Specific Projects

- GM0061 Virtual battery-based characterization and control of flexible building loads using VOLTTRON
- GM0062 Vehicle to Building Integration Pathway
- GM0063 Development of an Open-Source Platform for Advanced Distribution Management Systems
- GM0076 Emergency monitoring and controls through new technologies and analytics
- GM0085 Systems Research Supporting Standards and Interoperability
- GM0086 Modeling and Control Software Tools to Support V2G Integration
- GM0091 Unified Control of Connected Loads to Provide Grid Services Novel Energy Management and Improved Energy Efficiency
- GM0140 VOLTTRON Controller for Integrated Energy Systems to Enable Economic Dispatch Improve Energy Efficiency and Grid Reliability
- GM0172 VOLTTRON Message Bus Protocol Adapter
- GM0187 Community Control of Distributed Resources for Wide Area Reserve Provision
- GM0252 Optimal Stationary Fuel Cell Integration and Control (DG-BEAT)
- GM0253 Operational and Strategic Implementation of Dynamic Line Rating for Optimized Wind Energy Generation Integration
- SI-1673 Dynamic Building Load Control to Facilitate High Penetration of Solar PV Generation
- SI-1714 Enabling High Penetration of Distributed Photovoltaics through the Optimization of Sub-Transmission Voltage Regulation
- SI-1748 A ToolSuite for Increasing Performance and Reliability of Combined Transmission-Distribution under High Solar Penetration
- WGRID-04 Providing Ramping Service with Wind to Enhance Power System Operational Flexibility

Accomplishments and Emerging Opportunities

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Accomplishments

- 1.2.1: Stakeholder engagement initiated and inter-project collaboration underway for the development of architectural views and mappings that represent, requirements, use cases, emerging trends, and business models.
- 1.4.10: Documented architectural reference models for control that includes three key scenarios: legacy systems, communications-heavy systems, and communications lite systems.
- 1.4.11: Version 1 of use case document complete, communication and control requirements documentation in progress. Computational testing underway for unit commitment and economic dispatch controls.

Path Forward

- 1.2.1: Architecture development complete (FY17) and validated (FY18)
- 1.4.10: Hierarchical control theory with closed loop control and optimization (FY17) with analytical solutions developed and documented (FY18)
- 1.4.11: Demonstrate the integration of distribution management and building control systems; identify models and emulators for testing (FY17); full-scale demonstration deployed (FY18)

Summary

- System Operations, Power Flow, and Control technical area overview
- Elements of the Multi-Year Program Plan
- Foundational Projects
  - Architecture
  - Theory
  - Integration
- Regional Partnerships
- Program Specific Projects
- Accomplishments and Emerging Opportunities

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Thank you

GRID MODERNIZATION INITIATIVE PEER REVIEW

1.2.1 Grid Architecture

JEFFREY D. TAFT, PHD (PNNL)

April 18-20, 2017

Sheraton Pentagon City – Arlington, VA

Grid Architecture

High Level Summary

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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.

Value Proposition

- ✓ Relieve essential constraints that impede grid modernization
- ✓ Enable new grid value streams by identifying platforms and structures that provide secure interoperability and system integration,
- ✓ Manage grid complexity so as to assure successful investment in grid modernization across the industry

Project Objectives

- ✓ Build stakeholder consensus around a DOE-convened vision of grid modernization, expressed as a new set of grid reference architectures
- ✓ Enable superior stakeholder decision-making to reduce risk of poor functionality and stranded investments
- ✓ Provide a used and useful framework for GMLC projects
- ✓ Establish and win industry acceptance for the use of Grid Architecture work products and methodologies
- ✓ Supply a common basis for roadmaps, investments, technology and platform developments, and new services and products for the modernized grid.

Grid Architecture
Project Team

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Labs shown in table.
Lab members have various roles on the Grid Architecture team, including SMEs, validators, architects, and researchers.

External Partners:
- SGIP
- EPRI
- GWU Law
- Alstom-GE
- Omnetric Group
- CA ISO
- MISO
- Ameren
- SMUD
- GridWise Alliance
- Paul De Martini, Wade Malcolm (Industry SMEs)

PROJECT FUNDING				
Lab		FY16 $	FY17$	FY18 $
PNNL	*	500,000	500,000	500,000
ORNL	Arjun Shankar (+1)	100,000	125,000	100,000
LANL	Anatoly Zlotnick	100,000	50,000	50,000
ANL	Jianhui Wang	50,000	75,000	50,000
LBNL	Bruce Nordman	100,000	100,000	100,000
LLNL	Brian Kelley	50,000	50,000	50,000
NREL	Maurice Martin	50,000	50,000	50,000
SNL	Ross Guttromson	50,000	50,000	100,000

* Ron Melton, Steve Widergren, Olga Kuchar, Renke Wang, Jeff Taft

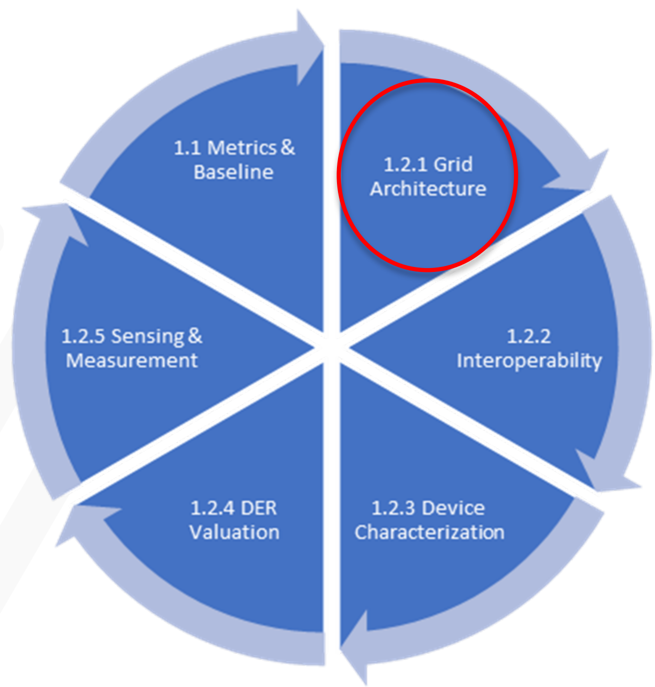
Grid Architecture

Relationship to Grid Modernization MYPP

Grid Architecture is fundamental to all aspects of grid modernization since it defines the basic structures of the grid and thus determines overall capability limits, removes legacy constraints, and manages the complexity of the modernization process. It provides the structures within which grid planning, grid operations, and markets operate, and therefore includes or impacts sensing and measurement, control, communications, interface and interoperability, and even industry structure.

Grid Architecture addresses electric infrastructure, industry structure, ICT, control structure, convergence with other networks (gas, transportation, etc.), regulatory and market structure (not rules), and most importantly, coordination framework.

Grid Architecture is a cross-cutting fundamental project that influences all six MYPP Technical Areas.



Cross-Cutting Projects

Grid Architecture

Approach

Project tasks:

- Architecture development
  - Develop an ensemble of architectures covering a range of scenarios and industry segments, using the discipline of Grid Architecture (see below)
- Stakeholder engagement
  - Three stage process; continual engagement
- GMLC Inter-project collaboration
  - Interaction with many other GMLC projects
- Grid Architecture tools development
  - Browser-based diagram tools
  - Comparative analysis
  - Evaluation and optimization

- Key issues: Bulk System/DSO interaction, structural securability, silo-to-layer conversion, and distributed coordination for distribution grid control, transactive energy, and DER integration. These are all primary grid modernization issues.

- Uniqueness: Grid Architecture is a combination of system architecture, software engineering, network theory, and control engineering applied to the grid. It focuses primarily on structure(s) and employs a range of new paradigms, including the grid as a network of structures concept.

Grid Architecture

Key Project Milestones

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Milestone (FY16-FY18)	Status	Due Date
1.1 Initialization	• Quality/property list and initial mapping complete • Architecture glossary complete • Emerging trends and systemic issues lists complete • Architectural views list generated, priorities received from external partners • Initial collaboration with 11 other GMLC programs established; architecture package delivered to 1.4.10	10/1/2016
1.2 Reference model development	Reference models for high DER grids, structure diagrams for market-control systems in high, medium, and low DER grids, and industry structure models for ISO/RTO industry segment completed	10/1/2016
1.3 Component/interface model development	Six models complete; interaction with 1.2.2 underway	4/1/17
1.4 Architecture development	One package completed for 1.4.10; others underway	10/1/17
1.5 Architecture validation	Simulation of distribution storage circuit models and wide area closed loop control with SDN underway	4/1/18
1.6 Architecture completion	Development underway	10/1/18

Grid Architecture
Accomplishments to Date

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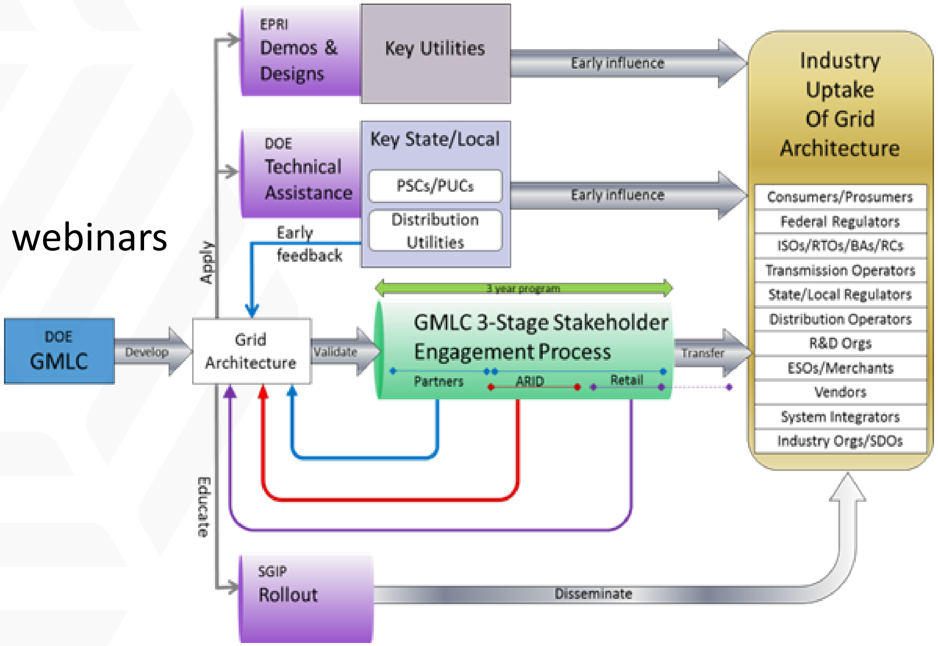
- Early Technical Insights
  - Use of sensor/comms layer networks and DSO structure to improve cyber security; structural securability
  - Use of layered decomposition to perform comparative architecture analysis; framework for distributed TE; impact on Grid Codes for DER
  - Grid services taxonomy & list development
- Stakeholder engagement
  - Extensive public and private presentations and webinars
  - DSPx project; CSIRO project
  - External partner engagement as per plan
- Early Stakeholder Adoption
  - NY PSC Order Adopting Distribution System Implementation Plan Guidance (Grid Arch.)
  - HPUC Order 34281 (Grid Arch., Sensor Nets)



Grid Architecture

Response to December 2016 Program Review

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Recommendation	Response
• Excellent outreach with IEEE (1,100 registrants on webinar!) and close interaction with SGIP and EPRI.	Will continue the process.
• Close interaction with other projects is excellent (1.4.10, 1.2.2).	Will continue the process.
• Please work with Sensing and Measurement Strategy (1.2.5) and Interoperability (1.2.2) to develop a webinar(s) that will support their understanding of grid architecture so they can incorporate it into their programs.	Have planned a webinar with 1.2.5; working with 1.2.2 on application of Grid Architecture to interface and grid services definition.
• Given the level of resources, the team needs to better prioritize their efforts around grid architecture. Please identify how this effort is unique compared to other similar efforts underway in grid architecture.	Have prioritized the 63 proposed views into five scenarios with a plan to maximize use of common elements; this effort has broader scope and uses methods not available to IT-based efforts; 1.2.1 is focused mainly on structures, whereas most other efforts focus on components (mainly IT components).

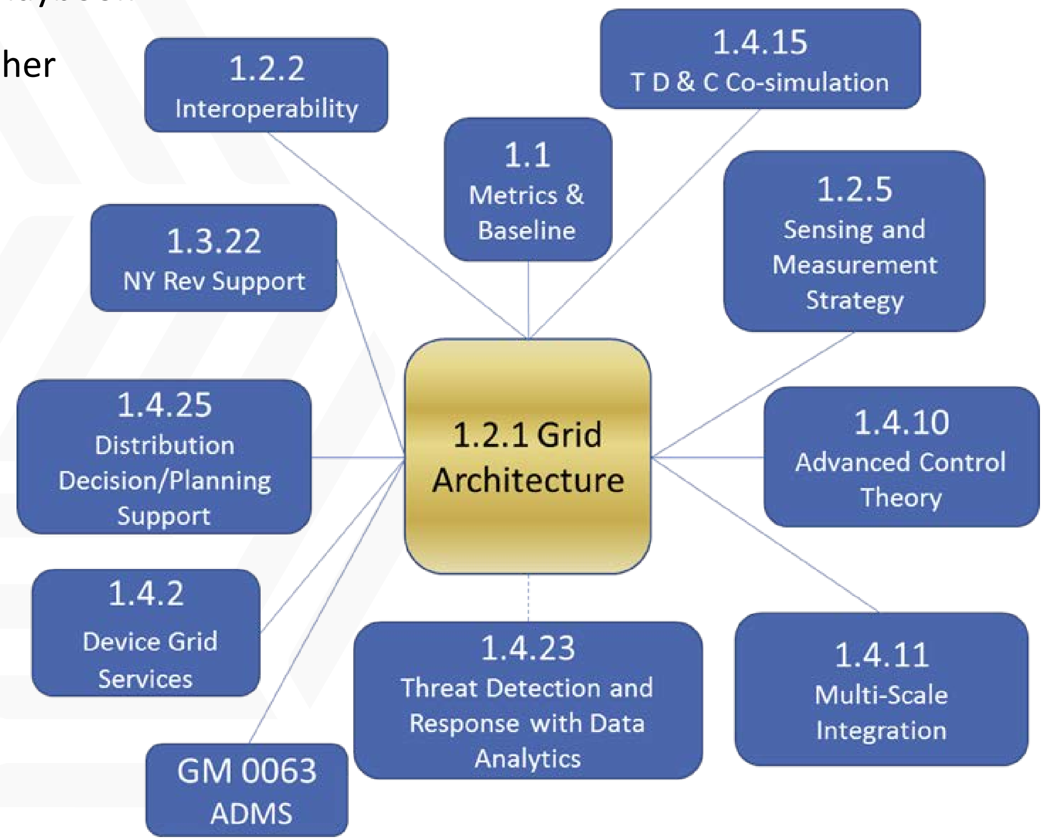
Grid Architecture

Project Integration and Collaboration

Grid Architecture provides the structural framework for the modernized grid and as such provides the playbook for the GMLC PIs and project managers. Grid Architecture is actively collaborating with 11 other GMLC projects.

Communications include:

- ► Incorporated into DSPx project
- ► Incorporated into CSIRO project
- ► IEEE Smart Grid Webinar
- ► EPRI Grid Architecture webinar
- ► CA ISO webinar
- ► GWU Regulatory Conference
- ► NERC meeting
- ► UTC Annual Meeting
- ► 2016 TE Systems Conference
- ► ISGT 2016
- ► EBA Conference
- ► SGIP Architect training
- ► GRID Management Group Meeting
- ► EPRI Sector Meeting



Grid Architecture

Next Steps and Future Plans

Both the Grid Architecture work products and the Grid Architecture discipline will be rolled out to the electric utility industry. This will have the impact of providing rigorous means for managing grid modernization complexity and enabling superior decision making about grid modernization investments, platform developments, and designs at all stakeholder levels.

Future projects will include applying Grid Architecture at all scales in the industry to assist utilities and others to adopt and adapt reference architectures and associated tools for meet specific regional, industry segment, and technology integration needs.

GRID MODERNIZATION INITIATIVE PEER REVIEW

GMLC 1.3.01 – Southeast Regional Consortium

JOE CORDARO

April 18-20

Sheraton Pentagon City – Arlington, VA

Southeast Regional Consortium

High Level Summary

Project Description

Create a consortium of utilities, universities, national laboratories, regulators, and industry in the southeast to address grid related technical challenges specific to this region.

Value Proposition

- ✓ The southeast has unique challenges to reliable and resilient energy delivery
  - ✓ Highest frequency of hurricanes in the U.S.
  - ✓ Higher failure rates of coal plants
  - ✓ Growing solar generation
- ✓ Increased resiliency can save billions of dollars each year[1]

Project Objectives

- ✓ Improve distribution system resiliency
- ✓ Increase DER concentration
- ✓ Foster dialogue between regional stakeholders
- ✓ Identify technical challenges in the SE
- ✓ Develop advanced sensing, communication, and controls to improve the visibility and recovery speed of the SE power grid
- ✓ Transition technology from national laboratories and universities to industry

[1] "Economic Benefits of Increasing Grid Resilience to Outages," Executive Office, August 2013.

Southeast Regional Consortium

Project Team

Project Participants and Roles

- **Savannah River National Laboratory**
  - Lead for wireless sensor network development
- **Oak Ridge National Laboratories**
  - Lead for distributed control, TSN, and optical sensors
- **University of North Carolina Charlotte /CAPER**
  - Modeling and sensors
- **Clemson University**
  - Optimization of restoration plan
- **Duke Power**
  - Provide technical details of distribution feeders.
- **Chattanooga, TN Electric Power Board (EPB)**
  - Time sensitive network testing
- **National Instruments**
  - Distributed control hardware and software
- **SmartSenseCom**
  - Passive optical sensors

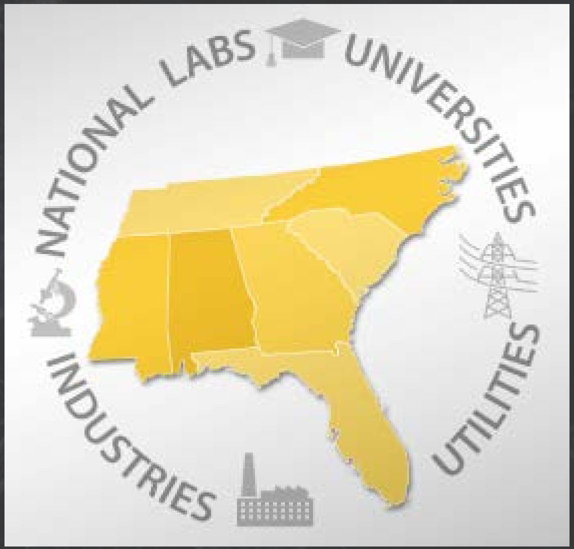
PROJECT FUNDING			
Laboratory	FY16 $	FY17$	FY18 $
SRNL	$200k	$300k	
ORNL	$220k	$280k	

Southeast Regional Consortium

Approach

Project Overview

- Develop tools for control, communication, and situational awareness to improve the resilience of the SE grid to low frequency – high impact events like hurricanes.
    - Dual Channel Wireless Network
    - Restoration Optimization
    - App Based Distributed Controls (CSEISMIC)
    - Time Sensitive Networking (Deterministic Data)
    - Distribution Step Distance Protection using Optical Sensors
- *Working with utilities and universities to develop and demonstrate these technologies.*



SRNL Resiliency Project

Project Description

To improve resiliency through a terrestrial and satellite based communication system for sensors on the grid and develop a tool for utility companies to improve their response to high impact low frequency events such as hurricanes. The program will determine all damaged location, optimize the order in which needed to be restored, and optimize first responders scheduling.

Project Participants and Roles

- Savannah River National Laboratory – Lead for wireless sensor network development
- University of North Carolina at Charlotte – Fault location through AMI and first responder scheduling
- Clemson University – Optimization of fault restoration sequencing
- Duke Power – Provide technical details of distribution feeders

Expected Outcomes

- ✓ Single iteration program to determine first responders scheduling
- ✓ Demonstrate cyber-resilient dual mode wireless control network
- ✓ Demo wireless and scheduling at UNC Charlotte Campus

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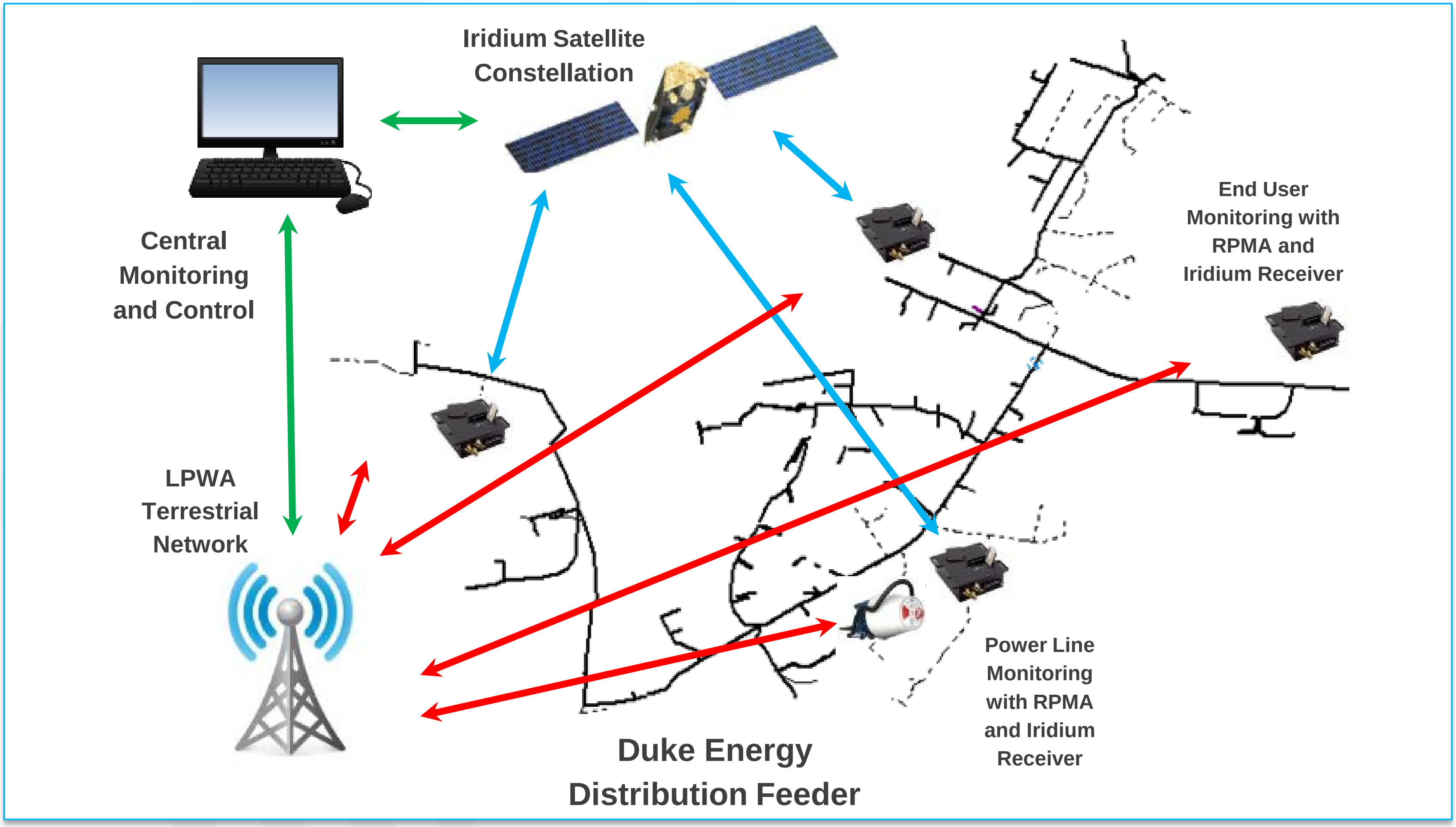
SRNL Dual Wireless Network Demo



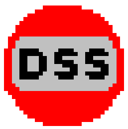
SRNL Overview of Restoration Optimization

SRNL develops demo network with cyber-resilient dual mode wireless control network which feeds data to UNCC

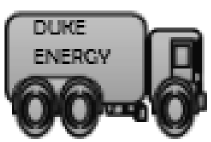
UNCC develops algorithm for detecting fault locations using AMI data.

UNC CHARLOTTE

Clemson develops optimization damage restoration scheduling



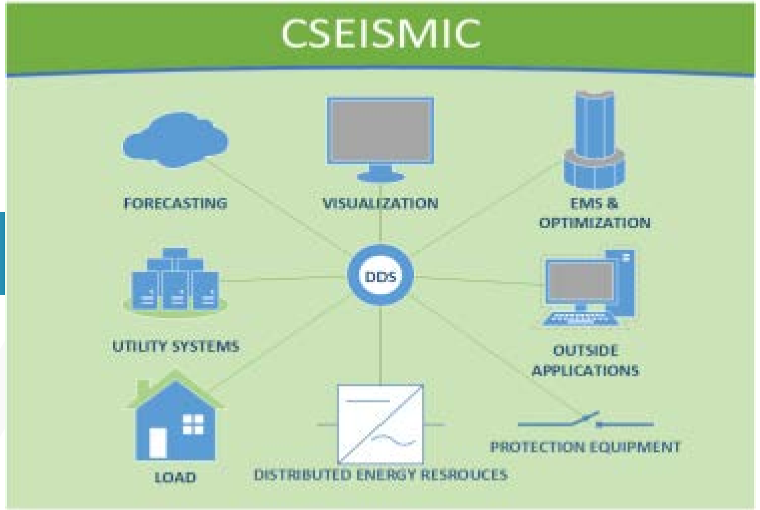
UNCC develops algorithm for scheduling utility crews to prioritized loads



UNC CHARLOTTE

CSEISMIC Distributed Control Platform

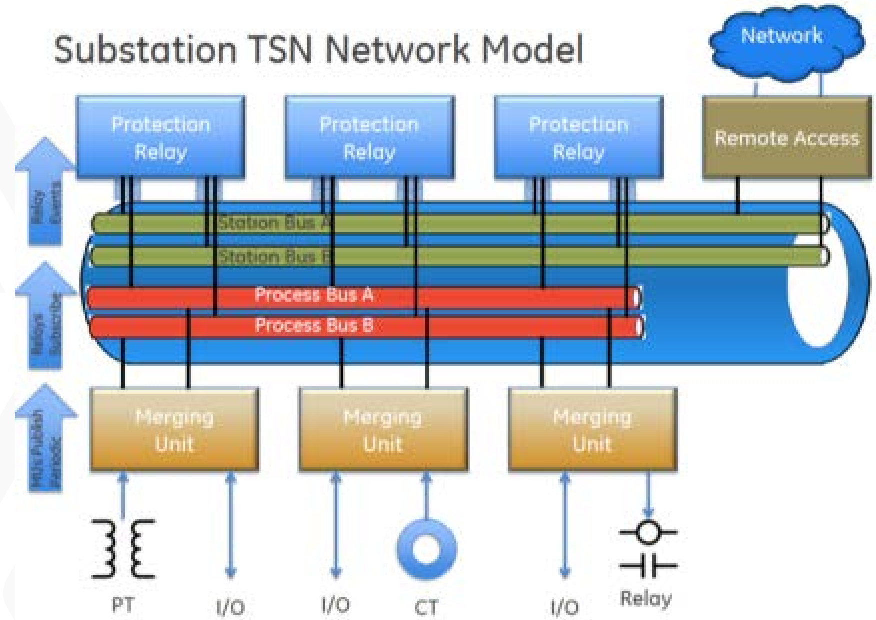
- Apply to a site-specific model (EPB Control Center microgrid.)
  - *App Based Energy Management*
    Forecasting, Resource Optimization, Dispatch, Load Shedding
  - *Protection*
    Relay Coordination
  - *Resiliency*
    Seamless islanding and resynching
  - *Communications*
    IEC 61850 (Substation Automation Systems)
  - *Inverter controls to support microgrids*
    V/F, P/Q, Droop with multiple sources (PV/Energy storage)



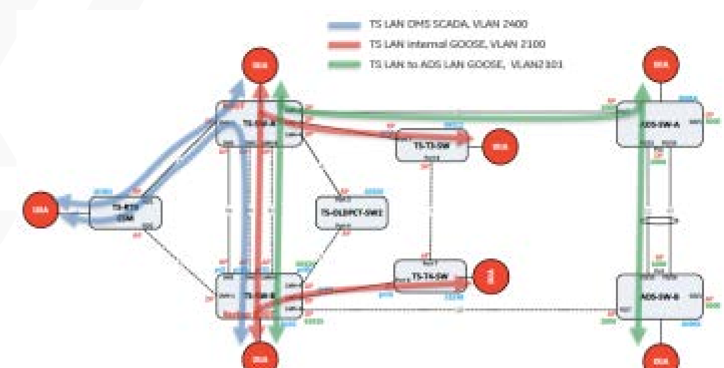
Southeast Regional Consortium
Approach

Time Sensitive Networking

- Microsecond Deterministic Data Transfer
- Low Latency / High Availability
  - *Increases distributed control and sensing capabilities for the grid.*
- *Approach*
  - *Deploy TSN network on an existing fiberoptic network in Chattanooga, TN*
  - *Test latency and data availability*
  - *Test impact on existing SCADA traffic*

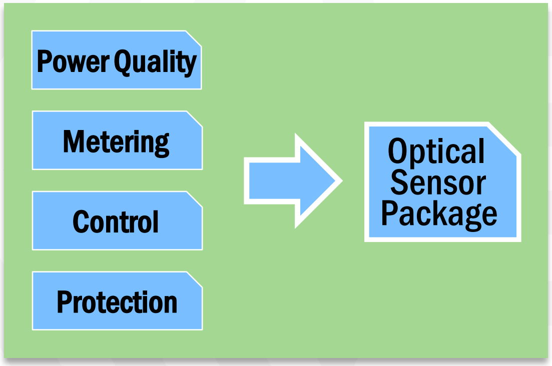


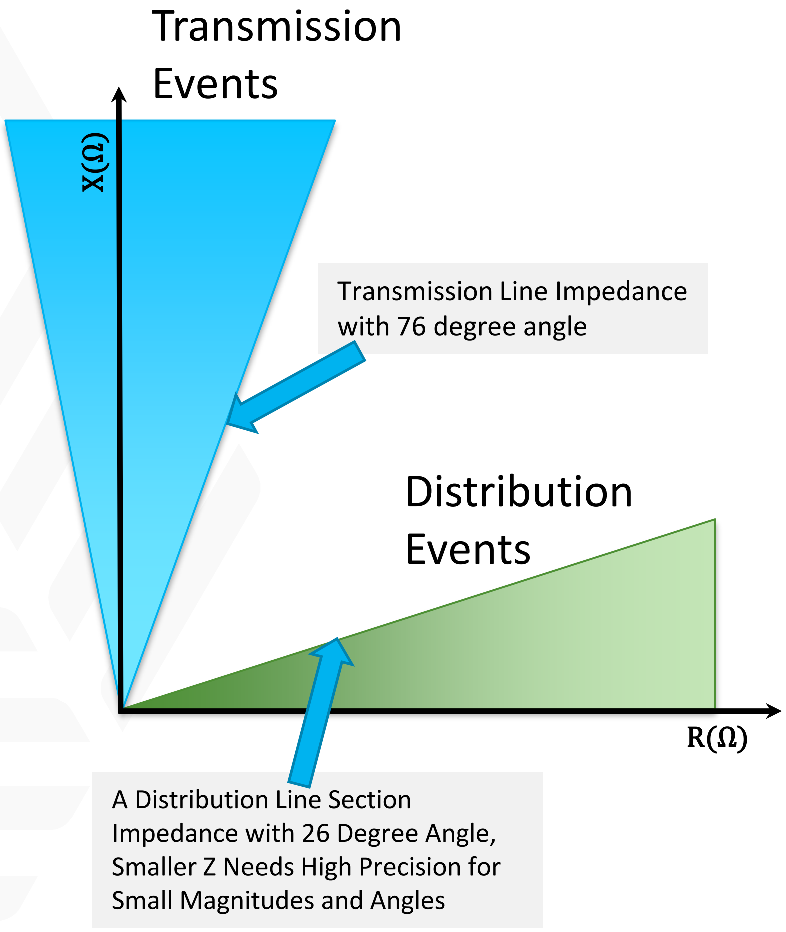
The TSN architecture will rely on multiple VCs/VLANs to differentiate the measurements/control traffic in consort with the TSN network manager.



