NREL
Transforming ENERGY

Advanced Inverters: (1547) Capabilities, Experiences, and Interaction with **Hosting Capacity**

Bryan Palmintier, PhD
Principal Research Engineer and Group Manager
National Renewable Energy Laboratory (NREL)

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Hosting Capacity with Advanced Inverter Functions
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Outline

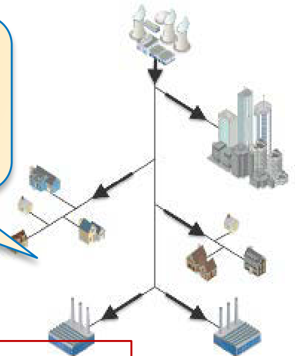
1. Smart Inverters and IEEE1547
2. Volt-VAR, Hosting Capacity, and Secondaries, Oh My!
3. Beyond Hosting Capacity (Upgrade Cost Estimates)
4. Communication & External Controls (& QSTS Hosting Capacity)
5. 1547 Round out
6. Thinking Beyond Distribution
7. Co-simulation and Data Support/Tools

Evolution of the Grid → Evolution of Distributed Energy Resource (DER) behavior

Slide courtesy of Dr. Ben Kroposki, NREL

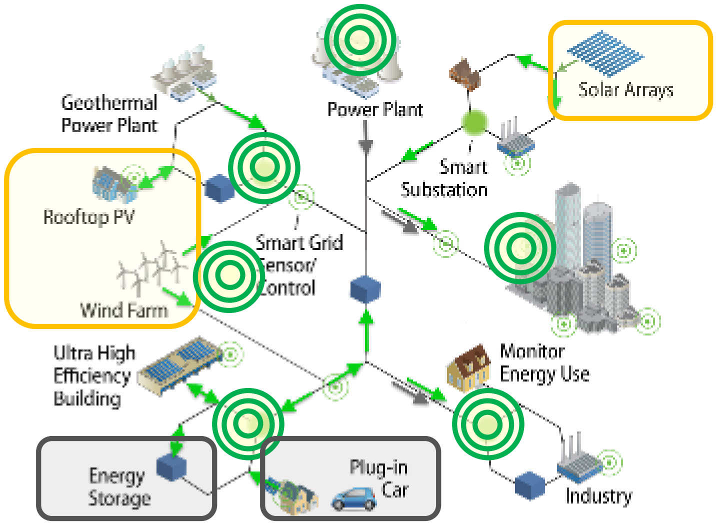
Current Power System

- Large Generation
- Central Control
- Highly Regulated



IEEE 1547-2003 World

Emerging Power System



IEEE 1547-2018 World

DRIVERS

- Increased variable generation
- More bi-directional flow at distribution level
- Increased number of smart/active devices
- Evolving institutional environment

Our Evolving Power System Context

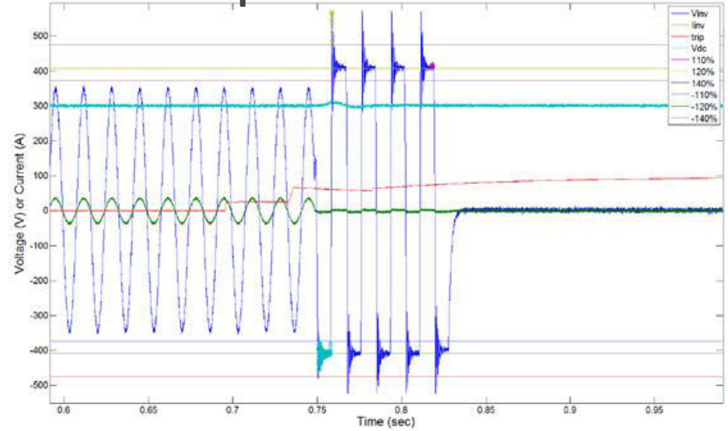
- New energy technologies and services
- Increasing penetration of variable renewables
- New communications and controls (e.g. Smart Grids)
- Electrification of transportation
- Integrating distributed energy storage
- A modern grid needs increased system flexibility
- Updated standards – e.g. IEEE 1547-2018

Early Advanced Inverter Success: NREL, HECO, and SolarCity

NREL with SolarCity and the Hawaiian Electric Company (HECO) completed preliminary work conducted at ESIF demonstrating the ability of advanced PV inverters to mitigate some transient overvoltage impacts of high pen PV on distribution grids.

As a result, HECO has now expedited the installations of solar PV systems on circuits with over 120% of daytime minimum load if the PV systems are installed with advanced inverters that meet stricter requirements.

Sample Waveform



What makes an inverter "smart"?

Frequency Ride-Through

Voltage Ride-Through

Frequency-Watt

Volt-Watt

Volt-VAR

Grid Forming

Virtual Inertia

Momentary Cessation

Reliability Services

Load-smoothing

Enhanced Controls

+ Existing Power Electronics

Grid Support

Anti-Islanding

Dynamic reactive current

Ramp Limits

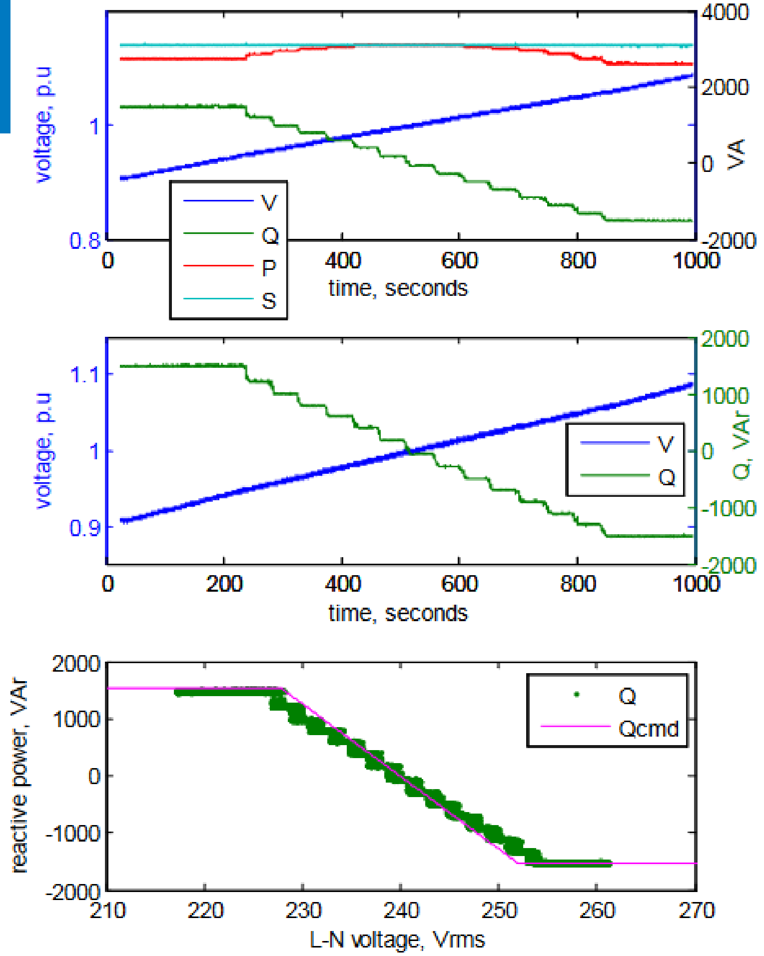
IEEE 1547 Evolution of Grid Support Functions

IEEE 1547-2003	• Shall NOT actively regulate voltage • Shall trip on abnormal voltage/frequency
IEEE 1547a-2014 (Amendment 1)	• **May** actively regulate voltage • **May** ride through abnormal voltage/frequency • **May** provide frequency response[1] (frequency-droop)
IEEE 1547-2018	• **Shall be capable of** actively regulating voltage • **Shall** ride through abnormal voltage/frequency • **Shall be capable of** frequency response[2] • **May** provide inertial response[3]

[1]Frequency response is capability to modulate power output as a function of frequency
[2]Mandatory capability for Categories II and III under high frequency conditions, Mandatory for Categories II and III under low frequency conditions, optional for Category 1
[3]Inertial response is capability for DER to modulate active power in proportion to the rate of change of frequency

2013: Find the Hidden Advanced Functions

- Many inverters sold in the US have had advanced capabilities for years that was not enabled
- At right: NREL lab test of 2012 off-the-shelf US-model inverter, with ride-through, volt-var, and frequency-watt control capability



https://www.nrel.gov/docs/fy14osti/60931.pdf

1547-2018 Active Voltage Regulation Capabilities

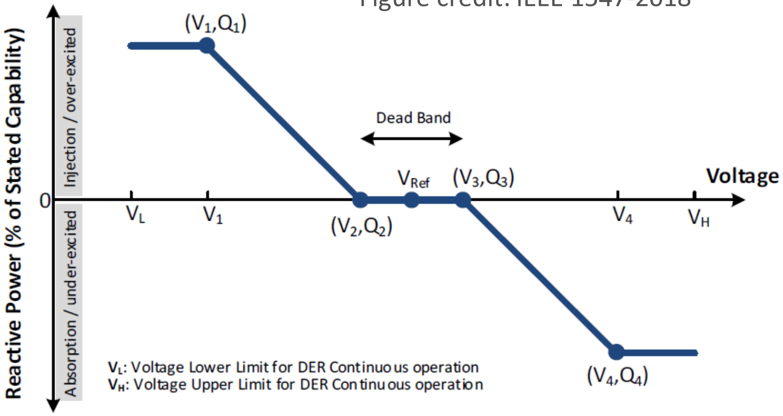
*“The DER shall provide voltage regulation **capability** by changes of reactive power. The approval of the Area EPS Operator shall be required for the DER to actively participate in voltage regulation.”*

Category A

Capability required for all DER – (Cat A, B)

- Constant power factor mode
- Constant reactive power mode
- Voltage-reactive power mode (“volt-var”) →

Figure credit: IEEE 1547-2018



Category B

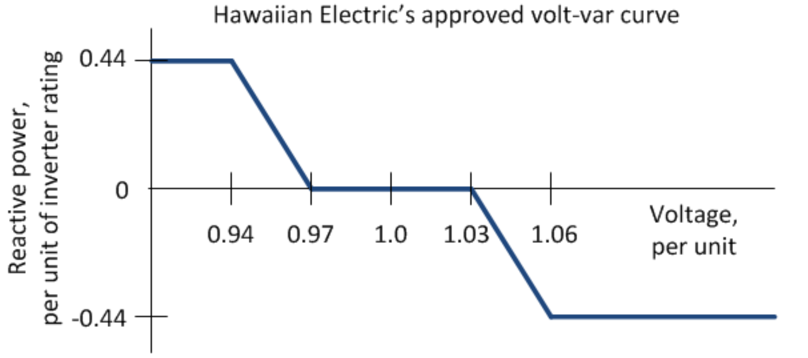
“State-of the art” DER – Cat B

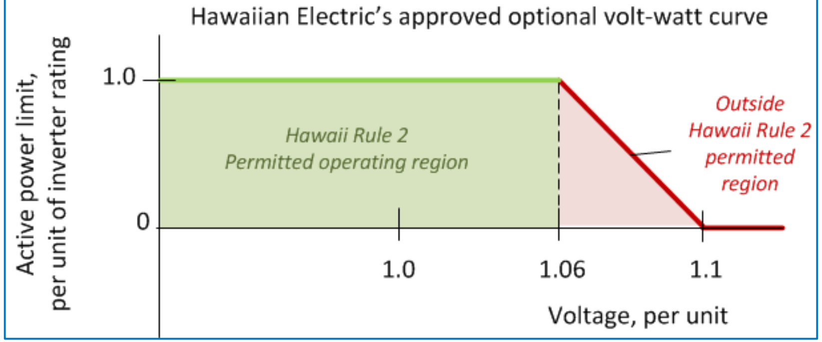
- Active power-reactive power mode (“watt-var”)
- Voltage-active power mode (“volt-watt”)

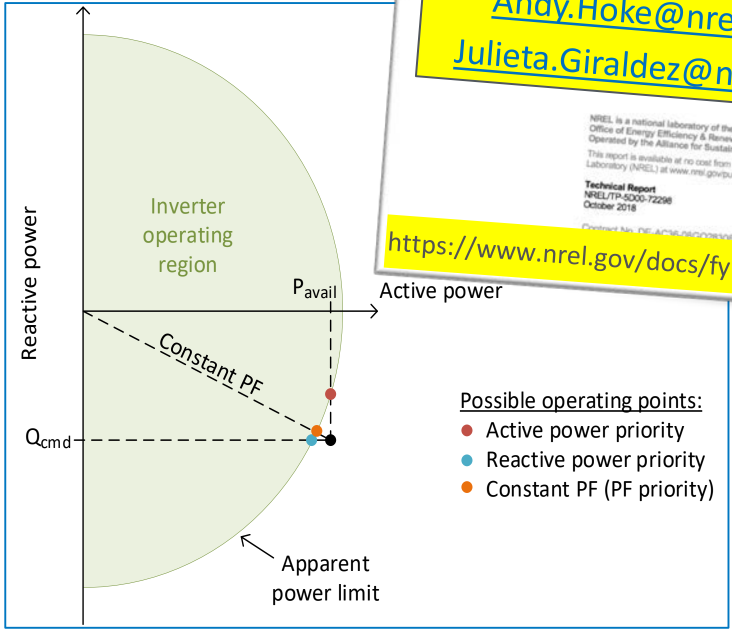
The area EPS operator (utility) shall specify the required voltage regulation control modes and the corresponding parameter settings. Modifications of the settings and mode selected by the EPS operator shall be implemented by the DER operator.

