Identifying Reliability and Variability Issues with Hi-PV on the Distribution System
HECO and SMUD Case Studies

Dr. Emma Stewart

Senior Engineer, Power Systems

BEW Engineering

Overview

- Who is BEW Engineering and why are we working in this area?
- Partnerships with SMUD and HECO
- Key Questions and Answers
- Case Studies

BEW/SMUD/HECO Partnership

- BEW is an internationally recognized consulting company specializing in wind, solar and T&D with over 45 professional engineering staff
- In October 2010, BEW was acquired by DNV, a Norwegian company with more than 9,000 staff and 300 office worldwide
- In 2007, DNV acquired Global Energy Concepts, an international wind consulting company

BEW/SMUD/HECO Partnership Cont.

- SMUD and HECO recognized that there was a need to study the distribution system impacts from high penetrations of PV
- They needed to define the current and future inverter requirements for maintaining reliability
- They retained BEW to provide consulting services to find common solutions

Key Perspectives

- Bringing conclusions together in multiple situations
  - How can we categorize feeder impacts?
- Synergizing schools of thought between multiple groups of utilities
- What are appropriate simulation techniques?
  - Importance of verified software tools and model development
  - Data collection and verification
- Results communication and presentation

Objectives and Overview of Hi-PV studies

- Assess potential system wide PV penetration on the distribution system
  - Feeder and System wide penetration limits
  - PV penetrations per individual feeders will vary
  - Summation of feeder PV not equals system total
- Study of individual feeder impacts provide insight to the potential barriers and issues, restricting high penetrations
  - Provide analysis framework on both a feeder and system wide scale

How are we enhancing distribution modeling and analysis?

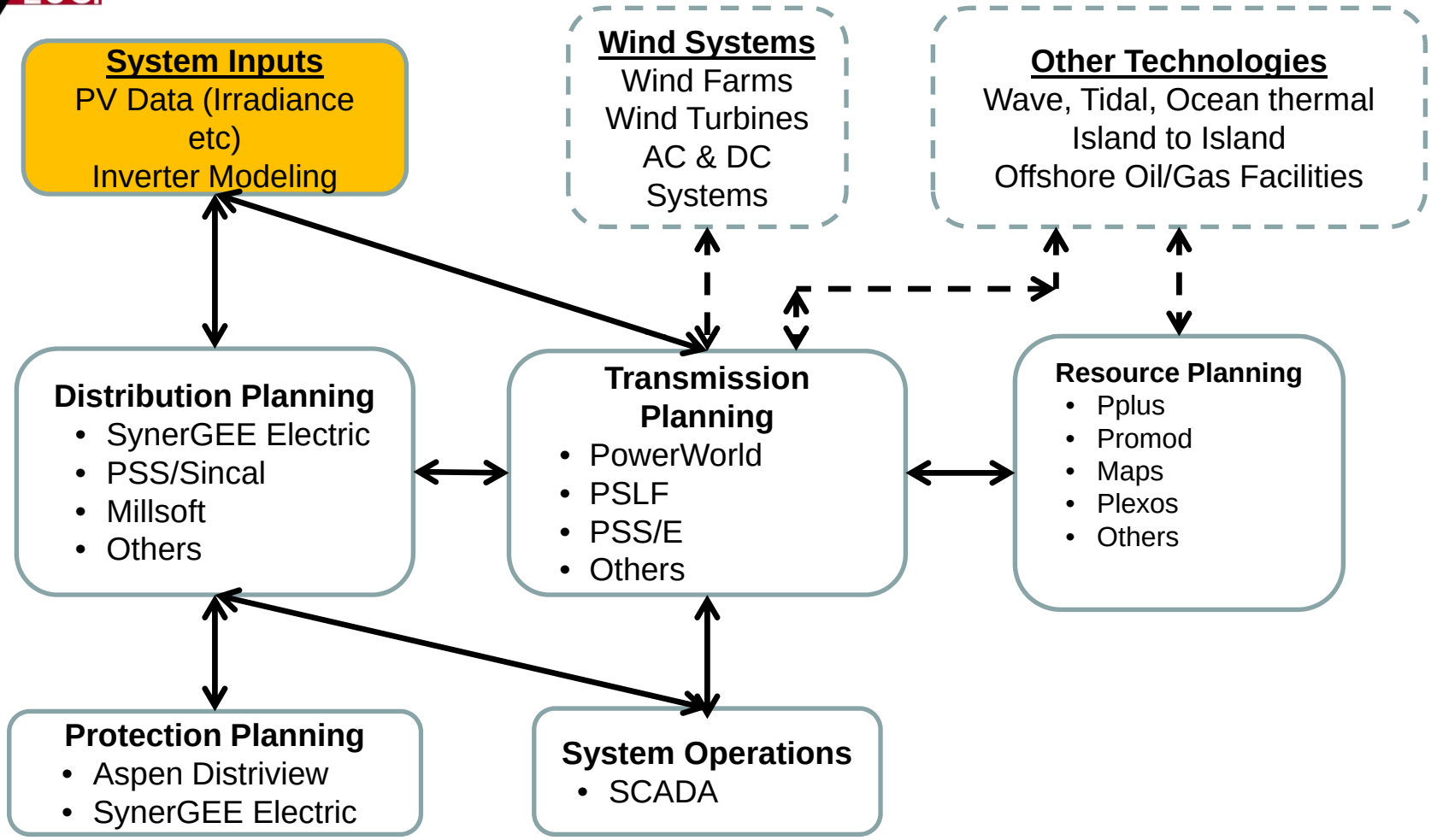
- Previous studies use three phase models focusing on sub-transmission and substation impacts
  - Simple impedance models are used
  - 3 phase aggregated load flow model
- Most impact studies only consider capacity and baseline generation impacts
- Variability of high penetrations of PV are not generally considered
  - Or accurately measured data is not available
- Detailed inverter/PV modeling
  - Incorporating detailed PV performance analysis
    - Quantify the importance of high resolution PV data in high penetration areas