Step Distance Protection

- Impedance based fault localization and protection
  - Currently used only in transmission systems
  - Allows bi-directional power flow
- Approach
  - Use high resolution isolated optical current and voltage sensors to test step distance protection for distribution
  - Develop and test hardware in the loop distribution step distance protection relays
  - Test using standard Doble test sets





Southeast Regional Workshop

March 22nd-23rd, 2017

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U.S. Department of Energy

- Held at the Zucker Family Graduate Education Center in North Charleston
- Organizations that attended:

DOE OE ISER, DOE SR, Duke Energy, Santee Cooper
SCE&G, Southern Company, Electric Power Board
EPRI, General Electric, Resilient Power Systems
Clemson University, UNC Charlotte, NC State, ORNL
SRNL, PNNL

- ORNL and SRNL had presentations and posters associated with Southeast Projects
- Focus of the Workshop was on Grid Resiliency and Restoration
- SCE&G and Santee Cooper gave presentations on the impact and recovery of Hurricane Matthew
- Several areas of future collaboration between SRNL, ORNL, universities, and the SE utilities were discussed

Southeast Regional Consortium
Accomplishments to Date

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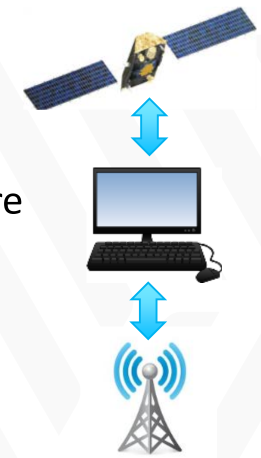
Dual-Channel Terrestrial and Satellite Wireless



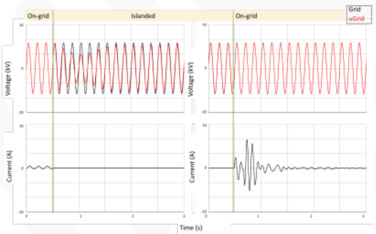
- Detect fault locations with Advanced Metering infrastructure
  - Using information coming from SRNL hardware and simulated outages
- Schedule first responders due to fault location and priority

Time Sensitive Networking

- Deployed TSN network on EPB fiberoptic network
- Tested performance with extended grid state IoT sensors
- Showed no impact on SCADA traffic

CSEISMIC App Based Distributed Controls

- Developed HIL simulation and testbed for EPB microgrid
- Integrated CSEISMIC with device controllers
- Demonstrated seamless islanding and re-synch



Optical Step Distance Protection for Distribution

- Created a relay model for HIL testing
- Characterized sensor performance
- Integrated with Doble test sets for HIL testing

Southeast Regional Consortium

Key Project Milestones – Milestones dates need to be approved by DOE OE

Milestone (FY16-FY18)	Status	Due Date
Complete Design of Design of Wireless Sensor Network	Complete	9/30/2016
Hold Southeast Region Workshop	Complete	3/30/2017
Documentation of optimization for restoration of at least one distribution feeder	Complete	12/31/2016
Report detailing the development of the Geographic Information System with Duke Energy's Distribution Feeders	In Progress	5/31/2017
Complete Demonstration of Wireless Sensor Network at Duke Facility	In Progress	6/30/2017
Report detailing test results of time sensitive network hardware and protocols	Complete	3/30/2016
Document functional verification of CSEISMIC distributed controls	Complete	3/30/2016
Document design and testing of optical step-distance protection	Complete	3/30/2016
Finish integration of distributed controls on EPB site-specific infrastructure	Complete	12/31/2016

Southeast Regional Consortium

Next Steps and Future Plans

Time-Sensitive Networking

- Use TSN for EPB SCADA traffic
- Use TSN for IoT substation sensor data
- Test distributed controls over TSN network

Distribution Step Distance Protection

- Deploy optical sensors at EPB in parallel with existing relay CT's and VT's
- Compare speed and accuracy of step distance protection with existing relays
- Test fault localization accuracy using optical sensors
- Test optical sensors as phasor measurement units

CSEISMIC

- Deploy CSEISMIC on the physical EPB microgrid
- Test forecasting, optimization, and islanding/re-synching

Dual Channel Wireless/Restoration Optimization Algorithm Development

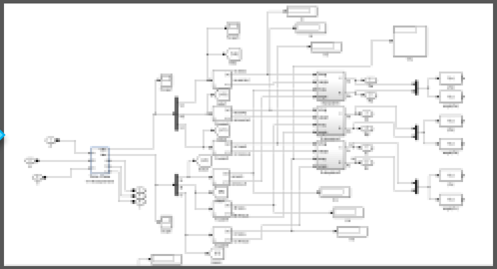
- SRNL, UNCC and Duke Energy will demonstrate the dual wireless sensor networks on various grid sensors at the UNCC Campus
- The Restoration Optimization Network will be demonstrated simulating power outages in the Southeast
- SRNL to compare performance of 24KV Smart Sense with ORNL low voltage sensor

BACKUP SLIDES

Step-Distance Protection with Optical Sensors

- Developed a software relay model (physics and relay logic)
  - Can't interface with existing analog hardware relay inputs
- Create a hardware in the loop test setup
- Using Doble test sets to simulate distribution faults
- Incorporated with the ORNL software defined low-voltage microgrid testbed

Relay Model

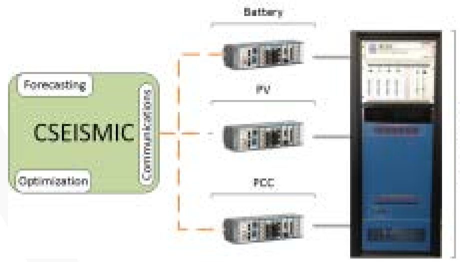


Doble Test Set

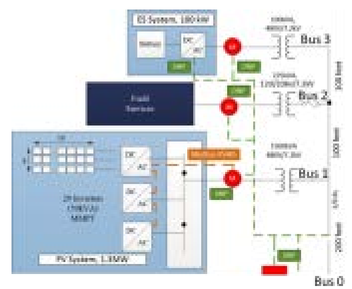
SI-Grid HIL Testbed

CSEISMIC

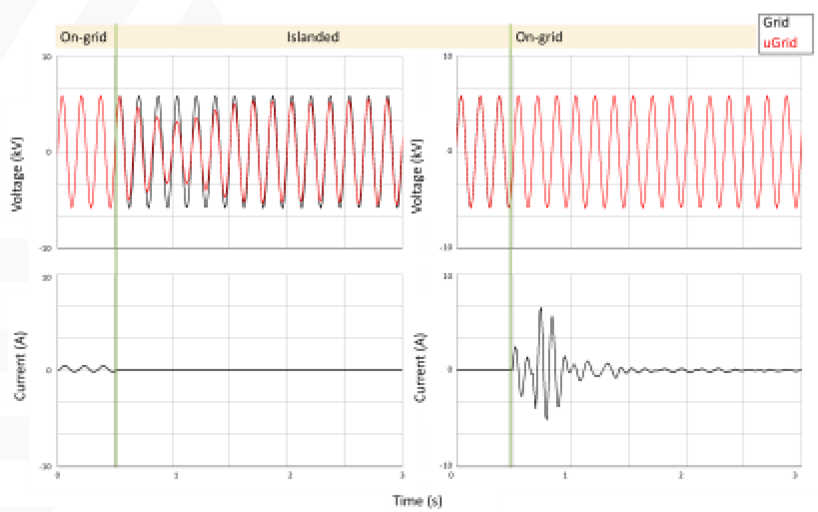
- Created a detailed model of the EPB Control Center, Flow Batteries, Solar Arrays, Inverters, Loads, and Busses
    - Power flow implemented in RTDS
    - Batteries, Solar, Inverters, Batteries, and Loads are implemented using FPGA’s
- Deployed the app based CSEISMIC distributed controller on the microgrid
- Tested controller functions
    - Demonstrated seamless islanding and re-synching
    - Demonstrated online battery management



Microgrid master controller consisting of an EMS and SCADA and IED controllers are implemented in hardware.



EPB Control Center Microgrid



Southeast Regional Consortium
Accomplishments to Date

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Time-Sensitive Networking

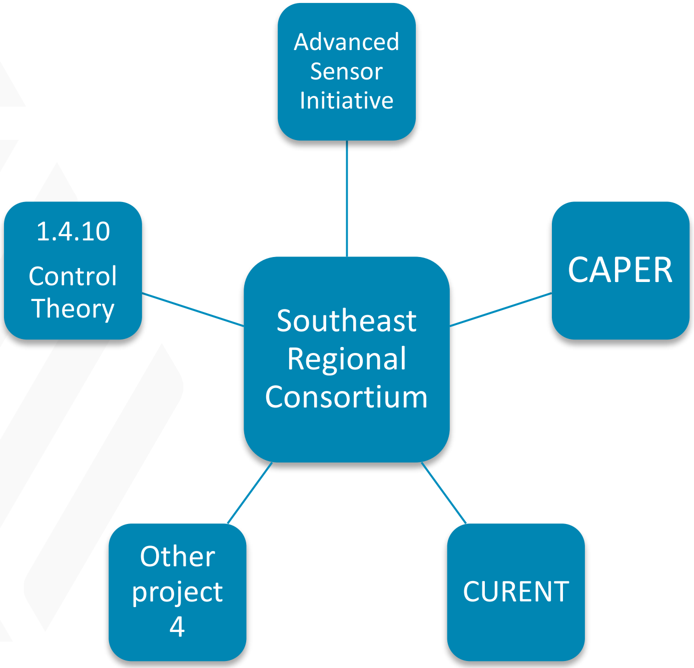
- Deployed a TSN network between two substations and the control center using the Chattanooga, TN Electric Power Board SCADA fiberoptic network.
- **Demonstrated no impact on existing SCADA network traffic**
- Using TSN network for extended grid state monitoring and remote drone operations

Southeast Regional Consortium

Project Integration and Collaboration

Describe how this project relates to other GMLC projects both Foundational and Program-Specific (From Project Negotiation Document)

The Southeast Regional Consortium presented our work at a regional workshop organized by the consortium to a group of 16 regional stakeholder.



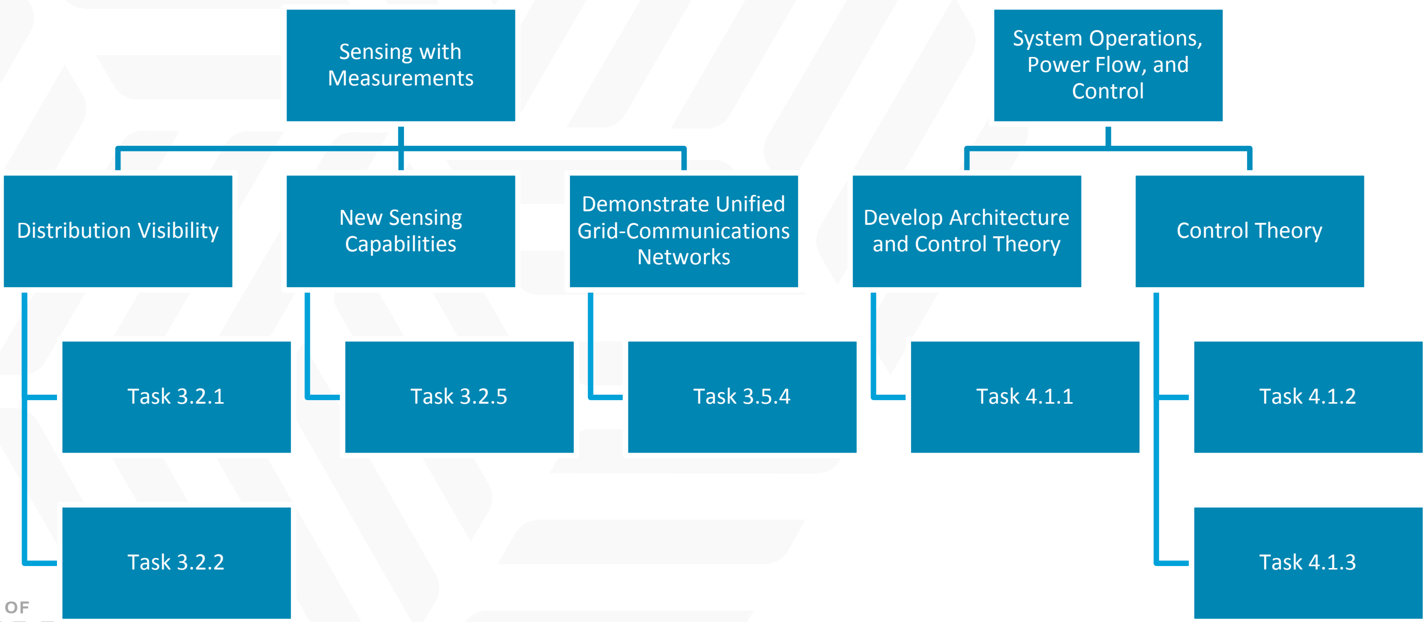
Southeast Regional Consortium

Relationship to Grid Modernization MYPP

This regional consortium is designed to facilitate the flow of information and technology between regional stakeholders to:

- Increase TRL levels of laboratory technologies from 3-4 to 5-6
- Transition laboratory technologies to industry for demonstration, testing, and validation
- Develop collaborative research project to address specific stakeholder needs.

The laboratory demonstrations under this project support the following MYPP goals



Southeast Regional Consortium

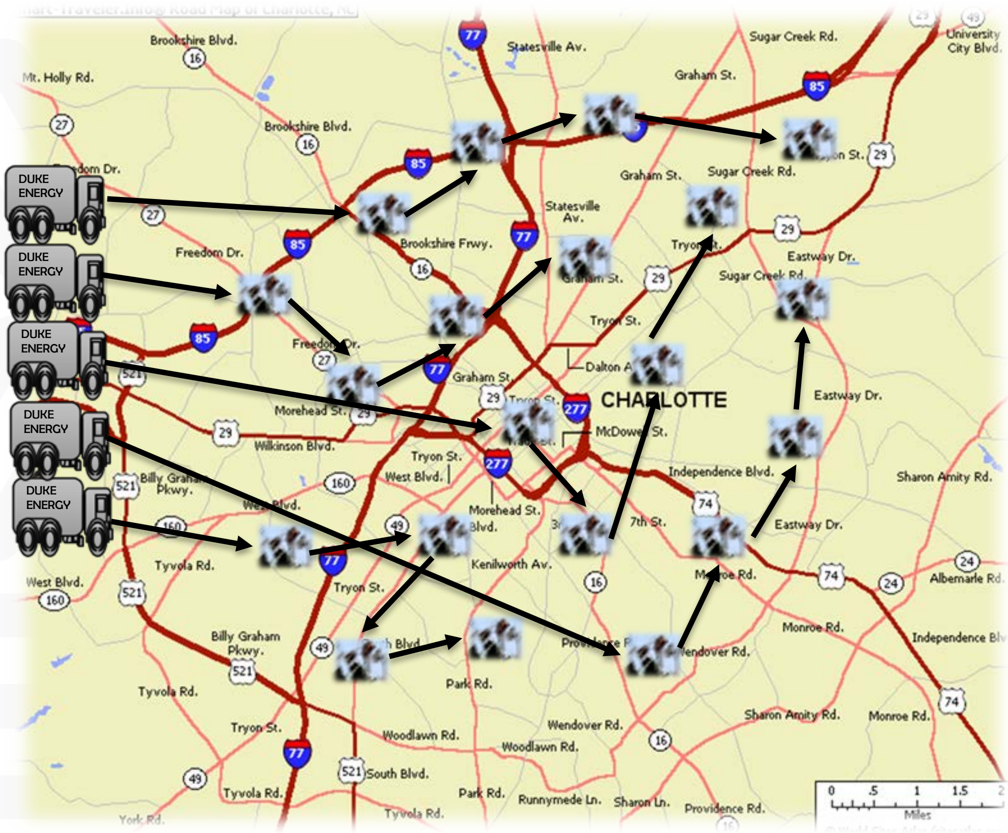
Response to December 2016 Program Review

Recommendation	Response
Reach out to other Category 1 Project to look for synergy	All Cat 1 PI were invited to the South East Workshop held in Charleston. Staff from PNNL, ORNL, and SRNL discuss areas of future collaboration

Restoration Optimization

GRID
MODERNIZATION INITIATIVE
U.S. Department of Energy

- Detect fault locations with Advanced Metering infrastructure
  - Using information coming from SRNL hardware and simulated outages
- Schedule first responders due to fault location and priority



GRID MODERNIZATION INITIATIVE PEER REVIEW

GMLC 1.3.09 – SMART RECONFIGURATION OF IDAHO FALLS POWER DISTRIBUTION NETWORK FOR ENHANCED QUALITY OF SERVICE

ROB O. HOVSAPIAN (INL), JAMES D. FOLLUM (PNNL)

April 18-20, 2017

Sheraton Pentagon City – Arlington, VA

Smart Reconfiguration of Idaho Falls Power Distribution Network

High Level Summary

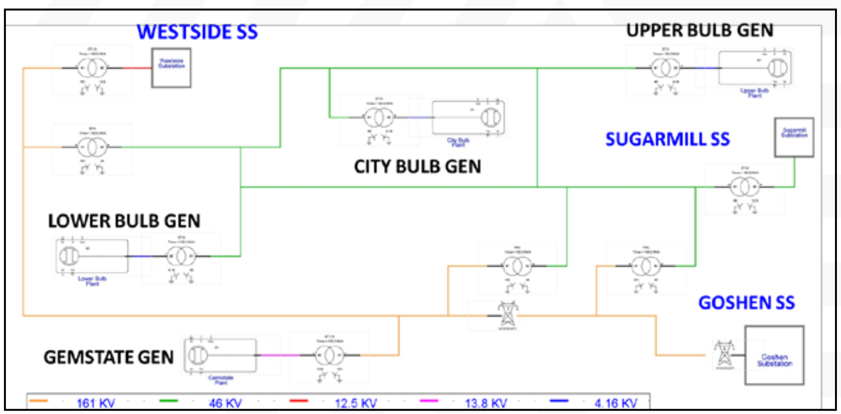
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Develop and demonstrate methods for keeping as much of the Idaho Falls Power system operating as possible during system events at transmission or distribution level

Value Proposition

- ✓ Maintaining supply to **critical loads** during loss of generation due to faults/events
- ✓ Improved **reliability** and **resiliency** in IFP grid



Project Objectives

- ✓ Develop methods for keeping as much of the system operating as possible during system events at transmission or distribution level by using functionalities such as **smart reconfiguration**, controlled and seamless **islanding**, **intelligent demand response** utilizing loads as a resource, **black start** for emergency , and **resynchronization** in presence of DERs
- ✓ Provide a **generalized roadmap**, including **best practices**, based on **regional case for IFP**, which utilities and system operators across the United States can apply to their respective distribution networks
- ✓ Show effectiveness of implemented **smart reconfiguration** by comparison with existing power system

Smart Reconfiguration of Idaho Falls Power Distribution Network

Project Team

Project Participants and Roles

INL – Lead lab, Real-time dynamic modeling, HIL testing, reconfiguration and protection schemes

PNNL – Partner lab, PMU data sets for validation, assist for reconfiguration algorithms

WSU – University partner for modeling and reconfiguration algorithm development

PROJECT FUNDING			
Lab	FY16 $	FY17$	FY18 $
INL	$600K	$150K	-
PNNL	$170K	$80K	-

IFP – Information and data for IFP grid

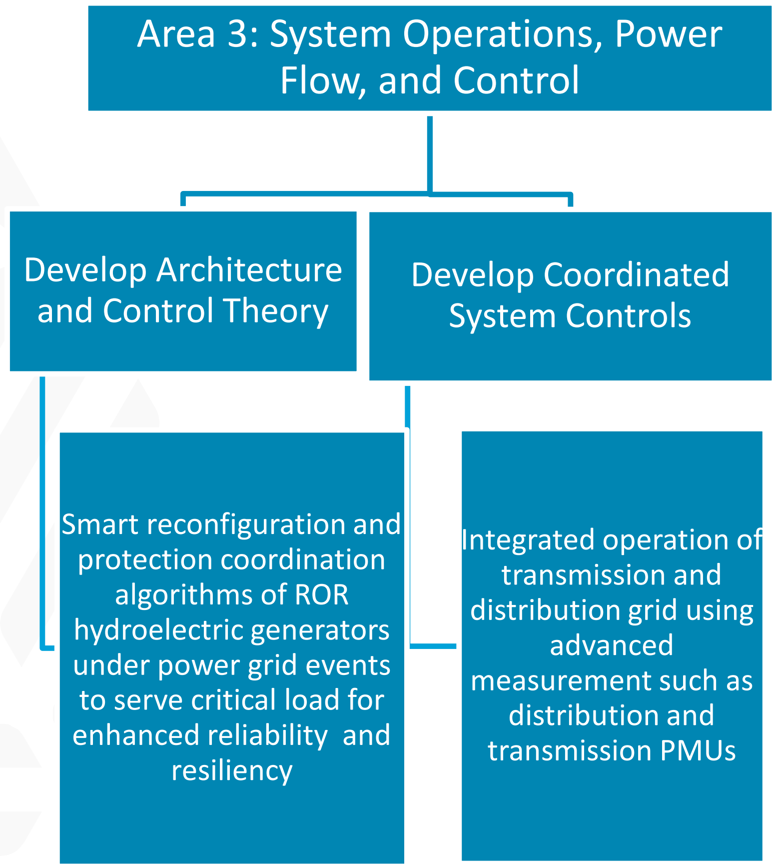
SEL – OEM, hardware requirement for reconfiguration, smart islanding, resynchronization, and protection

Smart Reconfiguration of Idaho Falls Power Distribution Network

Relationship to Grid Modernization MYPP

This project will contribute to the following 2025 goals of the Grid Modernization Multi-year Program Plan:

- ✓ **10% reduction in the economic costs of power outages** – by increasing availability, quality, and reliability of power through implementation of smart islanding and smart reconfiguration schemes
- ✓ **33% decrease in the cost of reserve margins while maintaining reliability** – by accelerating the de-risked integration of renewables and DERs through comprehensive integrated HIL testing in real time environment
- ✓ **50% decrease in the net integration costs of DERs** – through information dissemination for implementation of advanced measurement-based reconfiguration schemes in the distribution grid



Smart Reconfiguration of Idaho Falls Power Distribution Network

Approach

- ▶ Development of digital blueprint of IFP grid and baseline
  - Real-time dynamic modeling using Real Time Digital Simulator (RTDS®) to simulate power system in 50µs time steps
  - Use of historical outage/reliability data in IFP grid
- ▶ Modeling and validation and equivalent transmission interconnections
  - Simulations in other tools such as GRIDLAB-D, PSLF etc.
  - Validation process using realistic data from PMUs and simulations
- ▶ Identifying optimal location for smart switches, PMUs, and DERs
  - Information obtained and optimal locations for distribution PMUs is under progress using simulations
- ▶ Development of reconfiguration schemes
  - First-cut of reconfiguration code developed and including dynamic/transient effects in-progress

Smart Reconfiguration of Idaho Falls Power Distribution Network

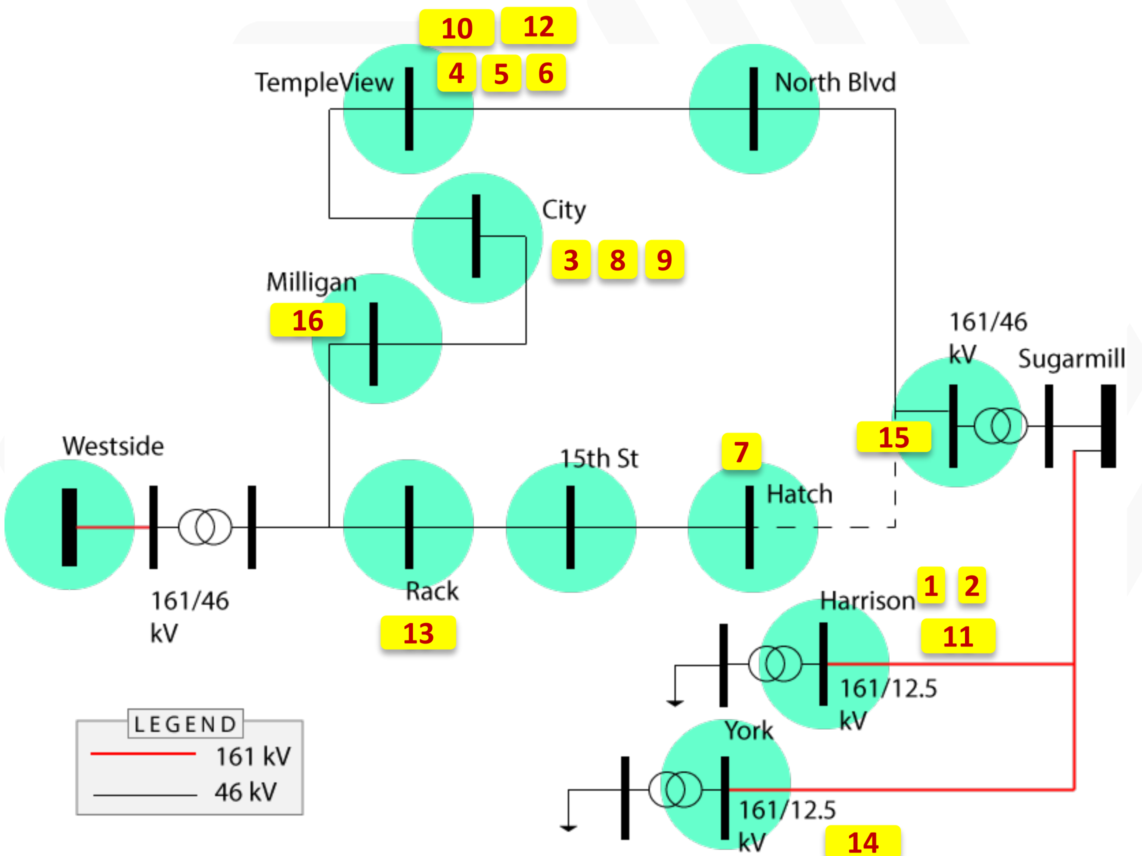
Approach

- ▶ Development and testing of new protection schemes
  - Locations and SEL protection devices identified for RT-HIL simulation and testing
  - Controller specification development is under progress with help from SEL
  - Six protection relays and one controller hardware are proposed to be tested using co-simulation of the communication layer and RTDS
- ▶ Due to non-availability of actual PMU data for events, synthetic PMU data is being generated by PNNL for realistic cases of faults/events
  - PSLF simulations of a WECC planning model are used to generate synthetic data
  - PMU data from distant substations will be used for validation if it can be obtained
- ▶ The event data will be imposed in RTDS for system response, along with protection HIL and controller testing
  - Replay synthetic simulation data at high rate in RTDS for validation and controls development
  - Playback of historical event data for scenario/disturbance simulations