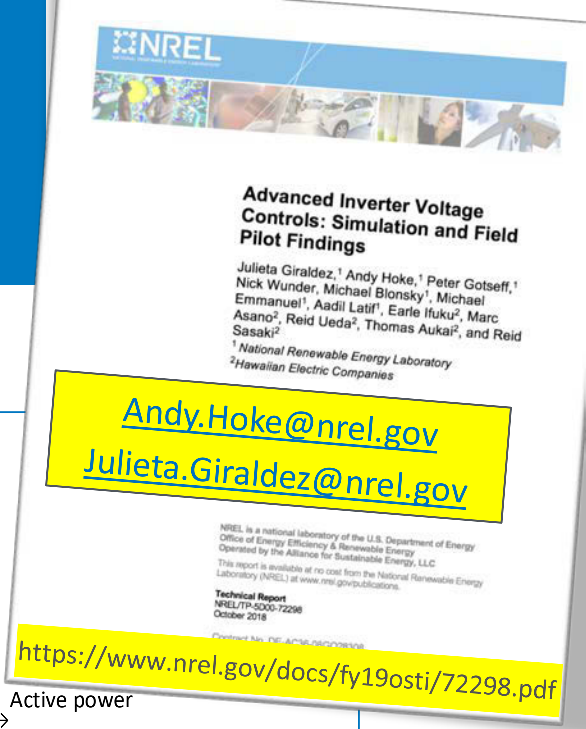
Settings can be adjusted locally or remotely

NREL-HECO Voltage Regulation Operating Strategies (VROS) with Customer-Sited Resources









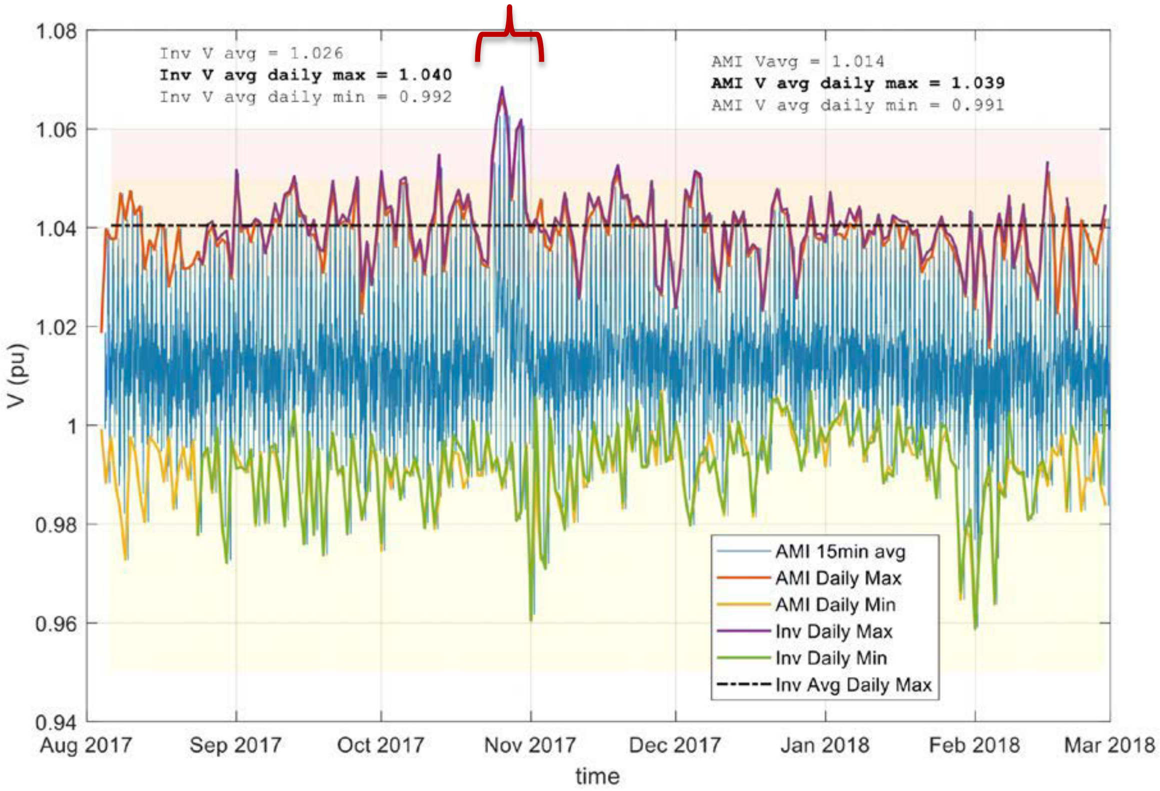
Andy.Hoke@nrel.gov

Julieta.Giraldez@nrel.gov

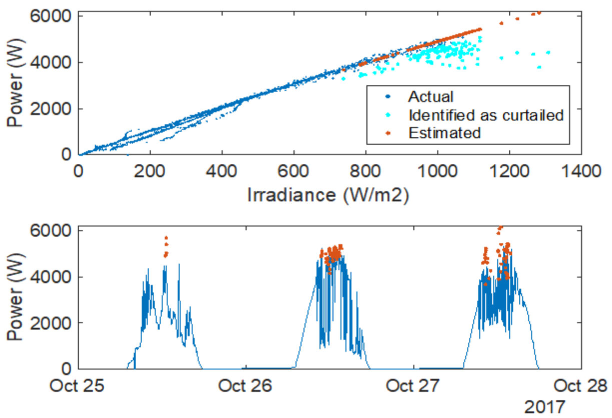
https://www.nrel.gov/docs/fy19osti/72298.pdf

Field pilot: Cluster 1 (on M34 feeder)

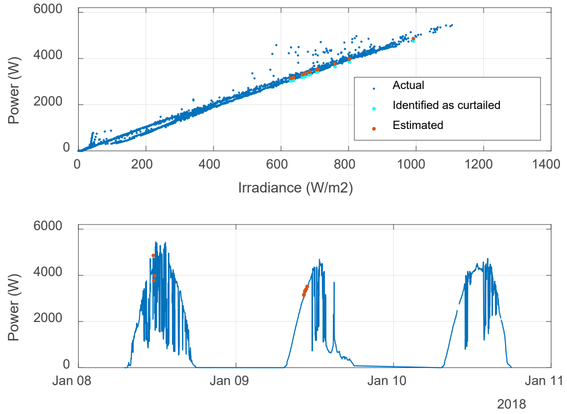
Higher voltages due to temporary primary configuration



Curtailment during high voltage period: 1.6%



Curtailment during typical period: 0.04%

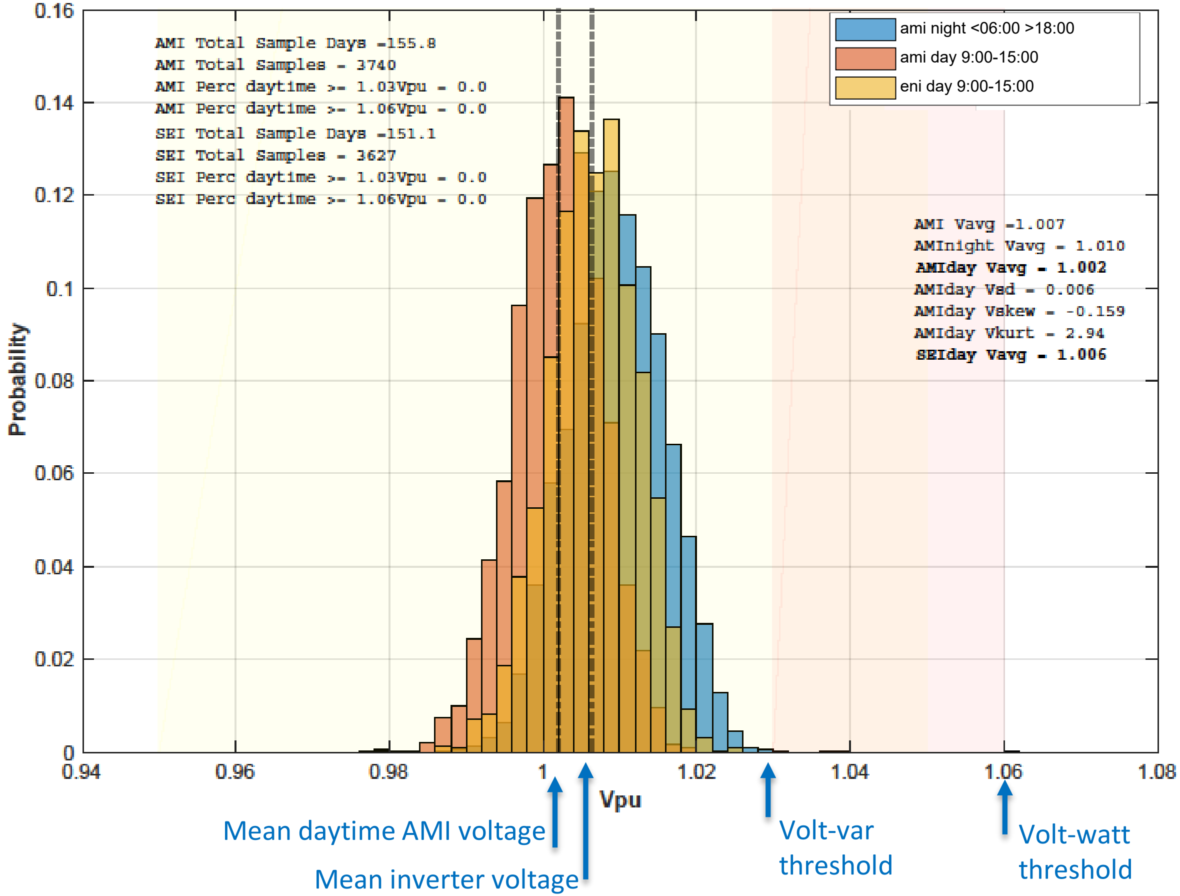


Key findings from report

- **For 99% of customers studied, any curtailed PV production resulting from system-wide activation of volt/Var-volt/Watt control for all new DERs is expected to be negligible**
  – Less than 2% of weekly energy production for a high voltage week, typically much less on an annualized basis since the average customer weekly curtailment is 0.23% for the high voltage week
- **The initial phase of field pilot confirms the expectation from the VROS simulations**
  – Curtailment caused by volt/Var-volt/Watt is typically low or negligible even though pilot project participants were selected from customers that failed interconnection sub-screens

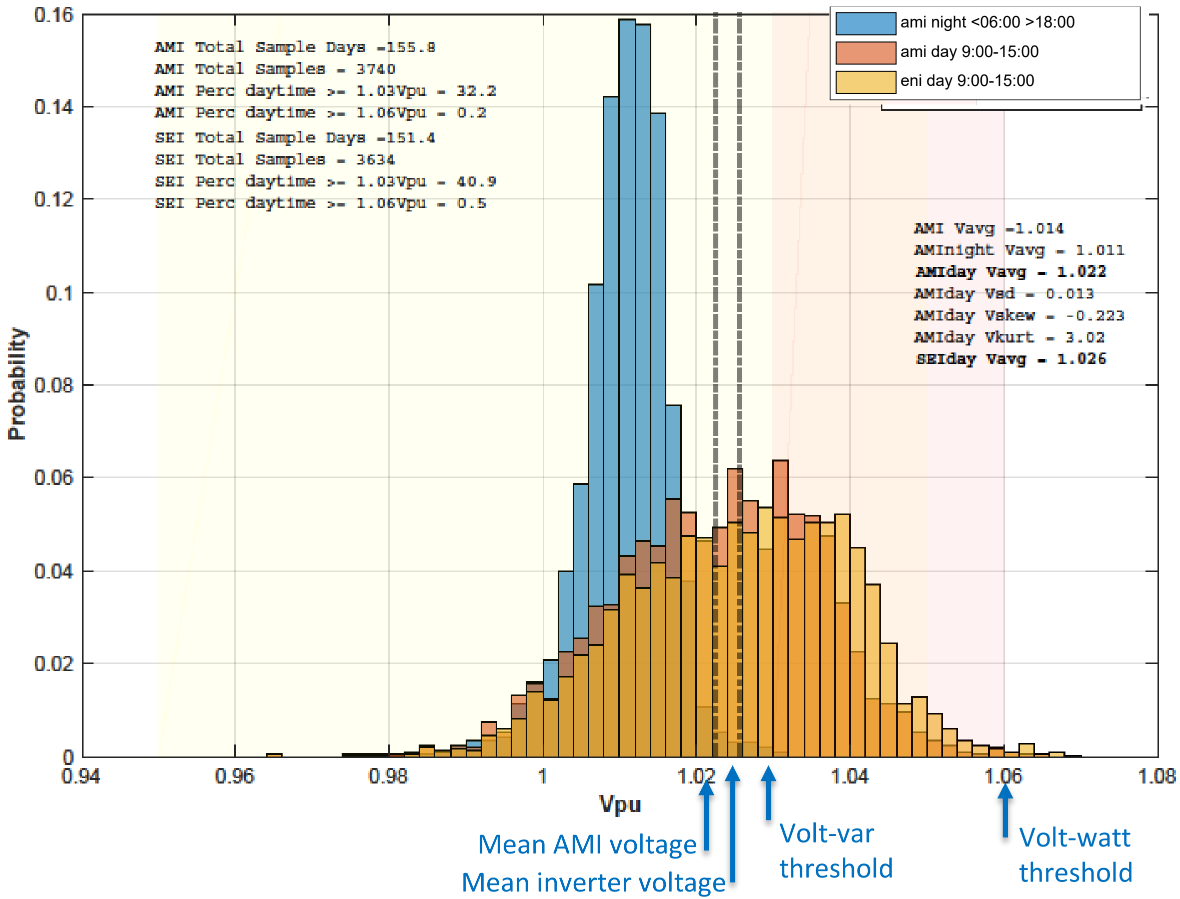
Daily maximum and minimum voltage histogram – strong secondary location

- Cluster 2 – circuit A – newer UG secondary (slide 11)
- Impact of PV on voltage distribution is minimal
- Minimal behind-the-meter voltage rise
- Volt-var is rarely active and volt-watt is never active
- Estimated curtailment of PV production due to volt-var and volt-watt at this location is zero.



