SAND2014-4781C

# Aggregating Distributed Energy Resources as Secure Virtual Power Plants

*Exceptional service in the national interest*

Sandia National Laboratories


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|---|---|
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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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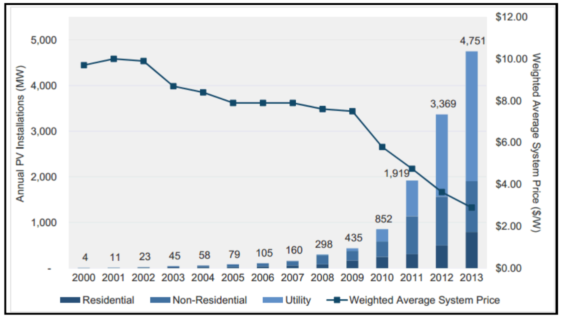
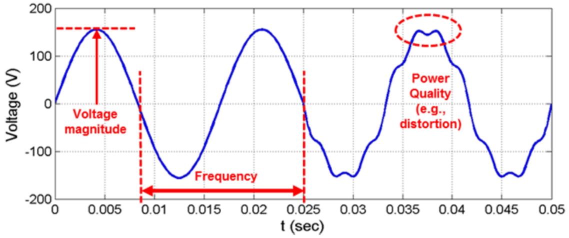
# Introduction

- Variable, non-dispatchable renewable energy is replacing traditional generators.
  - In the future, Distributed Energy Resources (DERs) will have communications and grid support functionality




- Aggregating DERs into virtual power plants enables:
  - voltage/frequency regulation and aggregate controls, e.g., dispatch, peak shaving, etc.

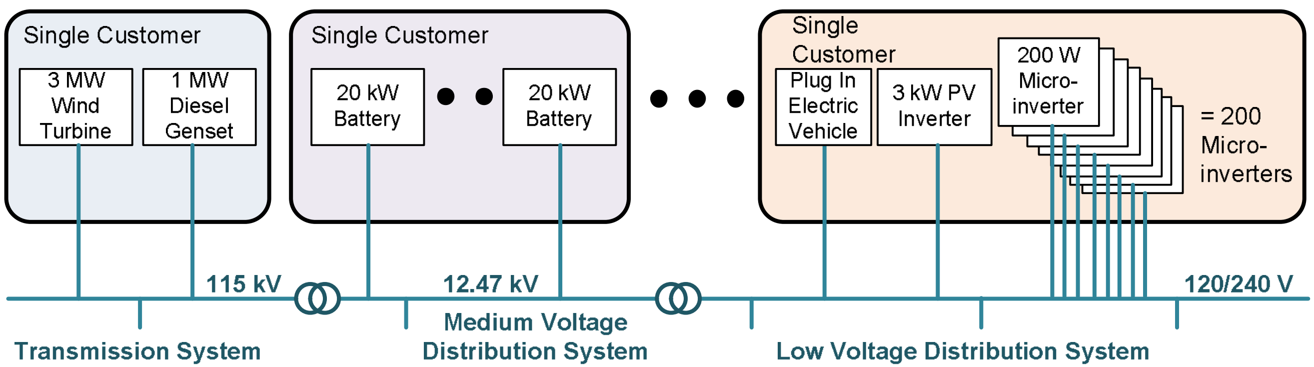



- The DETL-MdS VPP has the following novelty:
  - Employment of smaller residential-scale solar, wind, and battery systems
  - End-to-end cybersecurity over Internet networks
  - Adjust real and reactive power commands to the DERs with losses from communication failures or natural/adversarial attacks.
  - Multi-level hierarchical controls with autonomous functionality at the DER level

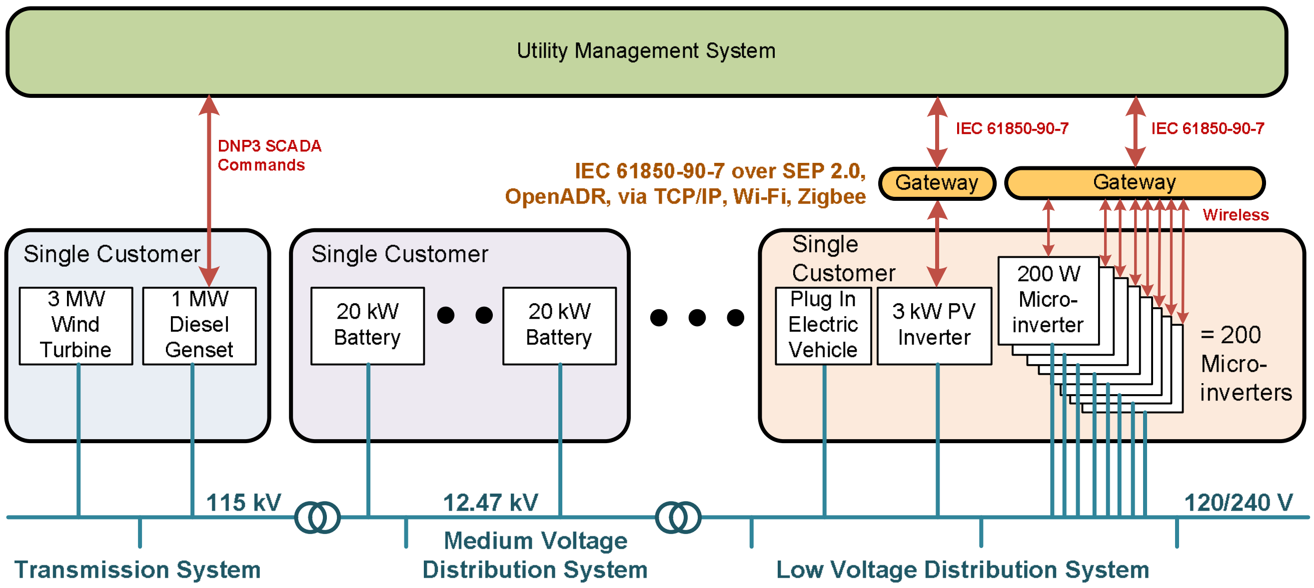
# Why fund us?

- IP: Sandia patents and publications!
  - Novel cybersecurity paradigms
  - VPP stochastic optimization incorporating forecasts
  - Coordination of DER systems to provide major grid services
  - Latency in real and reactive power commitments
  - Simulation of large advanced distribution systems using HIL techniques
- Builds a world-class research platform!
  - Ties cyber and renewable energy research programs at Sandia together for the first time!
  - Ties Sandia to Mesa del Sol for collaborative research programs!
  - The research testbed would set Sandia ahead in the following areas:
    - Virtual power plants
    - Microgrids
    - Secure communications
    - Hierarchical multi-layer controls: centralized and distributed
    - Advanced inverter functions
    - Hardware-in-the-loop simulations