Enhancements to the distribution model process

- Determine effect of variable resource/weather impacts on distribution grid as a whole
- Feed detailed distribution impacts back to the sub-transmission and transmission system models to determine whole system impacts from the distribution system
- Single phase distribution impacts can be quantified using detailed models
  - Improvement from either three phase balanced analysis, or simple impedance models
- Analysis of impact of changing inverter operational characteristics
  - Provide justification for requests to manufacturers
- Interaction of LTC, capacitors and multiple inverters
  - Provide operational recommendations

How will software be integrated?
How important are the tools and how do they interface?

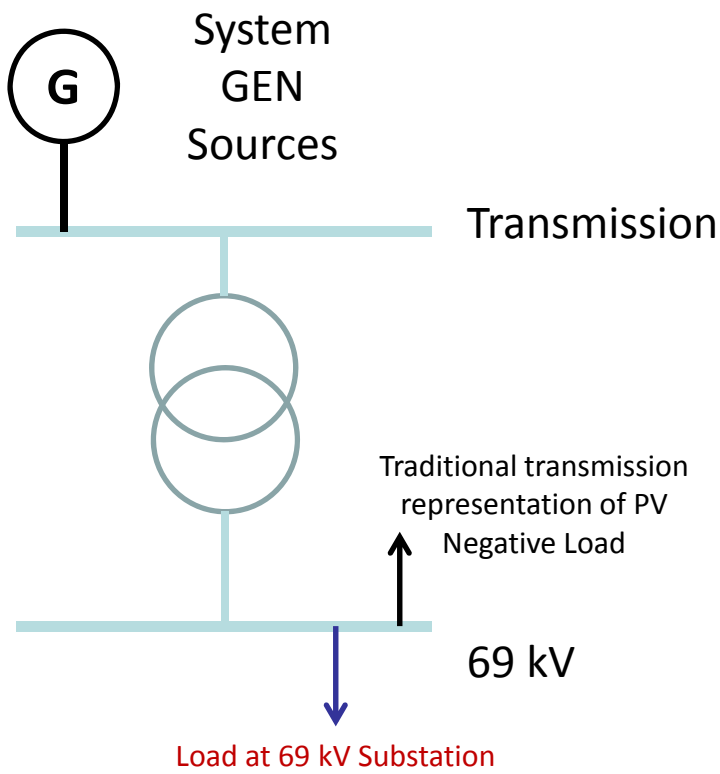
Graphical Flow of Model Interfaces



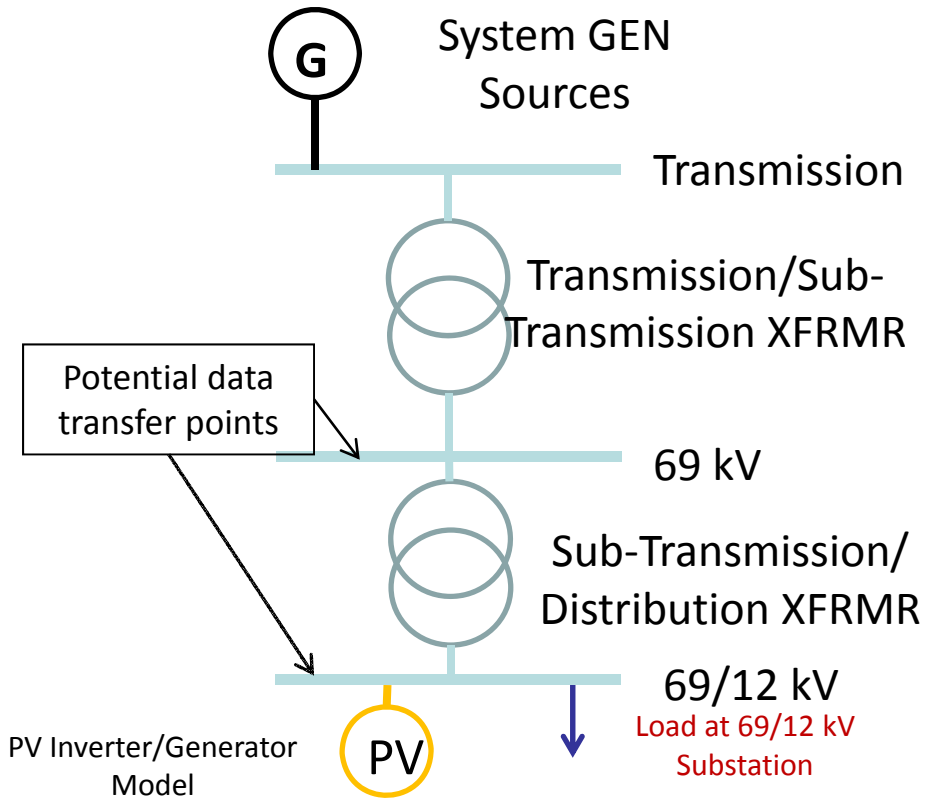
At what levels should issues be identified?

Two schools of thought for PV penetration impacts studies

Traditional Representation of PV from a transmission POV