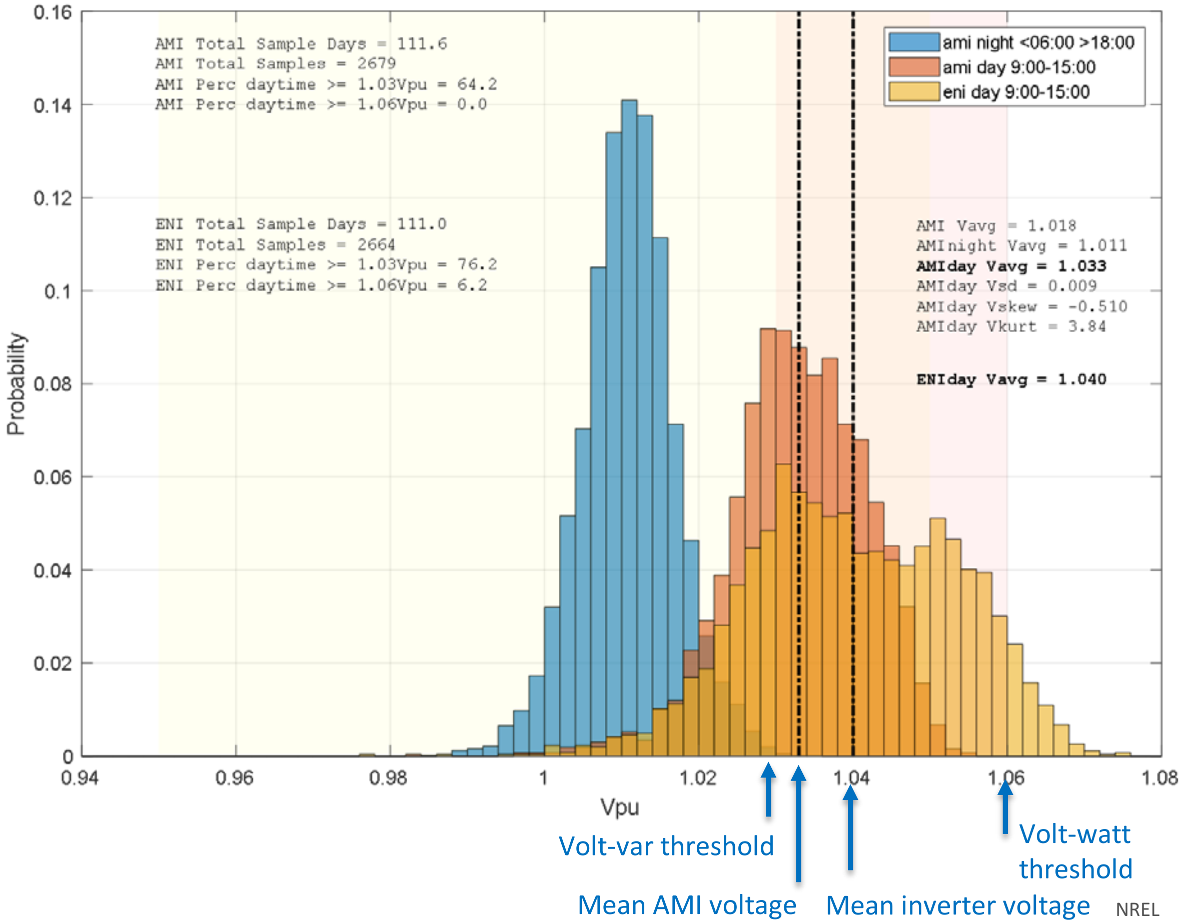
Daily maximum and minimum voltage histogram – weak secondary location

- Cluster 1 – circuit M3 – long shared OH secondary
- 2nd-highest voltage location in pilot
- Impact of PV on voltage distribution is clear
- Minimal behind-the-meter voltage rise
- Estimated curtailment of PV production due to volt-var and volt-watt at this location is < 0.5% of monthly energy production.



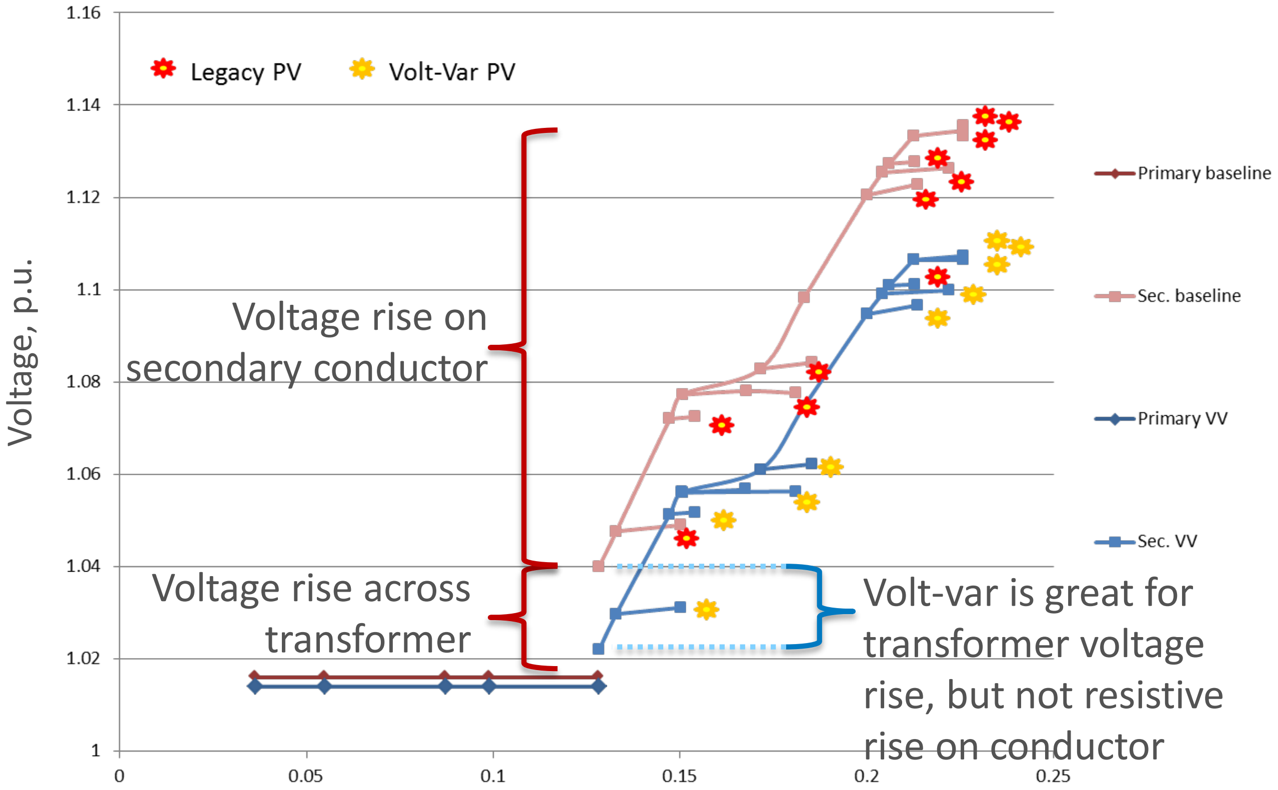
Daily maximum and minimum voltage histogram – highest voltage location

- Significant voltage rise both on secondary and behind-the-meter
- Volt-var active about 76% of the time between hours of 9am-3pm
- Volt-watt active about 6% of the time between hours of 9am-3pm
- Expected curtailment is difficult to quantify exactly without irradiance data at this location
  - Based on available data, estimated curtailment is < 5% of monthly energy production
  - Re-examine in 2nd phase of pilot with irradiance sensor installed



Modeled Secondary voltage rise (VROS report)

- For customers with highest voltage, rise often occurs mostly on secondary conductor
- Shown is a worst-case extremely high-penetration secondary from VROS simulations. (Highest voltage in pilot is about 1.08 pu.)
- Volt-var (or FPF) can only do so much on such a secondary.
- In such cases, distributed VAr sinks/sources (e.g. Varentec) will have similar limitations on effectiveness



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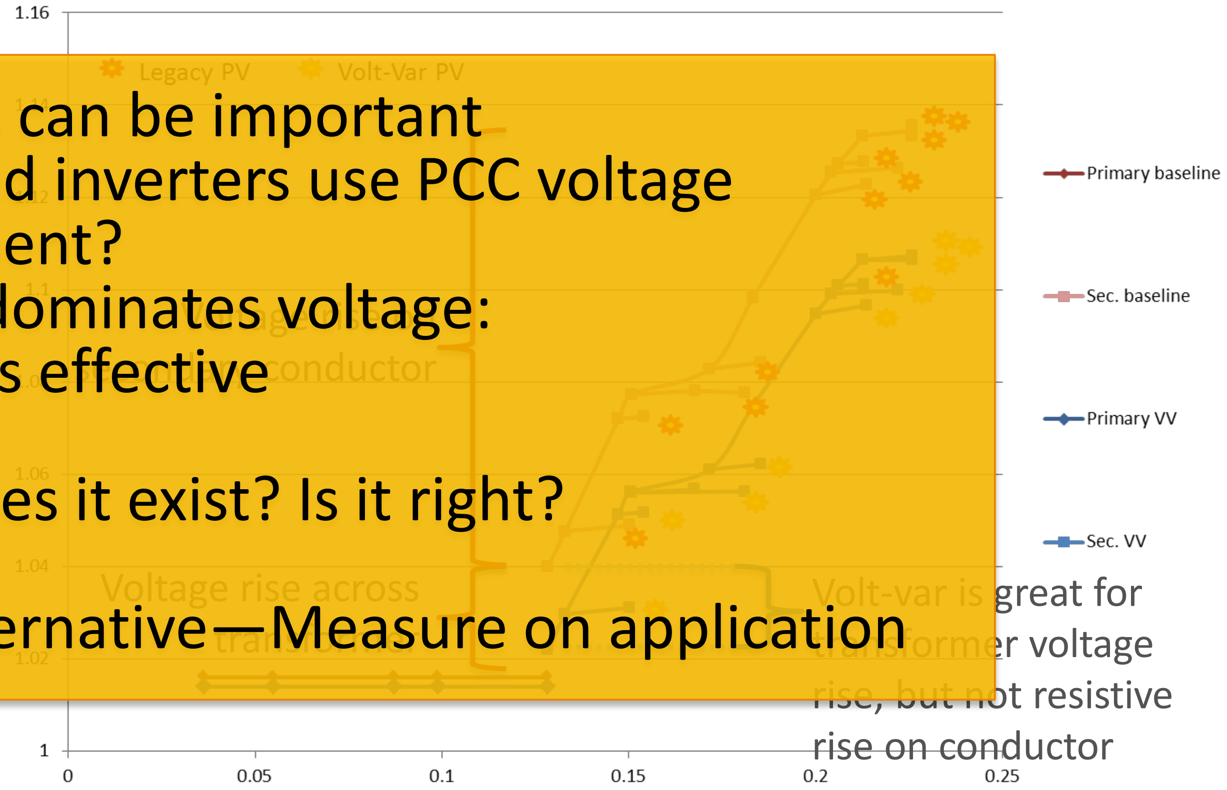
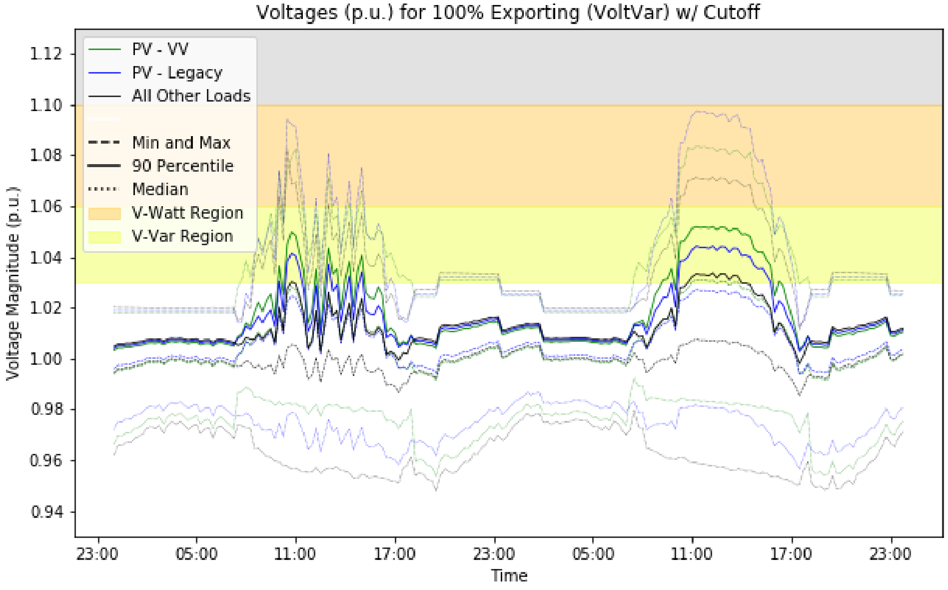


Volt-var is great for transformer voltage rise, but not resistive rise on conductor