# Electricity Grid

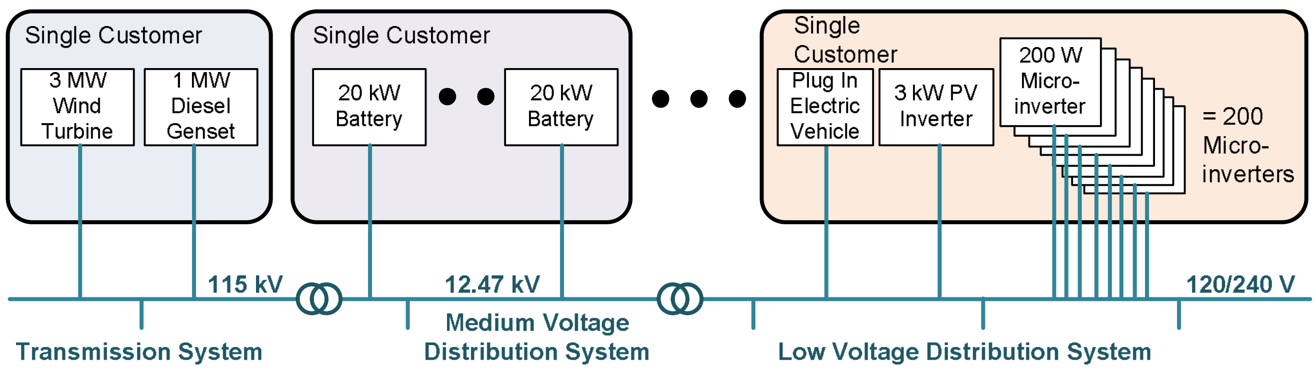


# “Smart” Grid

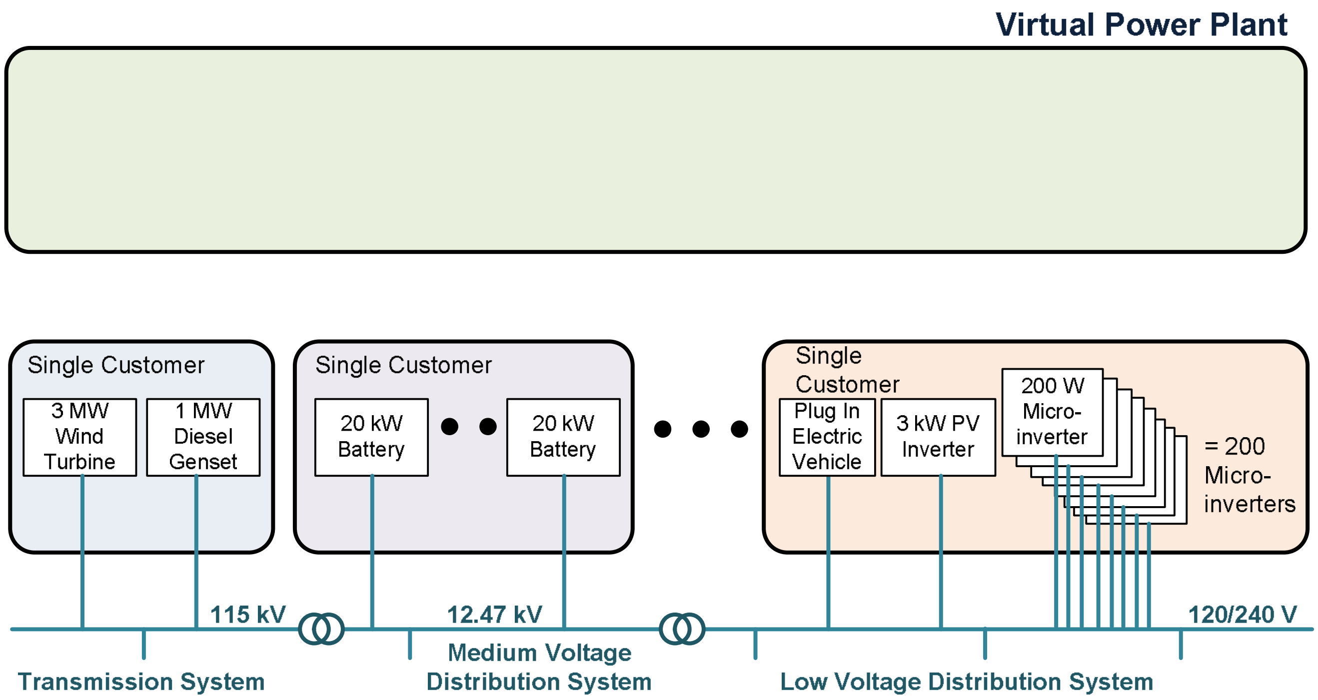


Utility Management System
DNP3 SCADA Commands
IEC 61850-90-7
IEC 61850-90-7
IEC 61850-90-7 over SEP 2.0, OpenADR, via TCP/IP, Wi-Fi, Zigbee
Gateway
Gateway
Wireless
Single Customer
3 MW Wind Turbine
1 MW Diesel Genset
Single Customer
20 kW Battery
20 kW Battery
Single Customer
Plug In Electric Vehicle
3 kW PV Inverter
200 W Micro-inverter
= 200 Micro-inverters
115 kV
12.47 kV
120/240 V
Transmission System
Medium Voltage Distribution System
Low Voltage Distribution System

