NREL Transforming ENERGY

What are DERs and how can they be used?

Andy Hoke

Modern DER Capabilities and Deployment Considerations Workshop

March 8, 2023

Outline

1. What are DERs?
2. Example of high-DER system – Hawaii
3. Selected technical challenges
4. Case study – volt-var and volt-watt, and AMI data
5. PRECISE – A DER interconnection tool
6. Conclusions and questions

What are DERs?

IEEE 1547 definition: DERs are energy resources connected to distribution systems and capable of exporting active power

- **Includes PV, storage, small wind, etc. (even if programmed not to export active power)**
- **Includes rotating machine-based generation**
- **Does not include loads (even smart loads)**
- **Could include V2G**

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An example of a power system with very high DERs: Hawai'i

- Highest distributed PV capacity of any state (as percentage of load)
  - ~50% of peak load
  - High electricity costs for geographic reasons
  - Historical PV incentives
- First state to mandate a 100% renewables goal (100% by 2045)
  - Distributed PV will play a major role due to land constraints
- Peak island-wide inverter penetrations of 50%-80% in 2018 (depending on island)

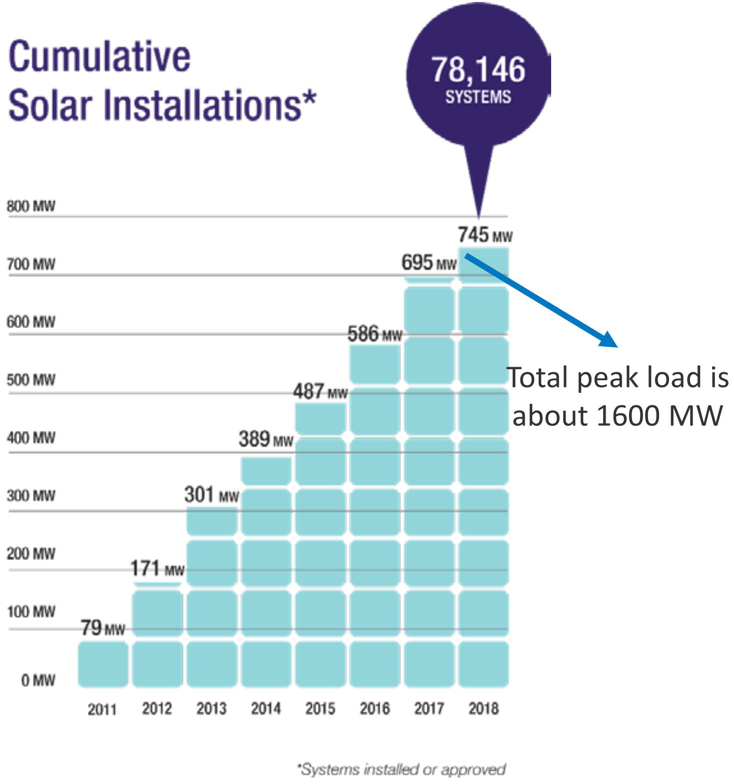
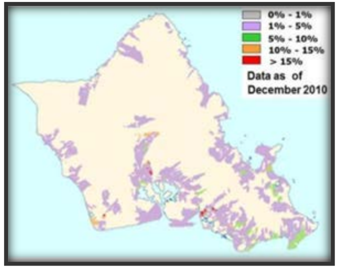


Figure Credit: Hawaiian Electric Companies

Why Hawai'i

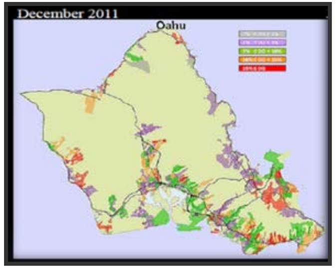
- Hawaii's Rule 14H (DER interconnection) has led the way in smart inverter functionality adoption in the U.S. (along with California's Rule 21)
- Hawaii required some advanced functionality even before it could be tested and certified under UL 1471 SA or IEEE 1547-2018
- Advanced inverter functions currently required in Hawaii:
  - Voltage and frequency ride-through
  - Transient overvoltage mitigation (self-certification)
  - Volt-var control
  - Frequency-watt control
  - Soft-start
  - Ramp-rate control
  - Volt-watt (currently optional; under discussion for blanket activation)
  - Remote upgrade capability
- So far, no requirement for communications between utility and inverter

Distribution PV Penetration (Oahu Example)



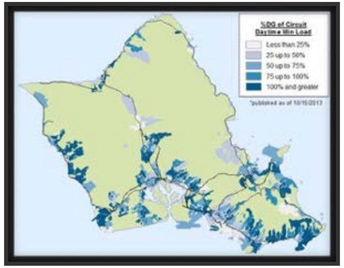
2010

Many feeders >
1%
Gross daytime minimum load (GDML*)



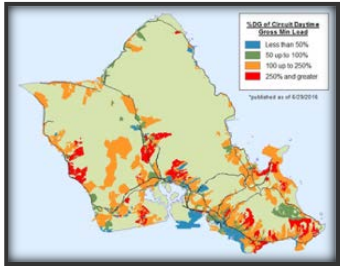
2011

Many feeders >
15%
GDML



2013

Many feeders >
100%
GDML



2016

Many feeders >
250%
GDML

*GDML = The minimum feeder load the utility would see during daylight hours if PV were not present

Slide courtesy of Adam Warren, NREL. (Modified)

System-Wide PV Penetration (Oahu Example)

Generating Facilities

These maps show existing and planned generating facilities and the maximum potential power in megawatts (MW) they can produce.

[F] **FIRM GENERATION:** Energy available on demand, which can be adjusted as needed.