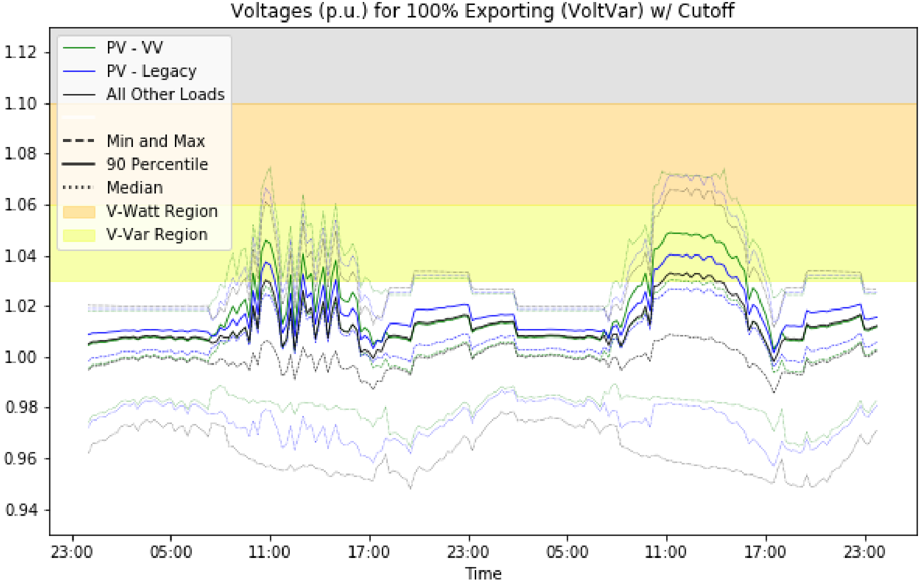
- Secondaries can be important
  - Advanced inverters use PCC voltage
  - Curtailment?
- Resistance dominates voltage:
  - VARs less effective
- Data?!
  - Ack… does it exist? Is it right?
- Possible Alternative—Measure on application

Impact of Secondary Upgrades

No-Upgrades

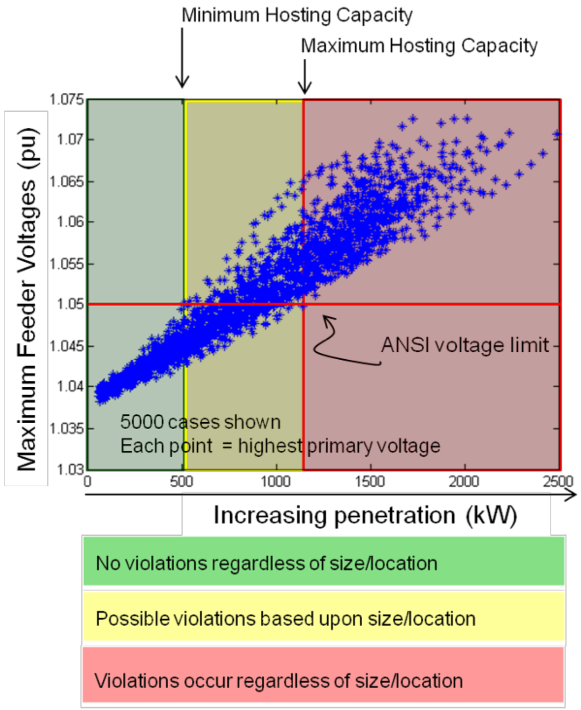


With Secondary Upgrades

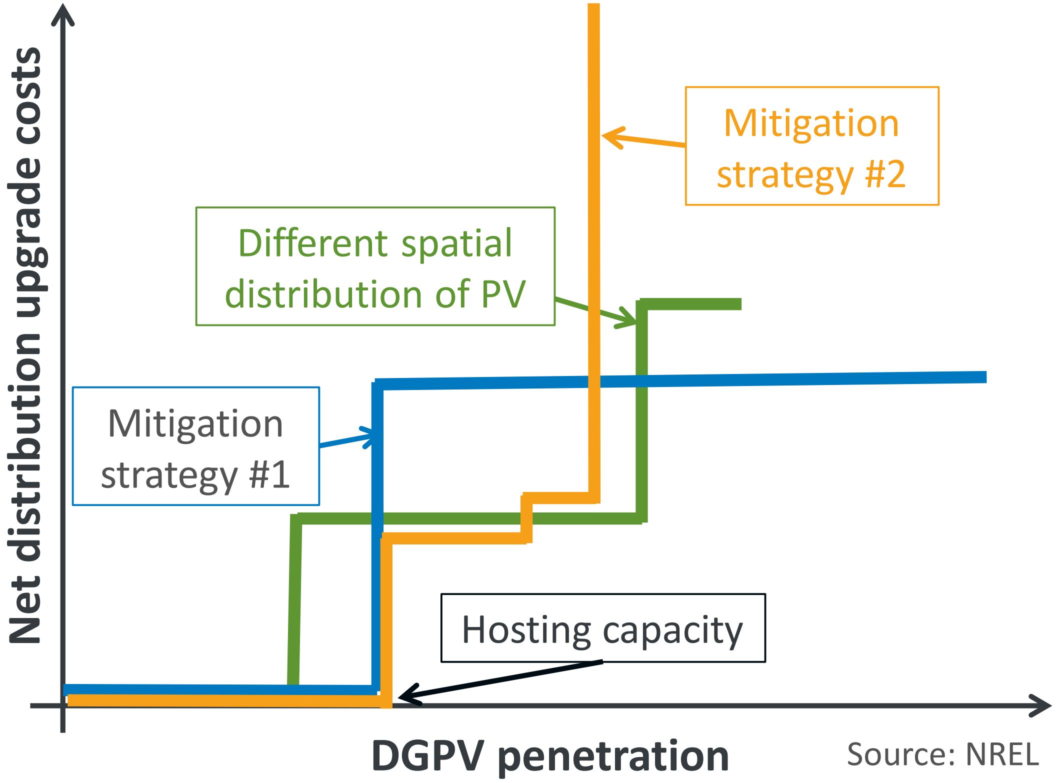


Main finding: volt-var and volt-watt control reduce voltage violations with minimal impact to customer and minimal negative impact to grid.

Beyond Hosting Capacity—Upgrade Costs



Source: EPRI



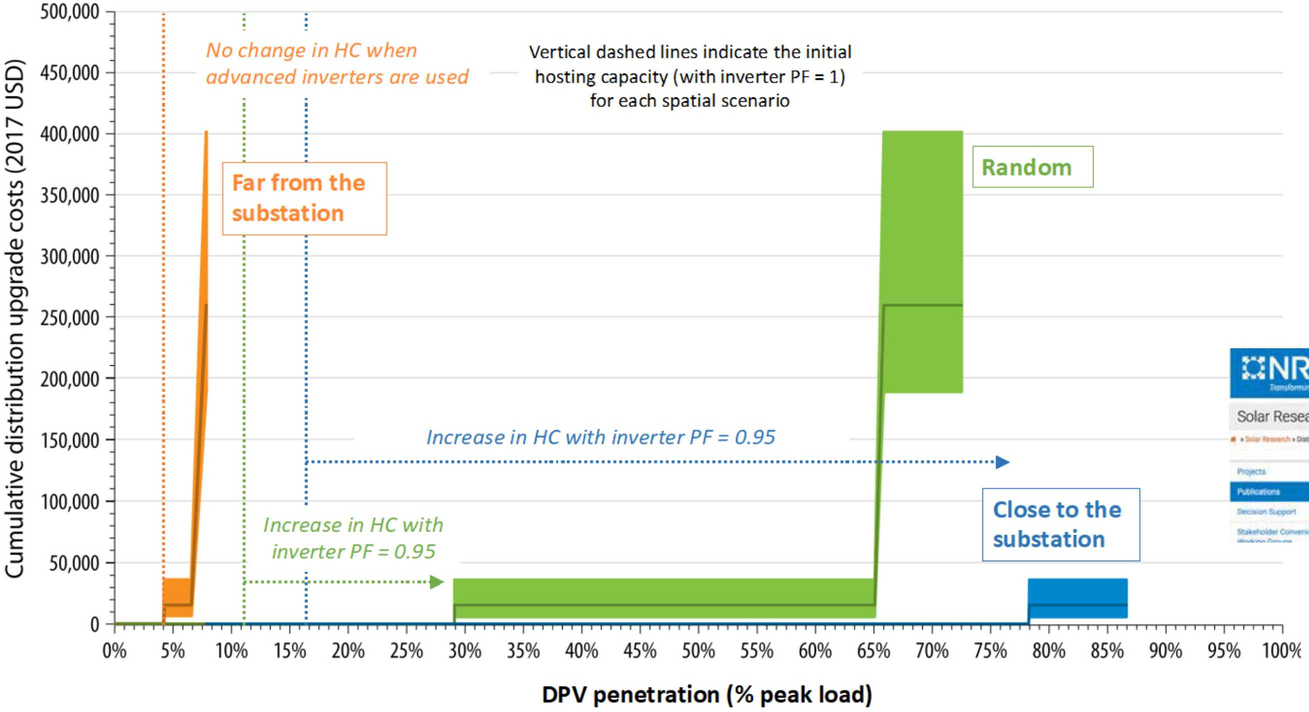
Source: NREL

Hosting depends a lot on where the PV is located

DISCO

OpenDSS

python™



Horowitz, Kelsey A. W., Fei Ding, Barry Mather, and Bryan Palmintier. "The Cost of Distribution System Upgrades to Accommodate Increasing Penetrations of Distributed Photovoltaic Systems on Real Feeders in the United States," April 2018. https://www.nrel.gov/docs/fy18osti/70710.pdf.

Hosting depends a lot on where the PV is located

DISCO

Where to put the PV…
- Purely Random (slow to cover)
- Heuristically far/close
  - Usually bounding
  - Too Strict?
- Adoption Forecasts
  - dGen: LIDAR, economics, & Bass diffusion

…remember this for pre-screening. How far to actually go?

Worst case deployment very unlikely

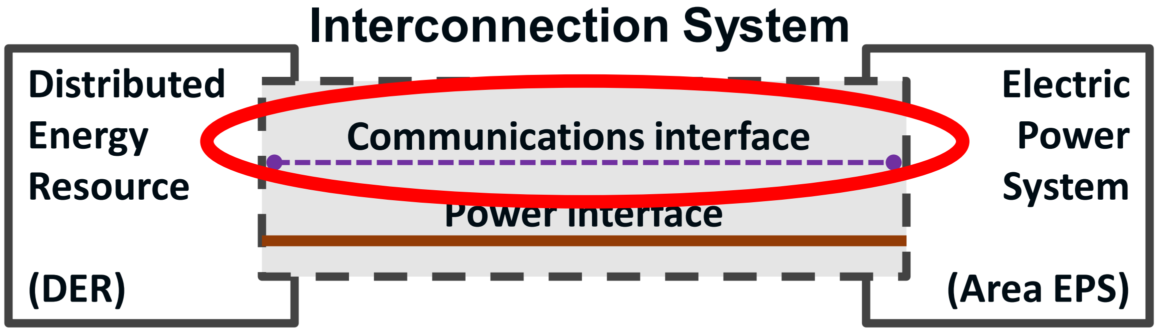
Eventually: Actuals

Horowitz, Kelsey A. W., Fei Ding, Barry Mather, and Bryan Palmintier. "The Cost of Distribution System Upgrades to Accommodate Increasing Penetrations of Distributed Photovoltaic Systems on Real Feeders in the United States," April 2018. https://www.nrel.gov/docs/fy18osti/70710.pdf.

IEEE 1547 Scope and Purpose

Title: *Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*

Scope: *This standard establishes criteria and requirements for interconnection of distributed energy resources (DER) with electric power systems (EPS), and associated interfaces.*



Purpose*: This document provides a uniform standard for the interconnection and interoperability of distributed energy resources (DER) with electric power systems (EPS). It provides requirements relevant to the interconnection and interoperability performance, operation, and testing, and, safety, maintenance and security considerations.*

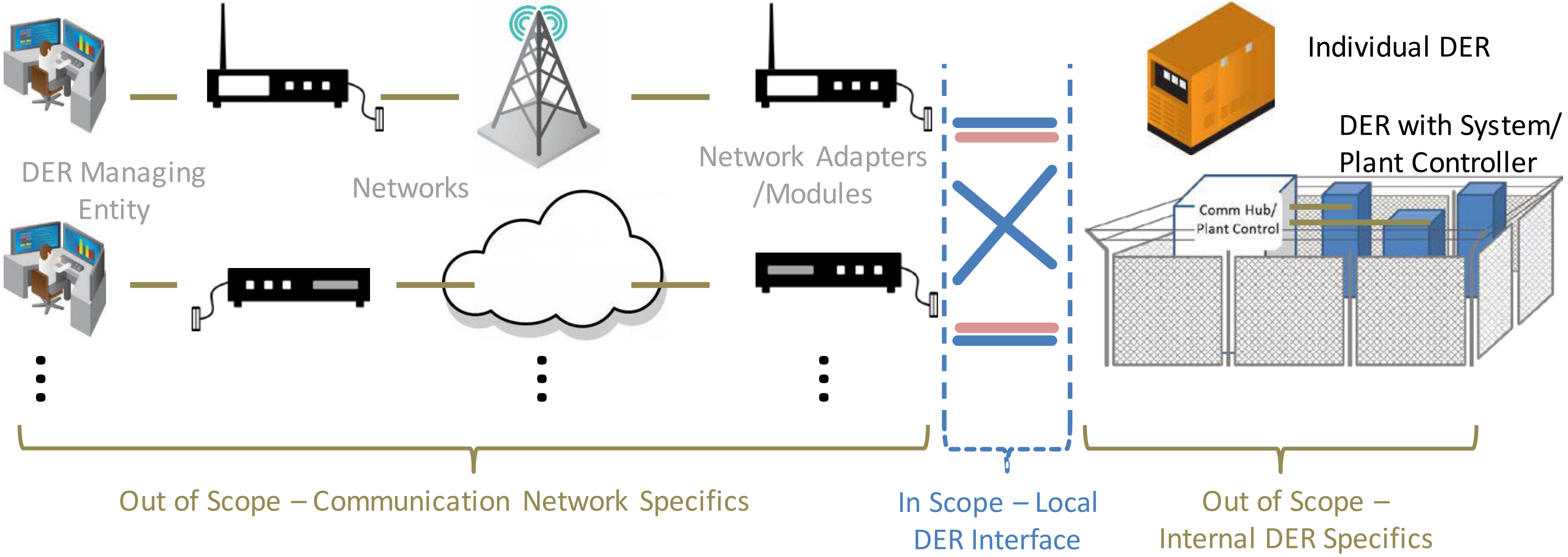
1547 IS

- A technical standard—functional requirements
- A single (whole) document of mandatory, uniform, universal, requirements apply at PCC or PoC
- Technology neutral—i.e., it does not specify particular equipment or type

1547 is NOT

- **A design handbook**
- An application guide (see IEEE 1547.2)
- **An interconnection agreement**
- **Prescriptive**—i.e., it does not prescribe other important functions and requirements such as cyber-physical security, planning, designing, operating, or maintaining the area EPS with DER

IEEE 1547-2018 Communications Interoperability Scope



1547 Interface (mandatory)   Other Interfaces (optional)   Out of Scope

Figure credit: IEEE 1547-2018

IEEE 1547-2018 Communications Protocols

IEEE 1547-2018 excerpt:

The DER shall support at least one of the protocols specified in Table 41. The protocol to be utilized may be specified by the Area EPS operator. Additional protocols, including proprietary protocols, may be allowed under mutual agreement between Area EPS operator and DER operator. Additional physical layers may be supported along with those specified in the table.