Smart Reconfiguration of Idaho Falls Power Distribution Network

Approach

Critical Loads as identified by IFP grid



Priority	Description
1 – 4	**Very High Priority Loads** (*Examples*: Hospitals, Control/Command center, Emergency Response/Dispatch)
5 – 9	**High Priority Loads** (*Examples*: Airport, Correctional Facilities, Police Department, Fire Station)
10 – 12	**Medium Priority Loads** (*Examples*: Fire Station, State Services)
13 – 16	**Low Priority Loads** (*Examples*: Water Treatment, Community Care)

Smart Reconfiguration of Idaho Falls Power Distribution Network

Key Project Milestones

Milestone (FY16-FY18)	Status	Due Date
Data collection required for modeling from Idaho Falls Power and modeling the **IFP grid and equivalent transmission interconnections.** Establish and capture the current baseline performance of IFP using known reliability metrics	IFP reduced-order system modeling is completed in RTDS. Reconfiguration algorithm development is in progress. HIL testing of one segment of IFP grid done and performance evaluated over baseline to show improvement.	PY1, Q1 **Project Start Date: 07/01/2016**
Validation of the IFP grid and equivalent transmission interconnections. **Information and data for optimal location of switches, PMUs, DERs** will be obtained.	PMU dataset are synthesized for validation process and T-grid equivalents developed. Information and data for location of existing switches, PMUs, and DERs obtained.	PY1, Q2

Smart Reconfiguration of Idaho Falls Power Distribution Network

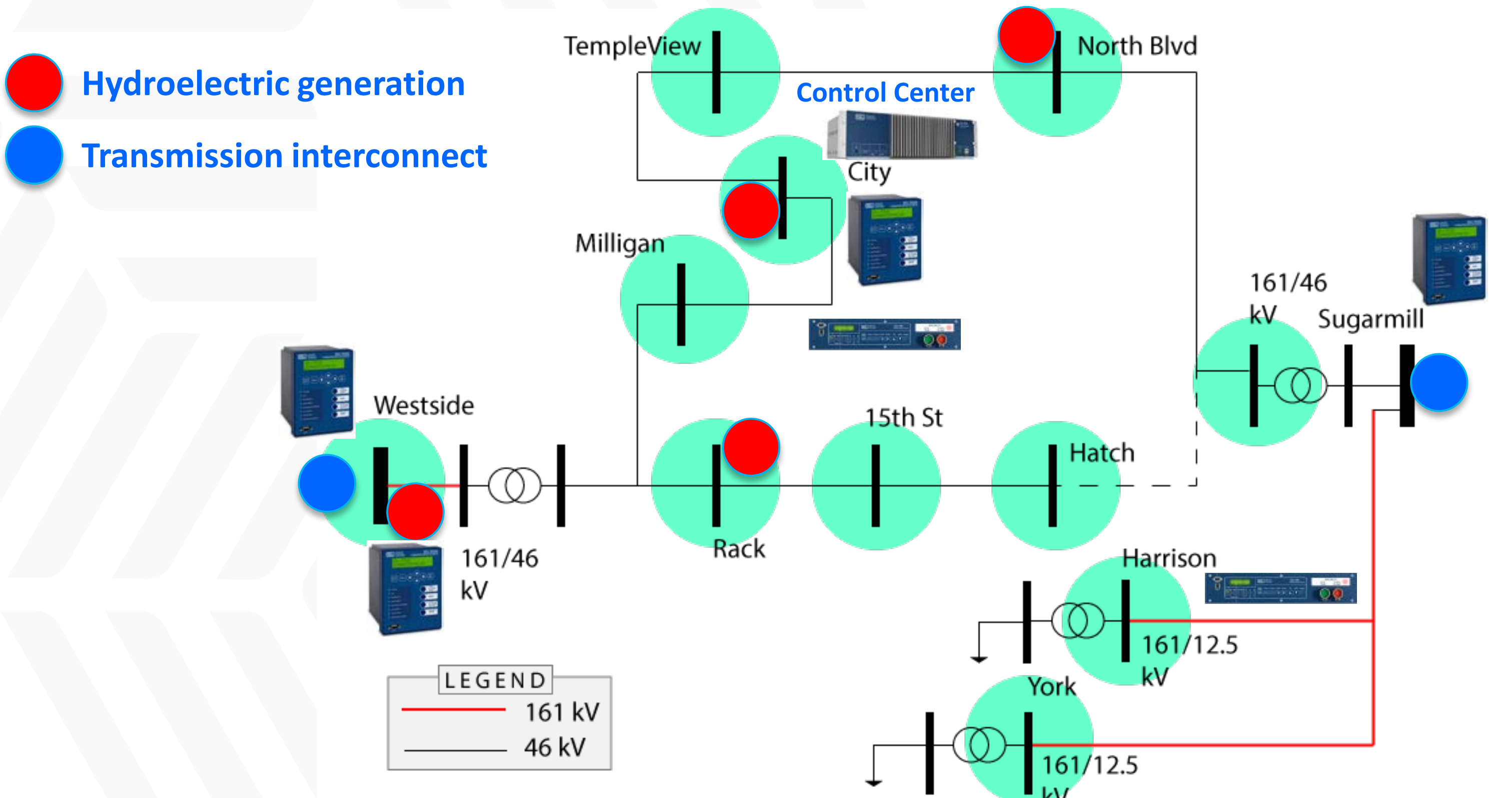
Key Project Milestones

Milestone (FY16-FY18)	Status	Due Date
Identification of optimal locations for switches, PMUs, and DERs will be completed.	Algorithm developed for observability-based approach for identifying optimal location of distribution PMUs.	PY1, Q3
Future Quarter		
Development and software simulation of **reconfiguration and protection schemes** will be completed. **Comparison with existing baseline** performance data using SAIDI, SAIFI indices.	A first version of reconfiguration algorithm was developed. Inclusion of dynamics during reconfiguration is in progress. Other tasks not started.	PY1, Q4

Smart Reconfiguration of Idaho Falls Power Distribution Network

Accomplishments to Date

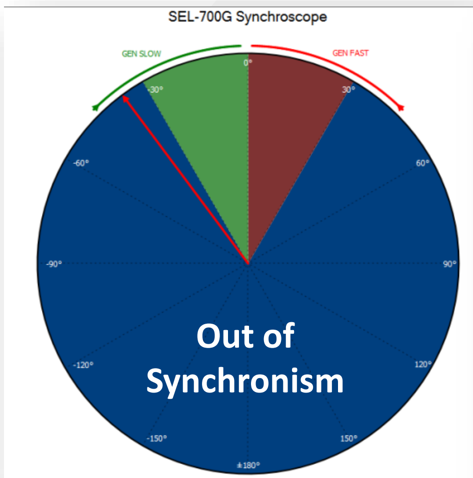
- Hardware device requirement provided to SEL – six relays (similar to 700G, 351S etc.) and one controller are proposed to be tested as HIL
- NDA with IFP for hydroelectric generator data

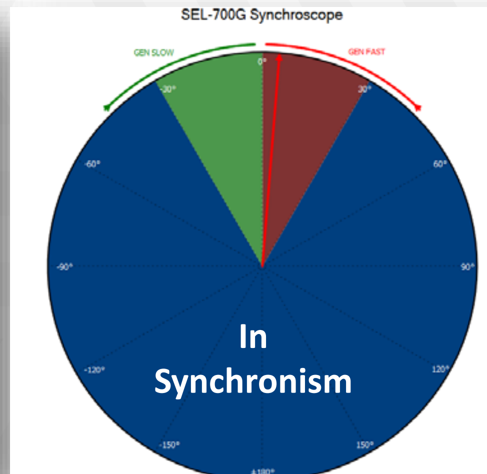


Smart Reconfiguration of Idaho Falls Power Distribution Network

Accomplishments to Date

- **Black Start of IFP grid** and re-synchronization to transmission grid
- One scenario is investigated to test synchronization of City Bulb generator to a T-grid source while City Gen is serving the local command center critical loads



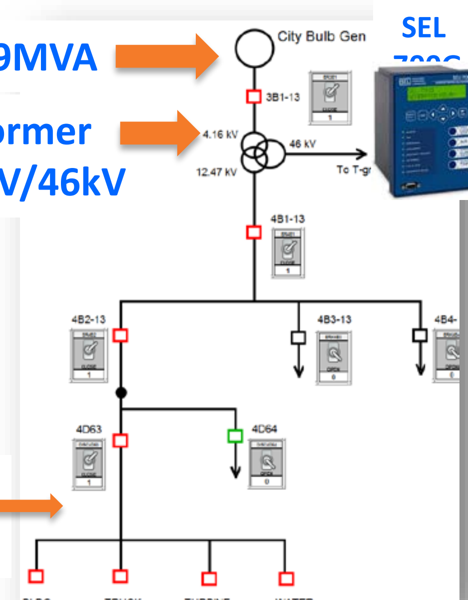


City Bulb: 8.9MVA

Station Transformer 4.16kV/12.47kV/46kV

T-grid kept at 46kV, 60Hz, 20degrees

Total load ~ 874 kW

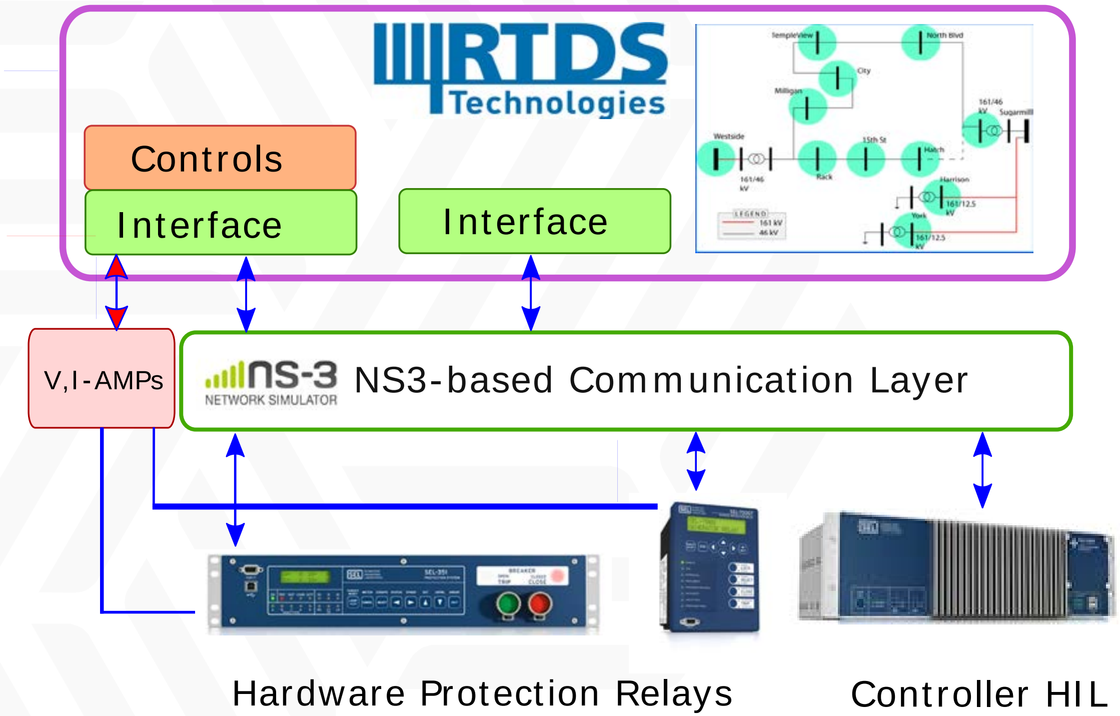


- Synchronization controls are modeled in RTDS-RSCAD for seamless resynchronization
- SEL 700GT+ Relay is used as Hardware-in-the-Loop (HIL) simulation with analog and digital interfacing with RTDS

Smart Reconfiguration of Idaho Falls Power Distribution Network

Accomplishments to Date

- NS3-based communication layer is emulated for co-simulation of power systems and control/communication network between hardware devices

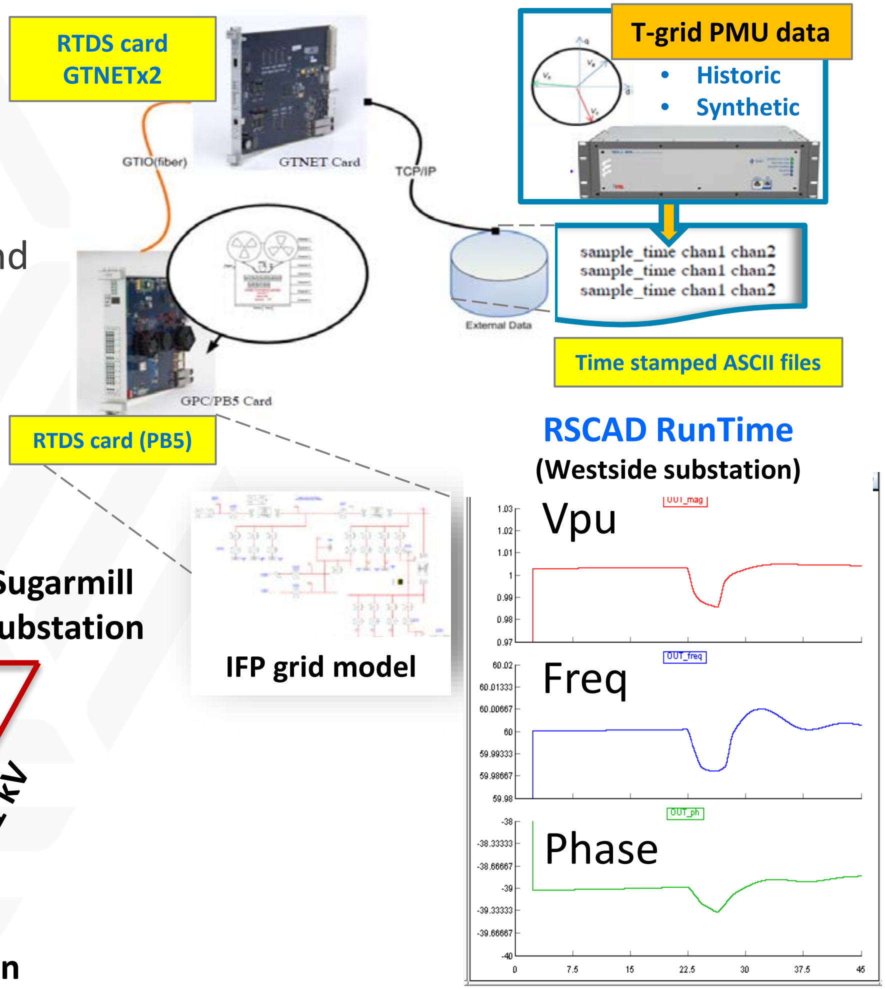


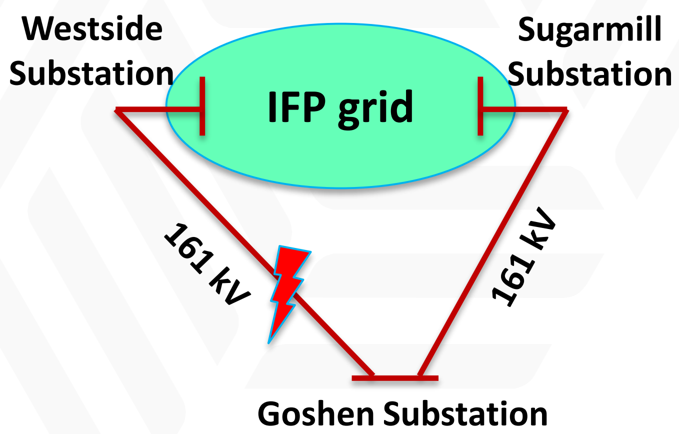
Smart Reconfiguration of Idaho Falls Power Distribution Network

Accomplishments to Date

- One of the challenges has been gathering PMU data for historical events for IFP grid
- Representative realistic cases are being synthesized in PSLF to overcome this issue
  - Phasor data for line outage and line-to-ground fault have been simulated
  - Known events will be reconstructed using sequence-of-events information
- Modeling transmission-grid equivalents is underway

IFP grid model validation using realistic PMU data

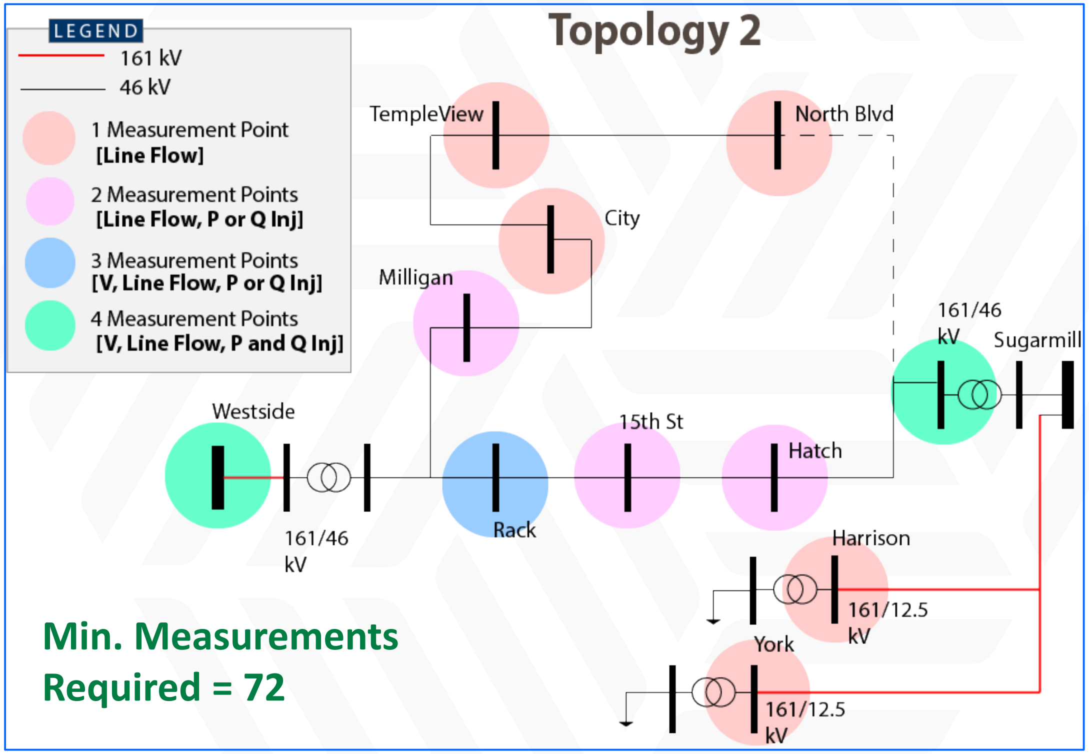




Smart Reconfiguration of Idaho Falls Power Distribution Network

Accomplishments to Date

- A first version of algorithm for placement of distribution PMUs in IFP grid is coded
- More work will be done to include HIL with critical loads, and communication between devices in the next quarter



Distribution PMU

- Provide fast, time-synchronized measurements
- **Reconfiguration, islanding,** planning, modeling, voltage monitoring, FIDVR analysis
- High-speed phase angle measurements allow system changes to be automated
- Relatively inexpensive and easy to install

Smart Reconfiguration of Idaho Falls Power Distribution Network

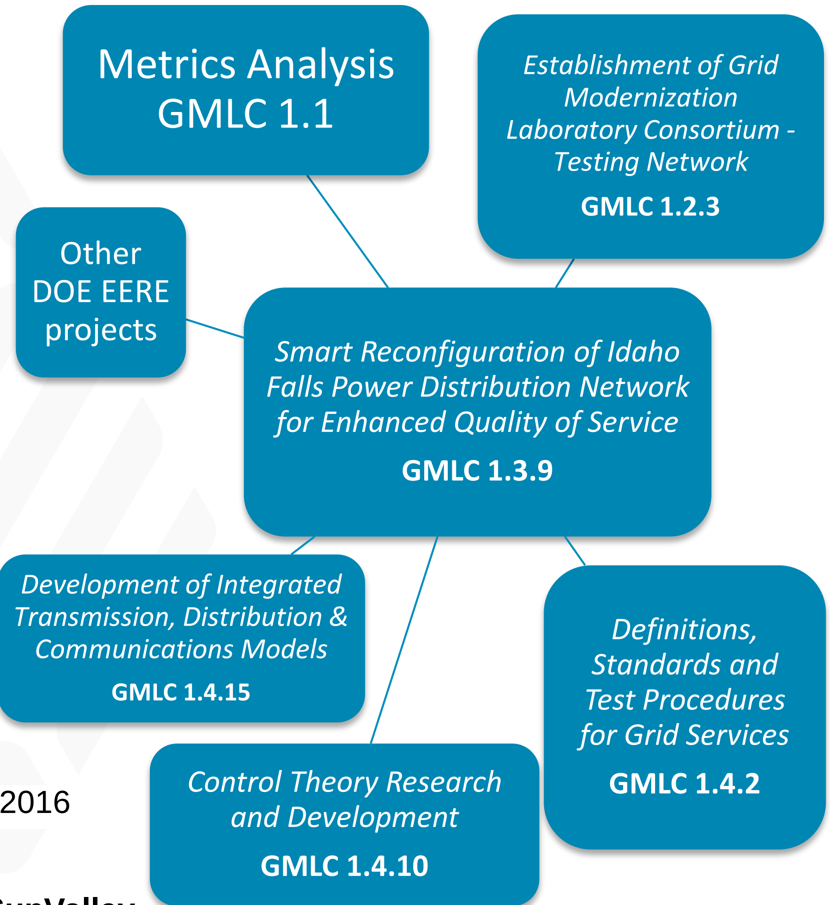
Response to December 2016 Program Review

Recommendation	Response
Please make sure to work closely with the Metrics Analysis team (1.1) as you develop a baseline for reliability and resilience at Idaho Falls	A teleconference call was done in February 2017 with participation from NREL, and ANL. A good productive conversation resulted in identifying the interdependencies and relationships between projects, and potential research areas closely associated with GMLC 1.3.9. Synergistic activities will be started from June/July 2017. Follow-up meetings will be held to define the scope and deliverables.

Smart Reconfiguration of Idaho Falls Power Distribution Network

Project Integration and Collaboration

Related Project	Coordination
GMLC 1.1	Evaluation of Metrics for Reliability, Resiliency, Security Availability, Flexibility against the baseline
GMLC 1.2.3	Contribute to development of power system protection and restoration testing models (non-proprietary) and resources
GMLC 1.4.2	Provide results from device testing activities, especially for H_2refueling stations in IFP grid operation
GMLC 1.4.10	Provide results from device testing activities HIL from SEL, and outcomes of testing in IFP grid
GMLC 1.4.15	Integrated operation of Transmission, Distribution and Communication – reconfiguration, protection coordination, and resynchronization in IFP grid
Other DOE EERE projects (FCTO, WPTO)	FCTO – Support in IFP grid for stability using H_2 refueling stations WPTO – Islanded operation, and resynchronization with Run-of-the-River (ROR) hydroelectric power generation in IFP grid



Communications:

- ✓ Project status presented as part of INL Internal Review in October 2016
- ✓ Go/No-Go decision review in December 2016
- ✓ Interest in similar projects from utilities: **Idaho Power Company**, **SunValley Institute,** Blaine County, ID, and **Richland Energy Services**, WA

Smart Reconfiguration of Idaho Falls Power Distribution Network

Next Steps and Future Plans

- **Dynamic validation of IFP grid** will be completed using **realistic PMU data** for events at transmission interconnections
- Implementation of **reconfiguration** scheme will be done in software with dynamics included and with HIL for IFP grid
- Integrated HIL for advanced measurement-based **reconfiguration** and **protection** system, **hardware controller** implementation and testing of **smart islanding**, **resynchronization**, and **black startup** algorithms
- Viability of **H_2 electrolyzers** for ancillary services in IFP grid under various scenarios
- **Expanding** the modeling and testing **results** to provide a **generalized roadmap**, including **best practices** from regional IFP grid to a similar utility grid with distribution PMUs

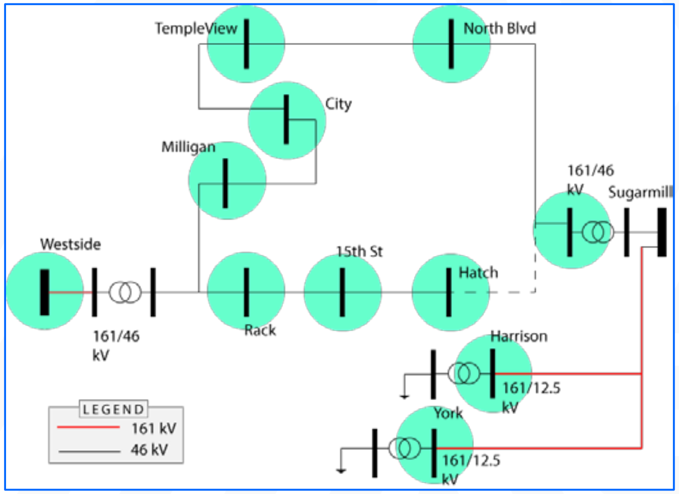
Image source: https://www.idahofallsidaho.gov/223/Idaho-Falls-Power

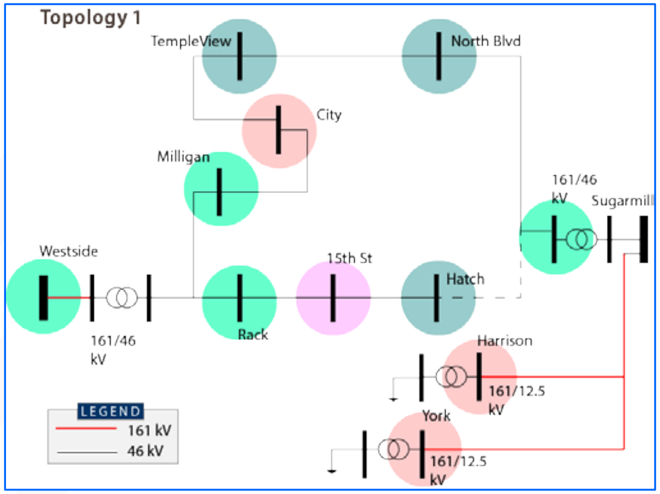
Thank You

Smart Reconfiguration of Idaho Falls Power Distribution Network

Technical Details

- Placement of distribution PMUs in IFP grid
- At each substation: Demand P, Demand Q, Generation P, Generation Q, Current, Voltage Magnitude (p.u.) [11 Buses, 8 Nodes. 19 x 6 = 114 measurements]
- For each line: P Flow, Q Flow [12 Lines, 2 x 12 = 24 Measurements]





Topology	Total Measurements	Min. Measurements Required	V_max	V_min
(1) Sugarmill-North Blvd (CLOSED)	138	84	1.0293	0.9742
(2) Sugarmill-Hatch (CLOSED)	138	72	1.0398	0.9695

GRID MODERNIZATION INITIATIVE PEER REVIEW

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

ROBERT BRODERICK (SNL)
MARK RUTH (NREL)

April 18-20, 2017

Sheraton Pentagon City – Arlington, VA

1.3.10 Vermont FEEDER project

High Level Summary

Project Description

Develop an optimal and replicable approach to DER integration at the distribution level to meet the state's goal of 90% renewable energy penetration by 2050.