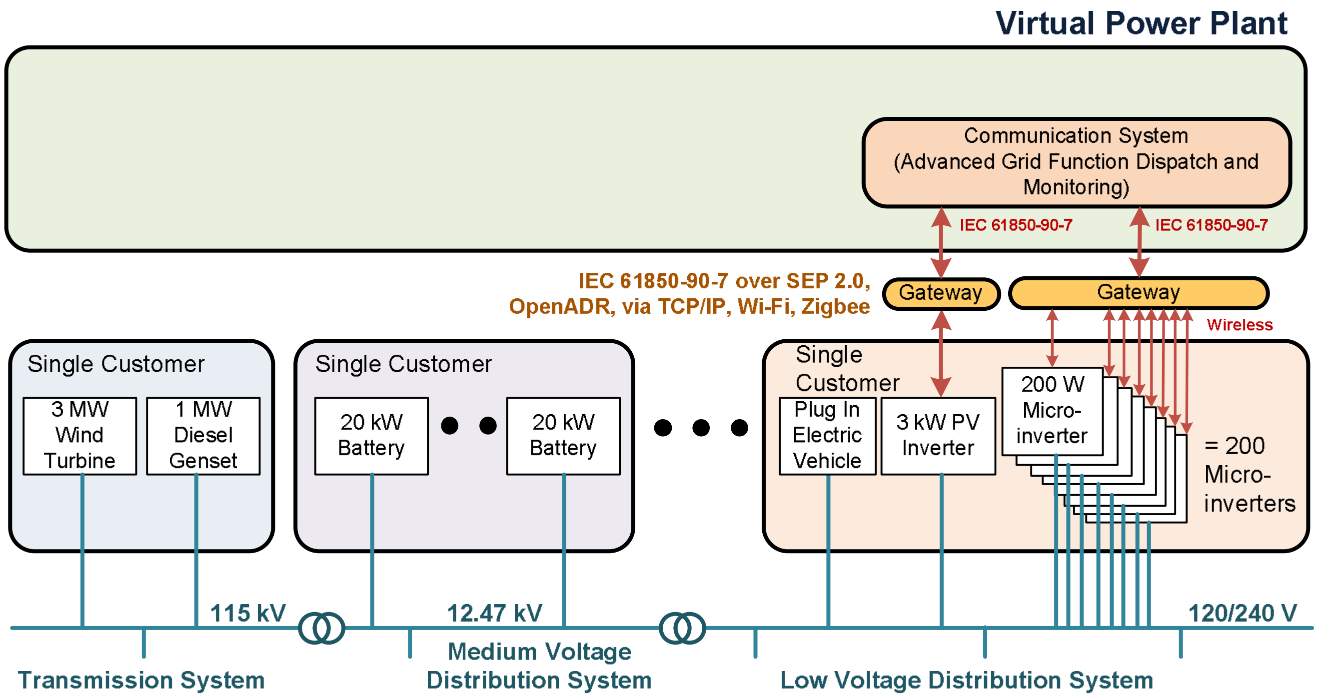
# Virtual Power Plants



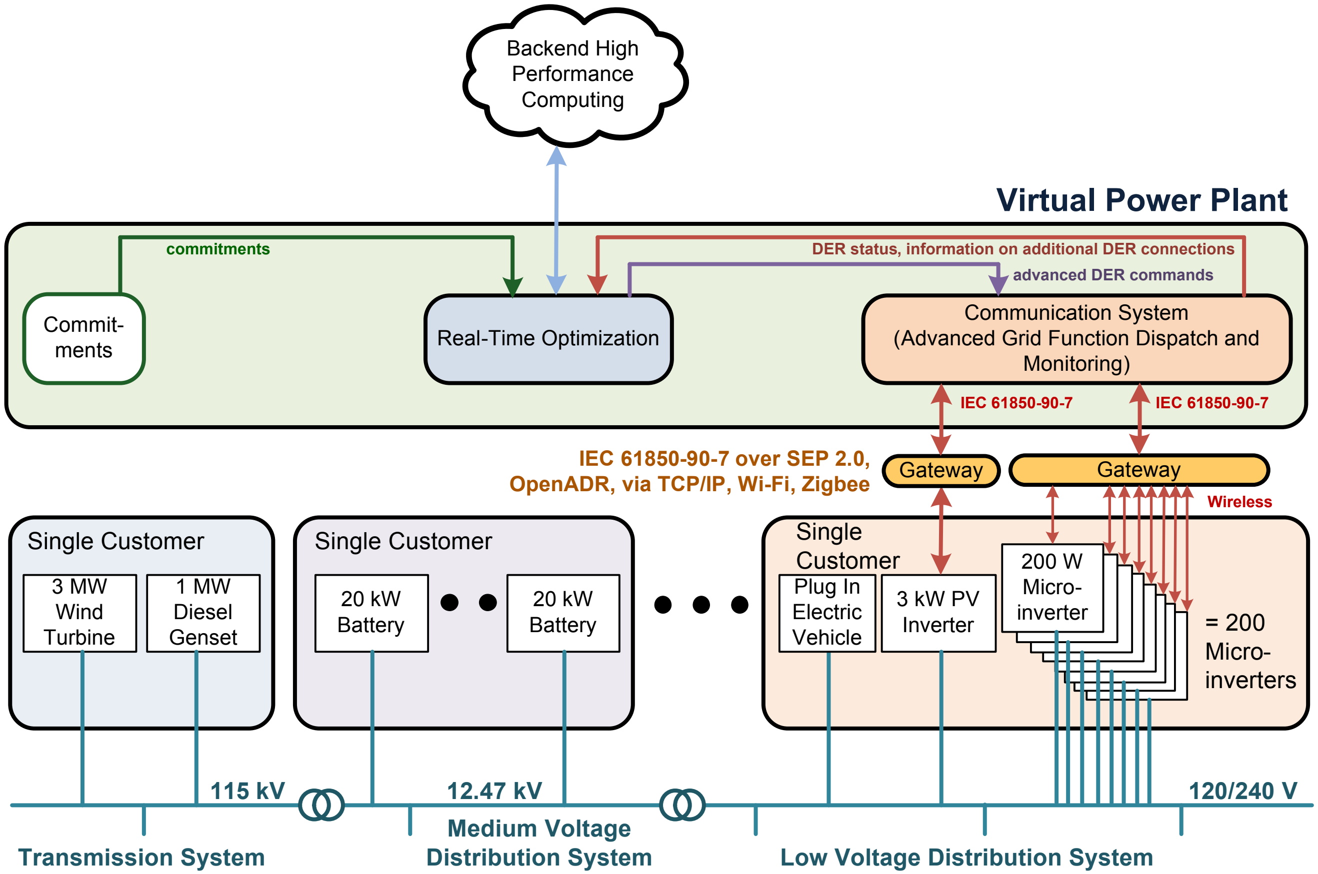
# Virtual Power Plants



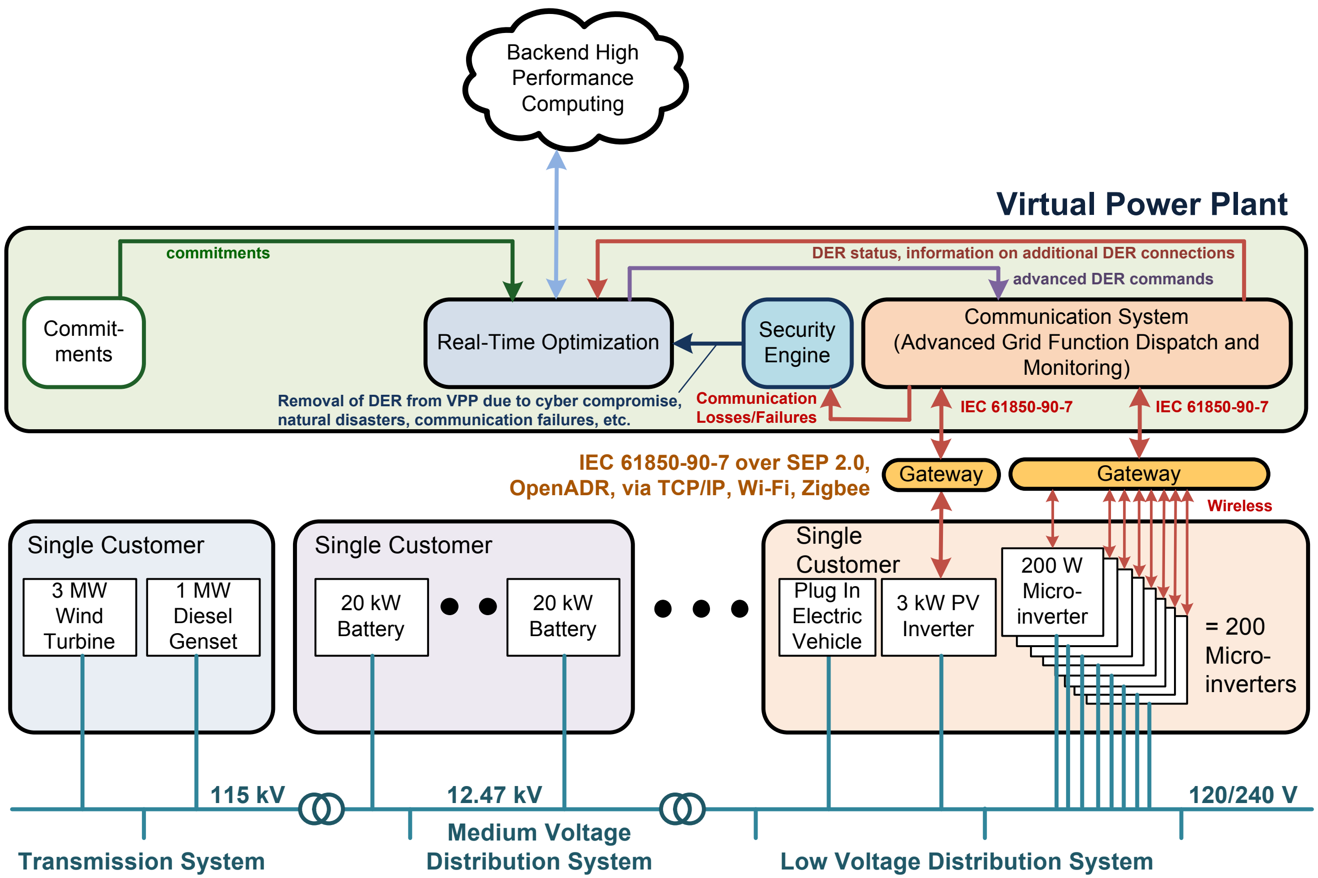