(V) **VARIABLE GENERATION:** Energy that may not always be available or controllable.

BESS: Battery Energy Storage System

- **BIOFUELS**
- **BIOMASS**
- **GEOTHERMAL**
- **HYDRO**
- **CUSTOMER-SITED SOLAR**
- **GRID-SCALE SOLAR**
- **STORAGE**
- **WASTE TO ENERGY**
- **WIND**
- **COAL**
- **OIL**
- **OIL (DEACTIVATED)**

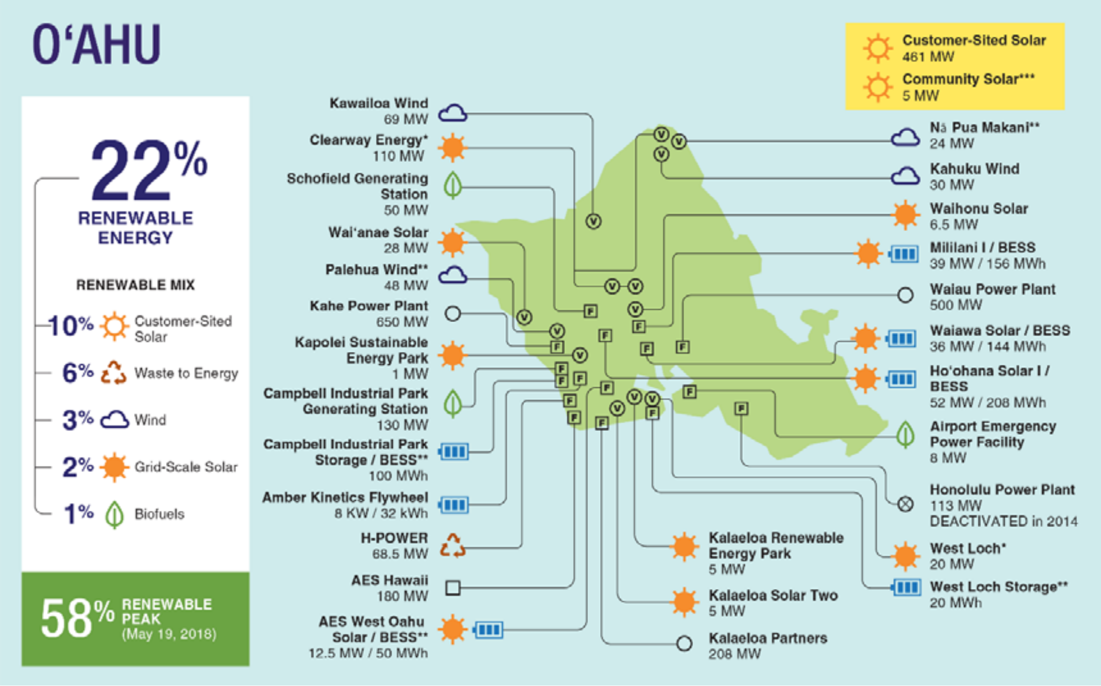
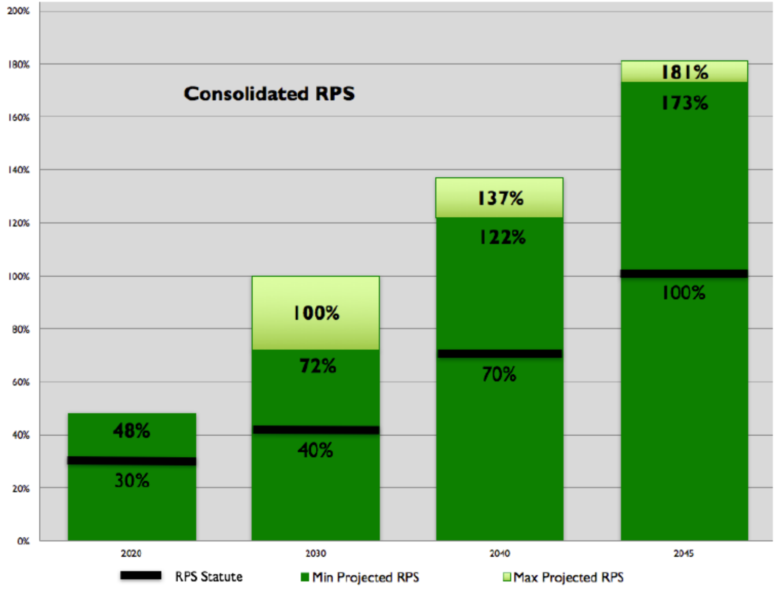


Figure Credit: Hawaiian Electric Companies

Future RE Expected

Total renewable penetration:

$$\equiv \frac{renewable\ kWh\ generated}{utility\ kWh\ sold}$$



Total distributed PV

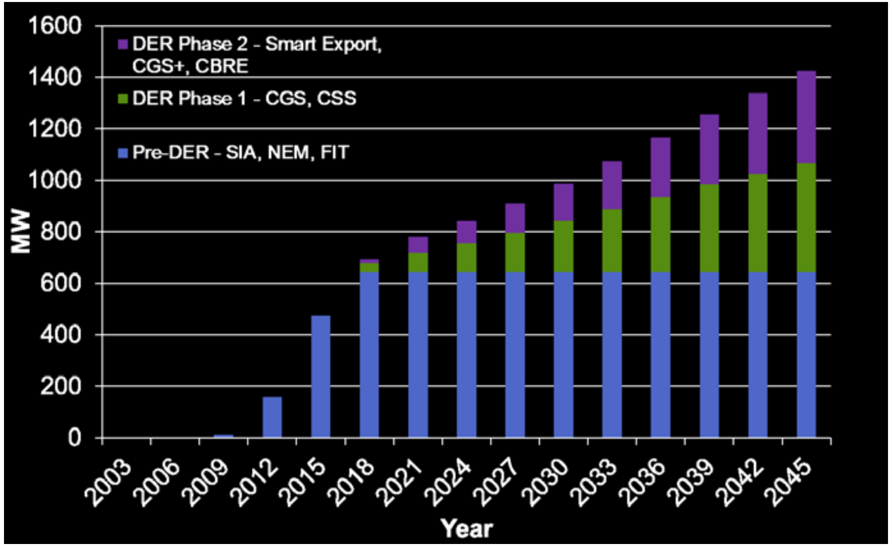


Figure Credits: Hawaiian Electric Companies

NEM – Net-Energy Metering
CGS – Net-Energy Billing
CSS, Smart Export – PV+ Baterias (No Exporte)
CBRE – Solar Comunitario

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Selected Technical Challenges

- **Existing and past challenges**
  - Steady-state voltage issues
  - Islanding and transient voltage issues (GFOV/TOV, LROV/TrOV)
  - Deterioration of frequency response (reduction of inertia, PFR, regulation)
  - Lack of visibility and controllability of DER and grid-edge conditions
  - Extremely difficult to change settings of legacy inverter fleet (due to logistical, cost, and policy challenges)
  - …

- **Emerging and future challenges**
  - Operation of very low inertia grids with 80-100% inverter-based generation at times
  - Balancing load and variable generation across multiple timescales
  - Control of thousands of individual customer-owned DERs
  - Cybersecurity of DERs (manufacturer communications; possible future utility/aggregator comms)
  - …

Solutions: Voltage and Frequency Ride-through

- Activating relatively **wide voltage and frequency ride-through capabilities is step #1** towards successfully operating a grid with high levels of PV
- “Legacy” inverters that don’t have ride-through capability (or can’t easily have ride-through enabled) are an ongoing system stability problem
  - Lesson learned: **require voltage and frequency ride-through capability and relatively wide trip settings early** to avoid future problems when more DERs come online
  - This required compromises between transmission and distribution planners
  - On mainland: Legacy inverters are still being installed today in many locations!
- By working with Enphase, Hawaiian Electric was able to retroactively widen voltage and frequency trip settings for many legacy DERs
  - This was a major effort and would be even harder in a market not dominated by one manufacturer

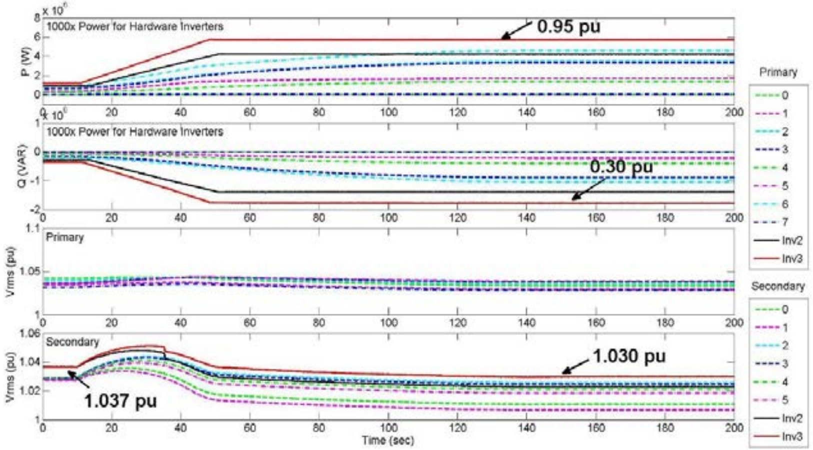
Solutions: Establishing Trust in Smart Inverters

- In 2015 and 2016, HECO and NREL tested advanced functionality of several inverters:
  - V and F ride-through
  - Ramp rate control and soft start
  - Fixed power factor
  - Volt-var and volt-watt
- Tests conducted at NREL's ESIF*:
  - Baseline tests to characterize inverter responses (pre UL1741 SA)
  - Power HIL tests to validate inverter behavior while connected to a real-time simulation of HECO's system

Conclusions:

- Inverters largely performed as expected
- Anomalous behavior was reported to manufacturers and fixed (firmware upgrade)
- Smart inverter functions generally benefit grid operations

Example power HIL test of two inverters at fixed PF of 0.95 (absorbing) in volt-watt control mode



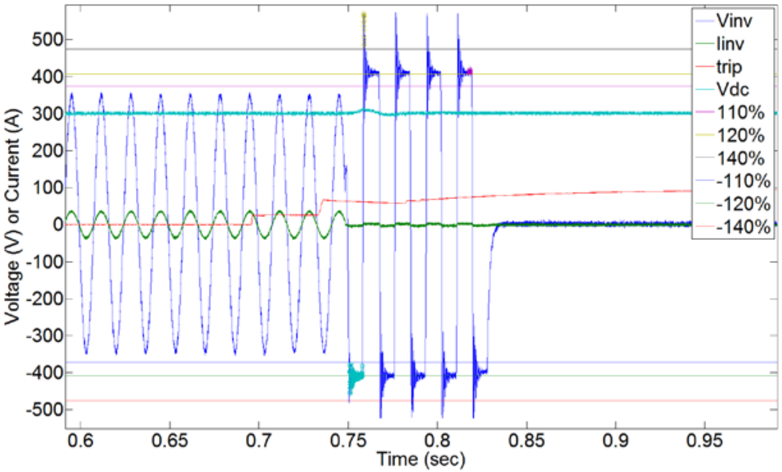
https://www.nrel.gov/docs/fy17osti/67485.pdf

*ESIF = Energy Systems Integration Facility, DOE's flagship lab for smart grid and related testing.
**HIL = Hardware-in-the-loop: A computer simulation running in real-time linked to actual hardware.