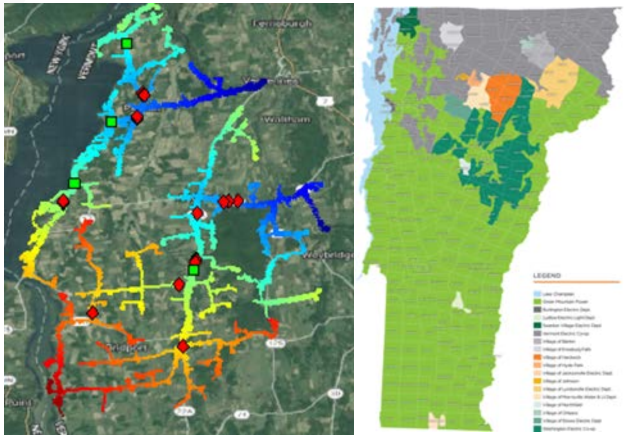
Value Proposition:

- *The VT FEEDER team—in partnership with VT's electric utilities—is developing an innovative and replicable approach to distribution-level DER integration.*
- *This multi-pronged approach combines optimal placement of DER within a distribution network with advanced control systems and high-resolution weather forecasting to enable the efficient harnessing of intermittent generation.*

Project Objectives

- ✓ Facilitate and optimize the integration of DER
  - ✓ New and optimized integration methods
  - ✓ Effective controls
  - ✓ Forecast evaluation
- ✓ Partner with multiple institutions in VT, a state ahead of the curve on grid-modernization

DER Integration in Vermont



1.3.10 Vermont FEEDER project

Project Team

Partners and Roles

Sandia National Laboratories	**Lead and PI for Tasks 1-3**
NREL NATIONAL RENEWABLE ENERGY LABORATORY	CO PI on Tasks 2 & 3
The University of Vermont; Georgia Tech	Modeling and optimizing DER integration (Task 1)
Green Mountain Power; Vermont Electric Co-op Inc; Vermont Electric Power Company VELCO	Utility Partners: data & DER challenges

Utility partners GMP, VEC, VELCO have provided <u>massive amount of data</u> and have provided direct feedback to guide our research.

PROJECT FUNDING		
Lab	FY16	FY17
SNL	$250K	$500K
NREL	$85K	$165K

1.3.10 Vermont FEEDER project

Relationship to Grid Modernization MYPP

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MODERNIZATION INITIATIVE
U.S. Department of Energy

This project's aligns with the Grid Modernization Multi-Year Program Plan (MYPP) to achieve an outcome of a "50% cut in the costs of wind and solar and other distributed generation (DG) integration" and to achieve "resilient distribution feeders with high percentages of low-carbon distributed energy resources."

Devices and Integrated Systems Testing

Activity: Energy Storage Systems

Task 2.1.3

System Operations and Power Flow

MYPP Activity 1&2

Task 4.3.1

Design and Planning Tools

Activity 2: Developing and Adapting Tools for Improving Reliability and Resilience

Task 5.2.6

Devices and Integrated Systems (MYPP Activity 1) – Our work will demonstrate the ability of ES to improve system reliability and provide improved benefit-cost ratio through valuable grid services, thus enabling higher penetration of other DER.

System Operations and Power Flow (MYPP Activity 1&2 and MYPP Task 4.3.1) – Develop and demonstrate advanced control-technologies for load management and ES systems in order to support high DER penetration.

Analysis and validation of high-resolution solar forecasting will enable predictive generation control and reduce the uncertainty associated with controlling for intermittent resources.

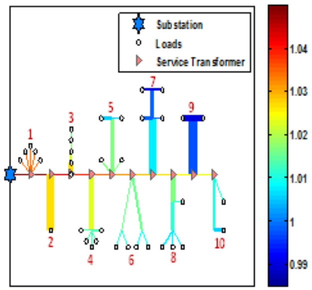
Design and Planning Tools (MYPP Task 5.2.6) –Develop algorithms and public-domain tools using big data (AMI) for model development and validation.

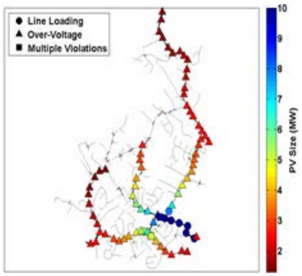
We will develop modeling tools for improving feeder performance and reliability when siting high DER penetrations.

1.3.10 Vermont FEEDER project
Approach

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

The overall objective of the FEEDER project is to develop an optimal and replicable approach to DER integration at the distribution level, utilizing the state of Vermont as a testbed.
In partnership with Vermont's largest distribution utilities, we have identified three task areas to promote a renewables-intensive 21st century grid:





DER Integration Modeling and optimizing:

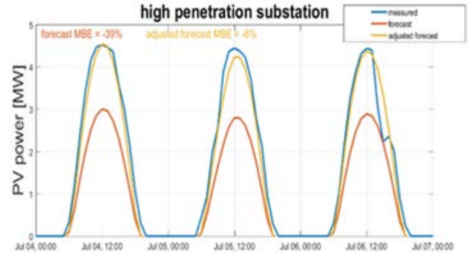
I. Create new accurate secondary system distribution models with AMI data and new, <u>innovative</u> parameter estimation methods that are not used today by utilities.
II. Determine the optimal amount and placement of DER (PV and storage) on distribution feeder using a <u>unique</u> advanced location specific hosting capacity analysis.
III. Determine the best energy storage amount and placement on the distribution system using <u>new</u> optimization methods.

DER Control Modeling and optimizing:

- Develop and validate new control strategies for managing DR rebound effects.

DER Forecasting:

- Improve the forecasting of solar and wind to enable more accurate and higher resolution generation prediction to reduce the uncertainty associated with controlling for intermittent resources.



1.3.10 Vermont FEEDER project
Key Project Milestones

Milestone Name/Description	Status	Due Date
Task 1 – DER integration Put in place all agreements needed to receive feeder data, AMI data and controller data from partners **Task 2– DER control** Complete the design of communications interfaces to ES and PV systems in the Spirae Wave™ controller for DR rebound effects. **Task 3– Validation and Improvement of Forecasting Engine.** Assemble and qualify existing data for comparison with weather, power and load forecasts. Quantify forecast performance using operationally relevant metrics and identify where additional data can significantly enhance forecast evaluation.	Complete. Complete. Complete.	**Sept 30, 2016**
Task 1 – DER integration Received at least two feeder models, AMI data and controller data. Begin conversion and data cleaning. Data integrated into models for running analysis and visualization **Task 2– DER control** Formulate network model and develop preliminary optimization algorithms. Grid LAB-D models, populated with residential ES system models, running in IESM. Update algorithms after analysis and simulation. Ability to control residential ES systems from aggregator module within IESM demonstrated.	Complete. Complete.	**March 30, 2017**

1.3.10 Vermont FEEDER project

Key Project Milestones

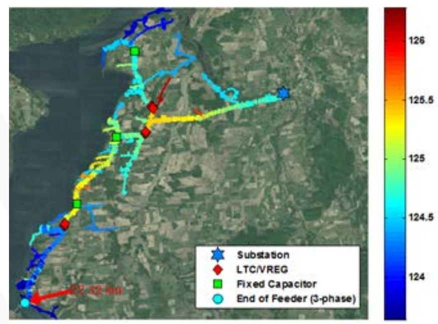
Milestone Name/Description	Status	Due Date
Task 1 – DER integration Detailed results and graphics of locational impacts and benefits of ES and PV. The locational PV hosting capacity analysis will be done on 7 feeders, parameter and topology estimation on 2 feeders, and optimal ES siting on 3 feeders **Task 2– DER control** Demonstrate algorithms on the Vermont system Update algorithms based on test results Scenarios selected and simulation of scenarios completed. Deliver report on simulation results **Task 3– DER forecast** Provide at least 3 areas for potential improvement of the VTWAC forecasts.	**In Process**	**Sept 30, 2017**

Other Key activities and industry involvement:

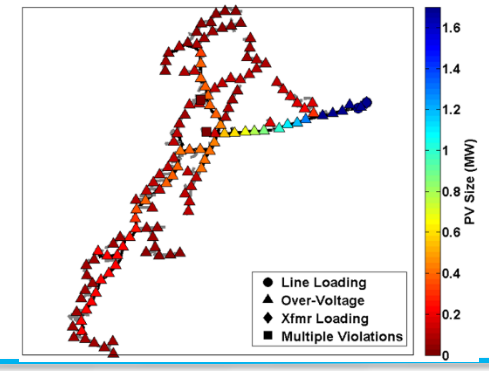
- Mid-Project status meeting with all Vermont partners on March 8th and March 9th, 2017
- Project kick off meeting with all Vermont partners on April 28th, 2016
- Bi-weekly coordination calls with stakeholder VELCO and monthly calls with GMP and VEC
- Upcoming papers and presentations at Photovoltaics Specialist Conference in June 2017:
  - ***"Targeted Evaluation of Utility-Scale and Distributed Solar Forecasting"***
  - ***"Full-Scale Demonstration of Distribution System Parameter Estimation to Improve Low-Voltage Circuit Models"***
  - ***"Demand Response of Electric Hot Water Heaters for Increased Integration of Solar PV"***

Task 1: DER Integration

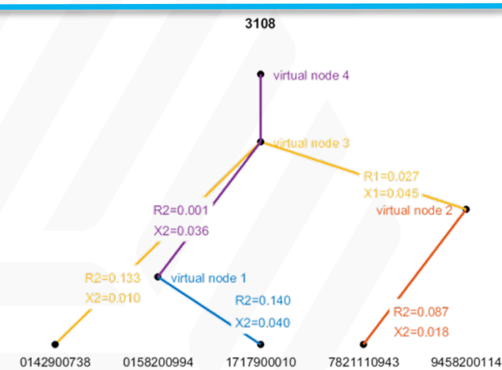
- ✓ 3 GMP feeders and 7 VEC distribution feeders have been received. GMP models have been converted and validated in OpenDSS using integrated data, and detailed location specific hosting capacity analysis has begun.

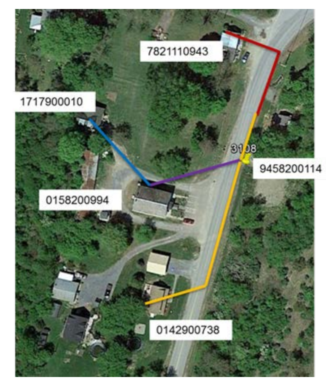


Feeder-9G2



- ✓ Parameter estimation on GMP feeder Panton – 9G2. Initial results at two transformers along Jersey Street show excellent estimation of the secondary system impedance which shows great promise to dramatically improve the accuracy of feeder models.





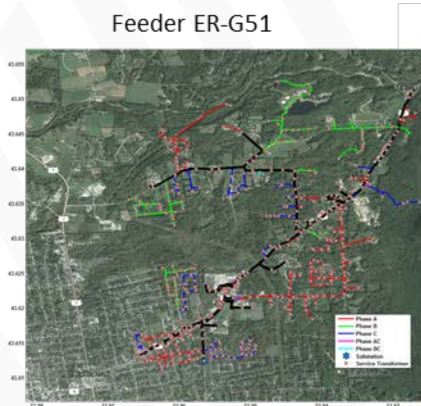
- ✓ Developed circuit reduction methods for energy storage optimization methodology to determine the optimal amounts and locations for new storage installations.

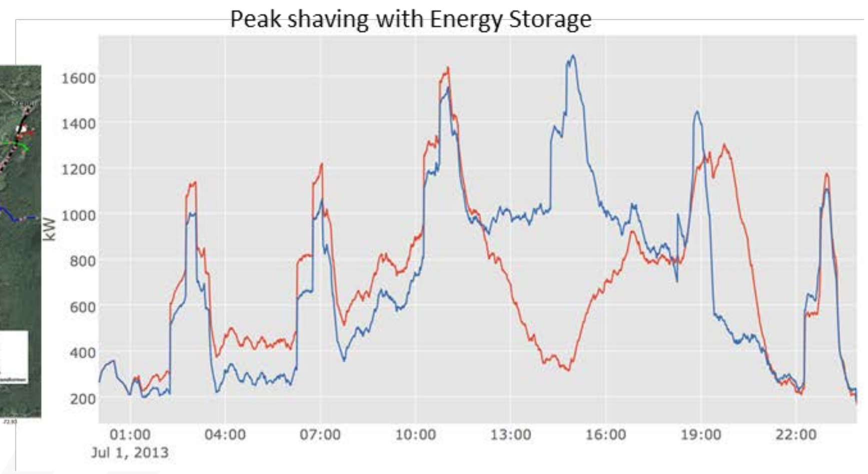
Circuit reduction results showing a reduced feeder model with ~10 representative nodes. Performed K-means clustering using electrical distances in combination with voltage data from QSTS model

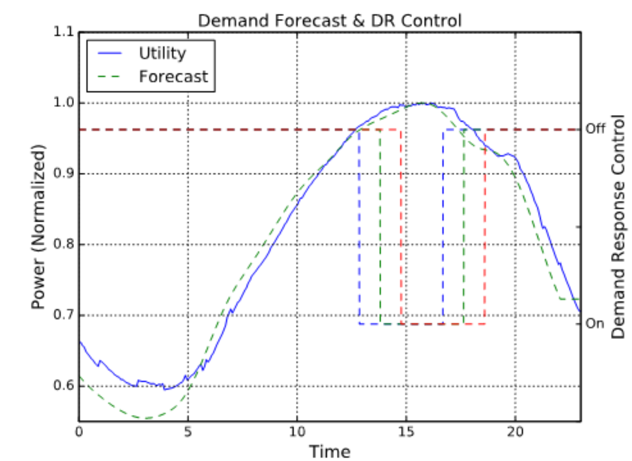
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

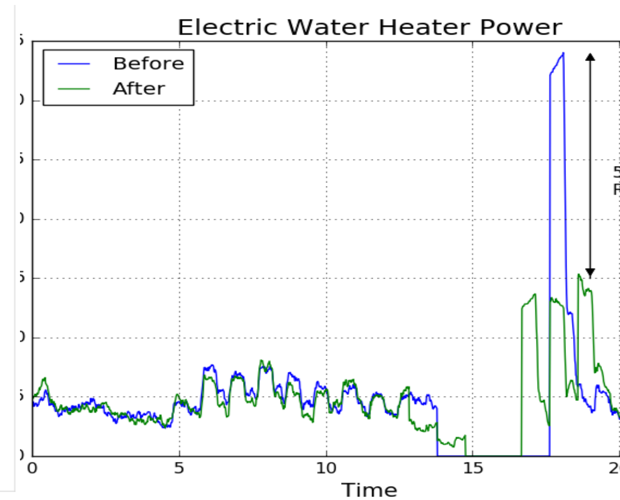
Task 2: DER control

- ✓ Converted Green Mountain Power feeder ER-G51 to GridLAB-D, populated with house models, and performed initial simulation runs with simple control strategies
- ✓ Grid LAB-D models, populated with residential ES system models, running in IESM.
- ✓ Developed multiple bin control approach that shaves water heater peak load while minimizing rebound
- ✓ This strategy was able to provide peak shaving at the time of the ISO peak and reduce the rebound by about 57% as shown





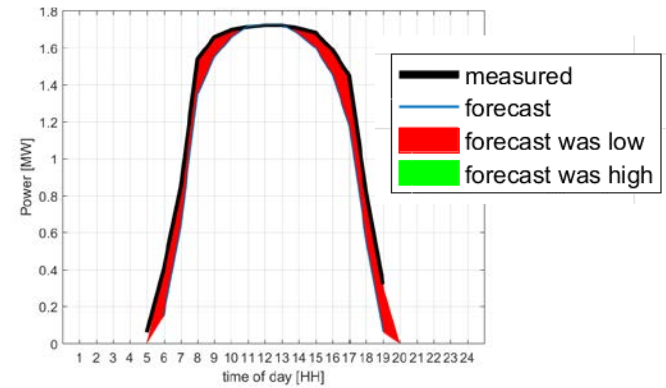




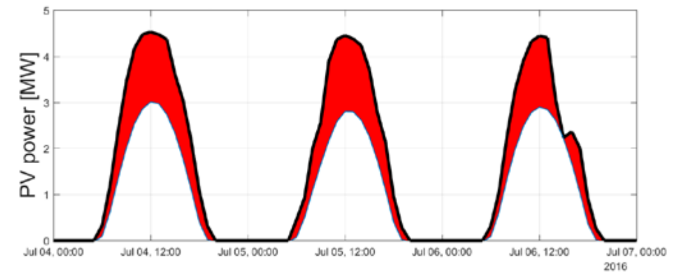
Task 3: Forecast Evaluation

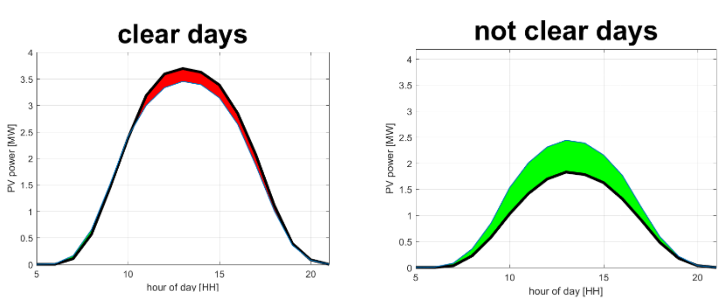
- Evaluated forecast data from:
  - 21 PV farms ~2MW each
  - 4 substation aggregates of distributed PV and load
  - Distributed PV for entire state of VT
  - 4 wind farms
- Directly presented results to VECLO, forecast provider, and distribution utilities
  - Feedback on important use cases has directed targeted evaluation
  - Suggested improvements to forecast methods directly conveyed to forecast provider
    - Account for azimuth of PV modules
    - Faster adjustments to changes in distributed PV capacity
    - Separate forecast training on clear vs. cloudy days

dual axis tracking not fully captured at PV farm



Added PV capacity makes substation forecast low





Forecast low on clear days, high on cloudy days

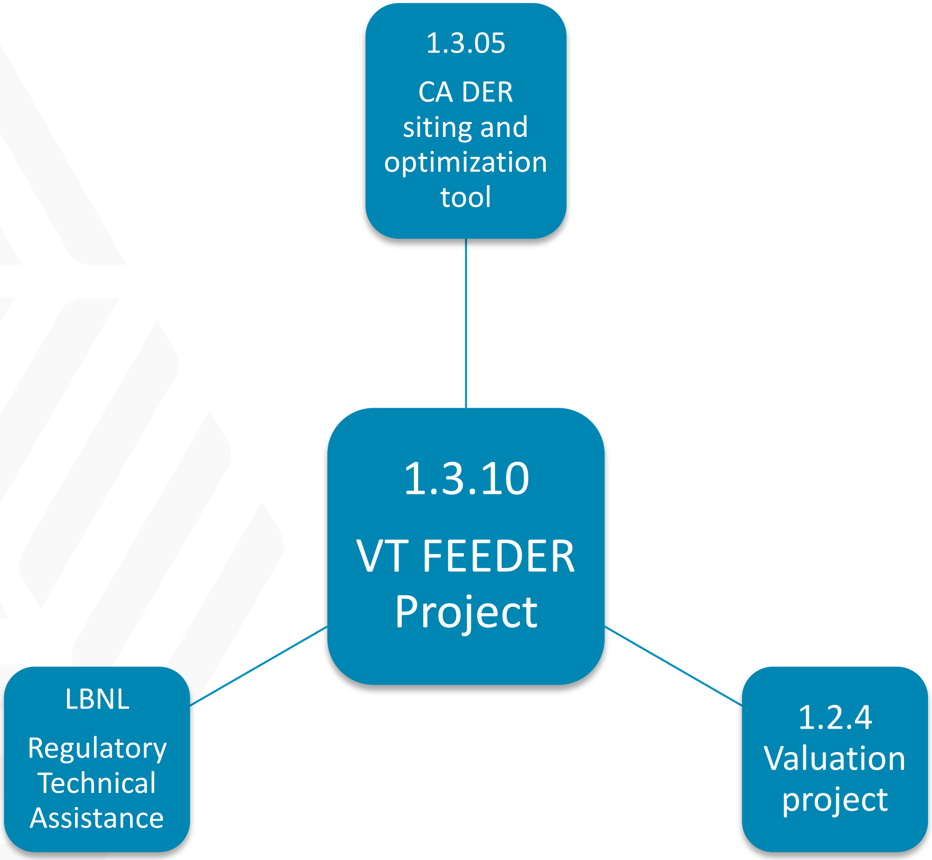
1.3.10 Vermont FEEDER project

Response to December 2016 Program Review

Recommendation	Response
While the optimization goals may be different, please work closely with the CA DER Regional Partnership (1.3.5) to make sure the approaches are similar where they need to be.	We are coordinating with John Grosh (LLNL) and Goncalo Cardoso (LBNL) focusing on areas where each project can complement the other for optimal integration and siting of DER on distribution feeders in their respective states.
Please coordinate with the valuation project as well 1.2.4.	Coordination is ongoing with Bobby Jeffers (SNL) and Mark Ruth (NREL) on the valuation project focused on energy storage.
Please coordinate with LBNL as they provide regulatory technical assistance to stakeholders in VT. Regulators should understand the implications of your work.	Coordination is ongoing with LBNL and key regulatory stakeholders in Vermont including the Vermont Energy Investment Corporation (VEIC).

1.3.10 Vermont FEEDER project
Project Integration and Collaboration

- Both the VT and CA Regional Partnership projects complement each other by investigating the optimal integration and siting of DER on distribution feeders in their respective states. We are coordinating with John Grosh (LLNL) and Goncalo Cardoso (LBNL) <u>focusing on comparing analysis methods and thresholds for impacts to determine optimal methods for different use cases</u>.
- Coordination is ongoing with Bobby Jeffers (SNL) and Mark Ruth (NREL) on the valuation project <u>to determine how the Energy storage installations in Vermont can be test cases for evaluating the methodologies.</u>



1.3.10 Vermont FEEDER project

Next Steps and Future Plans

Next Steps:

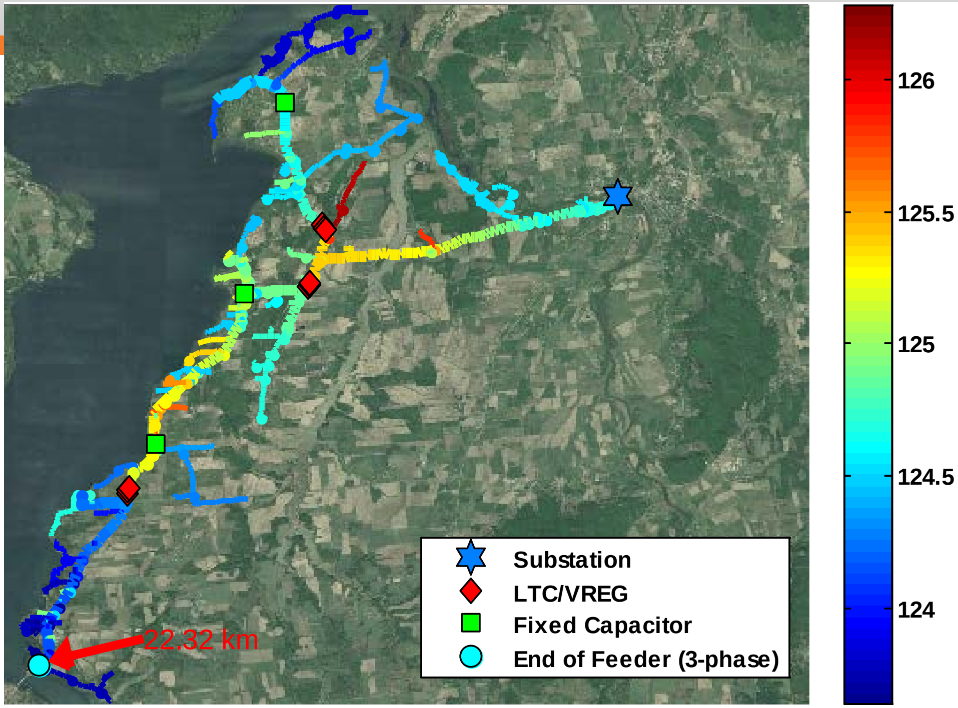
1) Detailed results and feeder map graphics of locational impacts and benefits of ES and PV.
2) Demonstrate DR control algorithms across a variety of simulation scenarios.
3) Provide at least 3 areas for potential improvement of the VTWAC forecasts

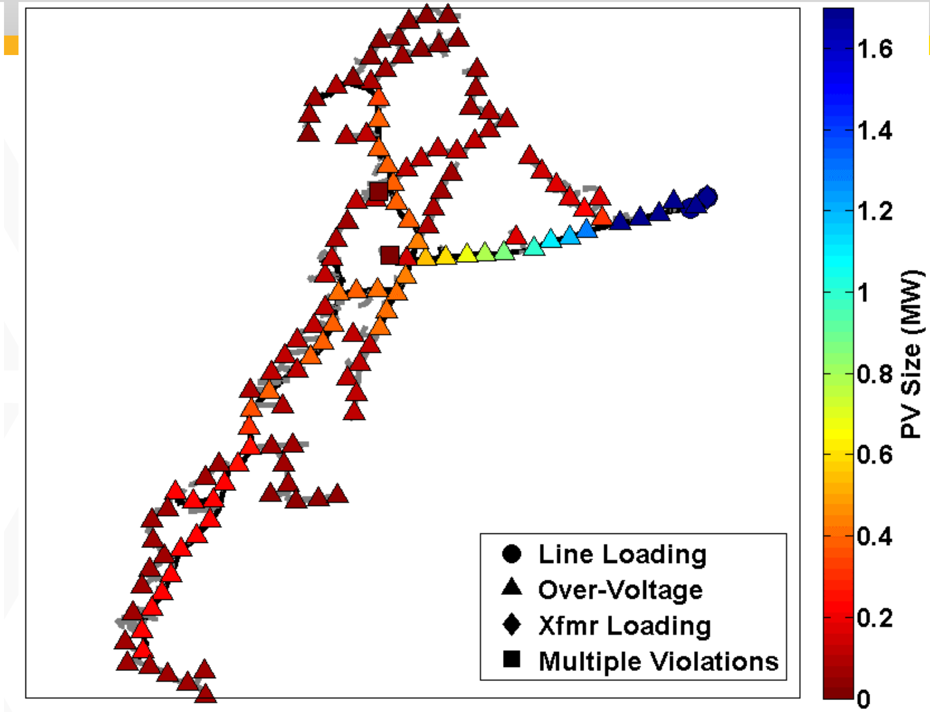
This project's key outcomes will be 1) to achieve resilient distribution feeders and the use of energy storage for high penetration of renewable energy generation without causing negative impacts to the distribution system. 2) develop a replicable approach and road map for DER integration at the distribution level in each of the three task areas and 3) Disseminate the results of this project to VT stakeholders and the Vermont Department of Public Service and to other utilities and stakeholders across US via conference presentations and publications.

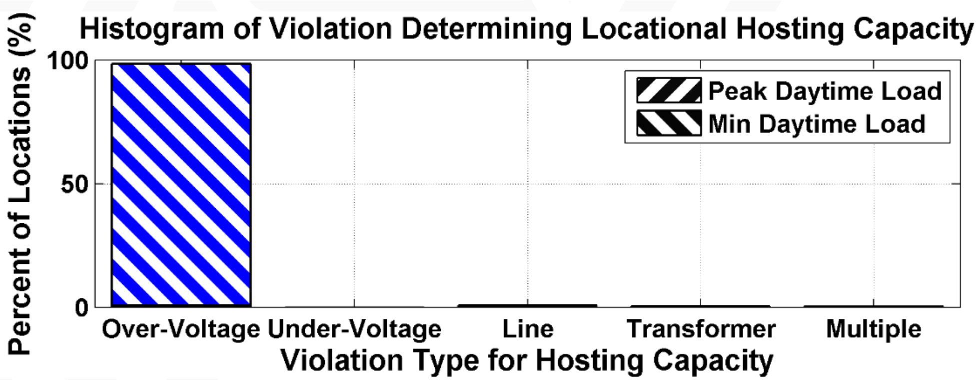
<u>Future Plans</u> with additional funding to expand project to achieve MYPP goals:

- ❑ Expand to include other New England utilities and COOPs
- ❑ Apply methodology for resilient distribution feeders for high penetration of DER to different utility service territories.
- ❑ Apply DER control and optimization in other regulatory frameworks and with different aggregators.
- ❑ Apply forecast improvements evaluation to other forecasting tools in other states.