# Virtual Power Plants



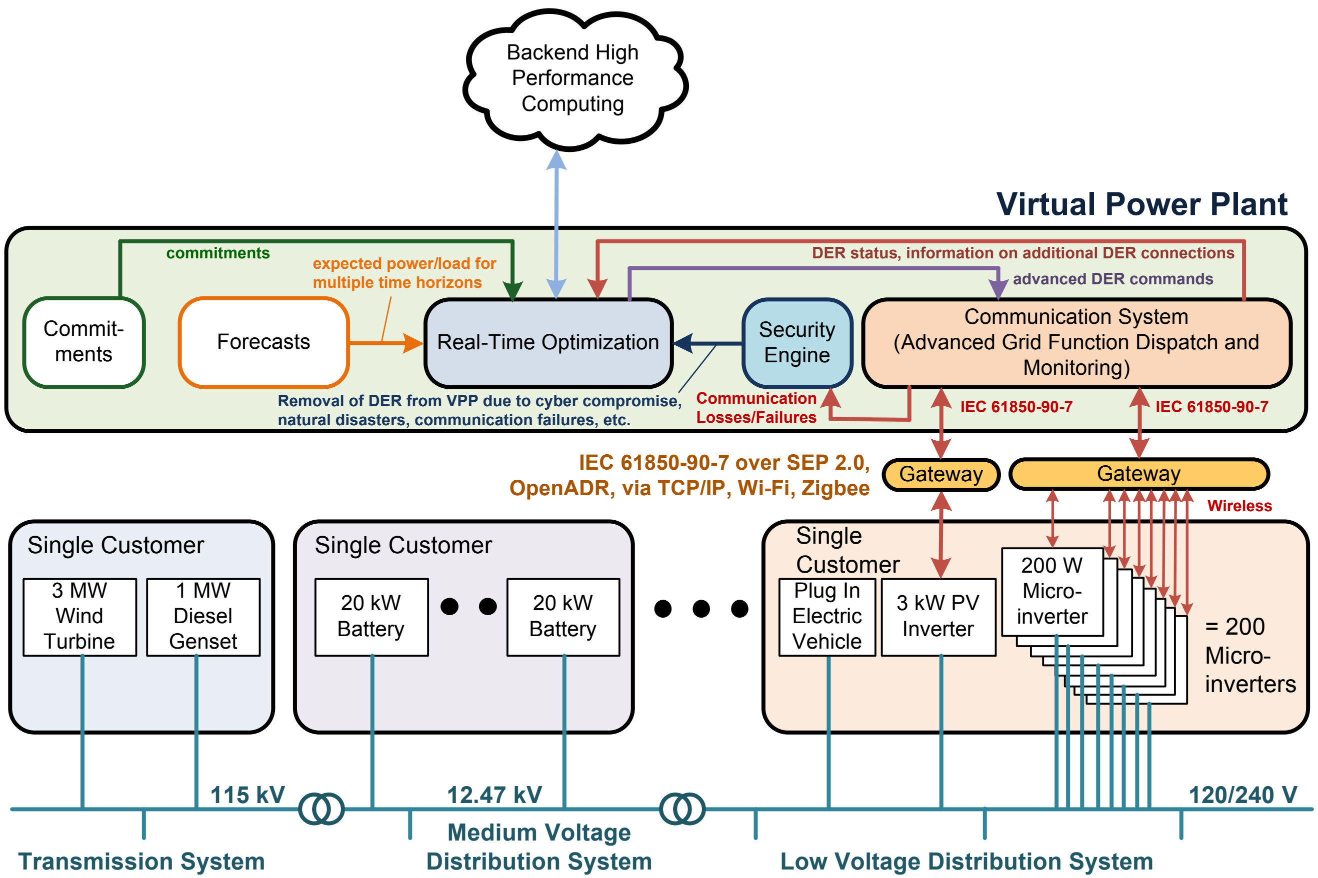
# Virtual Power Plants



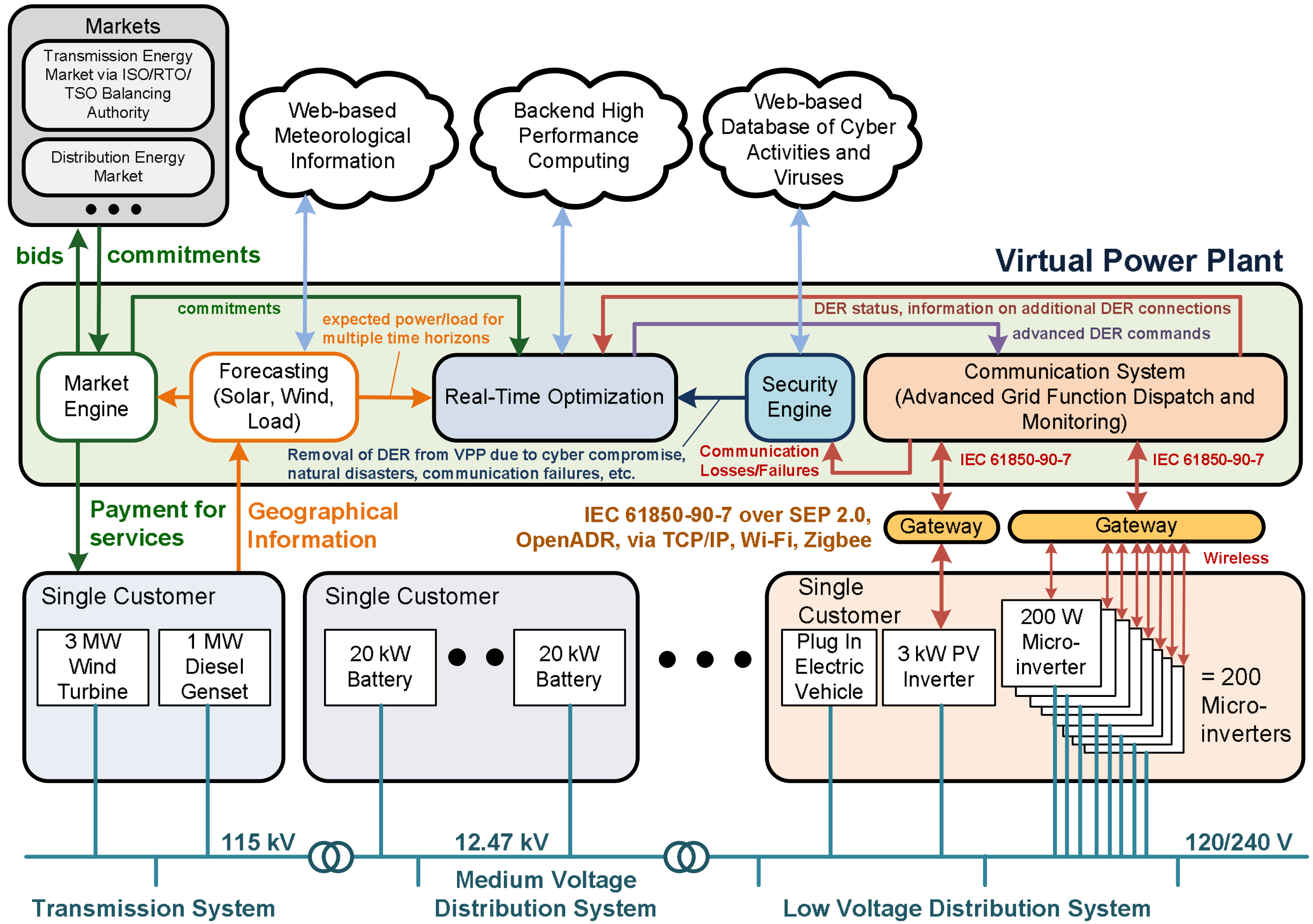
# Virtual Power Plants



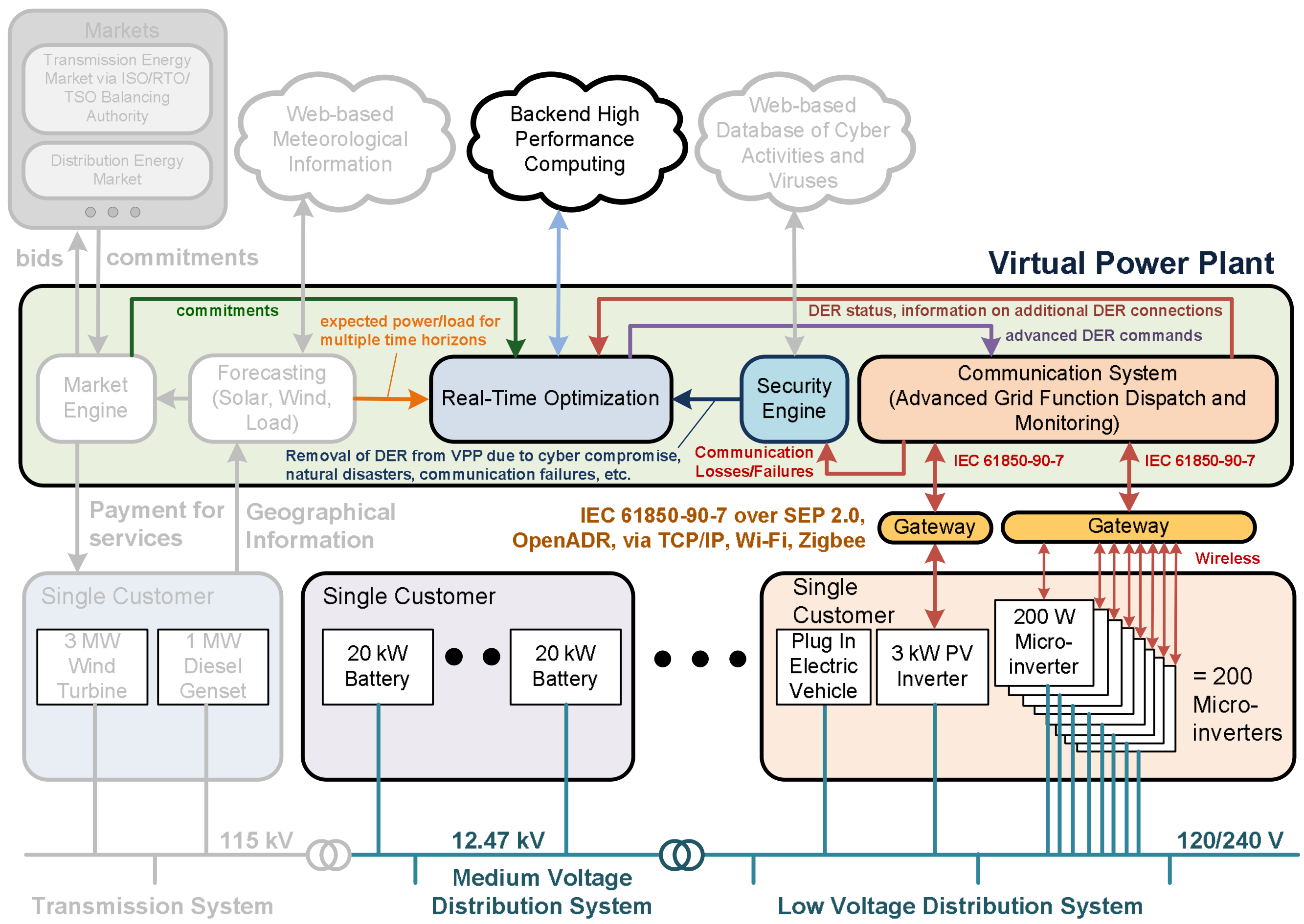