Solutions: LROV

- As feeders began backfeeding substations, load rejection overvoltage became a concern
- SolarCity, HECO, and NREL collaborated to test several inverters' load rejection responses
- FIGII* developed consensus test procedure to quantify LROV response
- NREL evaluated load rejection response of five inverters in ESIF lab
- Typically, inverters disconnected very quickly, avoiding potentially damaging overvoltage
- **Outcomes:**
  - HECO required all inverters be tested for LROV prior to interconnection, and increased feeder PV limit from 120% of GDML to 250% of GDML
  - LROV test now incorporated into IEEE 1547.1-2020

Example LROV test waveform at 10:1 generation: load ratio



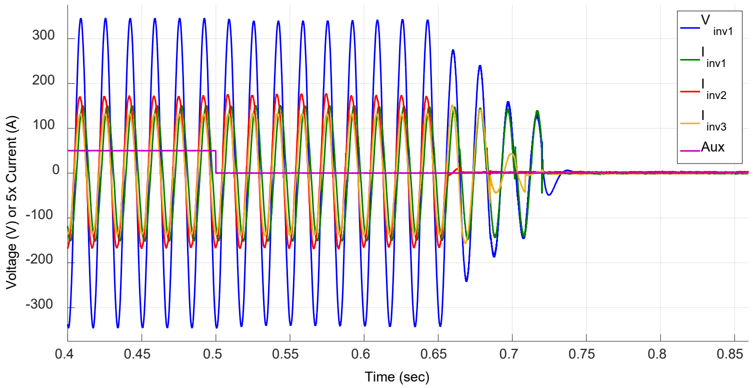
http://www.nrel.gov/docs/fy15osti/63510.pdf

*Forum on Inverter Grid Integration Issues, an industry group (formerly ITFEG)

Solutions: Unintentional Islanding

- With rollout of ride-through (V and f) and other smart inverter functions, possible conflicts with inverter anti-islanding controls became a concern
- HECO, NREL and SolarCity tested the effects of ride-through, volt-var, and frequency-watt on three inverters' anti-islanding performance
- Tests included cases with multiple inverters connected at multiple neighboring locations on the same feeder
- **Outcomes**
  - No islands were found to extend beyond 0.7 seconds
  - Volt-var and frequency-watt control had no statistically significant impact on island duration
  - Ride-through tended to extend island duration by ~75 ms
  - HECO relies on inverter anti-islanding in almost all cases. HECO recloser time settings are long enough to minimize the chance of out-of-phase reclosure

Example multi-inverter island test waveforms



https://www.nrel.gov/docs/fy16osti/66732.pdf

Future solutions?

- **Grid-forming inverters**:
  - Inverters that provide their own stable voltage reference
  - Can operate off grid (i.e. backup or microgrid applications) without rotating machine-based generation
  - Seeing increased attention for use in locations with extremely high levels of PV and wind (transmission-connected applications… not DERs)
- Contrast with **grid-following inverters**, which need an external voltage reference to be stable (>99% of inverters in the field today)
- Does a regulator need to care?
  - Probably not today
  - Except potentially for advanced microgrid or transmission-connected applications

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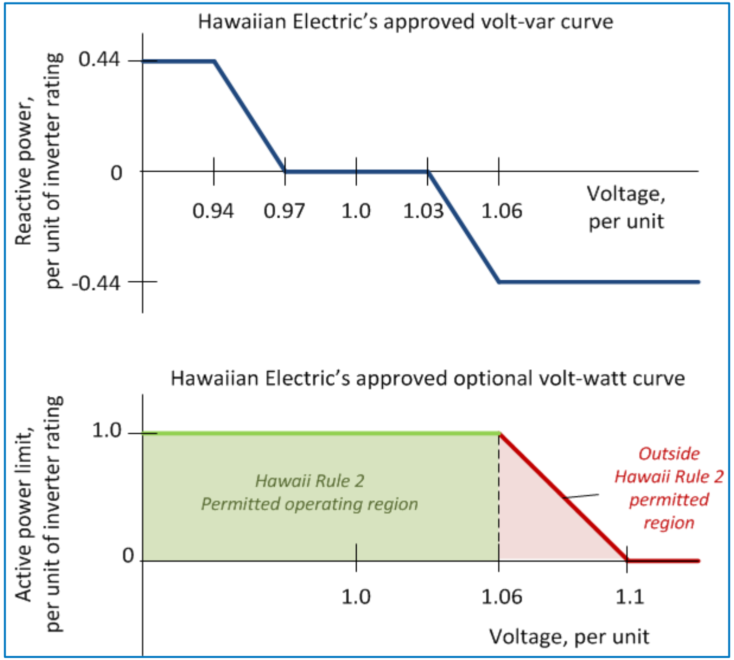
Case Study: Volt-Var and Volt-Watt Control

- PV at unity PF causes steady-state overvoltage issues in some locations
- Currently impractical to actively control thousands of individual PV systems