Hosting Capacity Results (9G2)

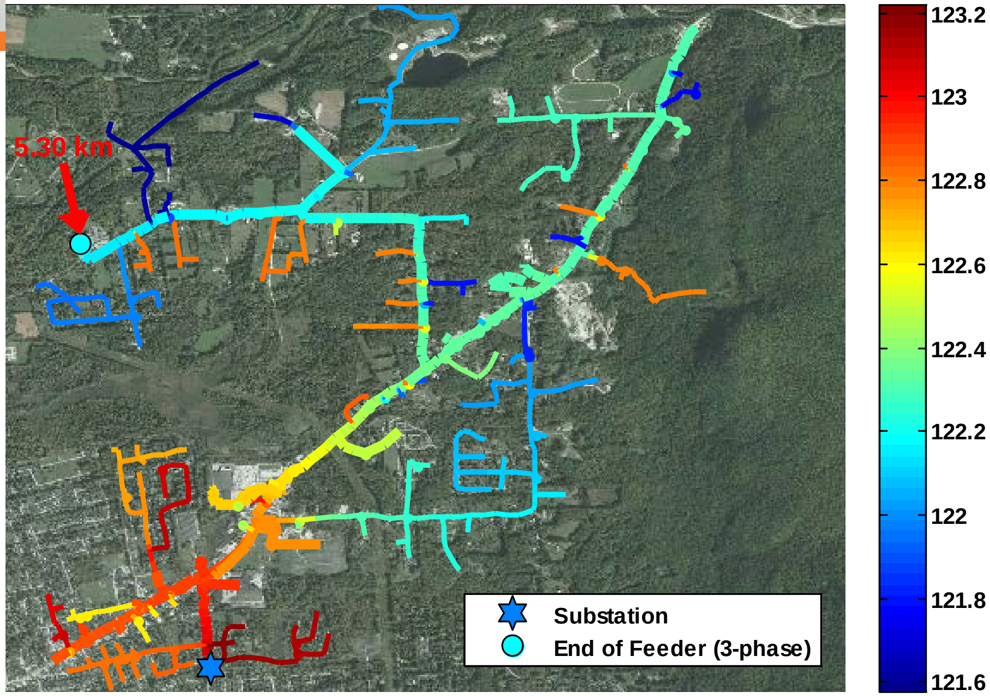


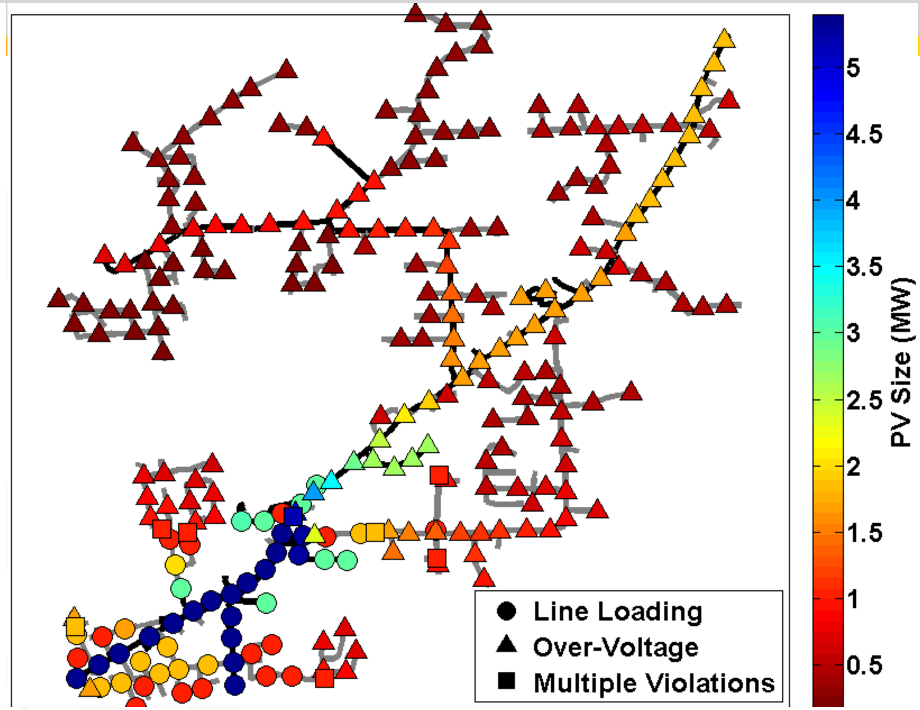


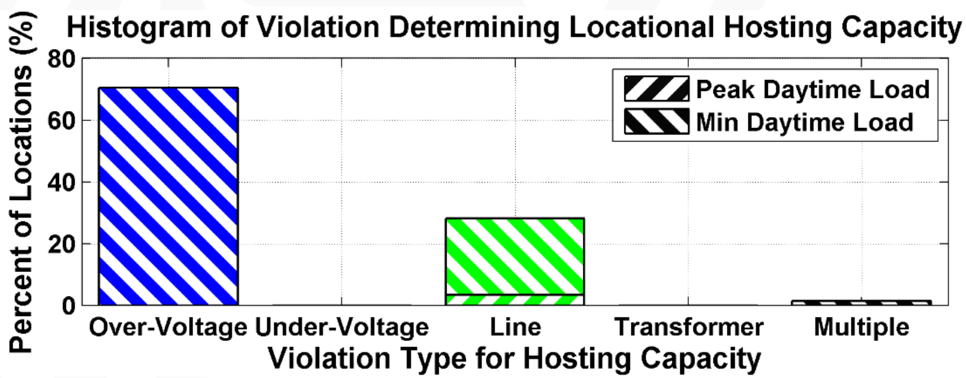


These are preliminary as we calibrate the distribution system models and define the thresholds and metrics

Hosting Capacity Results (ER-G51)

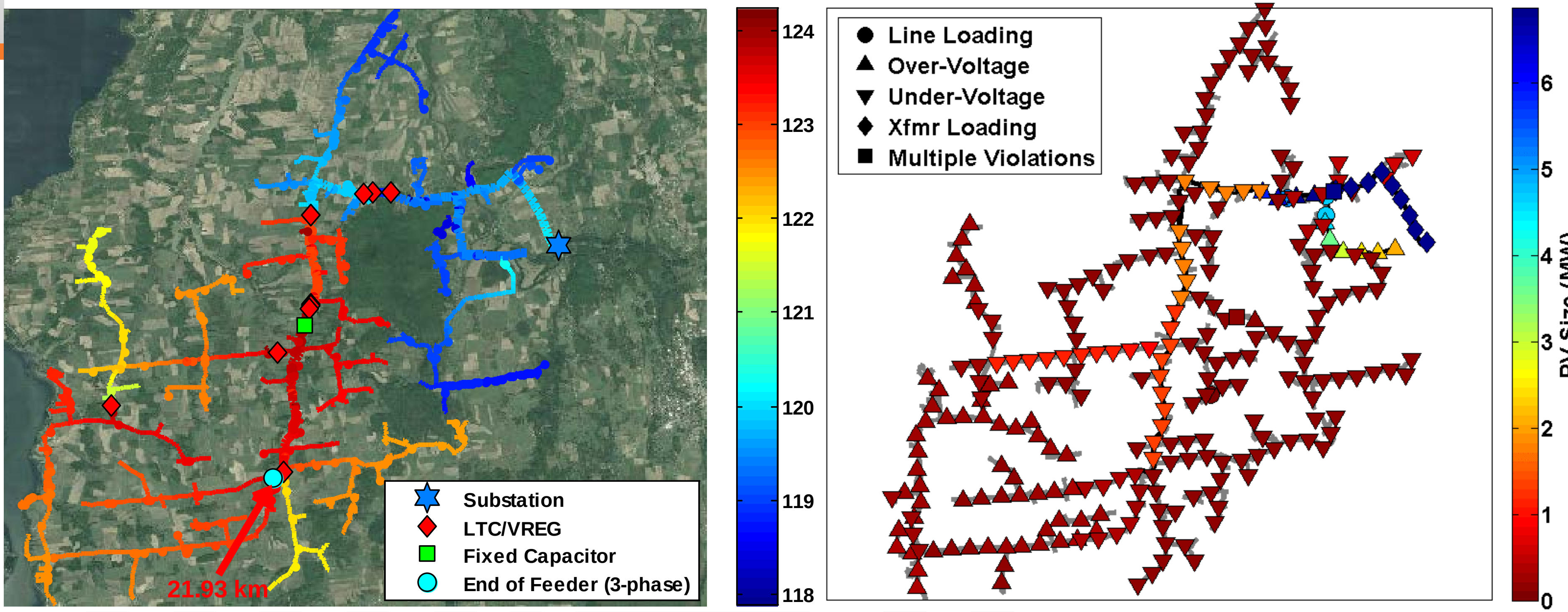


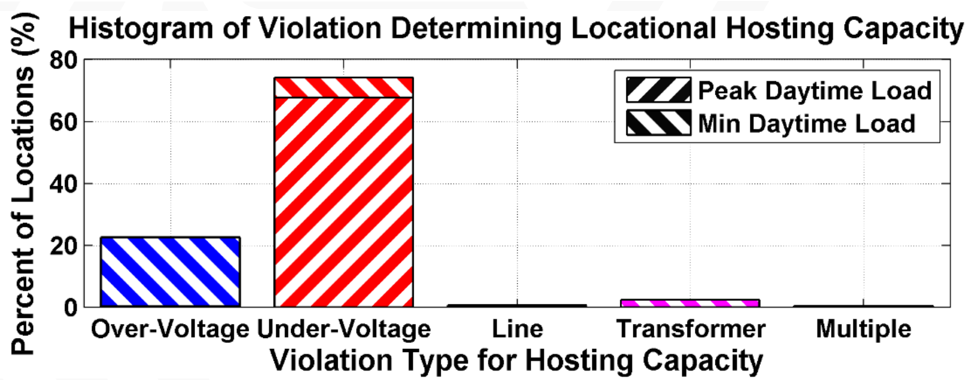




These are preliminary as we calibrate the distribution system models and define the thresholds and metrics

Hosting Capacity Results (WY-G81)





These are preliminary as we calibrate the distribution system models and define the thresholds and metrics

GRID MODERNIZATION INITIATIVE PEER REVIEW

GMLC 1.3.99 Clean Energy and Transactive Campus Project

PNNL-SA-125009

GEORGE HERNANDEZ, PNNL

April 18-20, 2017

Sheraton Pentagon City – Arlington, VA

Clean Energy and Transactive Campus Project (CETC)

Project Description

CETC will create a "recipe" to replicate and scale transactive control technologies for application in buildings, campuses, and communities across the nation. Transactive controls "recipes" will enable utilities and grid operators to actively engage buildings for mutual benefit. CETC will also establish a clean energy and responsive building load research and development infrastructure in Washington State

Value Proposition

- ✓ Vast opportunities for improved reliability, consumer benefits, and energy efficiency exist at the buildings-to-grid nexus; this requires research, development, and the development and demonstration of transactive controls for energy management
- ✓ Why do we care?
  - ✓ Transactive controls can reduce energy cost, improve reliability of the electric grid, and potentially improve building efficiency and comfort
  - ✓ Key step towards achieving a more modern, efficient, and reliable power grid

Project Objectives

- ✓ Scalable transactive controls in buildings
  - ✓ BEYOND DEMAND RESPONSE – enable buildings, fleets of equipment, and other building assets to deliver services to the grid while maximizing energy efficiency
  - ✓ GRID SCALE, RIGHT SIZED STORAGE – enable buildings to function as "virtual" storage devices to reduce the total capacity of grid storage needed to meet the needs of a utility
  - ✓ BEHIND THE METER RESPONSE TO PV – lessen, dampen, and otherwise minimize the effects of building and distributed PV as seen by the utility
- ✓ Create a recipe for replication of transactive equipment, buildings, campuses, districts, and fleets in real-life as utilities, municipals, and building owners are facing larger deployments of clean energy technologies, aging infrastructure, and new regulations

Clean Energy and Transactive Campus

Project Team

Project Participants and Roles

- PNNL:
  - Overall lead
  - Tests and validates transactive methodologies, develops technical documentation and user guides
  - Supports UW and WSU
- UW:
  - Develops smart grid testbed (battery energy storage system and adds inverters to solar arrays)
  - Develops methods for converting the project's building data to actionable information
- WSU:
  - Develops a testbed to examine transactive control strategies for a campus-scale/city-scale micro-grid, incorporating new solar arrays and access to a utility's grid-scale battery

PROJECT FUNDING*			
Lab	FY16 $K	FY17$K	FY18 $K
PNNL & Partners	2,885	6,707	3,000

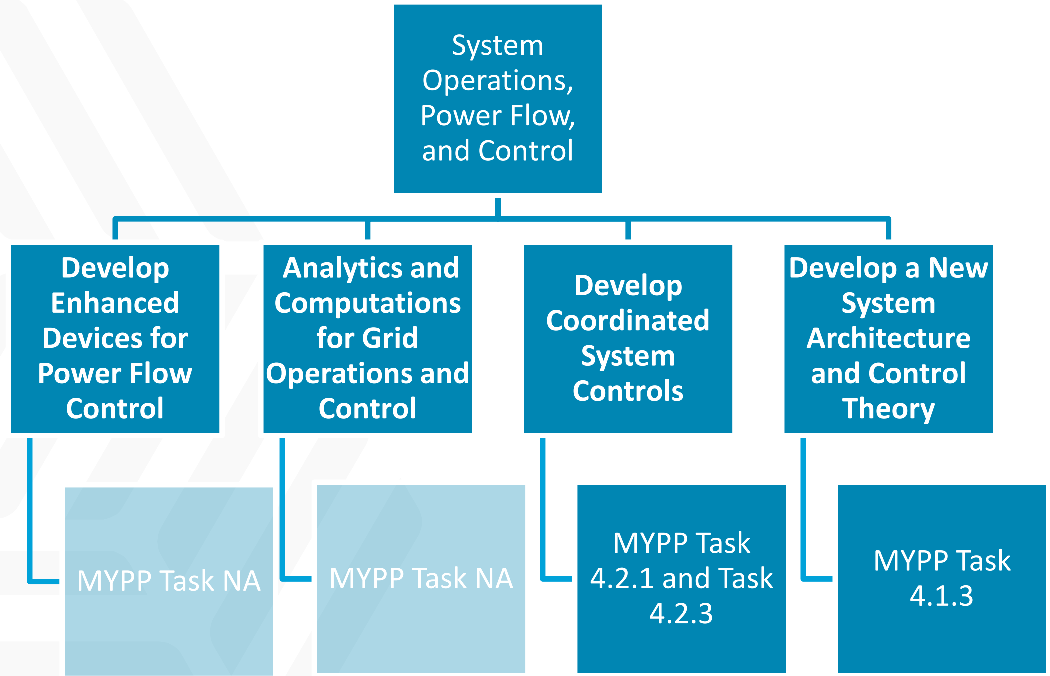
*50% cost-share from Washington State Department of Commerce

Project partners are: PNNL, UW, and WSU; Case Western Reserve University and University of Toledo were added in Phase II

Clean Energy and Transactive Campus

Relationship to Grid Modernization MYPP

- Primarily address three areas under System Operations, Power Flow, and Control focus area
  - Task 4.1.3 – Validation of transactive control strategies to achieve defined control performance objectives through testing in real buildings
  - Task 4.2.2 – Integration of buildings and grid using a innovative distributed sensing and controls platform – VOLTTRON™ and leveraging existing building management systems (BMS) for use cases involving high penetration of distributed energy resources or microgrids
  - Task 4.2.3 – Development of open source solutions for coordinating and integrating BMS with other local energy network controllers, such as PV inverters, battery energy storage systems, microgrid controllers, etc.



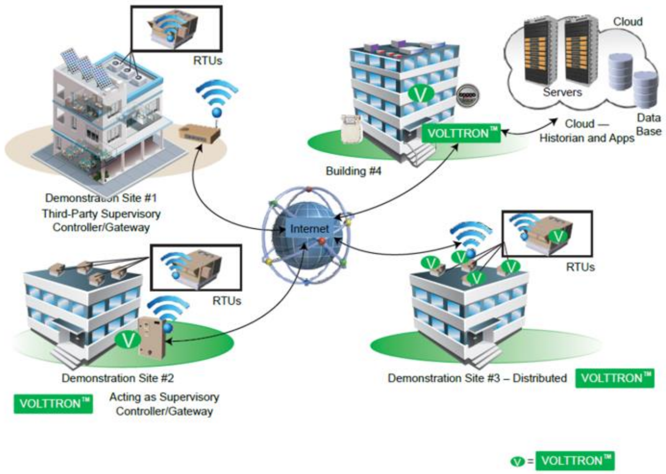
Clean Energy and Transactive Campus

Approach

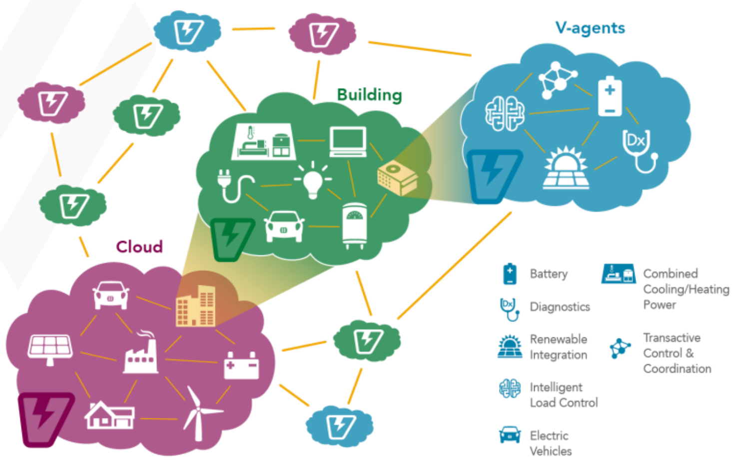
- PNNL:
  - Tests and validates transactive methodologies via experiments on the PNNL campus in multiple buildings
  - Produces user guides for broader implementation
- UW:
  - Acquires battery energy storage system (BESS) and adds inverters to solar arrays to test the coordination of campus assets
  - Develops methods to optimize charge/discharge cycles of BESS using transactive signals
  - Develops methods for converting the project's building data to actionable information
- WSU:
  - Develops a testbed to examine transactive control strategies for a campus-scale/city-scale micro-grid, incorporating new solar arrays and access to a utility's grid-scale battery
  - Develops resiliency strategies
  - Develops bilateral energy trading concept using block-chain technology

Clean Energy and Transactive Campus
Approach

- Develop and demonstrate transactive control technologies that improve building performance, management of building power loads, renewable energy integration, grid operations, cost, and efficiency



- Create methods that enable these approaches to be readily adopted and implemented in single buildings, sets of buildings, and communities at scale

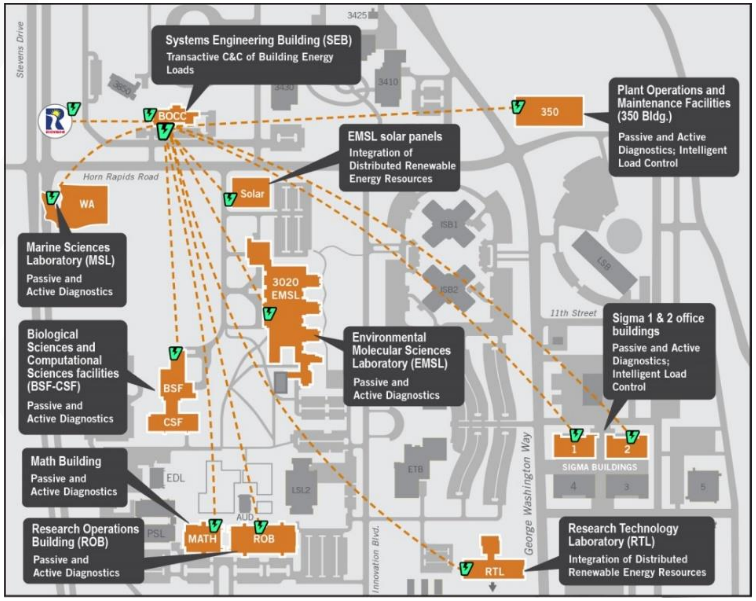


Clean Energy and Transactive Campus

Approach

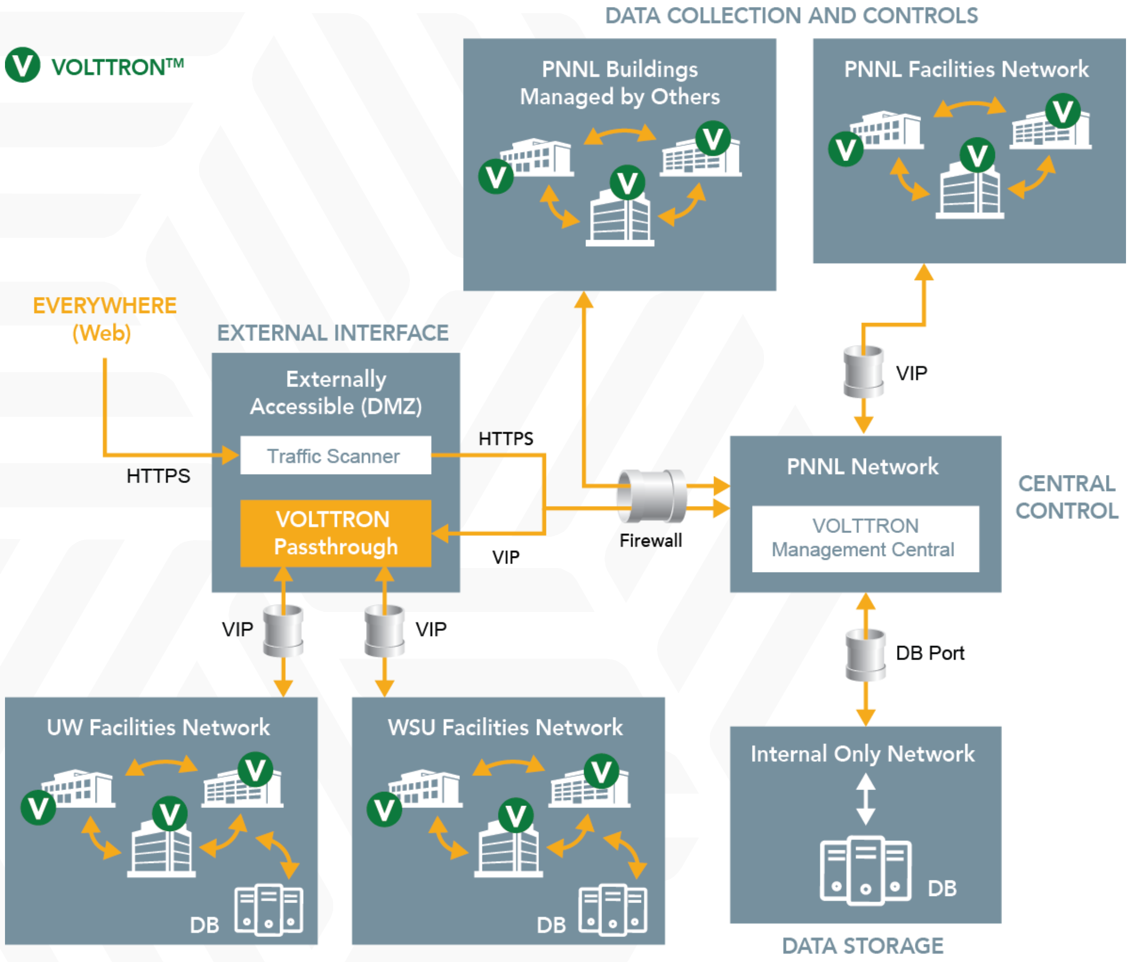
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

- 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 CETC experiments and connecting the partners' research activities
  - VOLTTRON deploys "V-agents" (algorithms) in building and other systems to coordinate various actions
- Technology can be launched from **inexpensive computing** resources



Clean Energy and Transactive Campus

Approach



Clean Energy and Transactive Campus

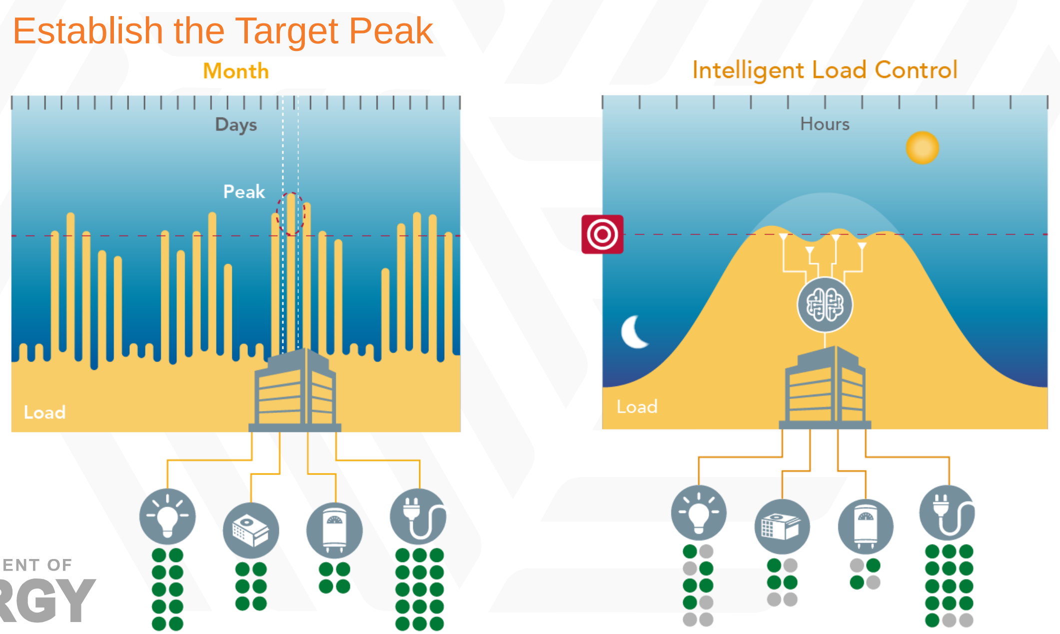
Key Project Milestones

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Milestone (FY16-FY18)	Status	Due Date
Preliminary report of transactive controls on PNNL campus project	Complete	9/30/16
Development and testing of “max-tech” controls complete	On track	9/30/17
Testing and validation of multiple-campus experiment complete	On track	12/31/18

Intelligent Load Control (ILC)

- Automated management of building electricity peak, energy consumption, or energy budget
- Deployed in three PNNL buildings, primarily to control operation of multiple heat pumps serving offices and other work spaces
  - Test results demonstrate that when building energy consumption peaked at different times during the day, ILC quickly prioritized heat pump operations, maintaining building comfort at acceptable levels and reducing load to the desired target

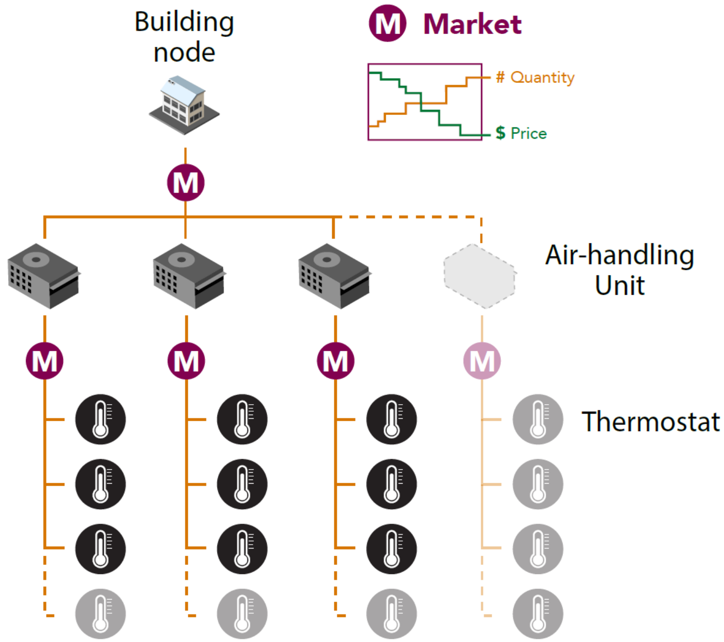


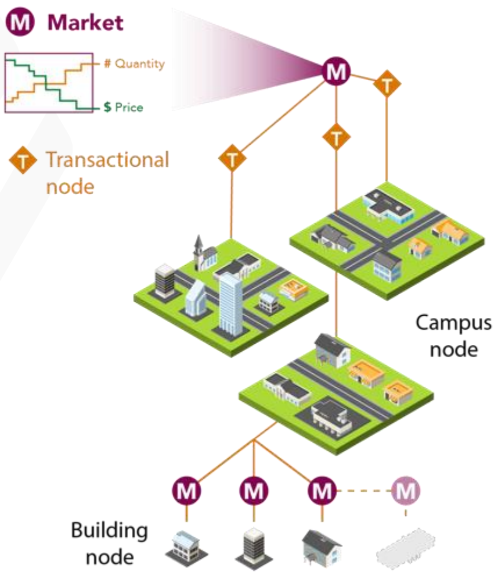
A. BEYOND DEMAND RESPONSE

B. GRID SCALE, RIGHT SIZED STORAGE

Transactive Control and Coordination of Building Energy Loads

- Creates markets within different building zones and devices as part of an automated, real-time process
- Deployed in a PNNL building's air handling unit, results have confirmed the ability of this method to achieve experiment objectives

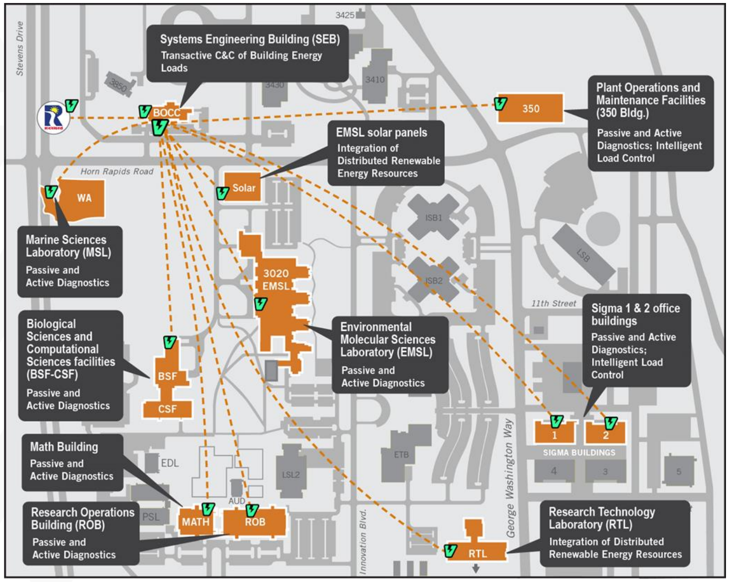




Clean Energy and Transactive Campus
Lessons Learned

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

- ▶ Facilities and operations (F&O) staff of buildings are concerned about cyber security of the controls infrastructure
  - Hesitant to introduce new hardware and software on to their networks
- ▶ Grid services that do not require fast response (>5 minutes) can be deployed easily using existing building control sequences to provide short-term (<30 minutes) and long-term (>30 minutes) grid services
- ▶ Grid services that require fast responses (in order of minutes) are harder to implement with existing control sequences
  - Some modifications and enhancements essential for fast response grid service
- ▶ F&O staff are willing to provide grid services, if there is a good business case



Clean Energy and Transactive Campus

Response to December 2016 Program Review

Recommendation	Response
The campus project has achieved the experimental results that were planned for the first phase. Further, the project has exceeded expectations by undertaking some experiments in multiple buildings (rather than single buildings as planned) and completing the work in 9 months (rather than the planned 12 months).	The project teams agrees with this assessment.
The university participants have made progress according to plan and will have their physical assets in place to support the second phase of the project. Of note, the labs have been much quicker to deliver than the universities.	Much of the university funding was for setting up the testbed, which caused some procurement delays.
The second phase of the project will provide the most important results for GMI, demonstrating how the methodologies developed by PNNL can scale. Furthermore, the teams will add enhancements related to battery management, PV integration, and incorporation into a micro-grid strategy.	The project teams agrees with this assessment and is looking forward to the challenge.
The project team needs to fully engage DOE in defining the details of some elements of this work, particularly the PV integration scaling at UW and WSU (engage EERE) and the micro-grid R&D at WSU (engage OE) to ensure that DOE needs are reflected in the work and are accomplished in this phase and that all DOE offices are engaged in the campus opportunity.	PNNL, WSU and UW held a webinar to update OE staff. PNNL also held a meeting with OE staff in February. Also, a number of OE and EERE staff attend the BTO Peer review meeting in March.
In addition to scaling the methodologies developed to date the team is encouraged to identify additional experiments relevant to transactive control of building loads that can be explored in the second phase.	The Phase II project team is extending the transactive control experiments in buildings.