# Virtual Power Plants



# Virtual Power Plants



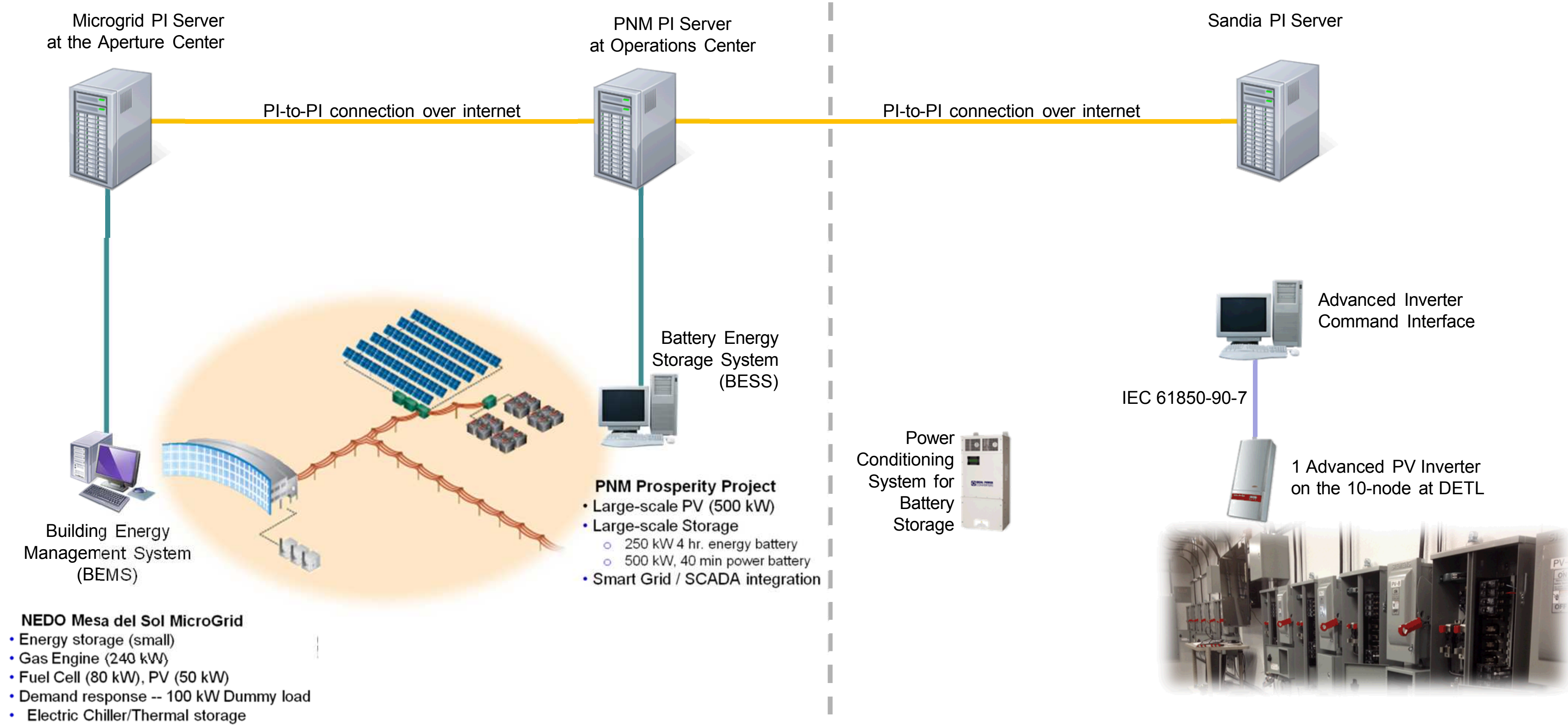
# Virtual Power Plants



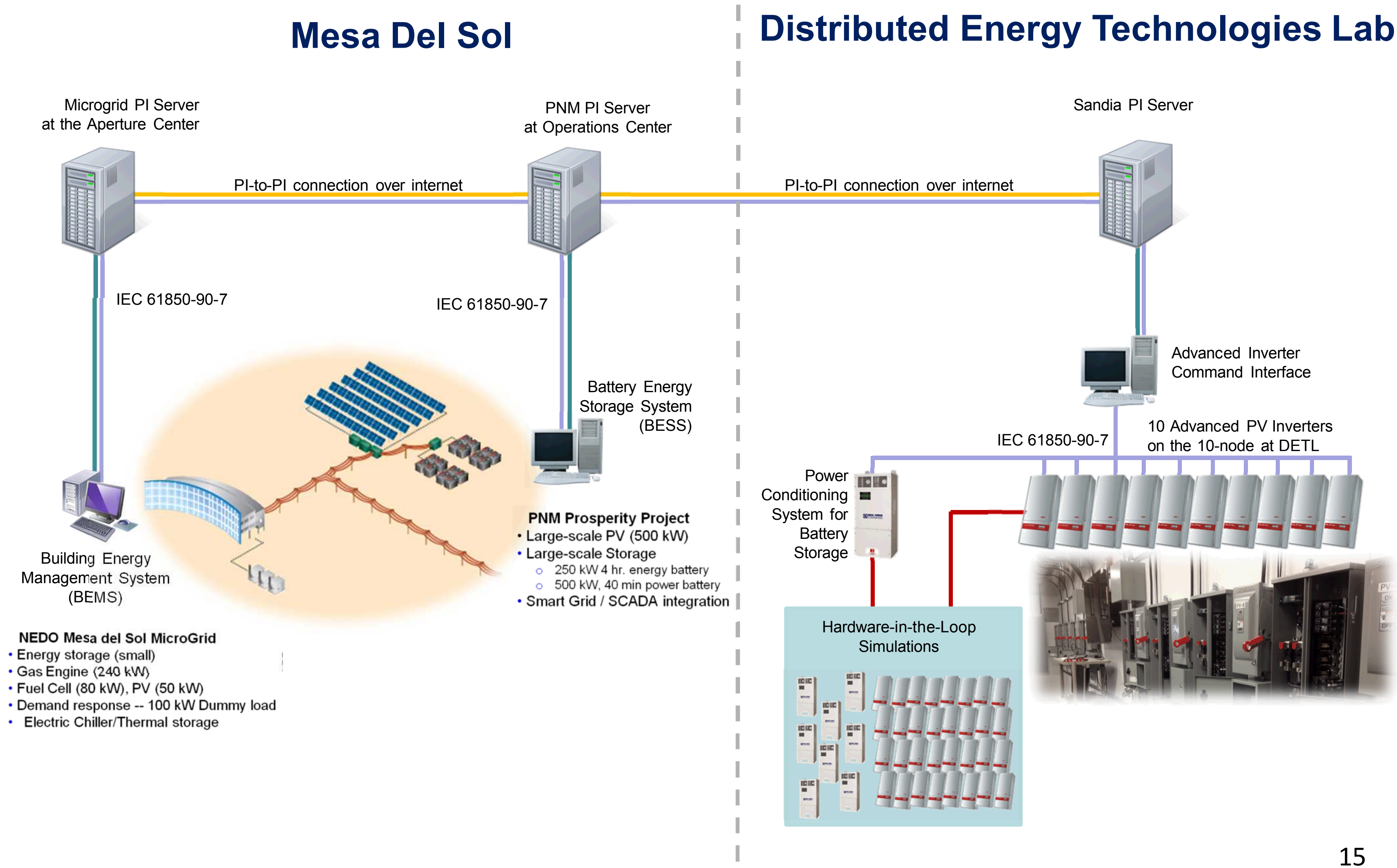
# Current Research Platform at MdS and DETL