Table 41 —List of eligible protocols

Protocol	Transport	Physical layer
IEEE Std 2030.5 (SEP2)	TCP/IP	Ethernet
IEEE Std 1815 (DNP3)	TCP/IP	Ethernet
SunSpec Modbus	TCP/IP	Ethernet
	N/A	RS-485

- 2030.5: Contains security provisions, but no DERs natively speak it today
- DNP3: Widely used for utility SCADA, but not implemented in most DERs
- SunSpec Modbus: Used by most new DERs, but contains little/no security

NREL-Duke Energy-Alstom (GE): Feeder Voltage Regulation with High Penetration PV using Advanced Inverters and a Distribution Management System

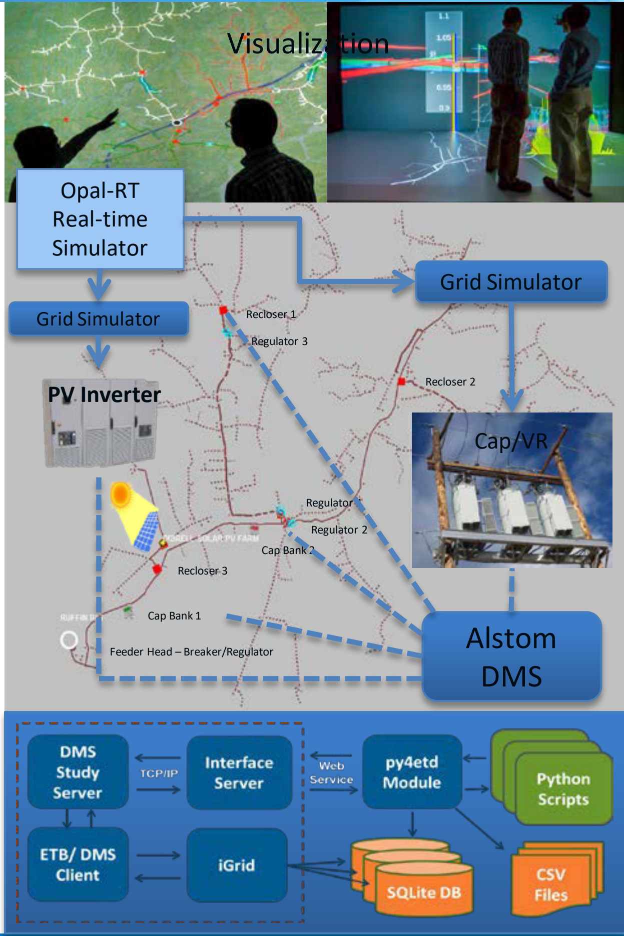
Objective:

Understand advanced inverter and distribution management system (DMS) control options for large (1–5 MW) distributed solar photovoltaics (PV) and their impact on distribution system operations for:

- Active power only (baseline);
- Local autonomous inverter control: power factor (PF) ≠1 and volt/VAR (Q(V)); and
- Integrated volt/VAR control (IVVC)

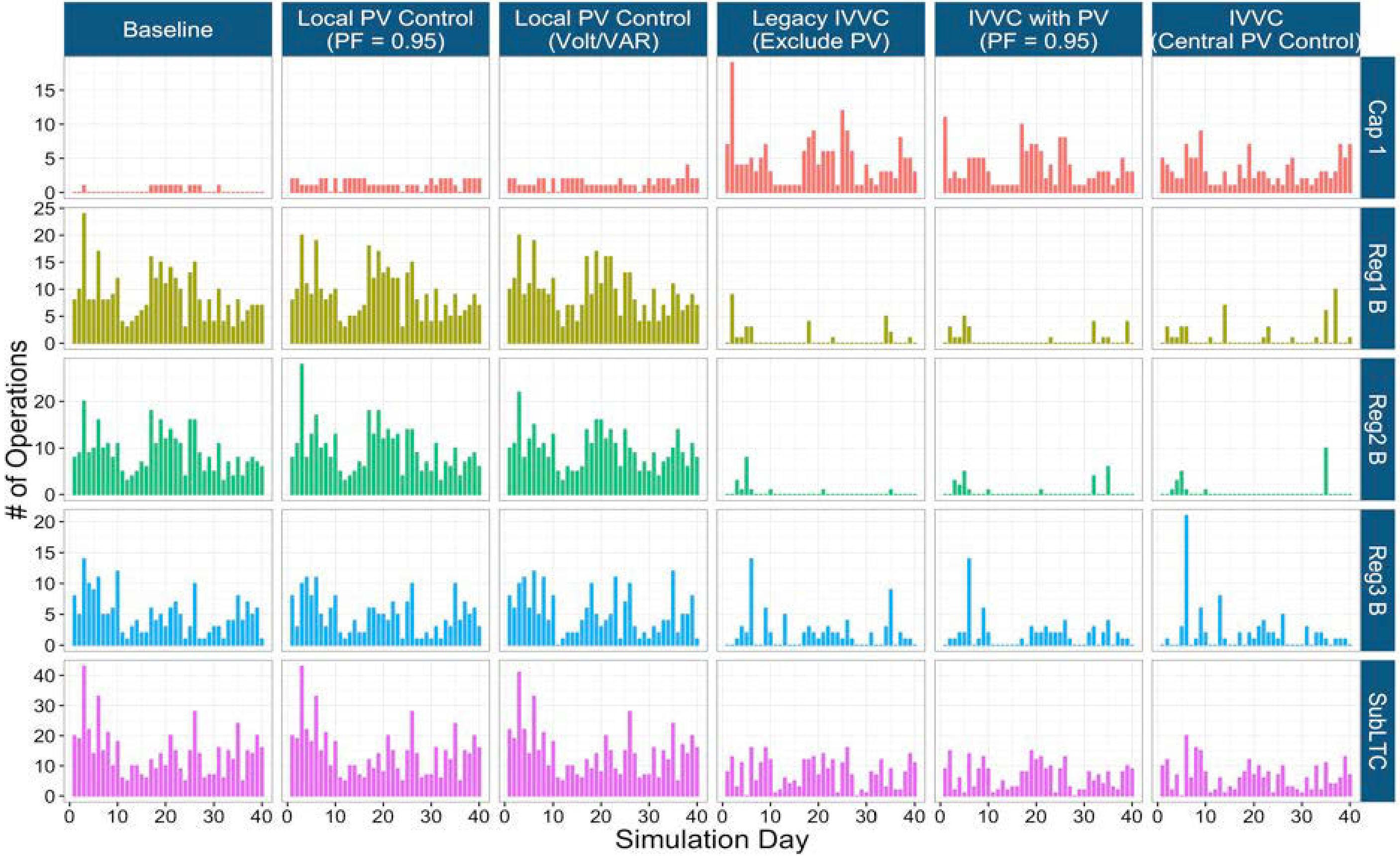
Approaches:

- Quasi-steady-state time-series (QSTS)
- Statistics-based methods to reduce simulation times
- Advanced visualizations
- Power hardware-in-the-loop (PHIL) and Co-simulation
- Cost-benefit analysis to compare financial impacts of each control approach.



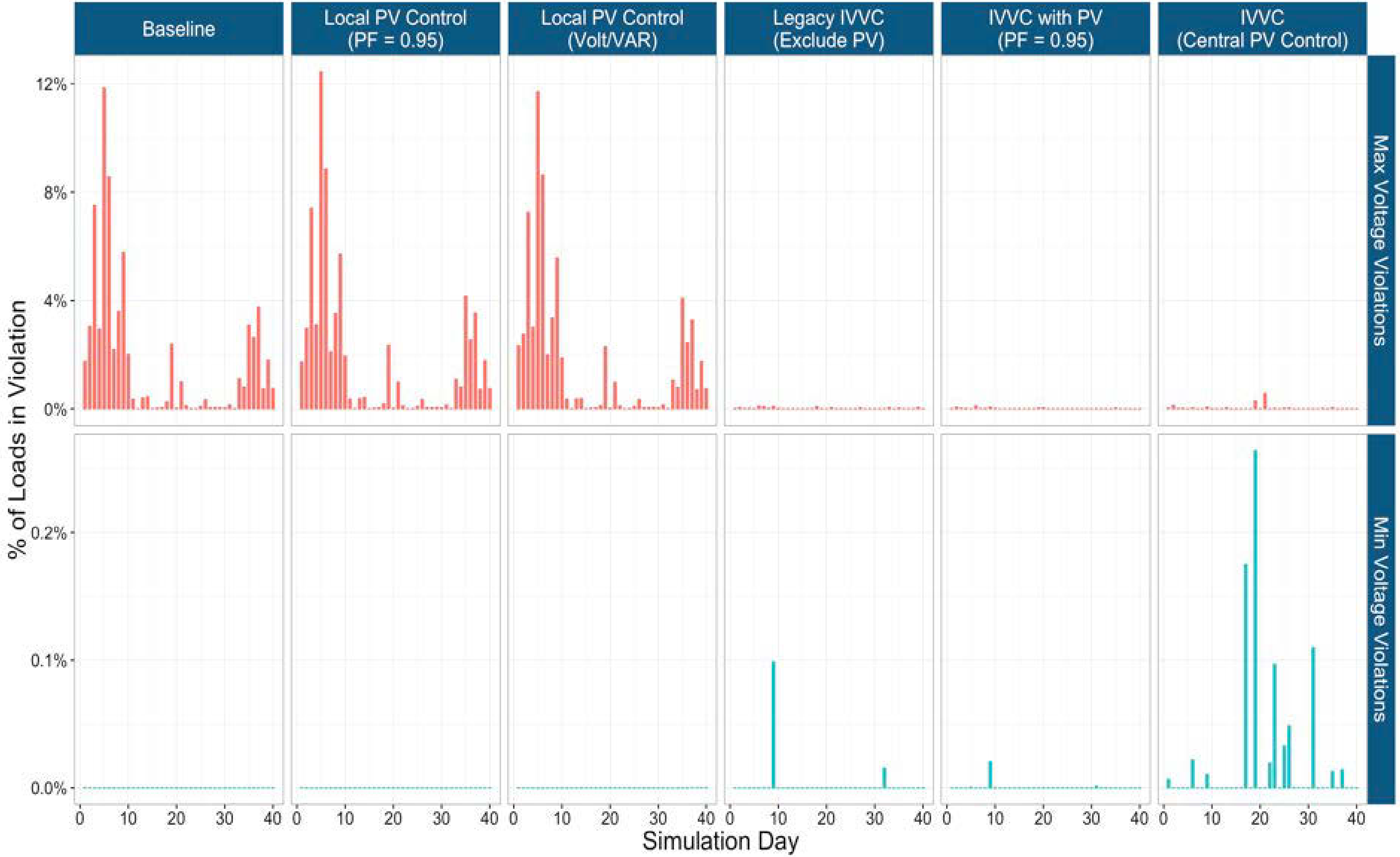
Palmintier, et al. 2016. "Feeder Voltage Regulation With High Penetration PV Using Advanced Inverters and a Distribution Management System: A Duke Energy Case Study." NREL Technical Report NREL/TP-5D00-65551. Golden, CO: http://www.nrel.gov/docs/fy17osti/65551.pdf