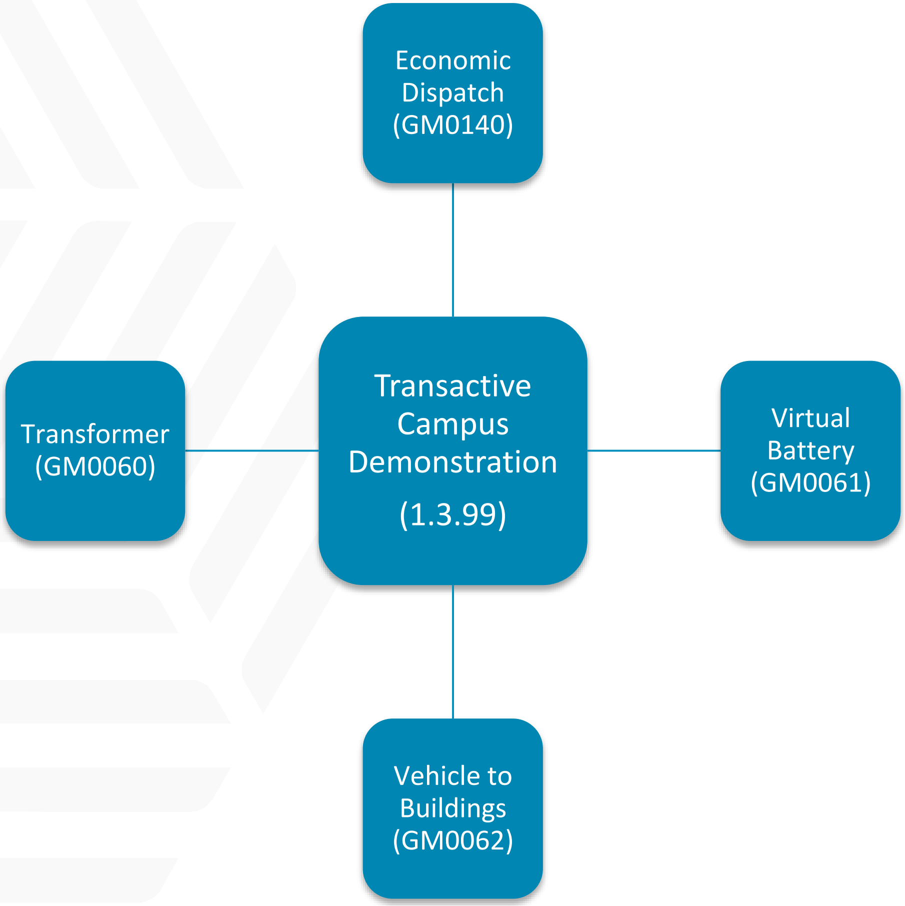
Clean Energy and Transactive Campus

Project Integration and Collaboration

Communications:

<u>Conferences:</u>

- "Regional Transactive Campus Testbed – Design and Initial Results," 2016 Transactive Energy Systems Conference and Workshop, May 17, 2016, Portland, Ore. Presented by Chad Corbin
- "Transactive Campus Energy," the featured session of the Energy Systems Innovation Center's annual Energy Summit at the Power & Energy Automation Conference, March 10, 2016, and March 23, 2017 Spokane, Washington



Clean Energy and Transactive Campus

Project Integration and Collaboration

Publications to Date: 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. "Trnsactive Control of Commercial Building HVAC Systems." PNNL-26083, Richland, WA.
- Katipamula S, RG Lutes, RM Underhill, W Kim, S Huang. 2016. "Automated Identification of Retro-Commissioning Measures." PNNL-XXXXX, Richland, WA.

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)

Publications to Date: Journal and Magazine Articles

- Katipamula S, J Haack, G Hernandez, B Akyol and J Hageman, "**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, "**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.

Clean Energy and Transactive Campus

Next Steps and Future Plans: Phase II

- Create network to connect the project partners and facilitate broader testing
- Expand experiments at PNNL
  - Includes extension of the experiments to the other partners
  - Create transactive market simulator
  - Further extend experiments to multi-building and multi-campus scale for automated implementation of transactive buildings
- UW and WSU begin testing assets they have acquired and installed
- Case Western Reserve University and the University of Toledo join the project
  - Install BESS at both Case and Toledo
  - Enable building-grid integration on number of buildings on both campuses
  - Will replicate and extend PNNL-developed experiments in their facilities

Backup Slides

Clean Energy and Transactive Campus

Transactive Controls Definitions (1)

These terms have been established in Building Technologies Office's (BTO'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

Clean Energy and Transactive Campus

Transactive Controls Definitions (1)

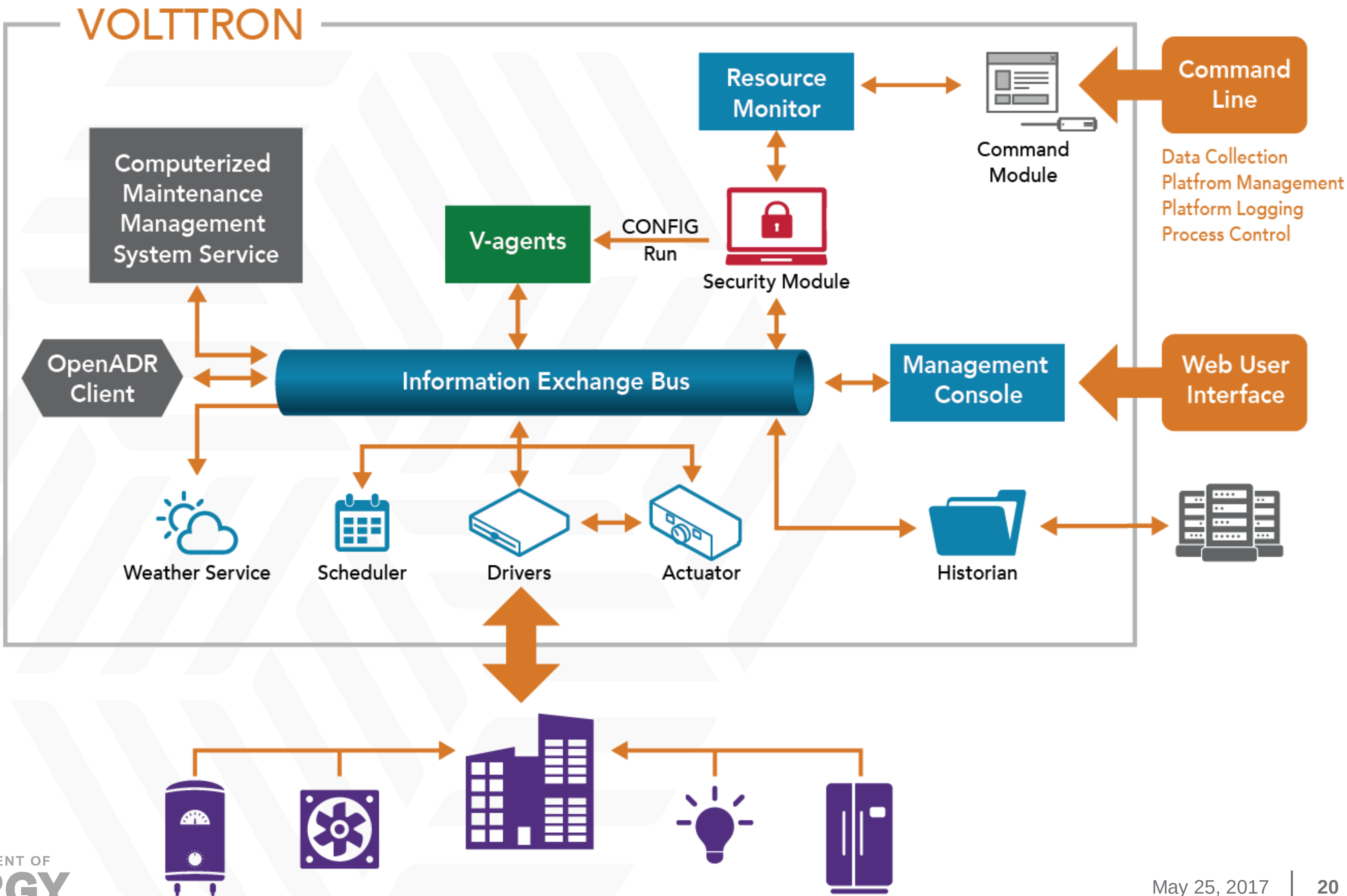
- **Transactive Devices** or **Connected Equipment** – consumer products with information and communication technologies (ICT) that enable them to be exercised through transactions – without boundaries
  - Many available technologies are typically proprietary (e.g. vendor specific ICT)

- **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

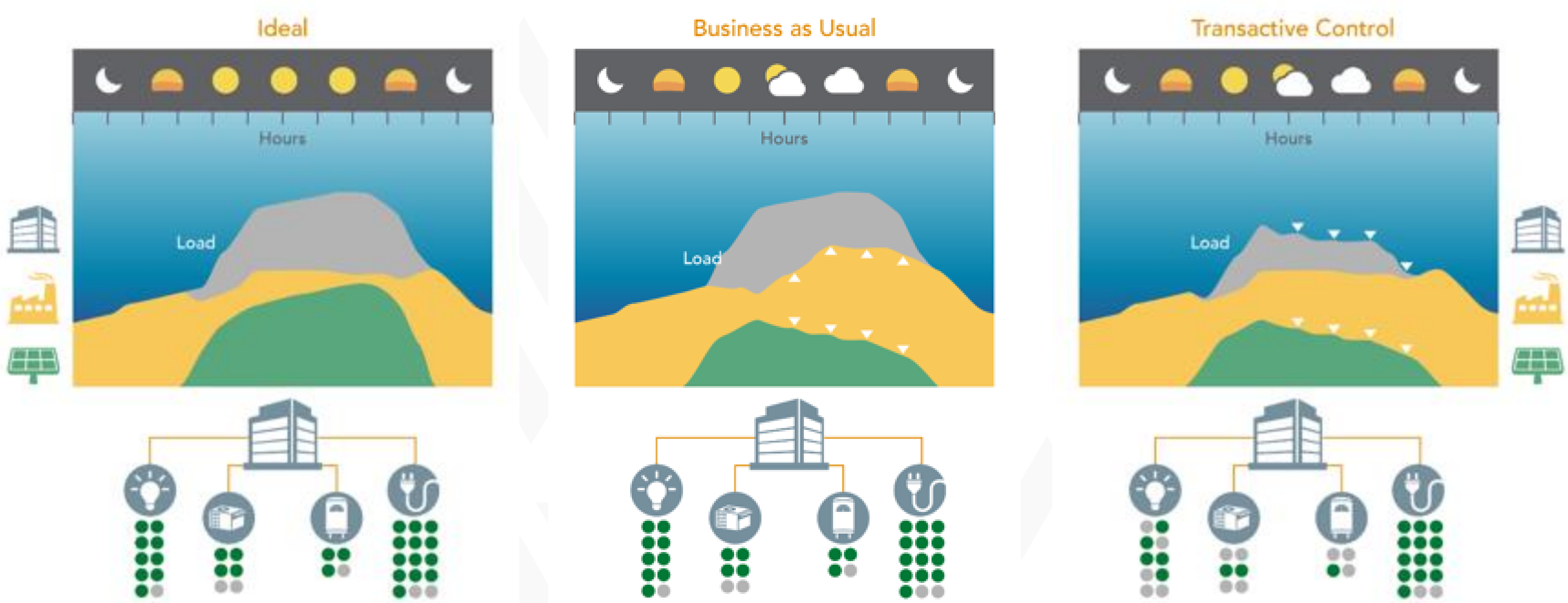
Clean Energy and Transactive Campus

Inside VOLTTRON™



Clean Energy and Transactive Campus

Renewables Integration



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

GRID MODERNIZATION INITIATIVE PEER REVIEW

GMLC 1.4.10—Control Theory

SCOTT BACKHAUS (PI), KARAN KALSI (CO-PI)

April 18-20

Sheraton Pentagon City – Arlington, VA

Control Theory
High-Level Summary

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description
Develop new integrated optimization and control solutions, including architectures, algorithms, and deployment strategies to transition to a large number of distributed energy resources (DERs) participating in grid control.

Value Proposition
- ✓ 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.

Project Objectives
- ✓ Ensure architectural compatibility of control theory and solutions.
- ✓ Coordinate time and grid scales across architecture to enable tractable control and optimization of >10,000 DERs.
- ✓ Coordinate and "homogenize" diverse DERs with widely different responses.
- ✓ Incorporate power flow physics and network constraints into control solutions.
- ✓ Systematically manage uncertainty from intermittent generation and from controlled response of a large number of DERs.
- ✓ Enable integration with legacy systems and bulk power system markets.

Control Theory
Project Team

Project Participants and Roles

R&D Team:

- ✓ LANL (lead)—risk-aware optimization, aggregate device modeling
- ✓ PNNL (co-lead)—real-time control, aggregate device modeling, simulation-based testing
- ✓ INL—metrics
- ✓ ANL—power flow
- ✓ ORNL, LLNL, SNL—testing and control design
- ✓ NREL—real-time control, aggregate device modeling

Industry Advisors:

- ✓ Oncor Electric Delivery
- ✓ PJM Interconnection LLC
- ✓ United Technologies Research Center

PROJECT FUNDING			
Lab	**FY16 $**	**FY17 $**	**FY18 $**
LANL	905,000	670,000	405,000
PNNL	785,000	525,000	720,000
INL	185,000	225,000	0
ANL	290,000	220,000	145,000
ORNL	50,000	50,000	0
LLNL	50,000	100,000	60,000
SNL	100,000	100,000	0
NREL	215,000	245,000	425,000

Control Theory

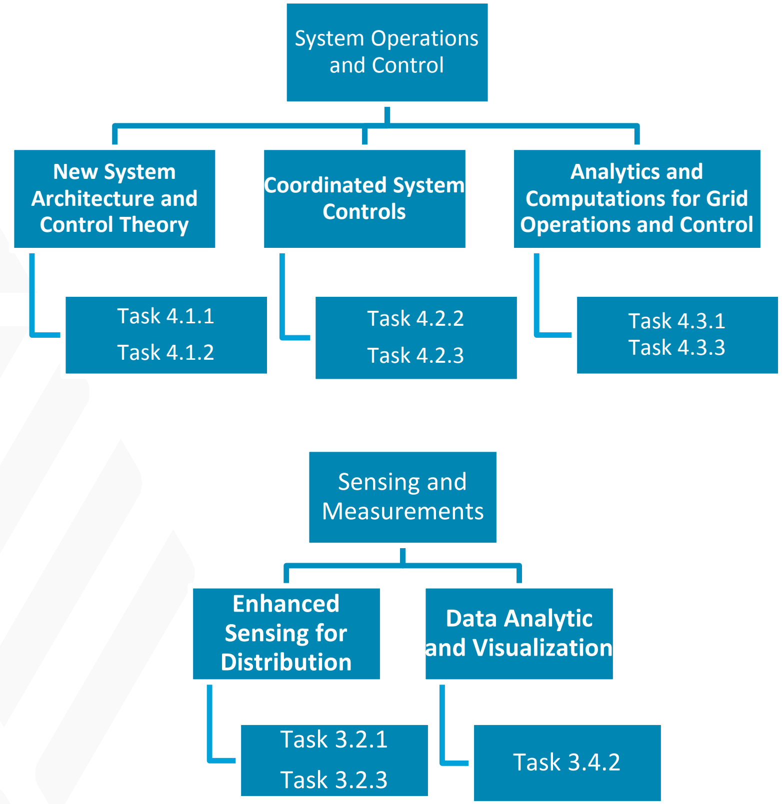
Relationship to Grid Modernization MYPP

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Relationship to Systems Operations, Power Flow, and Control area:

- ✓ Develop comprehensive architectural models, control theory, and algorithms
- ✓ Integrate bulk power systems, distribution systems, and end-use DERs
- ✓ Improve analytics and computation for grid operations and control.

The control theory effort will support the GMLC multi-year program plan vision for transitioning the power grid to a state where a huge number of DERs are participating in grid control.



Control Theory

Approach

Task 1: Architecture and metrics

- ✓ Develop new and evaluate existing control system architectural decompositions.
- ✓ Develop and apply metrics for architecture and control system performance evaluation.

Task 2: Integrated optimization and control

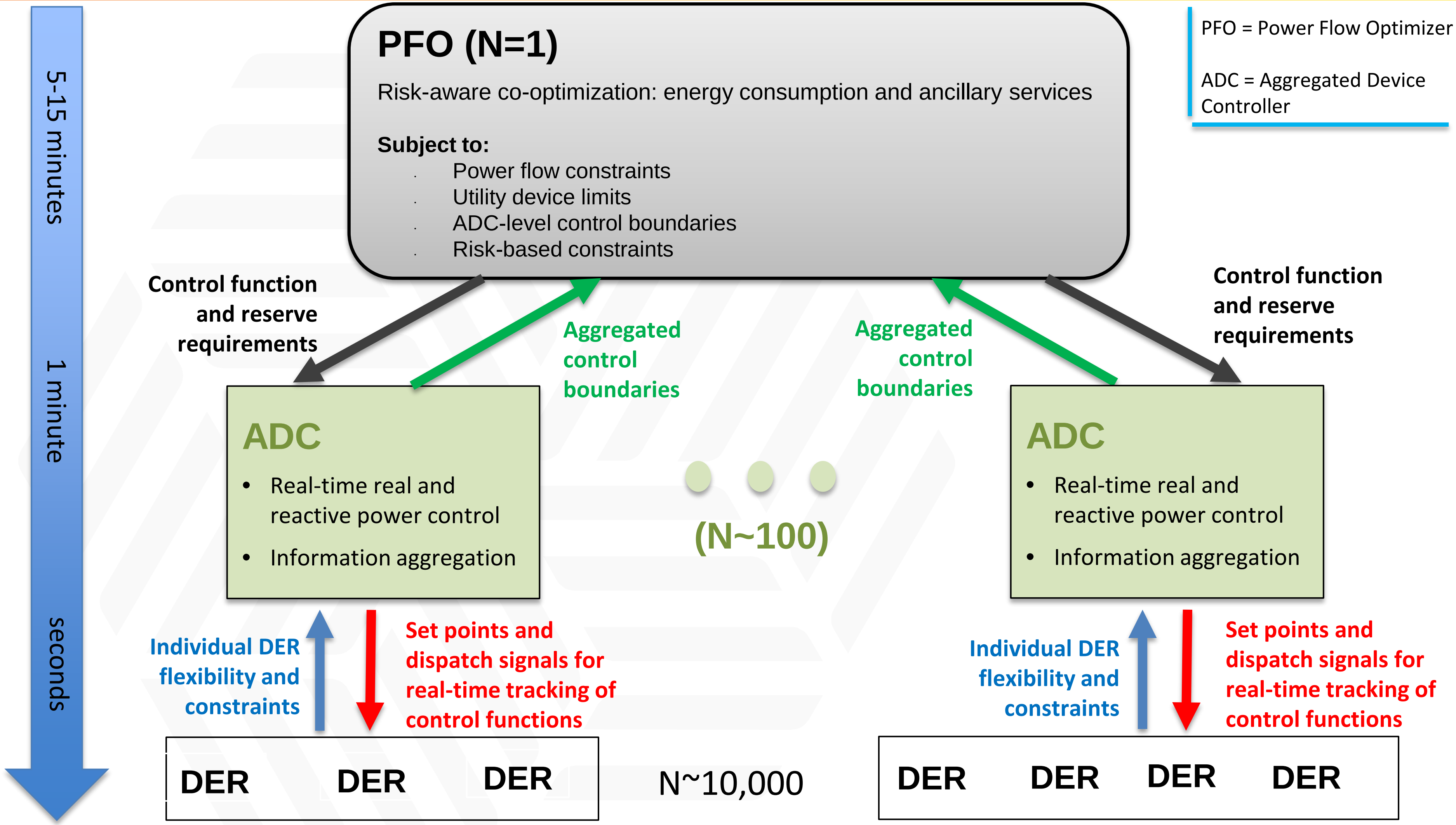
- ✓ Develop individual and aggregate DER flexibility models and associated constraints.
- ✓ Design real-time control strategies for aggregated DERs with uncertainty quantification.
- ✓ Develop power flow relaxation and approximation methods for distribution systems.
- ✓ Develop optimization methods that integrate uncertain real-time control into risk-aware power flow optimization.

Task 3: Numerical testing

- ✓ Specify and develop simulation test bed requirements.
- ✓ Test control strategies for aggregated DERs, including power flow models on ~10 distribution feeders including~10,000 DERs

Control Theory
Approach

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

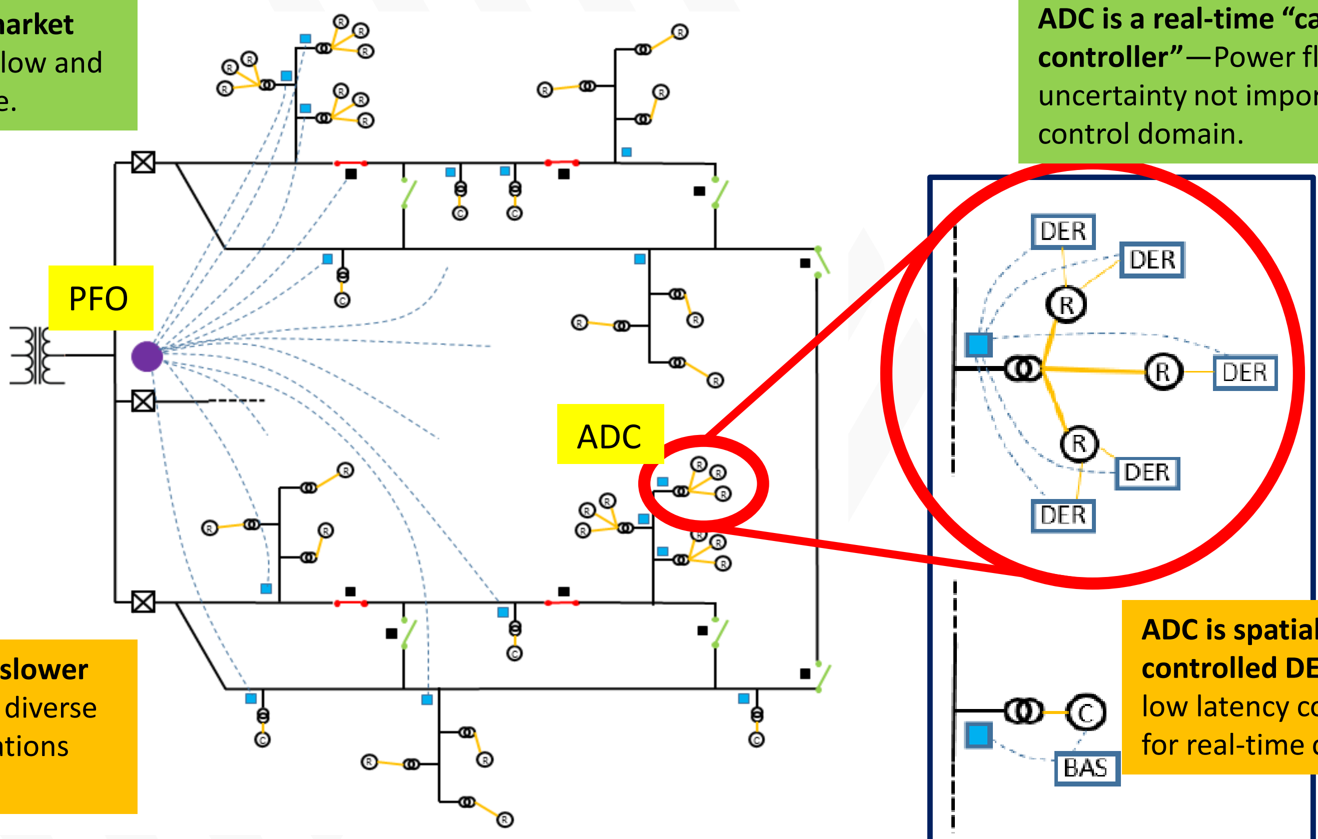


Control Theory
Approach

Coordination over both temporal and spatial/grid scales creates a theoretical framework for architecturally compatible solutions that integrate optimization and control.

PFO is a "network/market optimizer"—Power flow and uncertainty dominate.

ADC is a real-time "capacity controller"—Power flow and uncertainty not important in ADC control domain.



ADC is spatially adjacent to controlled DERs—enables fast, low latency communications for real-time control.

PFO optimization on slower time scales—enables diverse siting and communications options.