## Mesa Del Sol

## Distributed Energy Technologies Lab

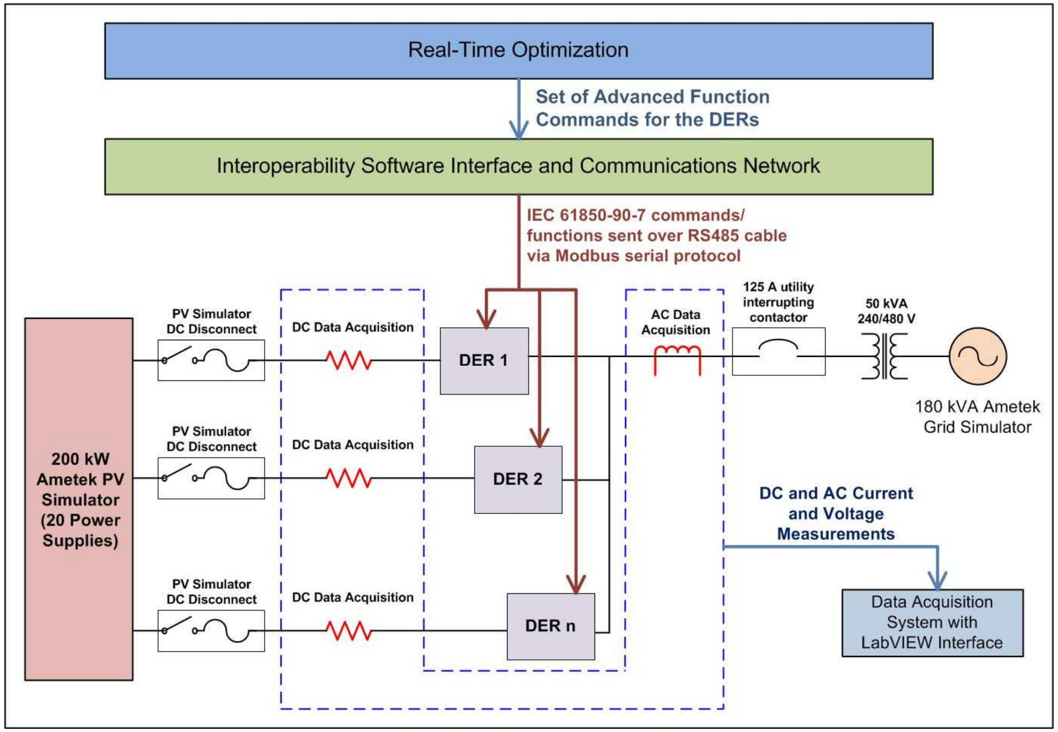


# VPP Research Platform at MdS and DETL



# Renewables Integration and Communication

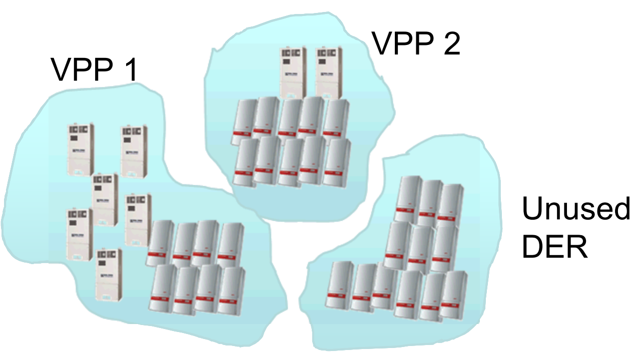
- Unique features of the DER integration and communications:
  - Incorporates residential, commercial, and utility-scale DER systems
  - Utilizes standardized IEC 61850-90-7 advanced interoperability functions
  - Development of hardware-in-the-loop capabilities at DETL will demonstrate the scalability of this concept (plus enhance the lab capabilities for future projects)
  - DETL-MdS VPP establishes end-to-end cyber-secure communications to DERs
- Why Sandia?
  - Leverages many SNL programs:
    - California Solar Initiative Grant
    - SIRFN, SNL/KERI interoperability programs
    - Smart inverter research for DOE
  - Good relationships with UNM and PNM allow integration of DETL, Prosperity, and MdS resources



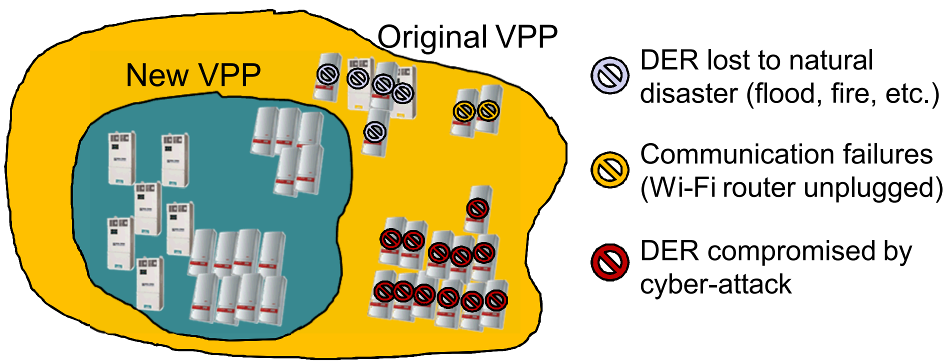
# Physical and Cybersecurity

- Unique features of the physical and cybersecurity development:
  - Robust to communication losses, natural disasters, and cyber-attacks
  - Incorporates cyber security into a large number of devices communicating over home area networks and other Internet communications
  - Segmentation strategy for cleaving DERs into resource pools that mitigate widespread corruption, and identifies and removes compromised DERs.
  - Novel data correlations to detect compromised DERs
- Why Sandia?
  - Control system cybersecurity is major area of expertise for SNL and the DETL-MdS VPP can leverage existing Critical Infrastructure Systems laboratory cyber capabilities to run cyber attacks, connect to existing infrastructure, etc.
  - Solving cyber issues for VPPs will give Sandia an edge in solving other cyber resilience problems.

**Encirclement Problem**

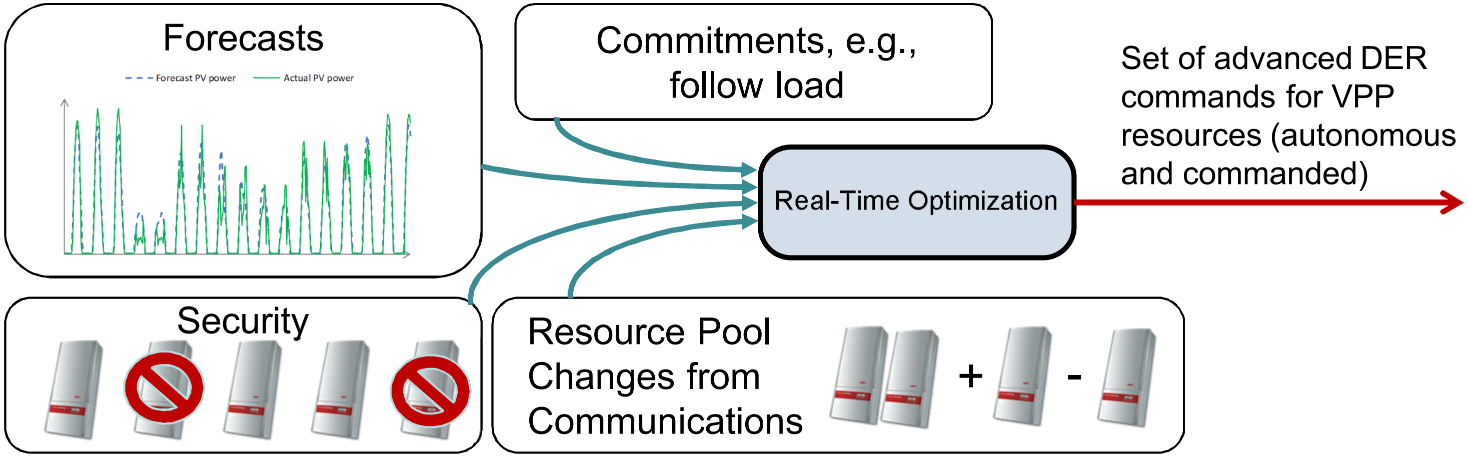



**Resource Verification Challenges**



# Controls/Optimization

- Unique features of control and optimization design:
  - Dynamically adjusts real and reactive power commands to the DERs when resources are unavailable.
  - Multi-level hierarchical controls:
    - autonomous functionality at the DER level for frequency/voltage regulation
    - commanded functions from the VPP level for slower bulk energy system needs (dispatch, peak shaving, etc.).
  - Optimal allocation of DER resources using stochastic programming (near and long-term forecasting)
  - Provides continuous corrections for forecast errors, communication failures, and cyber compromises
  - VPP autonomously dispatches commands to network of distribution-level DERs based on dynamic inputs:
    - Available resources, forecasts, commitments, prices for DER operation, fuel costs, wear/damage to DER, etc.
- Why Sandia?
  - Difficult problem to solve on multiple time scales - SNL has experience with similar optimization problems
  - Strong controls and stochastic optimization expertise with access to high performance computing support