Feeder 40-day results of number of operations of voltage regulation equipment



http://www.nrel.gov/docs/fy17osti/65551.pdf

Feeder 40-day results of number of load-voltage violations



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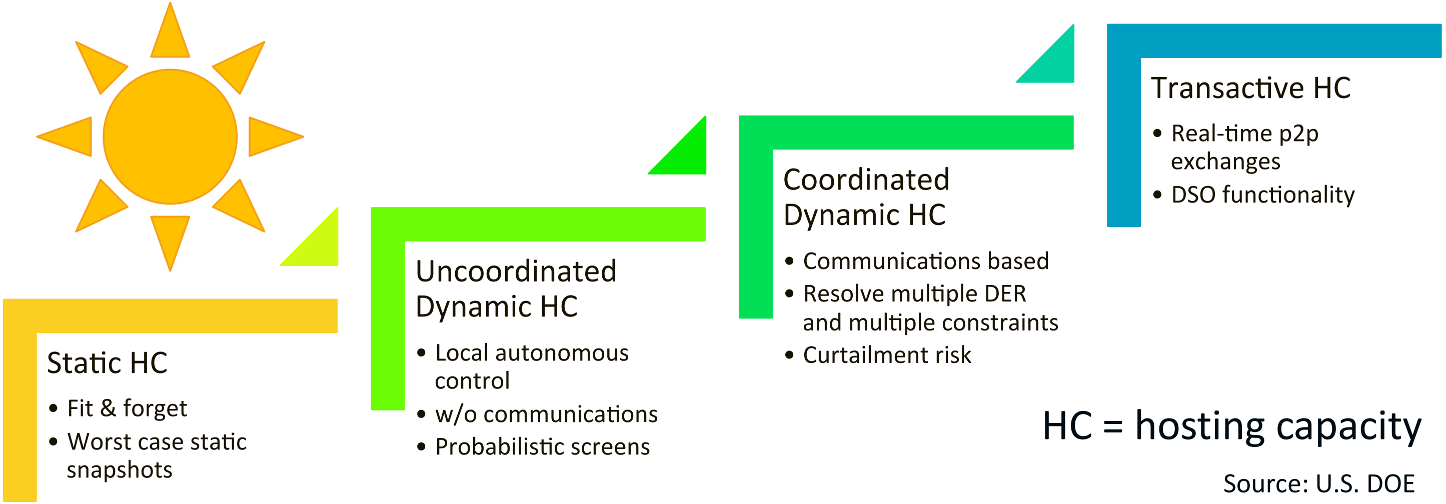
Thinking Past Static Hosting Capacity

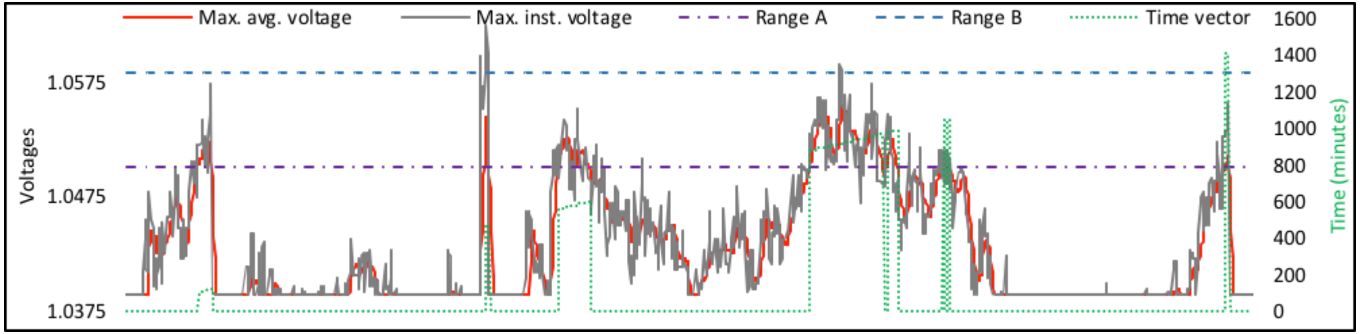


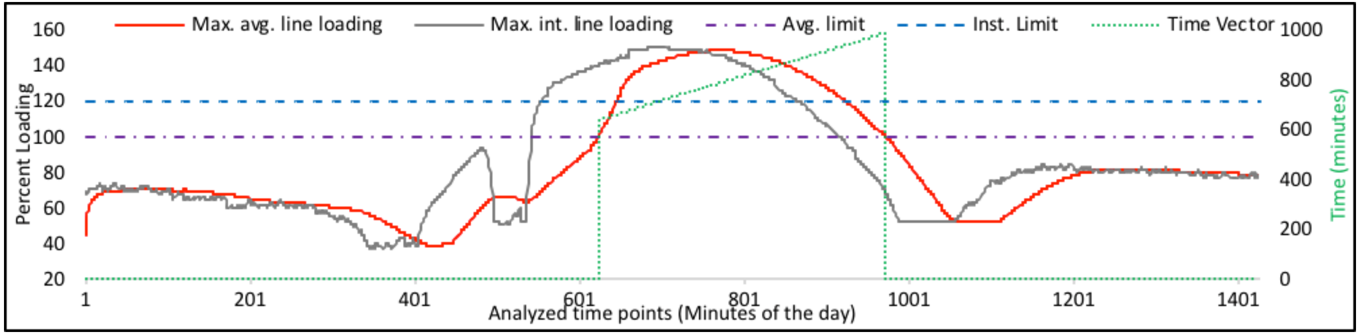
HC = hosting capacity

Source: U.S. DOE

- Most prior analysis has been performed using the static (conservative) definition of hosting capacity
- Dynamic and transactive regimes are based on dynamic, real-time operating constraints
- Each of these paradigms is associated with different set of upgrades to mitigate any impacts of DGPV on the system, and different costs
- Regulatory and/or market changes are required to fully implement coordinated dynamic and transactive HC approaches

QSTS for Hosting Capacity



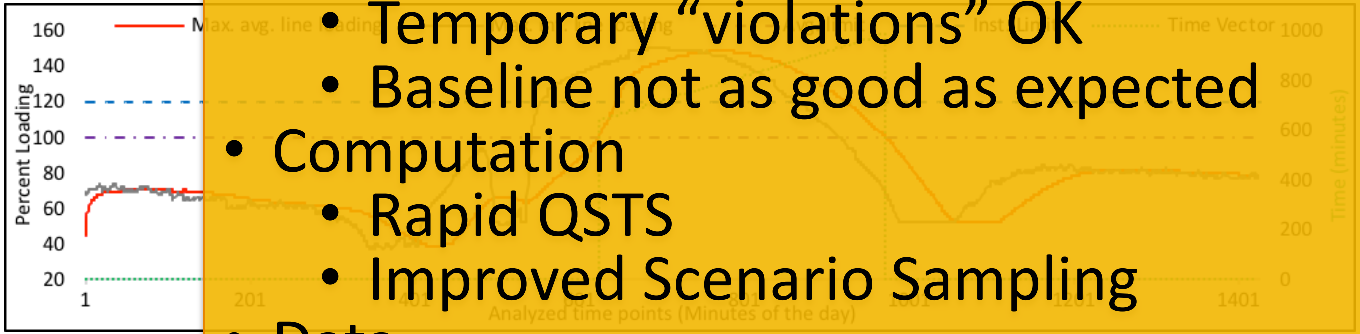


Metrics

- Voltage
  - Min/max
  - Customers
  - Moving average
- Loading
  - Instant
  - Moving Average
  - Utility-specific
- Equipment operations
- System-wide Controls
  - ADMS/DERMS
  - DER management
- Curtailment
  - Volt-VAR/Volt-Watt
  - Dynamic controls

Jain, Akshay, Kelsey Horowitz, Fei Ding, Nicolas Gensollen, Barry Mather, and Bryan Palmintier. "Quasi-Static Time-Series PV Hosting Capacity Methodology and Metrics," IGST, 2019.

QSTS for Hosting Capacity



Opportunities:
- More precise metrics (equipment, transients)
- Control Alternatives to Upgrades

Challenges:
- Metric Definition
  - Temporary “violations” OK
  - Baseline not as good as expected
- Computation
  - Rapid QSTS
  - Improved Scenario Sampling
- Data

Metrics
- Voltage
  - Min/max
  - Customers
  - Moving average
- Loading
  - Instant
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IEEE1547-2018 Additional points

Safety

- Visible-break isolation device
- Anti-islanding
- inadvertent energization of Area EPS

Tripping & reclose coordination

- Short-circuit faults
- Open phase conditions
- Coordination with Area EPS circuit reclosing

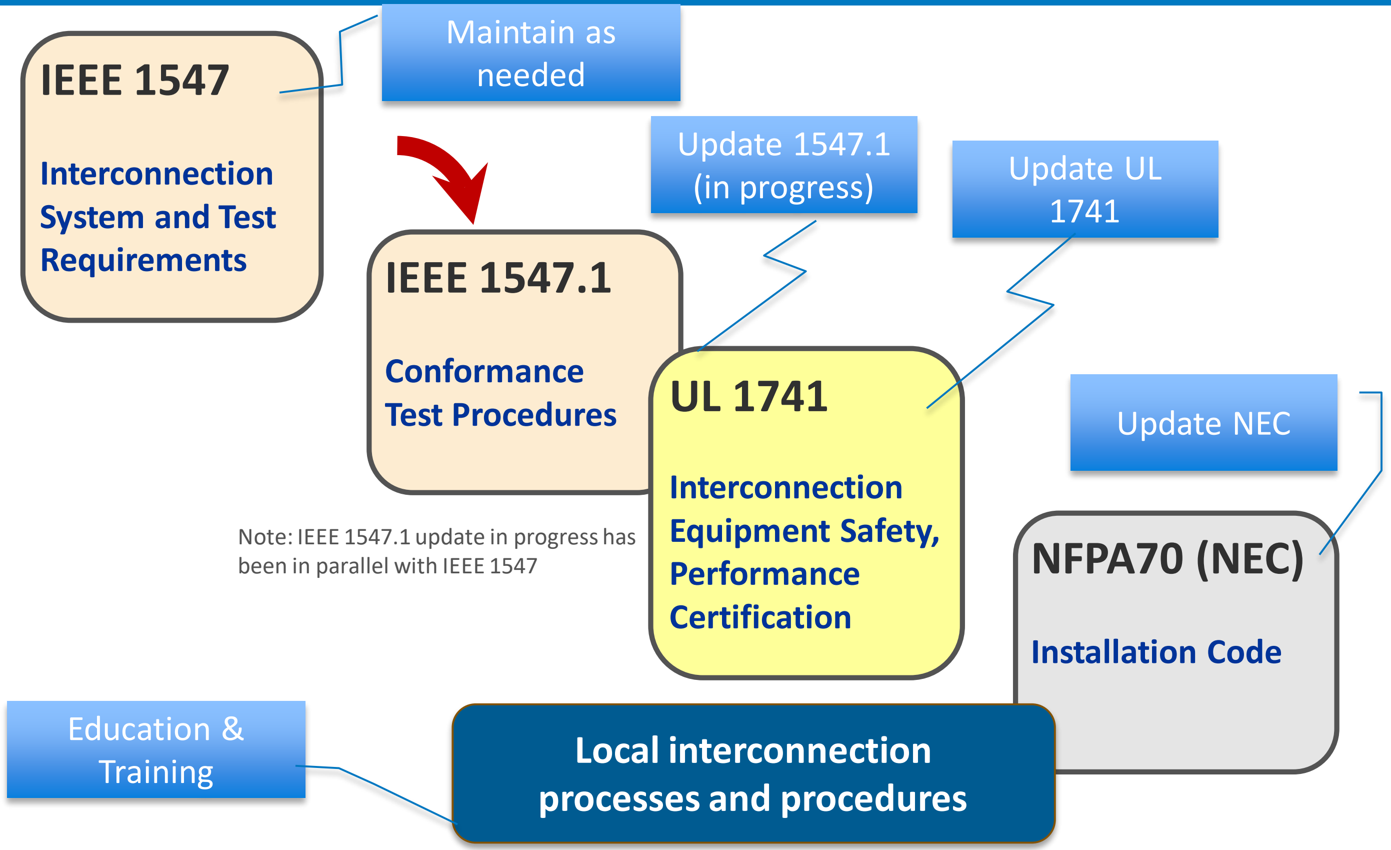
General

- Interconnect integrity
  - Protection from EMI
  - Surge withstand
- Integration with Area EPS grounding
- Synchronization limits for frequency, voltage and phase angle (IEEE 67 criteria ok for some types of synchronous generators)

Power Quality

- Limitation of dc current injection
- Limitation of DER-caused voltage fluctuations
  - Flicker (revised method),
  - Rapid voltage changes (new)
- Limitation of Current Distortion
- Limitation of over voltage contribution
  - Temporary over-voltage (TOV)
  - Transient overvoltage
- Harmonics

IEEE1547: What's Next?