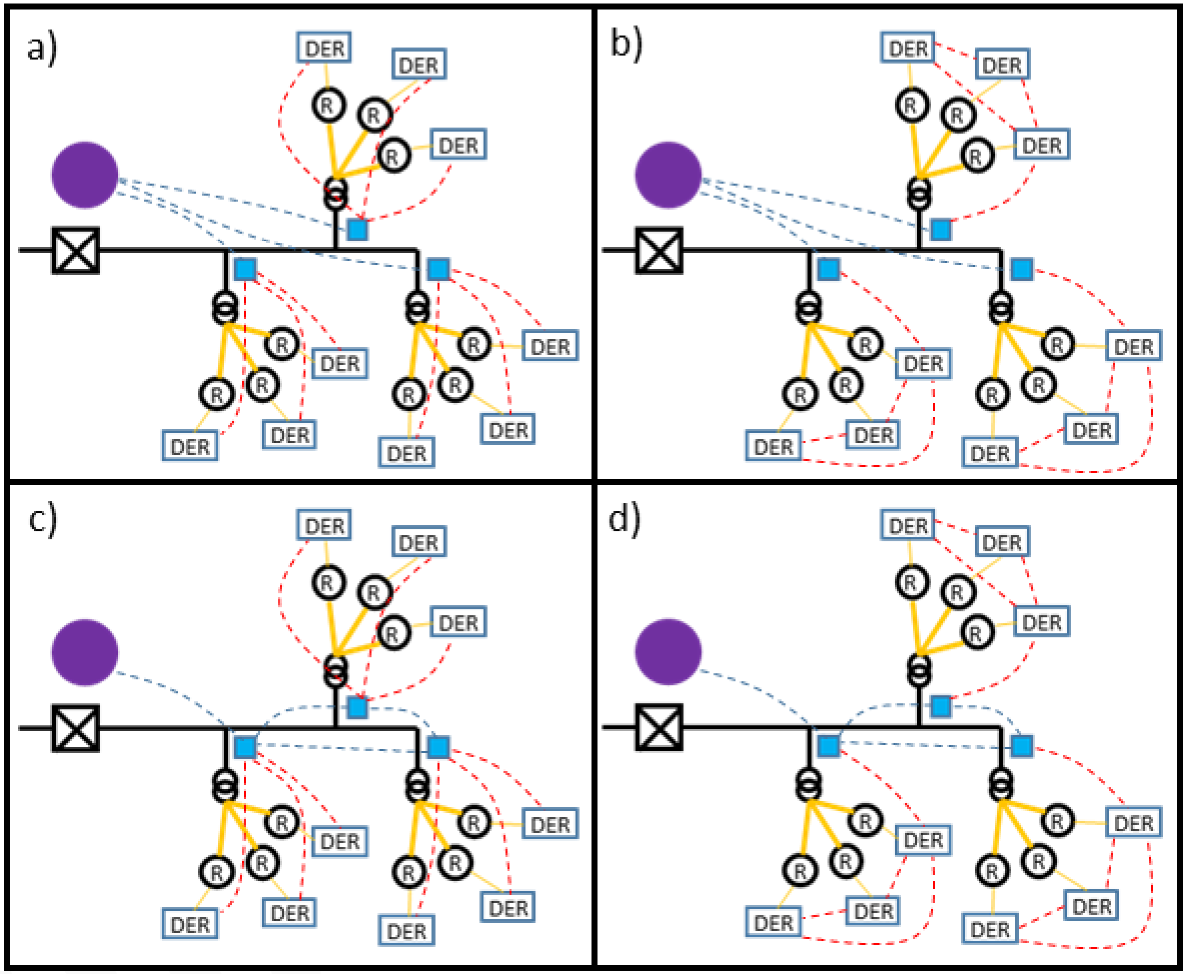
Control Theory
Approach—Alternative Frameworks

Planned work

ADC distributed control

PFO distributed optimization

Distributed PFO and ADC



Control Theory

Key Project Milestones

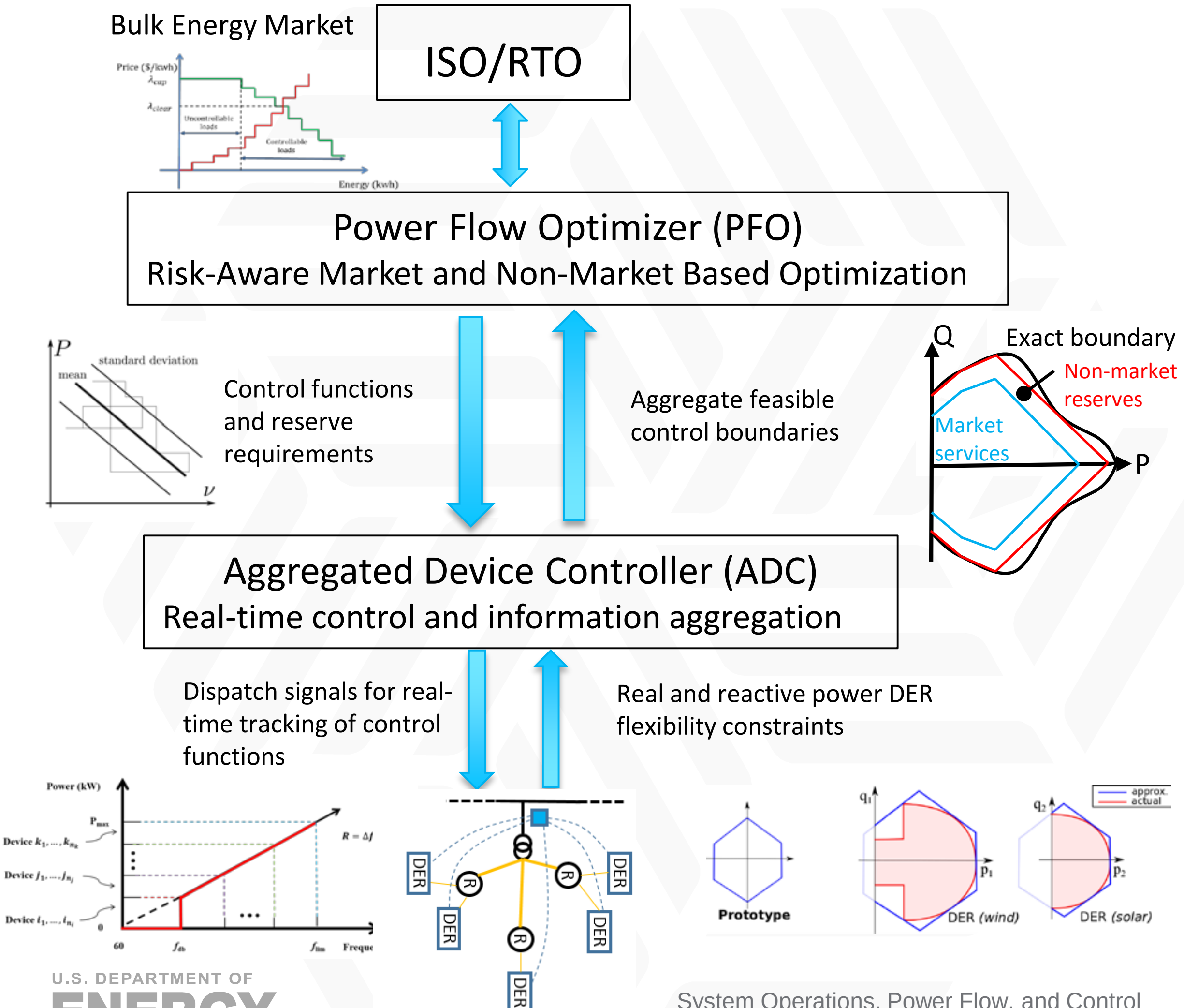
Milestone (FY16-FY18)	Status	Due Date
Control Theory Road Map Milestone	**Completed**	**11/1/16**
Task 1.1: Documented architectural reference models for control that includes three key scenarios: legacy systems, communications-heavy systems, and communications lite systems.	**Completed**. Integrated into the Control Theory roadmap	**11/1/16**
Task 2.1: Documented catalog of required individual and aggregate load/DER models and roadmap of theoretical development steps to achieve tractable load/DER models.	**Completed**. Integrated into the Control Theory roadmap	**11/1/16**
Task 2.2: Documented catalog of existing and alternative power flow relaxations and approximations for distribution systems with discussion of applicability to optimization and control of distribution networks and down select for further numerical testing.	**Completed**. Integrated into the Control Theory roadmap	**11/1/16**
Task 2.3: Documented preliminary formulation and development roadmap for risk-aware control of multiple distribution circuits with >10,000 DERs including power flow physics, legacy equipment and network constraints.	**Completed**. Integrated into the Control Theory roadmap	**11/1/16**
Task 2.4: Documented initial design of control methodologies for aggregated and individual load/DER models.	**Completed**. Integrated into the Control Theory roadmap	**11/1/16**

Control Theory

Key Project Milestones

Milestone (FY16-FY18)	Status	Due Date
Task 1.1: Documented architectural reference models with extensions to include market/control interactions, multi-structure architecture diagrams and detailed data.	Completed. High-level architecture package. Extension. Publication on detailed mathematical formulation of market integration in progress	4/1/17
Task 2.1: Aggregated energy and ancillary service bids and flexibility constraints formulated.	Completed. Initial formulation. Revision. Initial formulation required revision to enable all ancillary services anticipated in Task 1 and 2.3.	4/1/17
Task 2.4: Documented final specifications for the hierarchical control framework for each of the architectural reference models including topologies, communications, data exchange, and time scales.	Completed. Details presented in later slides.	4/1/17
Task 3: Documented numerical simulation test bed requirements and down select (adapt existing vs develop new).	**In Progress.** Completed initial test plan for addressing distribution level optimization and control of DERs.	**10/1/17**

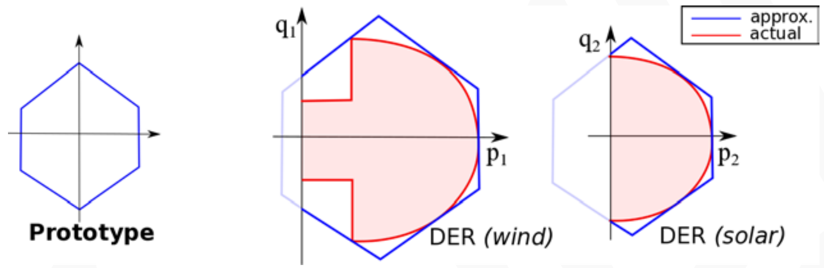
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy



Major accomplishments:

- ✓ Developed interfaces for PFO-bulk system, PFO-ADC and ADC-DER
- ✓ Completed initial mathematical formulations for each interface
- ✓ Submitted 5 conference papers and 2 journal papers

Algorithm for determining aggregate feasible control boundaries



Step 1: Choose a prototype domain (convex polygon)

$$\mathcal{Y} = \{(p,q) \mid F_1\, p + F_2\, q \leq d\} \xrightarrow{\mathcal{H}} \begin{cases} (p_1,q_1) \in \mathcal{Y}_1 \subseteq \alpha_1\, \mathcal{Y} + \beta_1 \\ (p_2,q_2) \in \mathcal{Y}_2 \subseteq \alpha_2\, \mathcal{Y} + \beta_2 \end{cases}$$

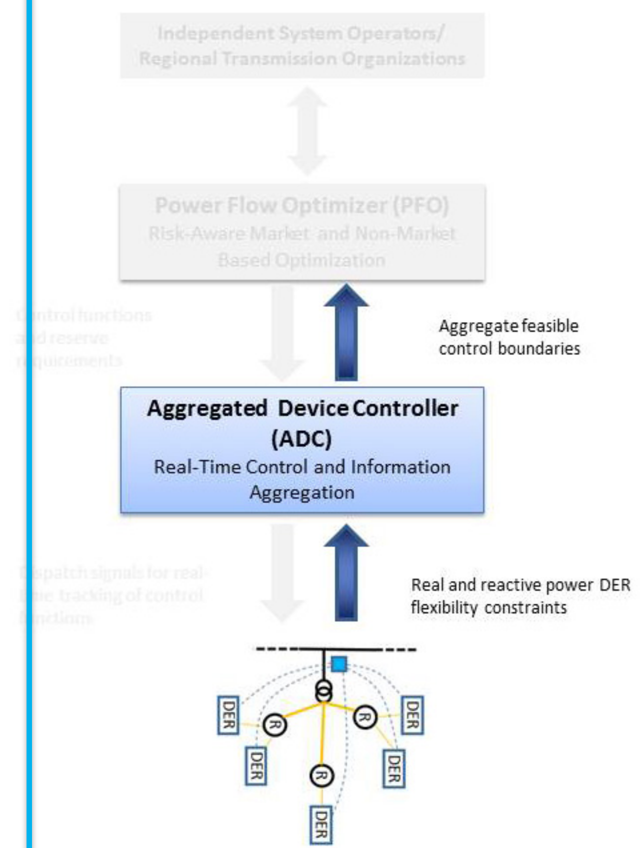
Step 2: Apply homothetic transformation (scaling and translation) to approximate (homogenize) DER flexibility

$$(p_1 + p_2\,,\, q_1 + q_2) \in \mathcal{Y}_1 \uplus \mathcal{Y}_2 \subseteq (\alpha_1 + \alpha_2)\, \mathcal{Y} + (\beta_1 + \beta_2)$$

Step 3: Compute algebraic calculations to approximate the aggregate flexibility (no Minkowski)

Key technical challenges

- Define and measure quality/tightness of approximation
- Capturing the (stochastic) uncertainties in DER flexibility

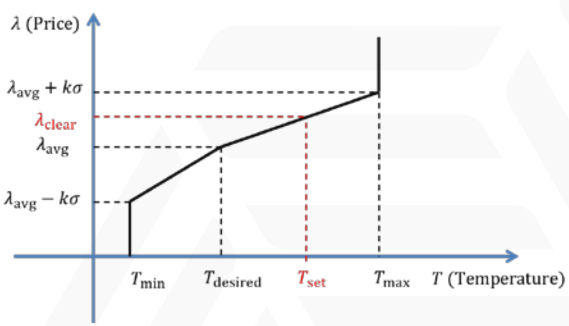


Control Theory

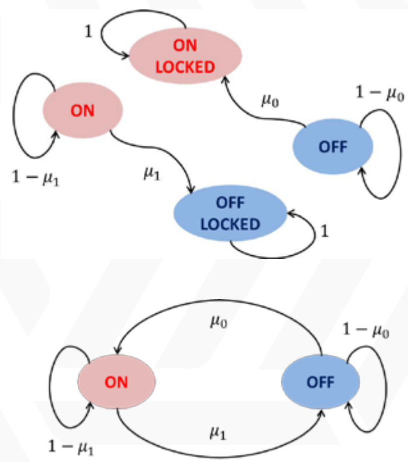
Accomplishments to Date—Project Wide

Real-time tracking of power set points and ancillary service control functions

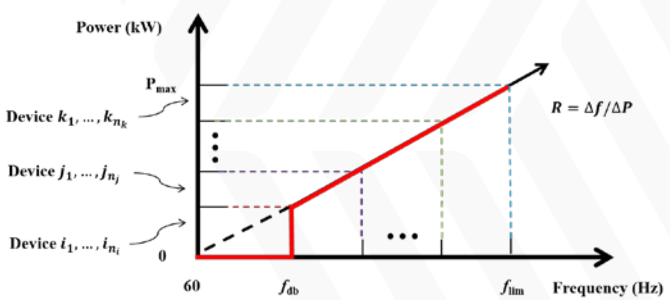
Energy Set point

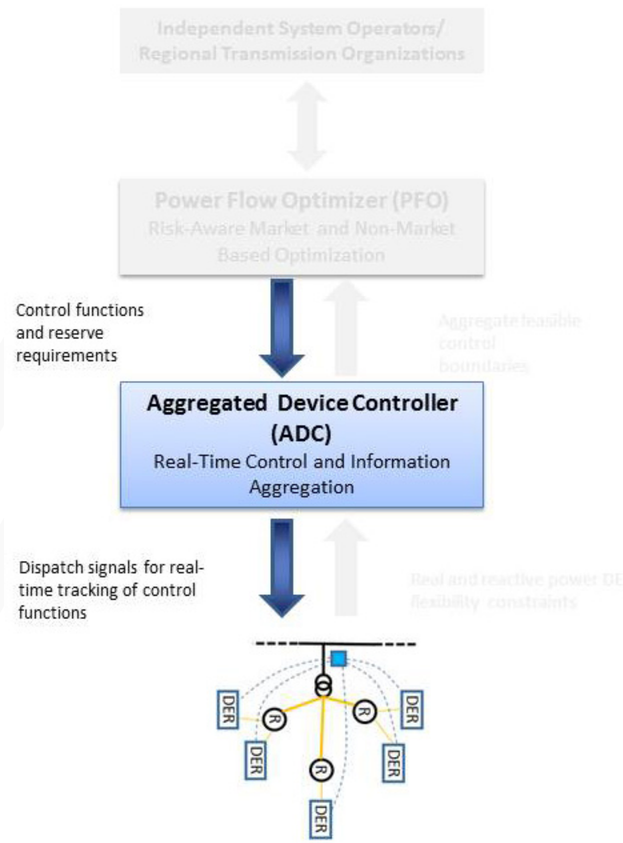


Frequency Regulation



Primary Frequency Control





Risk-aware power flow optimization

Power flow

$$\min_{p,v,\alpha,r^+,r^-} \sum_{i\in\mathcal{G}} c_i p_i + \sum_{j\in\mathcal{W}} c_j v_j + \sum_{i\in\mathcal{W},\mathcal{G}} \left(c_i^+ r_i^+ + c_i^- r_i^-\right)$$

$$P_{ij} = P_j + \sum_{k:(j,k)\in\mathcal{L}} \left(P_{jk} + R_{ij}\ell_{ij}\right)$$

$$Q_{ij} = Q_j + \sum_{k:(j,k)\in\mathcal{L}} \left(Q_{jk} + X_{ij}\ell_{ij}\right)$$

$$|V_j|^2 - |V_i|^2 = -2\left(R_{ij}P_{ij} + X_{ij}Q_{ij}\right) + \left(R_{ij}^2 + X_{ij}^2\right)\ell_{ij}$$

$$\ell_{ij}\,|V_i|^2 = P_{ij}^2 + Q_{ij}^2$$

Risk-aware ADC constraints

$$p + r^+ \le p_G^{max} \;,$$
$$p - r^- \ge p_G^{min} \;,$$
$$WCC\left(-\alpha_i\tilde{\Omega} > r_i^+\right) \le \epsilon_i \;, \quad \forall_{i\in\mathcal{G}} \;,$$
$$WCC\left(-\alpha_i\tilde{\Omega} < r_i^-\right) \le \epsilon_i \;, \quad \forall_{i\in\mathcal{G}} \;,$$

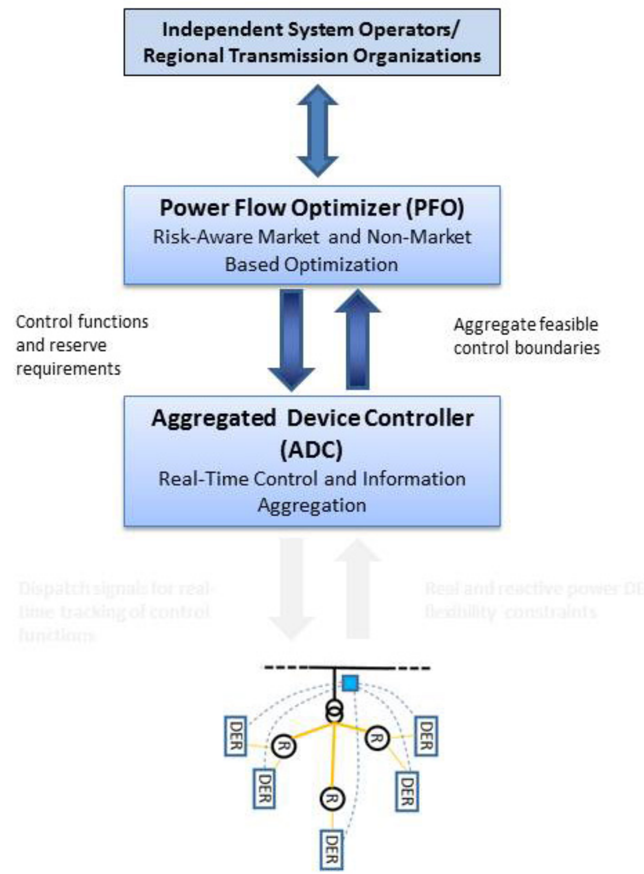
Risk-aware network constraints

$$WCC\left(\mathbf{M}_{(ij,\cdot)}(p - \alpha\tilde{\Omega} + \tilde{v} - d) > p_{ij}^{max}\right) \le \epsilon_{ij} \;, \quad \forall_{ij\in\mathcal{E}} \;,$$

$$WCC\left(\mathbf{M}_{(ij,\cdot)}(p - \alpha\tilde{\Omega} + \tilde{v} - d) < -p_{ij}^{max}\right) \le \epsilon_{ij} \;, \quad \forall_{ij\in\mathcal{E}}$$

Key technical challenges

- Nonlinear power flow equations
- Non-convex ADC control functions
- General probability distributions for uncertainty



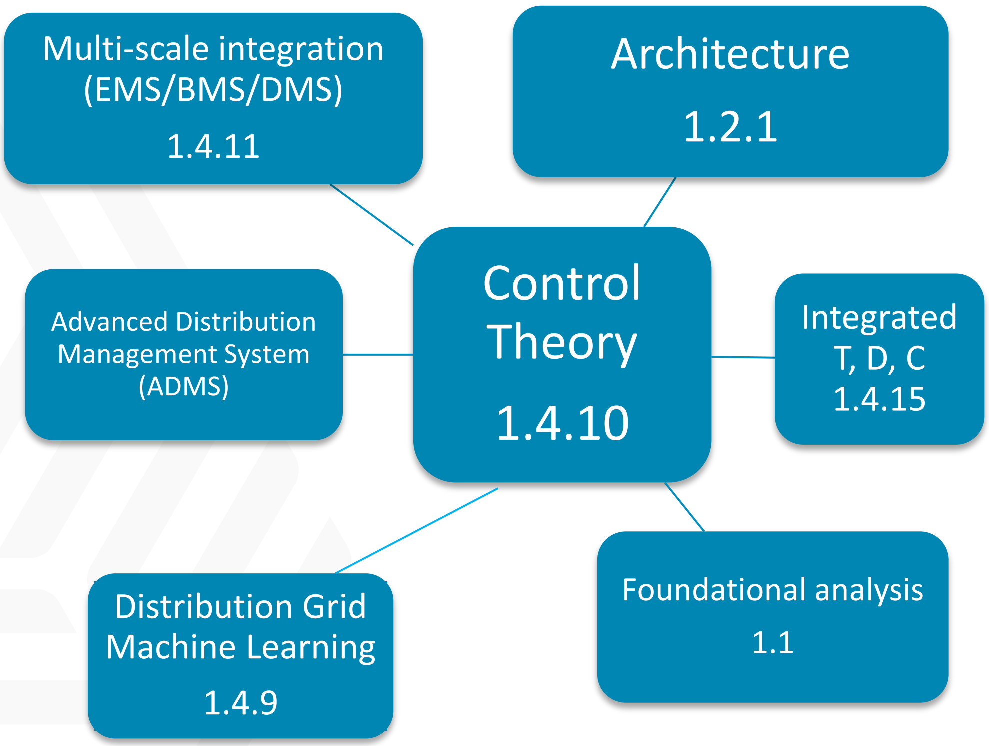
Control Theory

Response to December 2016 Program Review

Recommendation	Response
Please make sure there is "congruence" between the use cases/test cases in the TDC design and planning tools project with this Control Theory project	PNNL lead for HELICS (TDC) development (Jason Fuller) has written test plan to ensure proper use case crossover.
Realizing that this project covers difficult subject matter, better articulate the value and benefit of these activities as part of the Annual Peer Review in April. Please be mindful of the level of understanding of the audience.	Attempted to provide additional clarity through block diagram descriptions of approach.

Control Theory
Project Integration and Collaboration

- ✓ **1.2.1:** Architectural views developed used to inform control theory.
- ✓ **1.4.11 & ADMS:** Prototype systems developed will ensure compatibly of control solutions to ensure near-term adoption.
- ✓ **1.4.9:** Data-driven methods to characterize uncertainty at ADC/PFO interface.
- ✓ **1.4.15:** Co-simulation platform will enable control solution testing at scale.
- ✓ **1.1:** Adopt and adapt the system control metrics and extend them where needed to make the metrics useful for assessing advances in control theory and architecture.



Control Theory

Next Steps and Future Plans

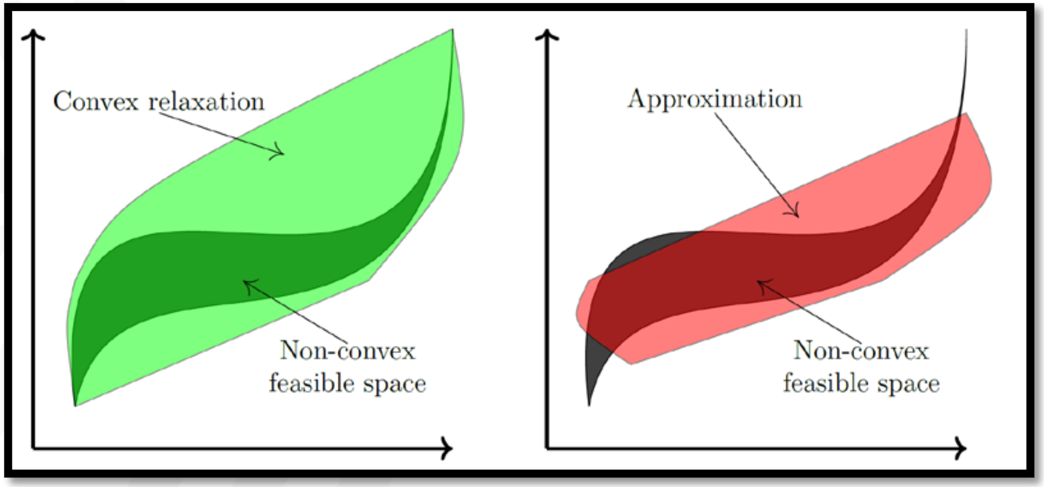
- ✓ **Extend control theory roadmap and developments** to distributed computational settings.
- ✓ **Small-scale field demonstration** to vet/test architecture in a real-world environment.
- ✓ **Workshop** with range of OE and EERE offices and industry representatives to further describe ADC functionality and PFO interaction across many DERs and create roadmap for coordinated controls development.