Recommended Representation of PV for a Transmission Analysis



Why even model the 12 kV distribution?

- Current models discount DG PV generation (treats as negative load) so utilities will never be able to separate and account for contributions in models
- Distributed feeder PV over a wide area can not be treated like a large central PV site
  - Lack of smoothing and averaging of power output
  - Less predictable due to climate and utility control
- Quantification of detailed feeder impacts on a per-feeder basis
  - Protection/Fault Current
  - Harmonics
  - LTC/Capacitor/Inverter interactions
  - Voltage and regulation implications
  - Seasonal impacts of high penetrations on the distribution side
- Distribution results transferred to transmission grid
  - Reduces data set size and run time
  - Provides detailed DG impacts to be considered
  - Allows for continued distribution studies with bi-directional flow of information and data consistency

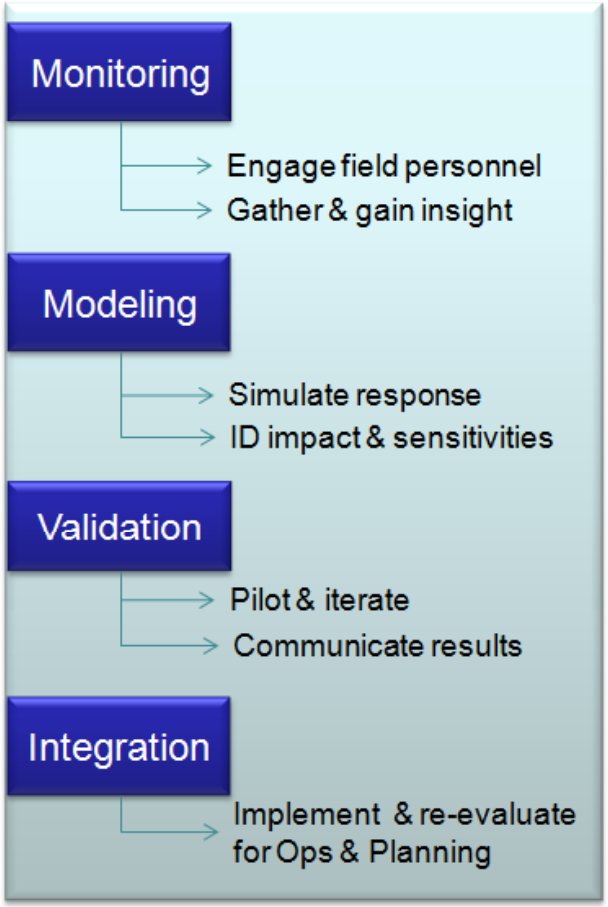
What benefits to transmission and generation planning?