Near-term solution: autonomous inverter responses

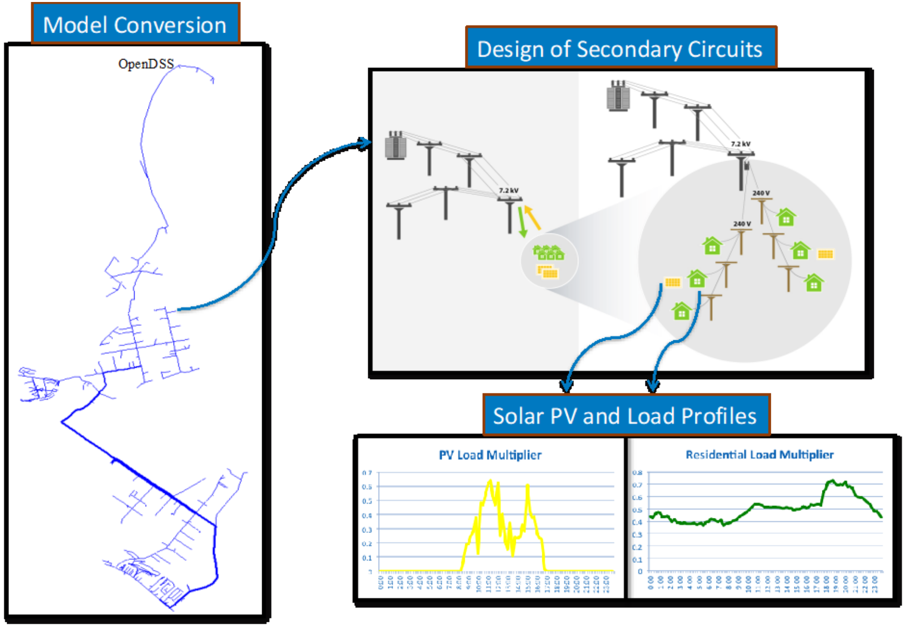
  - Fixed power factor operation
  - Volt-var control
  - Volt-watt control

- HECO initially required PV systems operate at 0.95 PF (absorbing vars)
- NREL, HECO, and industry collaborators expected volt-var control be more beneficial (to all) than fixed PF
- NREL and HECO conducted several studies
  - Detailed time-series simulation
  - Field pilot study
  - Lab testing at ESIF
  - Objective: Quantify impacts on utility and on customers (i.e. curtailment?)



Voltage Regulation Operating Strategies (VROS) Project - 2017

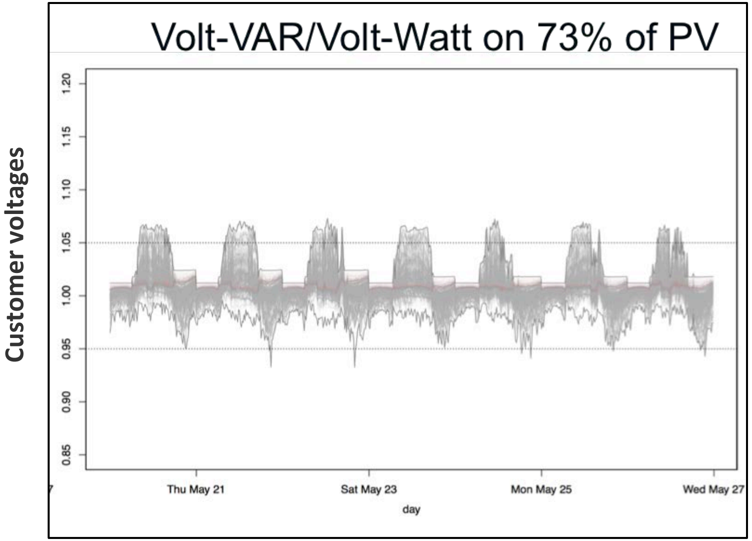
- **PV Penetration Scenarios**
  - Near-term: added pending rooftops and pending FITs to 2015 legacy PV baseline (>400% PV Penetration GDML)
  - Long-term: near-term + additional PV rooftop to equal feeder peak load (>600% PV Penetration GDML)
- **DER Tariffs**
  - All new rooftop PV systems added to the near and long term scenarios were fully exporting
  - Some PV systems added to the near and long term scenarios were modeled with a battery under customer self-supply (non-export)



Case Study: Volt-Var and Volt-Watt Control

- NREL and HECO performed detailed quasi-static time-series analysis of two HECO feeders to evaluate 0.95 PF, volt-var control, and volt-watt control
- Accurate analysis of volt-var and volt-watt requires modeling of secondary circuits
- Volt-var was found to result in fewer voltage violations, fewer tap-changer operations, reduced losses, and less PV curtailment than fixed PF of 0.95
- PV energy curtailment due to volt-var and volt-watt was near zero in almost all cases, with a few outliers
- Also simulated cases with self-supply PV-battery systems.
  - Lower voltages
- HECO now requires volt-var for all new DERs

Example weekly simulation of feeder with 6.8 MW of distributed PV



https://www.nrel.gov/docs/fy17osti/68681.pdf
https://www.nrel.gov/docs/fy19osti/72298.pdf

Case Study: Volt-Var and Volt-Watt Control

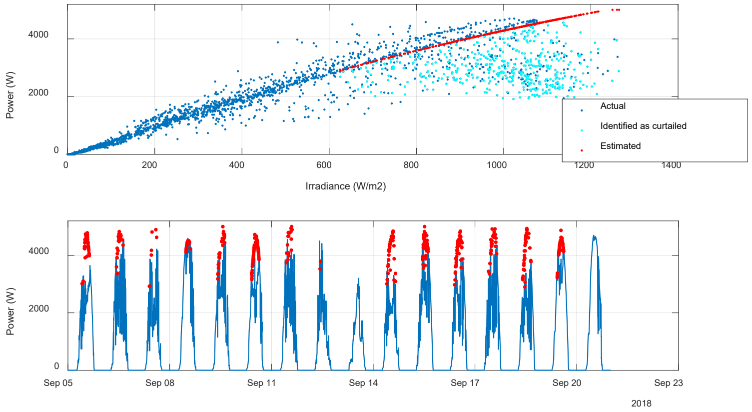
Pilot study:

- NREL and HECO installed monitoring, sensors, and communications to about 30 PV locations expected to have high voltage

Findings:

- Voltages were typically lower than expected
- Limited information available in planning studies leads to conservative assumptions
- PV energy curtailment due to volt-var and volt-watt was typically zero or near-zero
- Curtailment of >1% identified in two cases
  - One location mitigated through conventional (wires) solution
  - Other location has ~1.1% curtailment. Mitigation needed?
- Large-scale deployment of sensing for accurate curtailment estimates is cost-prohibitive for residential-scale PV

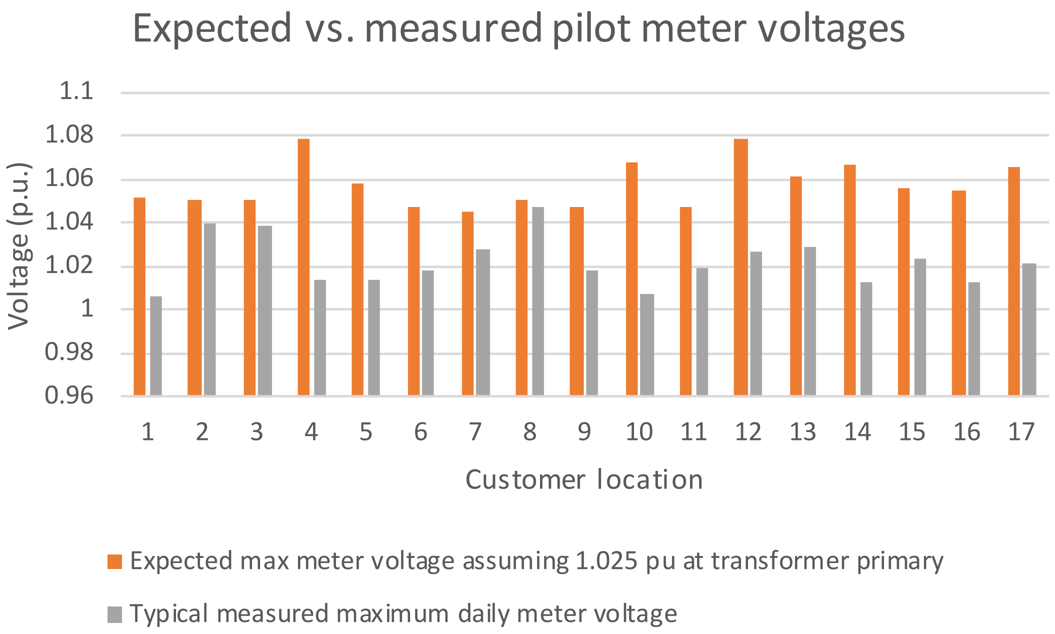
Estimating PV curtailment due to volt-var and volt-watt using plane-of-array irradiance data during an unusual high-voltage period



https://www.osti.gov/servlets/purl/1464444

Field pilot: Expected vs measured voltages

- Measured max voltages consistently lower than expected from detailed screen
- Distribution planners do not have information needed to accurately predict customer voltages; must make assumptions
- Leads to more systems than necessary being identified as problems
- Is there a better way?

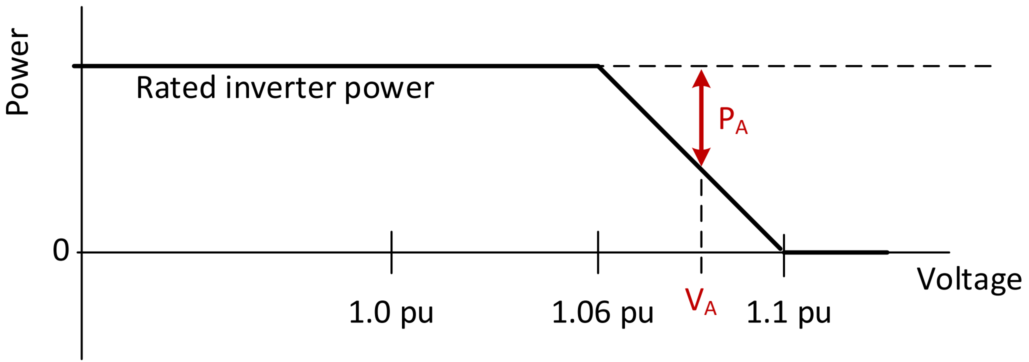


AMI data for DER integration

An alternative approach to DER studies: Interconnect and manage/mitigate based on AMI data

- While models must make conservative assumptions, AMI data can empirically determine which DER sites have voltage issues
- AMI voltage data can also be used to estimate DER curtailment[1]
  - Then what? …compensate? mitigate?

Volt-Watt Curve



1: Emmanuel et al, "Estimation of Solar Photovoltaic Energy Curtailment Due to Volt-Watt Control," https://drive.google.com/file/d/1EWK-y3SYuWQb-wE2XiQb5C10FU53Szrj/view

AMI Metrics

1. Processing of metrics

Raw data

- AMI Raw Data
- Customer Metadata (CIS/GIS)

ETL & Data joins, Filtering

- Joining and processing data
  Mapping meter IDs to customers

Processing and Calculations

- Calculating performance metrics

2. End-use of metrics

- **Automated performance metric report and graphs with:**
  - Voltage excursion reports
  - Curtailment reports
  - Net load profiles per tariff

- **Distribution engineers examine reports:**
  - High-level metrics
  - Metrics by company, circuit, transformer
  - Power quality reports
  - Metrics for both voltages and net load