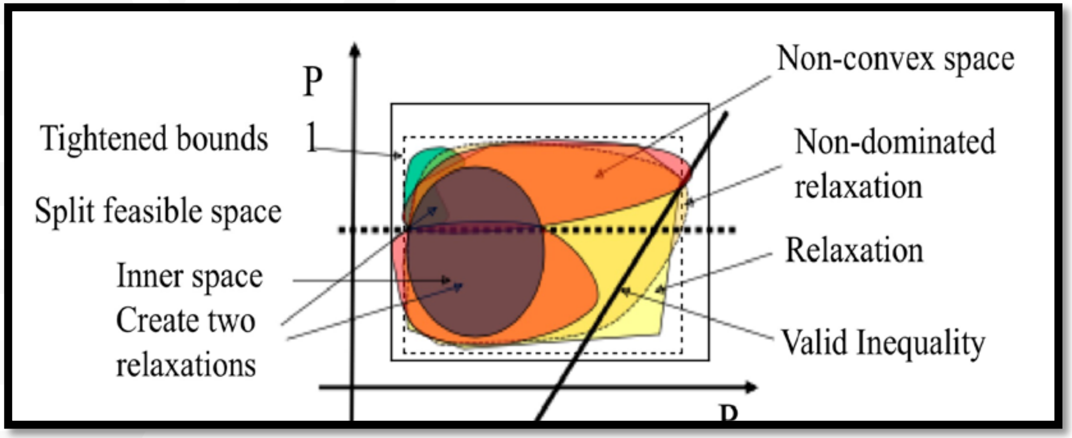
- Include technical backup here – no more than 5 slides

Control Theory
Accomplishments to Date

Power flow relaxations and approximations

- IEEE Review Article characterizing power flow formulations, relaxations, and approximations in final revisions for submission
- Developing metrics and methods for evaluation of accuracy and computational speed of each approach
- Testing will explore improvements in solution quality through simultaneous application of multiple methods
- Testing of computational efficiency and solution quality over next two quarters
- Down selecting based on qualitative assessments—probabilistic injections and power flows, discrete optimization variables



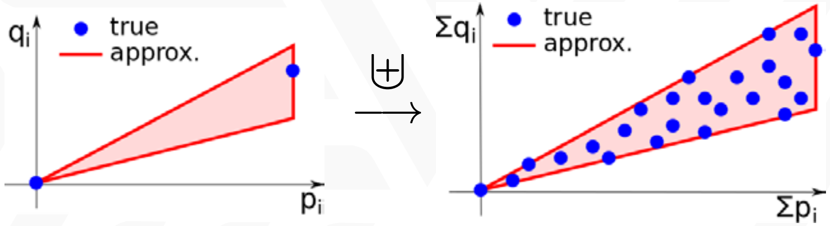


Algorithm for aggregating devices with discrete operating states

- Feasible set is a collection discrete points:
    - Switching devices (e.g. ACs, water heaters)

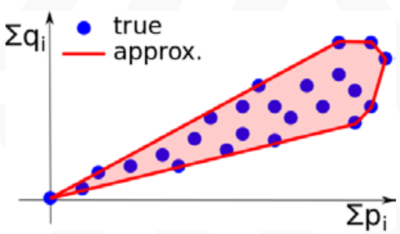
$$p_i \in \{0,\, p_i^{on}\}, \quad q_i = \gamma_i\, p_i$$

- **Method 1: Relax and aggregate** (using prototype)

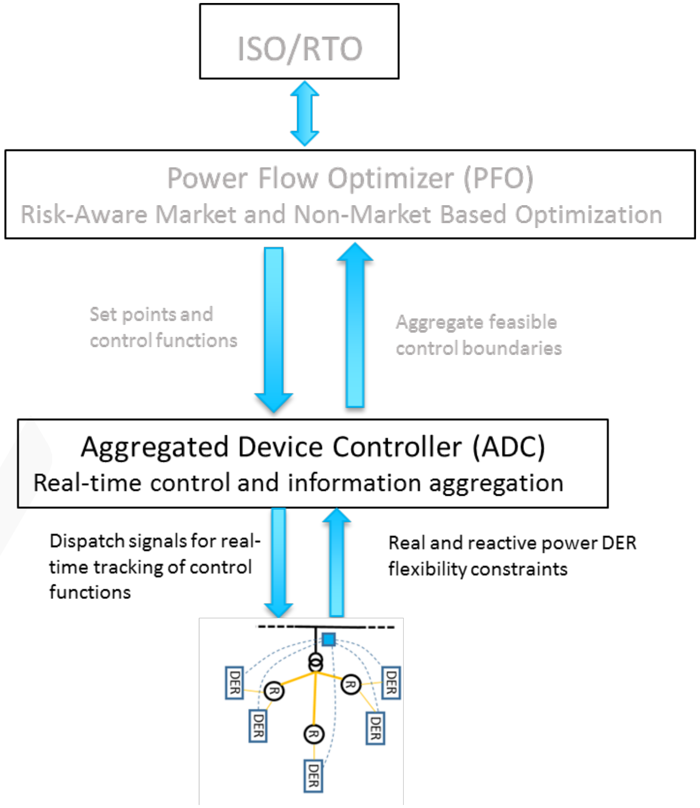


$$\mathcal{Y}_i^{\mathrm{relax}} = \left\{ (p,q) \,\middle|\, p \in [0, p_i^{on}] \,,\, q \in \left[\underline{\gamma}\, p \,,\, \overline{\gamma}\, p\right] \right\}$$

- **Method 2: Aggregate and approximate**



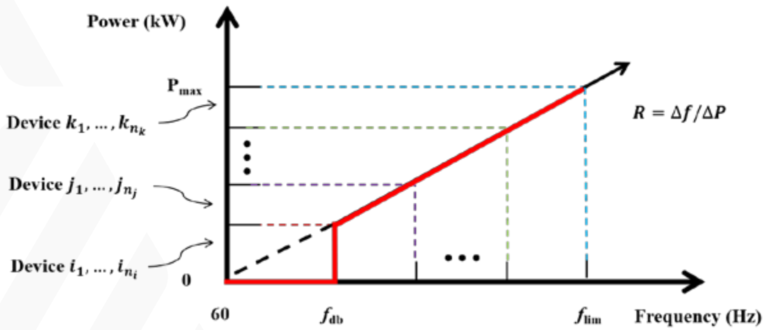
Q: Can we trace (or, approximate) the boundary of the convex hull directly?



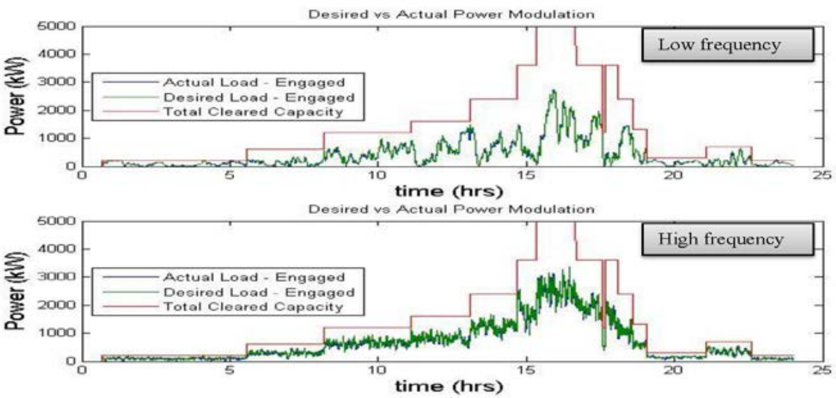
ADC level real-time controls

- Design appropriate control strategies for aggregations of heterogeneous DERs to deliver ancillary services
  - Primary frequency response
  - Secondary frequency regulation
  - Flexible ramping
- Ensure real and reactive power control requirements met simultaneously

Primary frequency response



Secondary frequency regulation



GRID MODERNIZATION INITIATIVE PEER REVIEW

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

LIANG MIN, LLNL

April 18-20

Sheraton Pentagon City – Arlington, VA

Lab team: Liang Min and Philip Top/LLNL, Mark Rice and Emily Barrett/PNNL, YC Zhang and Rui Yang/NREL, Cesar Silva-Monroy/SNL, Sidhant Misra/LANL, and Zhi Zhou/ANL

Multi-Scale Integration of Control Systems

High-Level Project Summary

Project Description

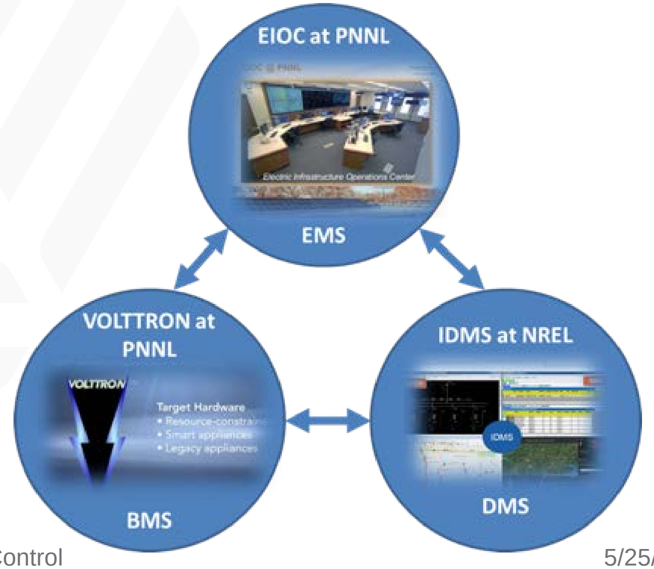
Create an integrated grid management framework for the end-to-end power delivery system – from central and distributed energy resources at bulk power systems and distribution systems, to local control systems for energy networks, including building management systems.

Value Proposition

- ✓ The current grid operating systems were developed over the last three to four decades using a piecemeal approach, within narrow functional silos.
- ✓ The rapid growth of DERs and the increased need to integrate customers with the power system are rendering the current generation of grid operating systems obsolete.

Project Objectives

- ✓ Develop an open framework to coordinate EMS, DMS and BMS operations;
- ✓ Demonstrate the new framework on a use case at GMLC national lab facilities.
- ✓ Deploy and demonstrate new operations applications on that framework.



Multi-Scale Integration of Control Systems
Project Team

Project Participants and Roles

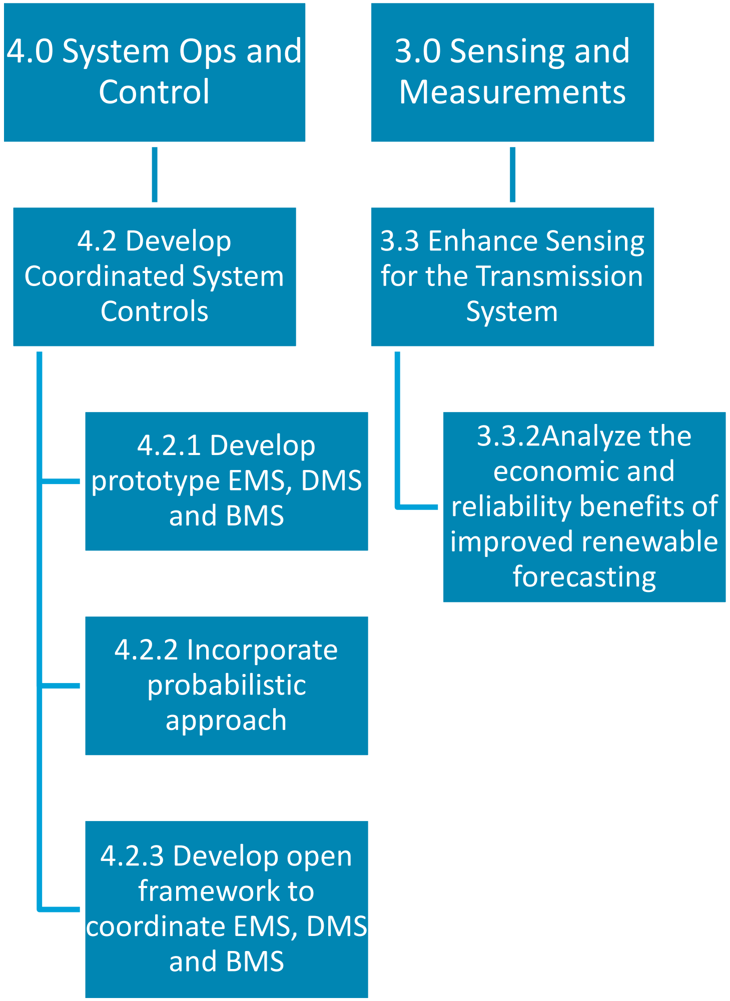
- LLNL – PI, Task 1 lead
- PNNL – Project "+1", Task 2 lead
- NREL – Key contributor to the task 1 and 2
- SNL – Task 3 lead
- LANL – Key contributor to the task 3
- ANL – Task 4 lead
- Industry partners:
  - GE– e-terra EMS and DMS providers;
  - Duke Energy – Distribution feeder data;
  - PJM Interconnection LLC – Transmission Data.

PROJECT FUNDING			
Lab	FY16 $	FY17$	FY18 $
LLNL	300	266	290
SNL	100	187	170
LANL	70	82	75
PNNL	380	276	270
ANL	150	142	150
NREL	200	197	195
Total	1200	1150	1150

Multi-Scale Integration of Control Systems
Relationship to Grid Modernization MYPP

This project will support DOE's GMI to accomplish the following three Major Technical Achievements that will yield significant economic benefits of a modernized grid

- **Reduce the economic costs of power outages.** It will help grid operators leverage distributed energy resources and avoid conditions that could lead to load shedding or cause outages.
- **Decrease the cost of reserve margins while maintaining reliability.** It will substantially reduce the amount of system reserve capacity needed to cope with generation and load fluctuations, while maintaining and even increasing system reliability.
- **Decrease the net integration costs of distributed energy resources.** EMS/DMS/BMS coordination with controllability to engage response loads will help balance the variability of DERs.



Multi-Scale Integration of Control Systems

Approach

- Technical tasks
  - Task 1: Use case development
  - Task 2: Open framework development for EMS/DMS/BMS integration
  - Task 3: Integration of new DMS/BMS applications into EMS operations models
  - Task 4: New application: EMS/DMS/BMS uncertainty modeling and forecasting method

- Key innovations and project uniqueness
  - An framework to coordinate EMS, DMS, and BMS operations, and being the FIRST in the industry to demonstrate the new framework on an industry test system.
  - New transformative operations applications (probabilistic risk-based operations and forecasting data integration and decision support) that transform or extend existing EMS and DMS applications.

Multi-Scale Integration of Control Systems
Key Project Milestones

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

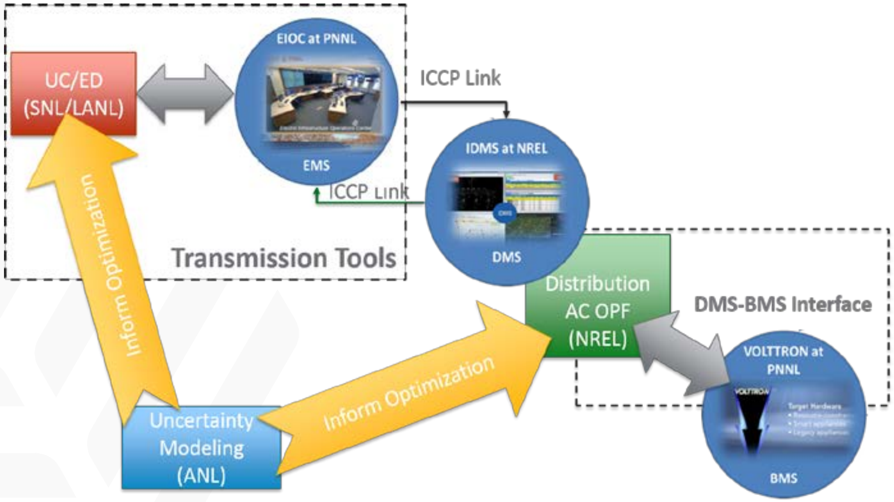
Milestone (FY16-FY18)	Status	Due Date
FY16 Mid-year Milestones: Completed the use case report and data exchange requirements/protocols report.	Done	12/1/2016
FY16 Annual Milestones: Complete integration of LANL ED with SNL UC engine; Complete integration of renewable forecasting into UC and ED.	Done	3/30/2017
FY17 Annual Milestones: Demonstrate integration of DMS and BMS information on the use case proposed under task 1; Complete the formulation of new DMS/BMS applications for EMS operations and implementation into UC/ED;	10%	3/30/2018
FY18 Annual Milestones: Successfully demonstrate integrated EMS/DMS/BMS platform; Demonstrate new DMS/BMS applications in UC/ED EMS; Demonstrate the uncertainty modeling and forecasting method in the integrated EMS/DMS/BMS system.	Not started	3/30/2019

Multi-Scale Integration of Control Systems

Accomplishments to Date

- Completed Version 1 of use case document and communication/control requirements document (Go/No-Go Milestone).
  - the connection between EIOC at PNNL and IDMS at NREL through the ICCP link (engaged the vendor, coordinating with another two GMLC projects.)
  - the connection between VOLTTRON™ at PNNL and IDMS at NREL through VOLTTRON™ Internet Protocol (Standardization is important)
- Collected Duke distribution data and Identified PJM transmission data for the Y2&3 demo.
- Presented the project goals and accomplishments at ADMS industry workshop and IEEE conferences.

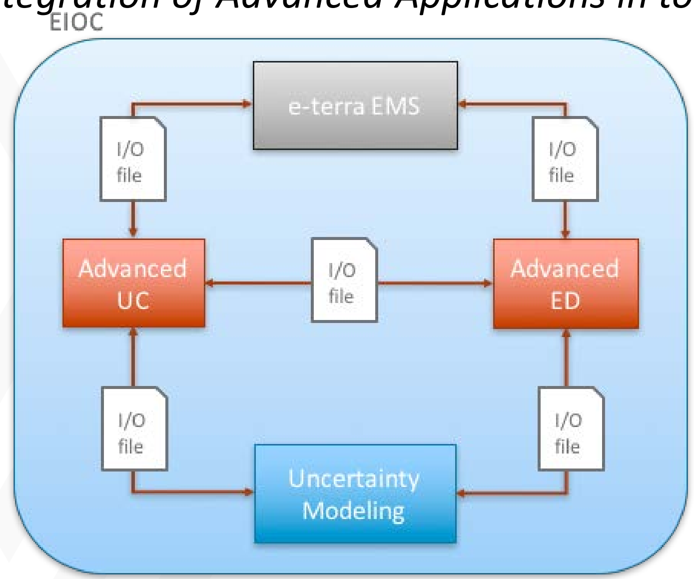
Interface Definition

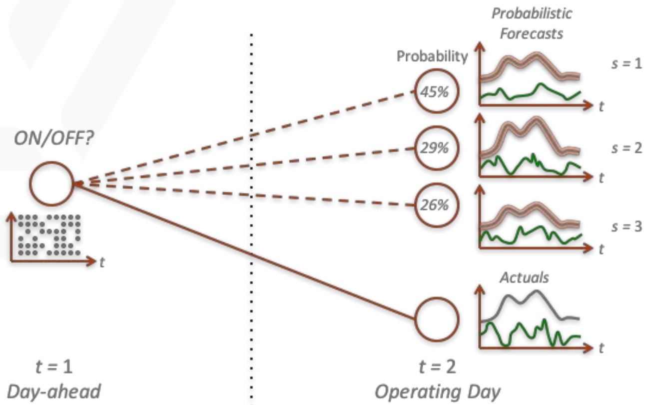


Multi-Scale Integration of Control Systems
Accomplishments to Date

- Completed the benchmarking of stochastic unit commitment and economic dispatch;
- Completed the report of a summary on major uncertainty sources for grid operations;
- Completed integration of LANL ED with SNL UC engine; Complete integration of renewable forecasting into UC and ED;
- Completed interface definition of integrating stochastic wind forecasting, stochastic UC and ED into EIOC.

Integration of Advanced Applications in to EIOC





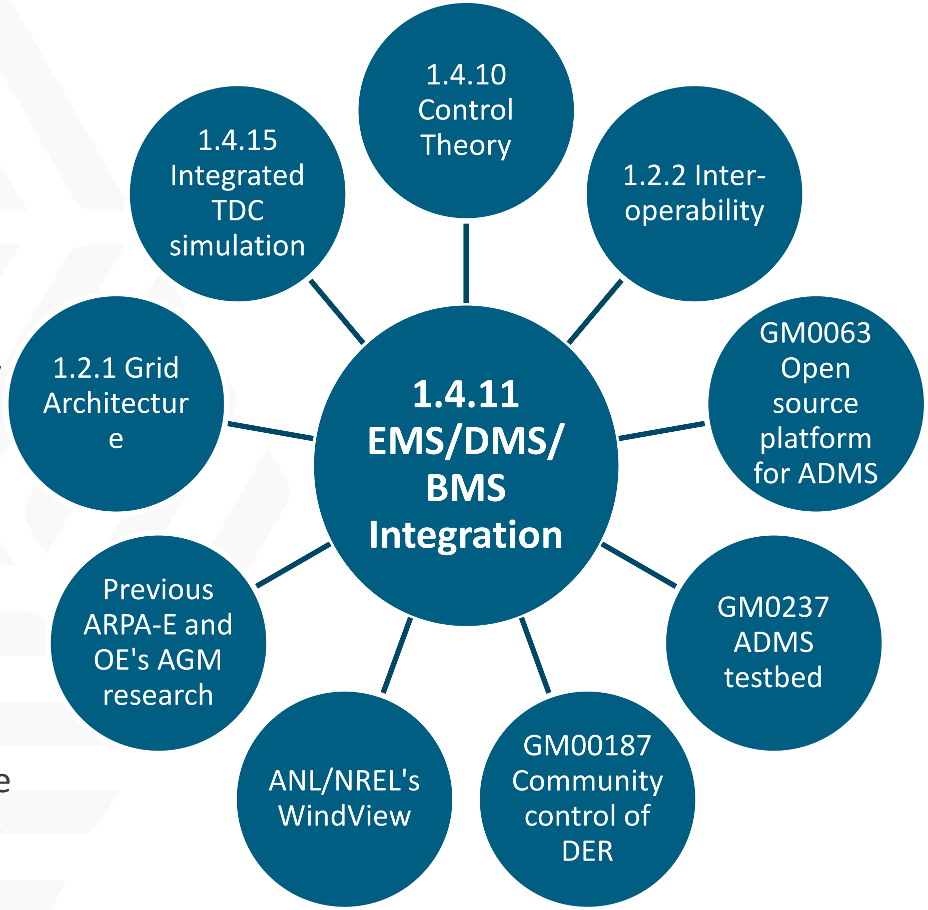
Recommendation	Response
Please make sure there is "congruence" between the use cases/test cases in the TDC design and planning tools project with this Control Theory project.	This project's use case focus on operations. The team has provided the use case to 1.4.15 Integrated Transmission, Distribution and Communication co-simulation project for coordination.

Multi-Scale Integration of Control Systems

Project Integration and Collaboration

- This project coordinates with another foundational projects -1.4.10 (control theory) and 1.4.15 (integrated TDC).
- This project coordinates with core areas 1.2.1 (grid architecture) and 1.2.2 (interoperability) to use appropriate future system architecture and interoperability standards to ensure project success.
- This project is a part of the DOE ADMS program and coordinates closely with other efforts under the program; this project coordinates with Cat 2 WindView project to visualize wind forecasting.
- This project leverages previous ARPA-E and OE’s AGM research results on stochastic optimization area.

- Participated and presented at the Advanced Distribution Management System (ADMS) Industry Steering Committee kick-off workshop, April 2016
- Participated and presented at the 2016 IEEE Innovative Smart Grid Technologies ADMS panel, September 2016
- Will present at the 2017 IEEE Innovative Smart Grid Technologies ADMS panel, April 2017.



Multi-Scale Integration of Control Systems
Next Steps and Future Plans

Key activities planned for FY17 include:

- Demonstrate the integration of DMS and BMS using Duke Energy's data by the end Q4 of FY17.
- Complete the implementation and testing of UC and ED into EIOC computational environment using PJM data by the end Q3 of FY17.
- Identify models/emulators for testing (FY17) with full-scale demonstration deployed in FY18 by the end Q4 of FY17

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Use Case Description

- Multi-scale integration of controls systems (EMS/DMS/BMS integrations) help coordinate and operate new distributed control schemes which utilize PV inverters and demand response programs to mitigate voltage instability issues.
- EMS - Out of the 10 PJM IROLs, 8 of them are reactive power interfaces. PJM dispatch utilizes the PJM Security Constrained Economic Dispatch (SCED) system to assist operators in making cost-effective decisions to control projected constraints and Reactive Interfaces.
- DMS - When voltage instability occurs, each PV inverter supplies the maximum available reactive power output and supports transmission Var emergency demand.
- BMS - Demand response programs can also be called to reduce air-conditioner compressor induction motor load. This helps recover system voltage to acceptable level instantly and prevent system voltage collapse.

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

1 Descriptions of Simulation Case

1.1 Background

Our of the 10 PJM IROL facilities, 8 of them area reactive power interfaces. PJM dispatch utilizes the PJM Security Constrained Economic Dispatch (SCED) system to assist operators in making cost-effective decisions to control projected constraints and Reactive Interfaces. PJM Real-Time Market uses the same SCED reactive interface constraints in calculating the real-time LMP. In case of voltage instability, the online VSA tool installed will provide control suggestions, for example, switching on/off capacitors and reactors, adjusting generator var output, re-dispatching generator MW output or load shedding. Besides these types of transmission level control schemes, we may also utilize distributed energy resource (such as smart inverters and demand response)-based distributed control scheme to prevent system instabilities.

Reactive Transfer Limit / Thermal Rating	Reportable IROL Violation
Eastern Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
Central Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
5004/5005 Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
Western Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
AP South Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
Bedington – Black Oak Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 minutes (T_v)
AEP-DOM Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 Minutes (T_v)
Cleveland Reactive Transfer Interface	Flow exceeds Last Convergent Case Limit for 30 Minutes (T_v)
Kammer 765/500kV Transformer Thermal Rating	Post-contingency Simulated Flows exceed the Load Dump Limit for 30 Minutes (T_v)
Belmont #5 765/500 kV Transformer Thermal Rating	Post-contingency Simulated Flows exceed the Load Dump Limit for 30 Minutes (T_v)

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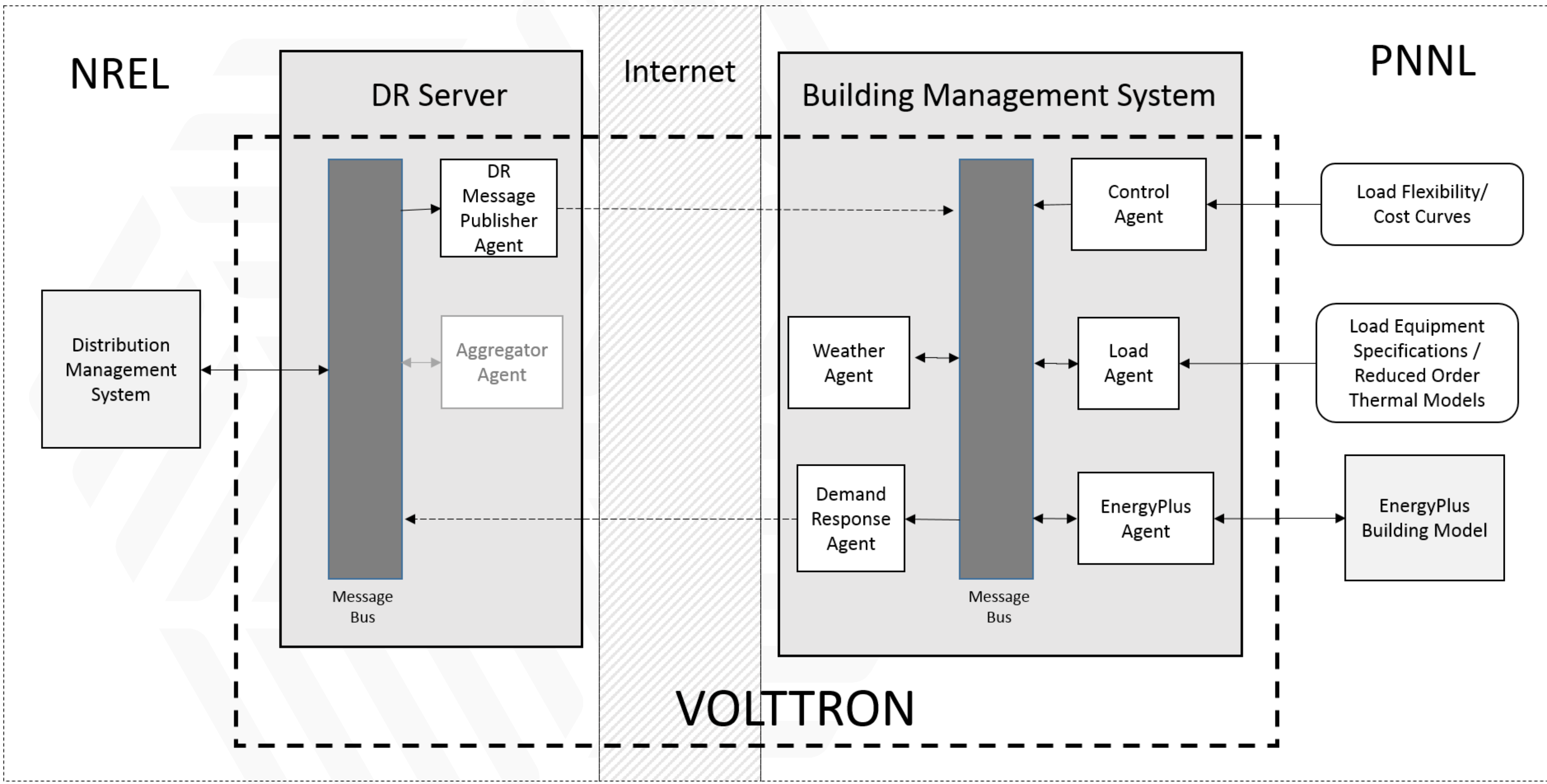
Multi-Scale Integration of Control Systems
Technical Details



Multi-Scale Integration of Control Systems

Technical Details

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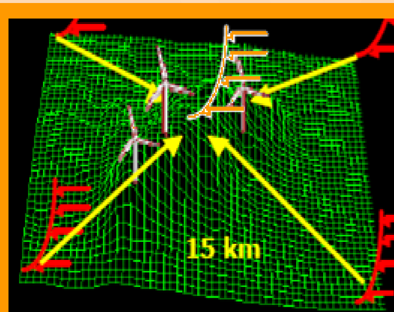
NWP Output Data

Weather Data

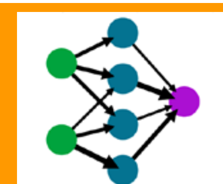
Off-site
Met Data

Site Power Gen
& Met Data



Physical Models

$$X_t = c + \sum_{i=1}^{p} \varphi_i X_{t-i} + \varepsilon_t .$$



Statistical Models

Wind Forecasts are the Result of Combination of a Diverse set of Models and Input Data

Forecast Results