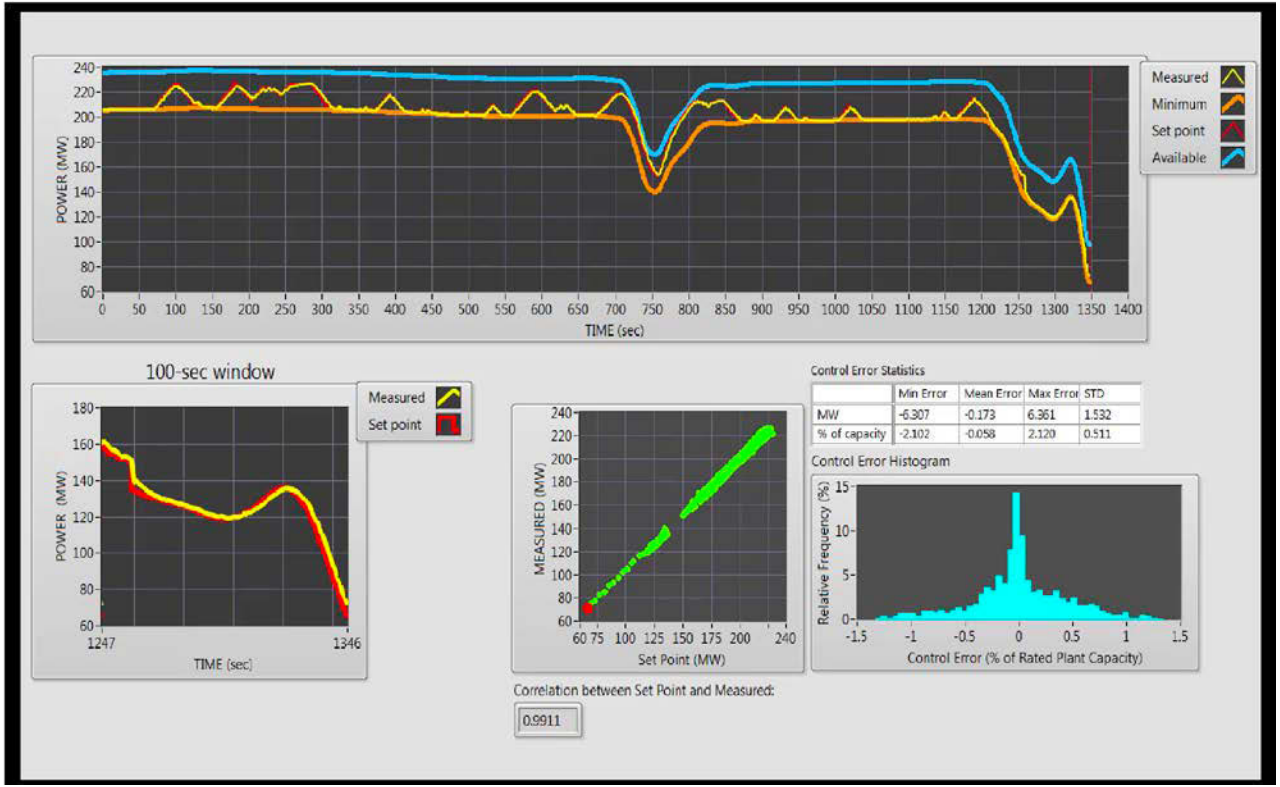


Thinking Beyond Distribution

Bulk Services: Solar can provide reserves

Measured AGC Test Data

- 300MW PV plant

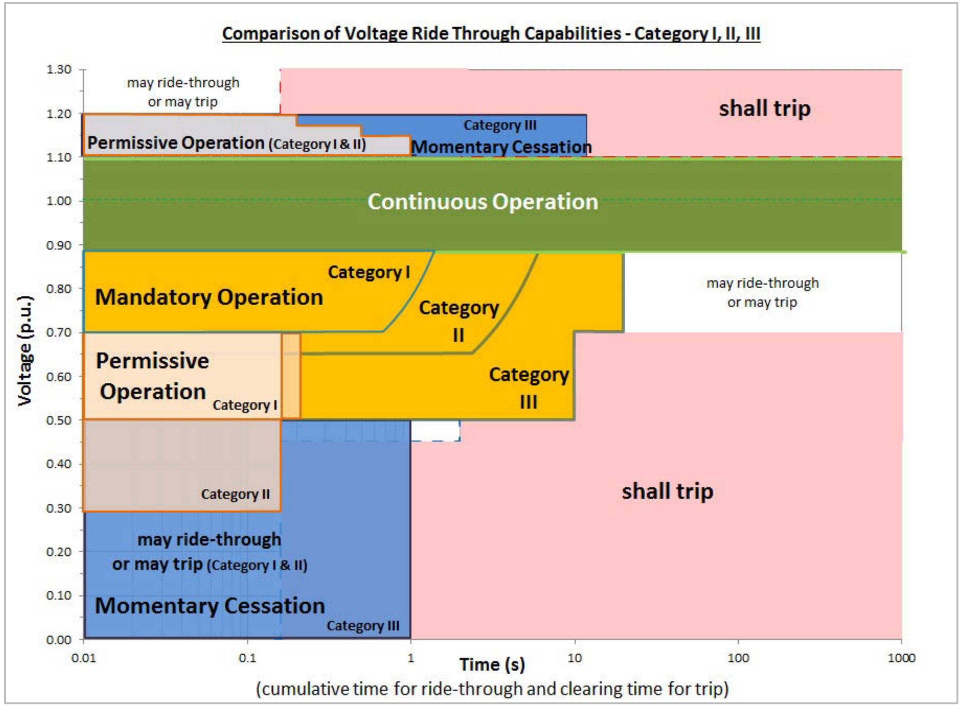


Contact: Vahan Gevorgian

IEEE1547-2018 Voltage Ride-Through

Key take aways:

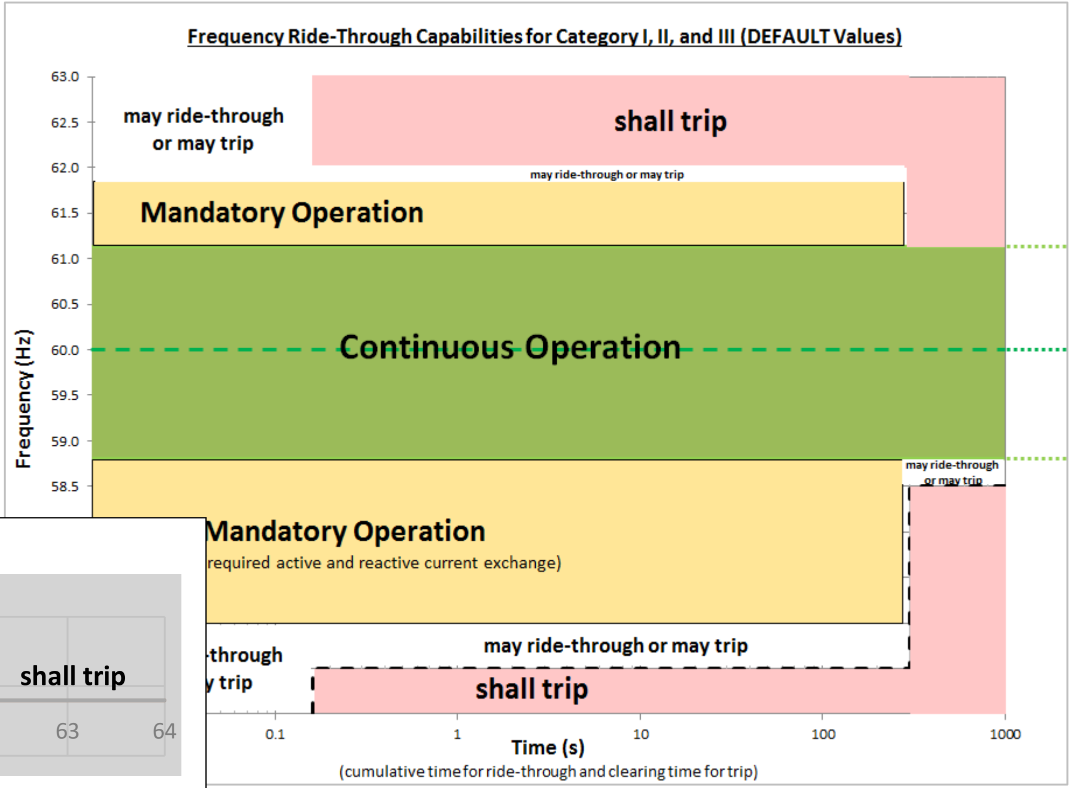
- Performance categories
- Modes of operation
- Requires coordination with bulk power system



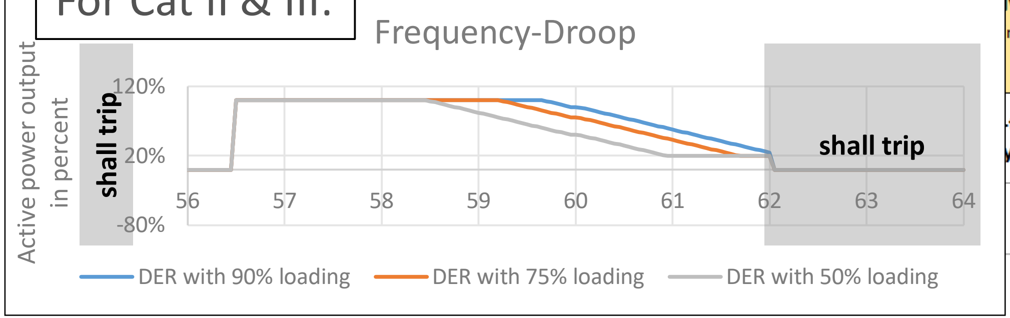
Category	Objective	Foundation
I	Essential bulk system needs and reasonably achievable by all current state-of-art DER technologies	German grid code for synchronous generator DER
II	Full coordination with bulk power system needs	Based on NERC PRC-024, adjusted for distribution voltage differences (delayed voltage recovery)
III	Ride-through designed for distribution support as well as bulk system	Based on California Rule 21 and Hawaii Rule 14H

IEEE1547-2018: Frequency Ride-Through

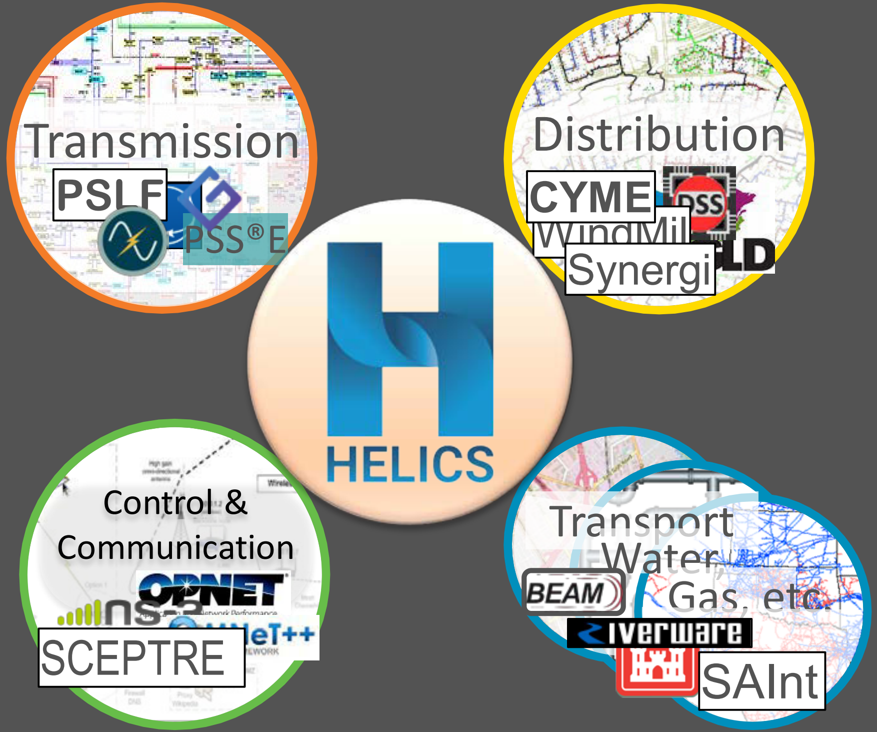
- Harmonized with Bulk Requirements
- Range to accommodate small, isolated grids
  - OF: 61.8 – 66.0 Hz
  - UF: 50.0 – 57.0 Hz



For Cat II & III:



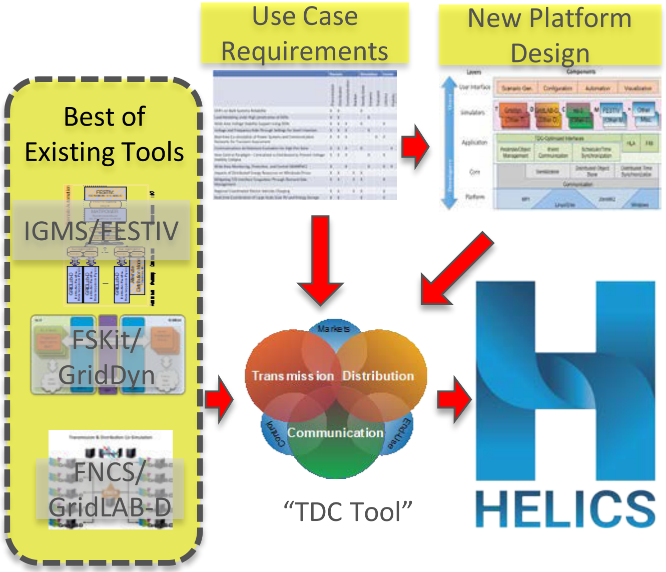
HELICS enables easily bringing together two or more existing tools, exchanging data as time advances, to form a tightly integrated ***co-simulation***.