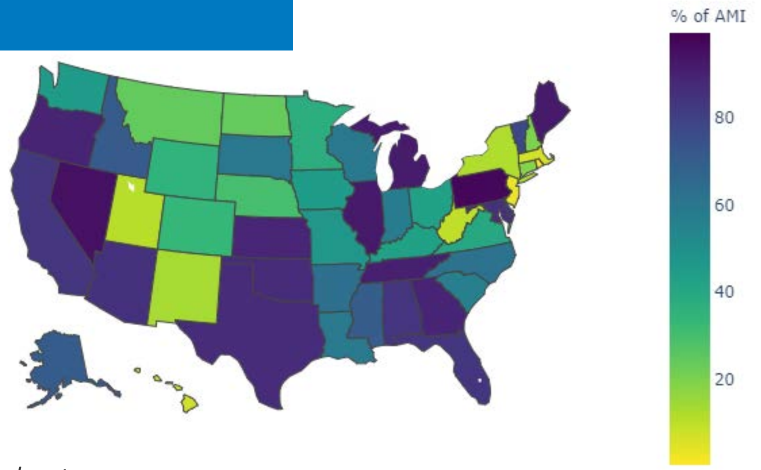
- **Use the reports to satisfy regulatory requests**
  - Relevant extract or materialized view

- **Use the reports to identify network problems**
  - Send engineers to investigate

Evolution of Metering

- **Standard Meters (non AMR/AMI):** Electromechanical/Watt-hour meters requiring a technician to visit and collect readings.
- **Automatic Metering Reading (AMR):** Collect meter readings of aggregate kWh usage retrieved by drive-by vehicle/walk-by handheld system.
- **Advanced Metering Infrastructure (AMI):** Collect meter readings with interval reads (hourly or more frequently) with daily or more frequent transmittal measurements over a communication network to a central collection point.
- **Next Generation AMI:** Potential features include; EMS integration, DER integration, power quality, high fidelity measurements, AMI for operations and integration to ADMS

Electromechanical meter



U.S. roll out of AMI, data from E.I.A.

Digital AMR

AMI/Smart meter

As of 2020 100M+ meters, Energy Information Administration (EIA)

Smart Grid Chip

Why, oh why, AMI?
Reduced meter reading costs
More efficient billing
Greater visibility

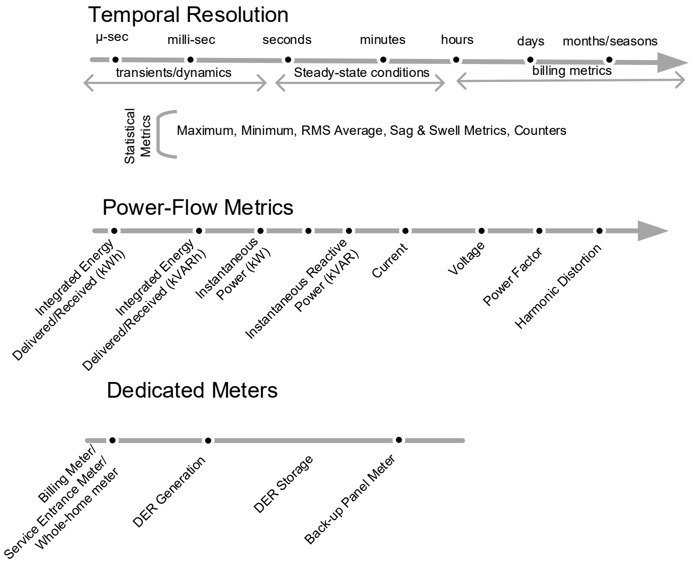
pricing (e.g., TOU)
Outage detection/OMS

But – Are utilities using AMI data to its full potential?

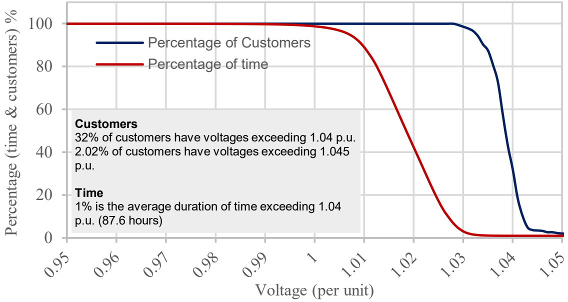
AMI Analytics

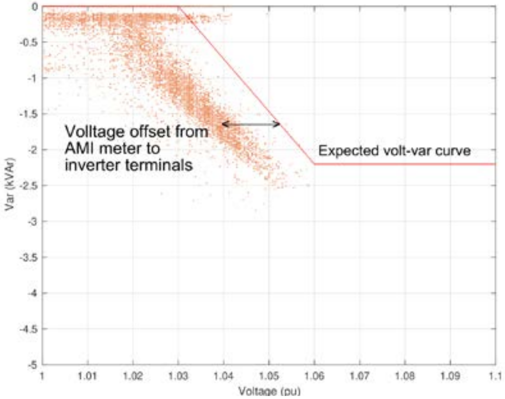
- **NREL** has been working with Hawaiian Electric and other utilities on **advanced AMI analytics for:** distribution planning, DER performance, smart inverter function activation, customer segmentation, DER disaggregation, and voltage performance.
- Creating QA/QC, integration with CIS/GIS/DER metadata and analyzing 100k's of customers to produce succinct reporting for distribution engineers and aggregation layers (statistics by transformer, circuit, tariff, DER programs, etc.)