# Funding and tasks for the 3-year project

| | Communication System (Advanced Grid Function Dispatch and Monitoring) | Security Engine | Real-Time Optimization |
|---|---|---|---|
| **Year** | **Renewables Integration** | **Cyber** | **Control/Optimization** |
| FY15 | FY Funding: 40%<br>• Build the physical DETL testbed with 2-5 PV inverters<br>• Build the communications network to DETL and MdS<br>• Begin mapping advanced grid functions (AGFs) to aggregated results | FY Funding: 30%<br>• R&D assessment<br>• Initial list of power system / network data correlations to detect compromised DERs<br>• Design power network segmentation (compromised DER containment) | FY Funding: 30%<br>• Create 1st edition of controller with cyber and communication losses.<br>• Optimization on preliminary or artificial data<br>• Map in forecasting (placeholder)<br>• Map in commitments (placeholder) |
| FY16 | FY Funding: 40%<br>• Complete mapping advanced grid functions (AGFs) to aggregated results<br>• Find battery partners for DETL energy storage system (ESS) demonstration<br>• Begin hardware-in-the-loop system design and construction.<br>• Close the control loop by sending DER measurements to the optimizer through the communication system | FY Funding: 30%<br>• Perform laboratory testing to evaluate efficacy of initial cybersecurity solutions<br>• Refinement of data correlations and segmentation strategy | FY Funding: 30%<br>• Optimize the system with real-time DER losses<br>• Incorporate commercial real-time forecasting tool for the renewable energy sources at MdS and DETL<br>• Improve accuracy of meeting commitments |
| FY17 | FY Funding: 20%<br>• Final DETL implementation with 10 inverters and ESS and HIL.<br>• Final MdS and Prosperity implementation with optimized communications to the DER. | FY Funding: 40%<br>• Hardware and software implementation - Demo: baseline vs. advance cyber tool | FY Funding: 40%<br>• Fully implement the optimization with forecasting, cyber tools, and communications links to life DER<br>• Demonstrate the commitments are met for different scenarios. |

# Conclusions

- Sandia development of Secure Virtual Power Plants will:
  - Increase the quantity of renewable energy on the electricity grid
  - Improve the electric grid resiliency and safeguard U.S. energy infrastructure
- This multi-disciplinary research builds on close relationships with research and utility partners
- Major advances (IP!) will be made in:
  - stochastic optimization
  - advanced coordinated DER controls (both centralized and decentralized)
  - secure communications and cybersecurity
  - DER interoperability and advanced functionality
- The project will align Sandia to do renewable energy and cyber research in the future!
  - MdS-DETL-Cyber Lab research platform would be extremely powerful
  - Funding opportunities from DOE, DOD, and others

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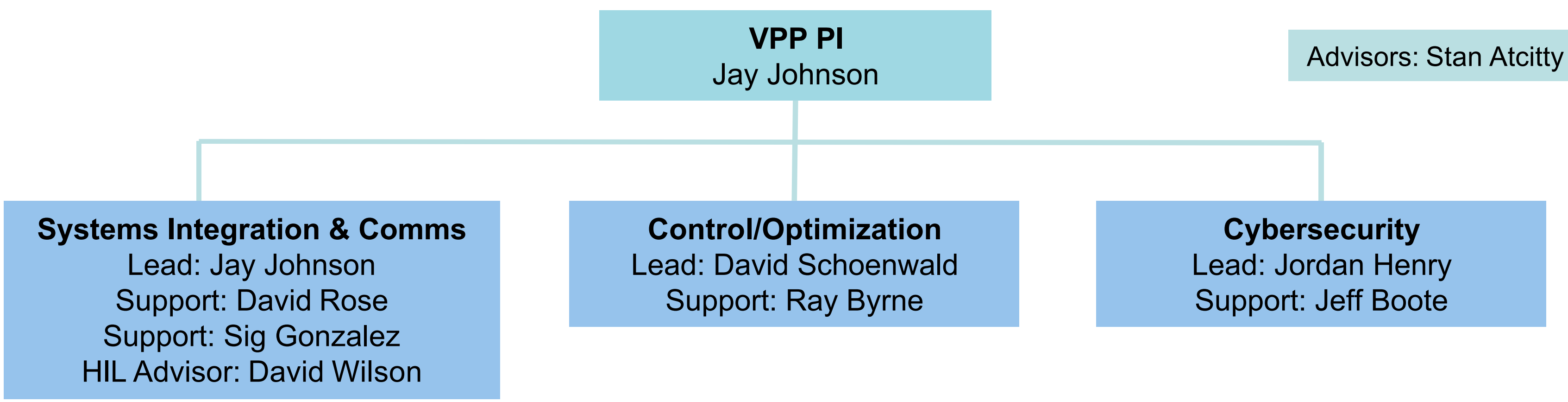
# Backup Information

# Team Organization

| Name | Org | FTE | Role |
|---|---|---|---|
| Jay Johnson (PI) | 6112 | 0.35 | PI, system integration |
| Jordan Henry | 5628 | 0.25 | Cybersecurity lead |
| David Schoenwald | 6113 | 0.20 | Control algorithm development |
| Sigifredo Gonzalez | 6112 | 0.20 | DETL DER integration lead |
| David Rose | 6111 | 0.15 | Storage integration |
| David Wilson | 6122 | 0.10 | Optimization and hardware-in-the-loop |
| Stan Atcitty | 6111 | 0.10 | Power electronics and controls |
| Jeff Boote | 8961 | 0.10 | Networking and cybersecurity |
| Raymond Byrne | 5511 | 0.10 | Aggregator control development |



# Budget

| FY | Labor | Purchases | Subcontracts | Travel | Total |
|---|---|---|---|---|---|
| FY15 | $410k | $60k | $20k | $10k | $500k |
| FY16 | $450k | $20k | $20k | $10k | $500k |
| FY17 | $470k | $0k | $20k | $10k | $500k |

- The $20k/year subcontract will fund PNM and UNM personnel to support VPP experiments at MdS.