Note: OpenDSSDirect (Cross-platform in Python)

HELICS™: Hierarchical Engine for Large-scale Infrastructure Co-Simulation

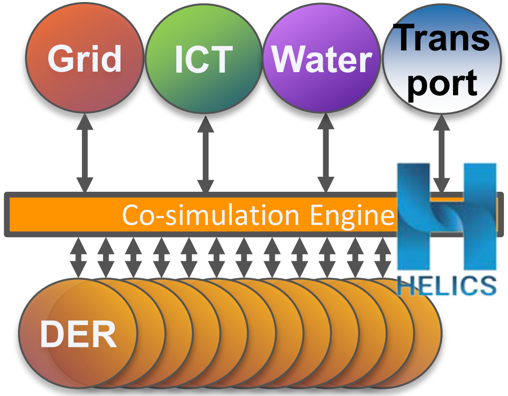
High-performance co-simulation to combine best-in-class tools for breakthrough ESI analysis



Capabilities:

- **Scalable:** 2-100,000+ Federates
- **Cross-platform:** HPC (Linux), Cloud, Workstations, Laptops (Windows/OSX)
- **Modular:** mix and match tools
- **Minimally invasive:** easy to use lab/commercial/open tools
- **Open Source:** BSD-style.
- **Many Simulation Types:**
  - Discrete Event
  - QSTS
  - Dynamics
- **Co-iteration enabled:** "tight coupling"

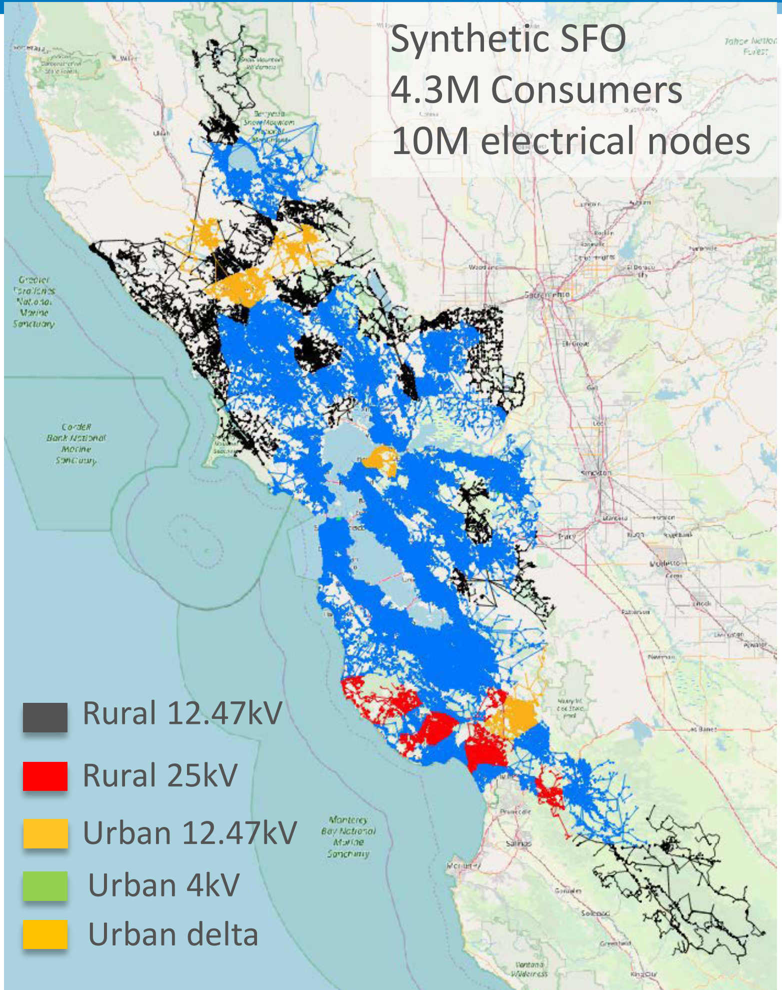
v2.0RC available now at https://www.github.com/GMLC-TDC/HELICS-src



Project funding: GMLC 1.4.15

B. Palmintier, et al., "Design of the HELICS High-Performance Transmission-Distribution-Communication-Market Co-Simulation Framework," Workshop on Modeling and Simulation of Cyber-Physical Energy Systems, Pittsburgh, PA, 2017.

Smart-DS Large synthetic test system: Bay Area, CA (SFO, v1.0)



Design Diversity:

- Voltage class: 12.47kV, 4kV, 25kV
- Voltage Management: Regulator, Capacitors
- Arrangement: Wye, Delta
- Area type: Urban-suburban, rural
- Networked secondary

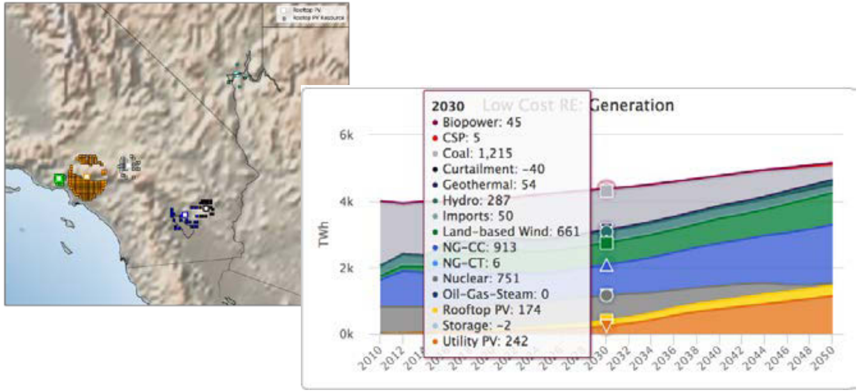
	20180510	20181115
Number of different catalogs used	3	8
Power line types	24	232
HV/MV substation types	7	42
Distribution transformer types	12	44

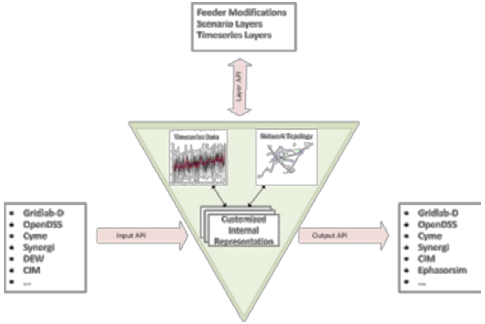
Rich Scenarios:

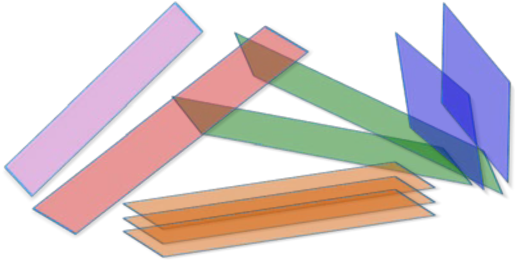
- 1yr x 15min ZIP loads for all customers
- Defined DER adoption
  - Low, Med, High PV, etc.
- **Use cases:** Volt/Var, OPF

Research Scenario Tools

- R2PD: Renewable Resource and Power Data Tool
  - Wind, Solar & Weather
  - Actuals & Forecasts
- sssmatch
  - Create generation mixes
  - Based on NREL Standard Scenarios
- DiTTo: Distribution Transformation Tool
  - Many-to-1-to-many conversion
  - Merge, Modify, & Add
- layerstack
  - Encapsulate user-specific layer logic
  - Manage and share workflow stacks







Questions?

Bryan.Palmintier@NREL.gov

Acknowledgements: Andy Hoke, Kelsey Horowitz, Fei Ding, Barry Mather, Ben Kroposki, and the NREL Power Systems Engineering Center team

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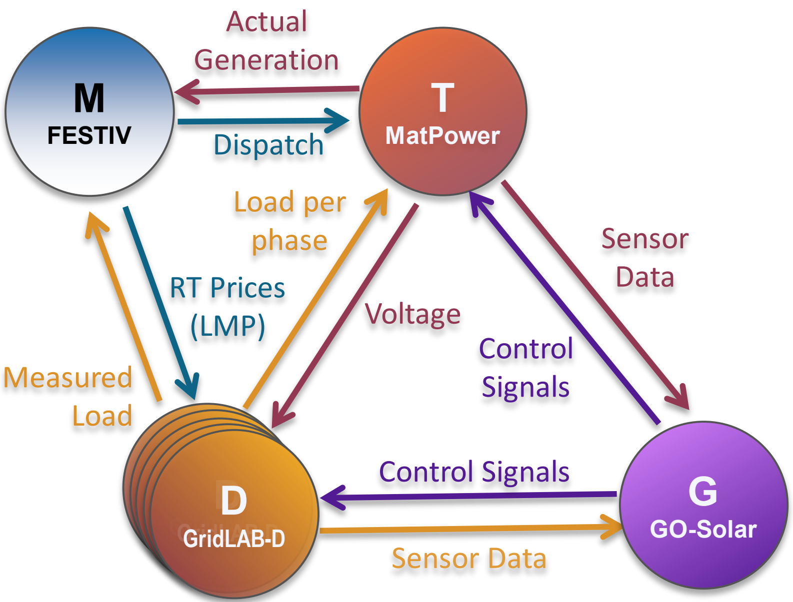
Cyber-physical co-simulation

HELICS

- Ex: Integrated Transmission-Distribution
  - Day-Ahead Unit Commitment
  - 5-minute Dispatch (& LMP)
  - 6-second updates (AGC-like)



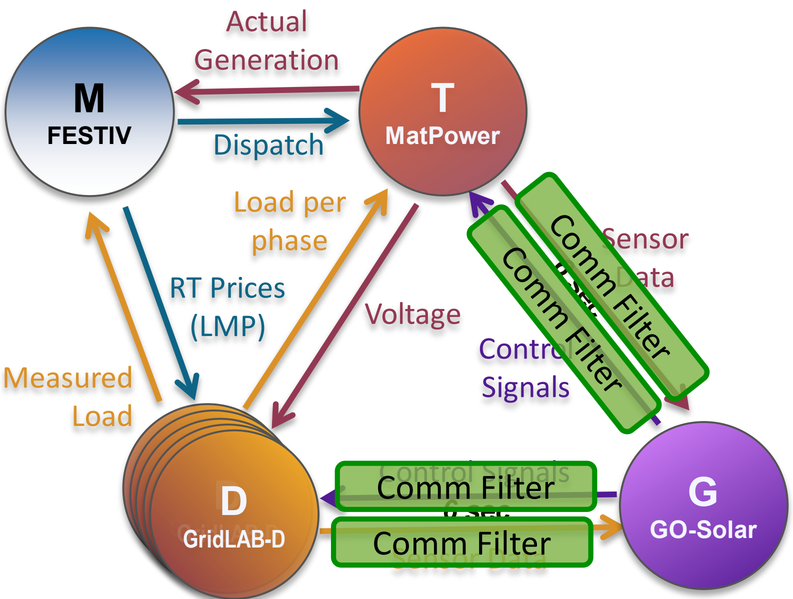
Example projects:

- North American Resiliency Model (NARM)
- T&D Tool Suite (SuNLaMP)
- LA100
- IGMS-HELICS
- ADMS Testbed
- Integrated Energy System Model

Simple Communication for Controls and Cyber Security

HELICS

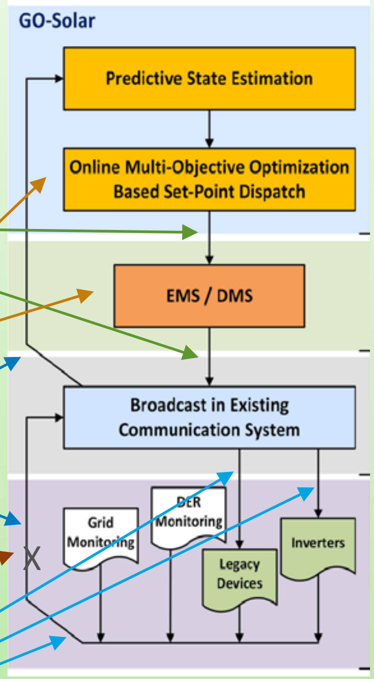
- HELICS Filters for simple comm. simulation
  - Delays
  - Random delays
  - Random drops
  - Other message effects (packetization)



Highlight: GO-Solar (SETO ENERGISE)

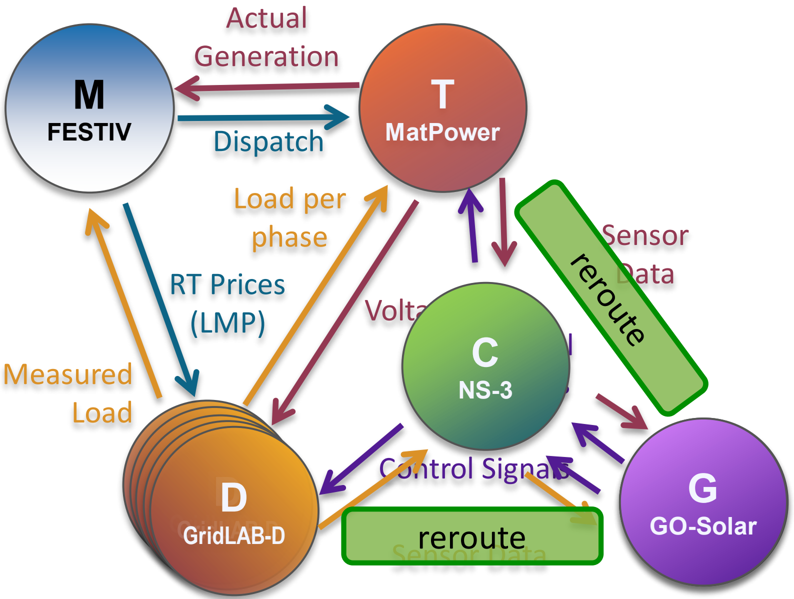
Entire Island of Oahu, HI with >1M electric nodes

1. Control signal spoofing
2. Control node compromise
3. Sensor data spoofing
4. Communication Denial of Service
5. Communication Latency Margin

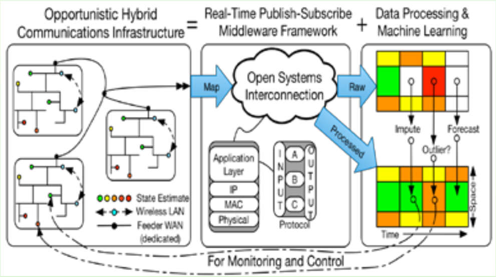


Adding Complex Communication

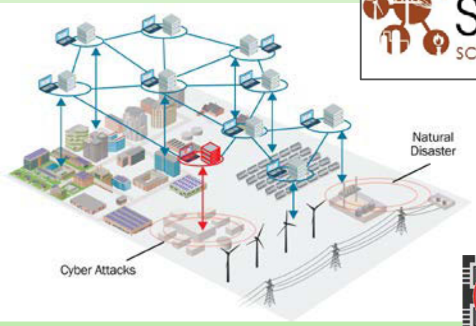
- Full communication simulation:
  - Multiple communication paths sharing bandwidth
  - Interference with other traffic
  - Tools: ns-3, Opnet++, SCEPTRE, etc.



Protocol/Full-Stack Performance



Project Ex: SuNLaMP Hybrid Comms



SCEPTRE scada-as-a-platform™

HELICS

DSS

Ex: Power-Comm. Emulation LDRD