Huge diversity in the temporal resolution, collected metrics, and number of dedicated meters utilities are deploying



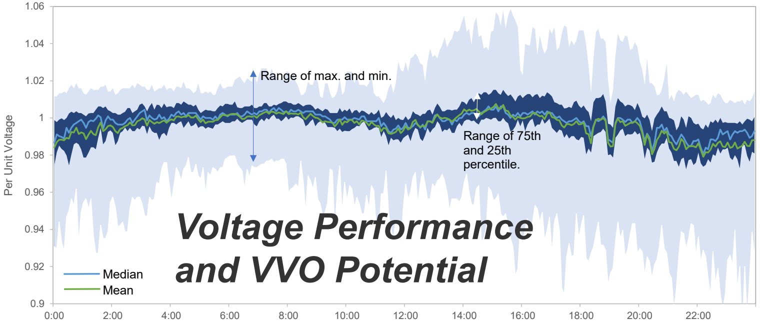
Establishing normal bounds of voltage operation





Advanced inverter function activation and validation

Estimated curtailment calculations from Volt-VAR and Volt-Watt



Voltage Performance and VVO Potential

Case Study: Volt-Var and Volt-Watt Control

Conclusions:

- Volt-var and volt-watt control are useful tools for mitigating high customer voltages due to behind-the-meter DERs
- Volt-var curtailment impacts on PV production are typically near zero (at least for the volt-var curve used in Hawaii)
  - If the sloping region of the volt-watt curve is outside ANSI Range B (1.06 pu), volt-watt provides a backstop against occasional high voltages while maintaining near-zero curtailment
  - It is difficult to predict in advance exactly which locations will have high voltages, and periods of high voltage sometimes occur for a few days at a time due to feeder reconfigurations (utility switching)
- Volt-var and volt-watt are most beneficial if deployed system-wide

Ongoing work and next steps:

- HECO deploying AMI with all new PV systems
  - AMI data is used to identify any customers with persistent high voltage problems
  - HECO takes responsibility for fixing problem locations. Very few exist
- Most new PV systems in Hawaii now have integrated battery storage – daytime export is no longer economical under latest tariffs
  - This helps maintain voltages within ANSI Range A
  - Leverage storage for other purposes?

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PRECISE – Automating DER Technical Screens and Leveraging Advanced Inverter Functions

An **automated interconnection evaluation tool** that quickly assess the impact of solar on the grid, makes accept or modify decisions, and leverages advanced inverter functions (volt-var, volt-watt) to help accelerate grid integration.

PRECISE helps utilities/grid-operators accelerate the interconnection process, through **automated detailed technical screening**, and **leverages advanced inverter functions** *as needed.*

R&D 100 Award Winner 2019

Fully integrated and deployed at SMUD Spring 2022

PRECISE™ integrates siloed data systems and performs comprehensive QA/QC to model the impact of DERs on the distribution system

SMUD

1. DER Interconnections
2. Automated DER Technical Screen
   PRECISE
   Performs 8760 power-flow at point of interconnection
3. Evaluates Network Impacts
4. Enables fast turnaround approval

- Advanced Metering Infrastructure
- Geographical Information System
- Customer Information System
- Interconnection Technical Data
- Power-Flow Models (e.g., Synergi, Cyme)
- Supervisory Control and Data Acquisition (SCADA)

PRECISE Deployed at SMUD

SMUD
Powering forward. Together.

- Deployed in February 2022
- Automatically evaluates all incoming rooftop solar PV applications

Stats on deployment

1,700 applications processed in the first 6 months

Avoided thousands of man-hours of planning engineers' time

Enabled the interconnection over 10 MW of rooftop solar to date

Processed an average of 13 applications a day

Runs thousands of power-flow scenarios for each incoming application

Modeled over 800 feeders and thousands of secondaries capturing the entire service area

Able to accept 71% of applications with no modifications, 12% with standard advanced inverter functions, and 14% were recommended reduced capacity

Applications processed within minutes rather than days-to-weeks

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Conclusions

- Activating relatively wide voltage and frequency ride-through *early* is step #1 towards successfully operating a grid with high levels of PV

  → Adopt IEEE 1547-2018, preferably Category III

- Inverter anti-islanding controls were found reliable even with grid support active, and even in the multi-inverter, multi-PCC scenarios tested
- Field data, detailed simulations, and power HIL tests validate the benefits of advanced inverter functions
- For feeders with very large numbers of distributed inverters, volt-var control is more beneficial to the utility and the customers than fixed power factor
- Volt-watt control is beneficial as a backstop against high customer voltages, especially given limited grid-edge visibility
- Ensuring the correct inverter settings are deployed in field requires verification
- For subtransmission applications, it may be preferable to apply IEEE 2800 (not 1547)

Conclusions

- Autonomous, local DER controls:
  - Relatively easy to deploy and **reliable** – capability required by 1547-2018 and UL 1741 SB
  - **Proven** through widespread use in some states for several years
  - Little to no downside for utility or DER owner
  - **Help with voltage-related** DER integration issues
  - Do not help (or hurt) thermal/capacity-related DER integration issues
- Centrally coordinated DER controls:
  - Are enabled by 1547-2018 communication functionality
  - Can **help with thermal/capacity-related** DER integration issues (among others)
  - Could also enable **bulk grid services** from DERs
  - Requires **rollout, integration, and maintenance of a communication network** (or use of manufacturers' propriety communications)
  - No large-scale field application examples outside pilot projects (that I'm aware of)

Questions & Future Directions

- How to transition older “legacy” PV systems to advanced inverters?
- Grid services from DERs?
  - Bulk grid services? Local services? Aggregators? DERMS? … Cybersecurity?
- Inverter data integration into utility systems?
  - Planning? Operations?
- Coordinated control of DERs? Or stick with status quo of autonomous DERs?

Thank you

www.nrel.gov

NREL Power Systems Engineering Center

https://www.nrel.gov/grid/

Andy.Hoke@nrel.gov

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