# Milestones

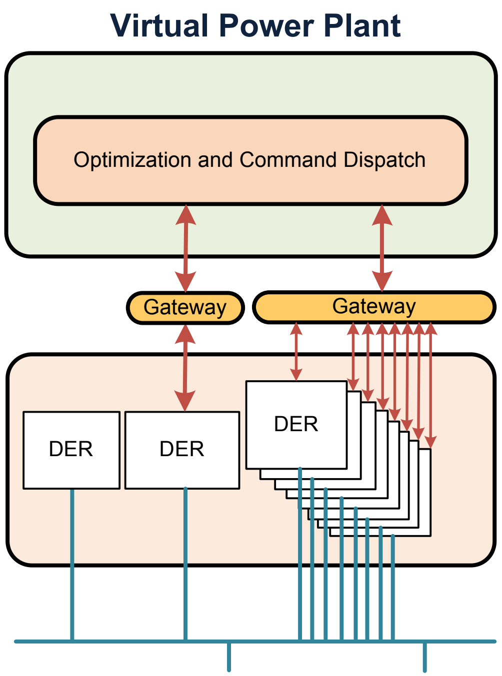
| Objective/Milestone | Date |
|---|---|
| **Objective 1 – Cybersecurity:** Develop a secure end-to-end VPP cybersecurity framework that establishes a robust and secure communication overlay infrastructure for VPP communications, implements novel methods of detecting compromised devices, and segments devices into resource pools to mitigate the effects of successful attacks. | 9/30/2017 |
| **Milestone:** Develop:<br>1) a comprehensive list of novel data correlations between DER power information and network information that can be used to detect compromised DERs, and<br>2) a segmentation strategy specific to VPPs that cleave DERs into power pools in a way that maximizes security and minimizes consequences and common-mode vulnerabilities. | 9/30/2015 |
| **Go/No Go Milestone:** Evaluate:<br>1) the efficacy of power and network system data correlations that successfully detect compromised DERs, and<br>2) the effectiveness of the proposed segmentation strategies to mitigate and recover from successful attacks. | 9/30/2016 |
| **Milestone:** Deploy effective and resilient cyber security framework on the fully-integrated VPP platform, utilizing combined DG at DETL and MdS, and extended with HIL simulation. | 6/30/2017 |
| **Objective 2 - Stochastic Controls:** Design control architecture and stochastic control methods for handling cyber/communication losses, optimization on DER field measurements, forecast information, and commitment satisfaction. | 9/30/2017 |
| **Milestone:** Create first version of control architecture and model VPPs for validation. | 9/30/2015 |
| **Go/No Go Milestone:** Create second version of controller to enable optimization using real-time forecasting and model DETL-MdS VPP for validation. | 9/30/2016 |
| **Milestone:** Deploy control and communications architecture on the fully-integrated VPP platform, utilizing combined DG at DETL and MdS, and extended with HIL simulation. | 6/30/2017 |
| **Objective 3 – System Integration:** Demonstrate integrated VPP control and cybersecurity paradigms in the complete DETL-MdS implementation, verifying all control, optimization, integration, and cybersecurity functions. | 9/30/2017 |
| **Milestone:** Expand DETL hardware/software and use real-time simulation capabilities to establish preliminary research environment which supports mapping advanced grid functions (AGF) to aggregated results. Evaluate effectiveness of commitment-to-AGF command deployment. | 9/30/2015 |
| **Go/No Go Milestone:** Complete mapping of AGFs to aggregated results, finalize optimization and communication system control loop, and demonstrate proof-of-concept HIL development. | 9/30/2016 |
| **Milestone:** Based on input from a technical review committee, implement and verify a secure VPP in the DETL-MdS research platform by simulating adversarial attacks. Validate adaptability and resiliency of the VPP framework compared to an unsecure baseline system. | 6/30/2017 |
| **Milestone:** Collaborate with PNM to demonstrate utility-scale VPP capabilities. | 8/30/2017 |
| **Milestone:** Final SAND Report | 9/30/2017 |

# Rule 21 Functions

| Appendix | Function or Communication Verification | Rule 21 Name | Central or distributed control |
|---|---|---|---|
| 1 | Anti-Islanding Protection (AI) | R21-1-AI | D |
| 2 | Low/High Voltage Ride-through (L/HVRT) | R21-1-L/HVRT | D |
| 3 | Low/High Frequency Ride-through (L/HFRT) | R21-1-L/HFRT | D |
| 4 | Volt-Var Mode with Watt-Priority | R21-1-VV11 | D |
| 5 | Ramp Rates | R21-1-RR | D |
| 6 | Fixed Power Factor | R21-1-INV3 | D |
| 7 | Soft Start | R21-1-SS | D |
| 14 | Monitor Alarms | R21-3-A | C |
| 15 | Monitor DER Status and Output | R21-3-DS93 | C |
| 16 | Limit Maximum Real Power | R21-3-INV2 | C/D |
| 17 | Connect/Disconnect | R21-3-INV1 | C |
| 18 | Provide DER Information at Interconnection/Startup | R21-3-INFO | C |
| 19 | Initiate Periodic Tests of Software and Patches | R21-3-TEST | C |
| 20 | Schedule Output Limits at PCC | R21-3-WSchd | C |
| 21 | Schedule DER Functions | R21-3-Schd | C |
| 22 | Schedule Storage | R21-3-SSchd | C |
| 23 | Frequency-Watt Mode | R21-3-FW | D |
| 24 | Voltage-Watt Mode | R21-3-VW | D |
| 25 | Dynamic Current Support | R21-3-TV31 | D |
| 26 | Limit Maximum Real Power | R21-3-Wlim | C |
| 27 | Set Real Power | R21-3-INV4 | C |
| 28 | Smooth Frequency Deviations | R21-3-Ffix | D |
| 29 | Backup Power | R21-3-BP | C |
| 30 | Imitate Capacitor Bank Triggers | R21-3-CAP | C/D |
| 31 | Operate within an Islanded Microgrid | R21-3-I | C |
| 32 | Provide Low Cost Energy | R21-3-COST | C |
| 33 | Provide Low Emissions Energy | R21-3-LEE | C |
| 34 | Provide Renewable Energy | R21-3-RE | C |
| 35 | Execute Schedules | R21-3-ES | C |
| 36 | Issue Generation and Storage Schedules | R21-3-S | C |
| 37 | Provide Black Start Capabilities | R21-3-BS | C |
| 38 | Participate in Automatic Generation Control | R21-3-AGC | C |
| 39 | Provide Spinning or Operational Reserve | R21-3-R | C |
| 40 | Real Power Response to Demand Response Price Signals | R21-3-PS | C/D |
| 41 | Manage Ancillary Service Response to Demand Response Signals | R21-3-INV5 | C/D |
| 42 | Registration (Automated DER Discovery) | R21-3-REG | C |

# VPP Functionality and Operating Modes

- Multi-level Control Concept




**Global, centralized, slow control**
- Provide Spinning or Operational Reserve
- Backup Power
- Operate islanded
- Provide Low Emissions Energy
- Participate in Automatic Generation Control

**Local, decentralized, fast control**
- Frequency control and ride-through (FW, FRT)
- Voltage control and ride-through (VV, VRT)
- Ramp rates
- Watt-Power factor
- Volt-Watt

# Optimization

- VPP optimizes based on
  - Profits from provided power (market situation)
  - Costs due to providing power or other services (fixed revenue situation or completely contained within a single utility).
    - Includes fuel costs and other operations and maintenance issues for each technology.
  - Renewable energy provided (green initiatives/constraints)
  - Minimizes wear on DER
- VPP handles:
  - DER availability/capability events (e.g. DER full and partial failures)
  - Communication losses/failures
  - Cyber compromises
  - Power flow contingencies (e.g. transmission/distribution events within VPP boundaries)
- VPP incorporates one or more of
  - Load forecasts
  - Renewable energy forecasts

# Optimization Phases

- Create simulated VPPs for testing and validation of control/optimization designs
  - Assemble and/or develop models of different types of DERs
  - Assemble and/or develop models of simple power flow networks connecting DERs
  - Assemble and/or develop models of simple power flow networks connecting VPP to larger grid
  - Validate models using simple data
- FY15 - Design version 1.1 control/optimization engine that provides power flow assignments with few constraints to DERs within a VPP
- FY15 - Upgrade version 1.1 control/optimization engine to version 1.2 control/optimization engine which will additionally incorporate cyber security measures to handle cyber events and comm losses
- FY15 - Upgrade version 1.2 control/optimization engine to version 1.3 control/optimization engine which will additionally incorporate the capability to utilize forecasting information
- FY15 - Upgrade version 1.3 control/optimization engine to version 1.4 control/optimization engine which will additionally incorporate the capability to satisfy commitments
- FY16 - Create simulated VPP that mimics MdS and DETL satisfactorily for testing and validation of control/optimization designs
- FY16 - Undertake major revision to version 1.4 control/optimization engine to version 2.1 control/optimization engine that is more specifically developed for the DETL-MdS VPP and incorporates real-time forecasting tool for the renewable energy resources at MdS and DETL
- FY16 - Upgrade version 2.1 control/optimization engine to version 2.2 control/optimization engine to significantly improve accuracy in meeting commitments for DETL-MdS VPP
- FY16 - Substantially improve version 2.2 control/optimization engine to version 3.1 control/optimization engine to fully incorporate forecasting information, cyber tools, and communication links for the DETL-MdS VPP
- FY17 - Fully implement version 3.1 control/optimization engine on actual DETL-MdS VPP
- FY17 - Design demonstration scenarios to show essential features of version 3.1 control/optimization engine
- FY17 - Demonstrate version 3.1 control/optimization engine on various scenarios