- Determine major events or operations on distribution that could impact total system
- Simulate high risk case scenarios, to inform new operations and emergency plans for most efficient system recovery with high penetration
- Consistent methodology to address PV penetration limits before impact is more severe
- Get head start with tools to create remediation plans, for larger PV penetrations
  - Equipment replacement/upgrades

Key analysis steps and methodology

Methodology Overview for system level and feeder level studies

- Review existing models to develop baseline distribution dataset model
- Integration of datasets (or PV aggregation analysis)
- Development of tools and inverter data sets
- Scenario development with SMUD/HECO team



Determine Time Periods of Interest for Transmission and Distribution

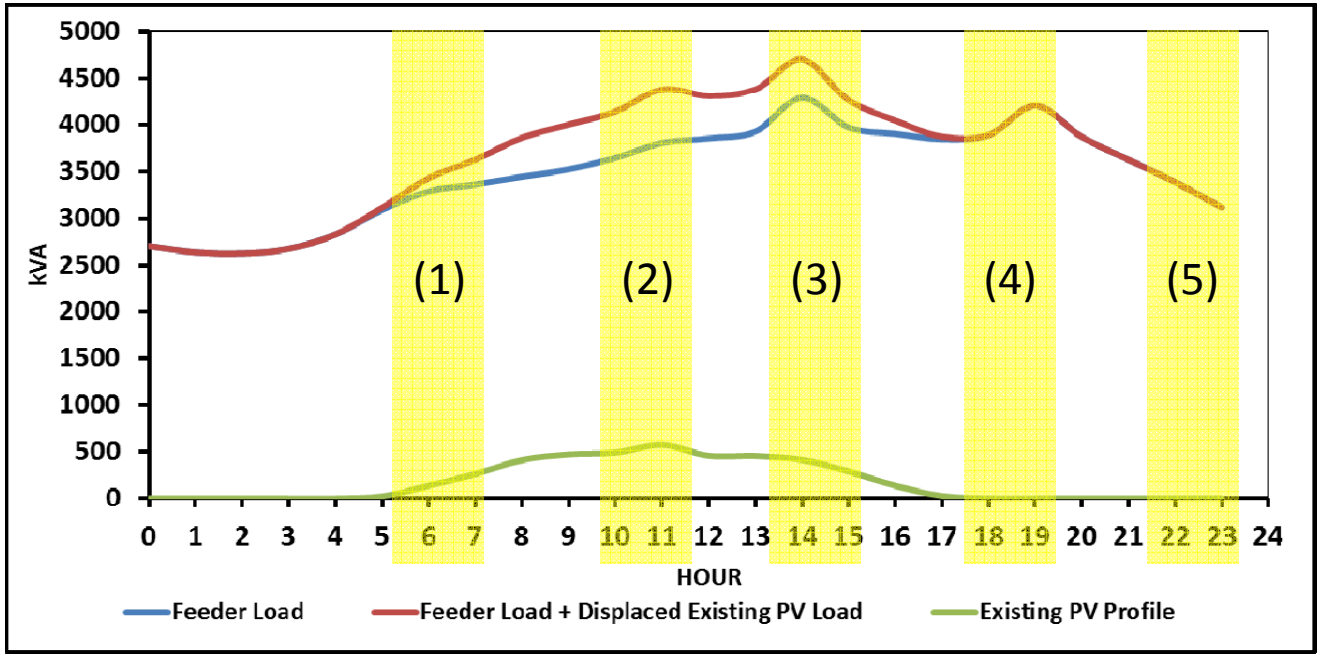
(1) Demand daytime increase

(2) PV Peak generation time

(3) Demand Super Peak time

(4) Evening Demand Peak

(5) Demand decrease in the evening



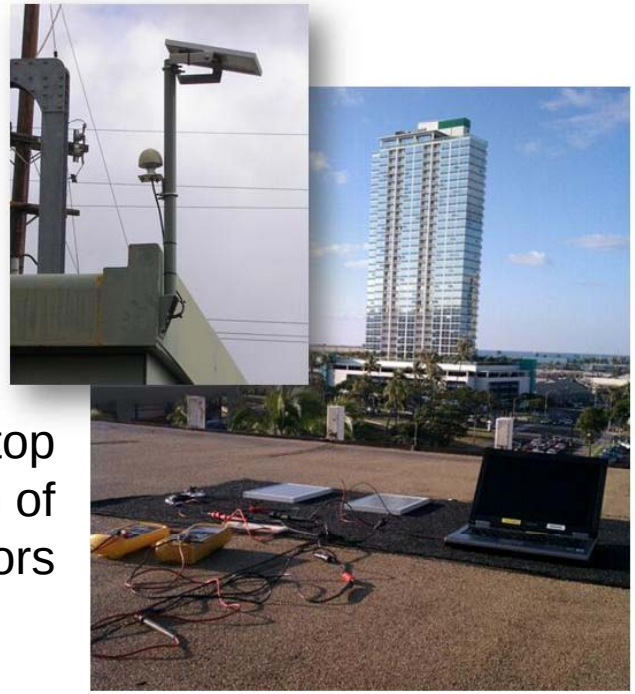
- Significant operational considerations for each time period.
- Minimum load conditions profile is either 40% of peak, with the same form as the peak curve for this example and demonstration
  - Or available measured substation load data for a more accurate representation

Methodology Cont'd

- Dynamic distribution/transmission study in PSLF
  - Thermal limitations
  - N-1 scenarios (steady state and dynamic)
  - Worst case high variability (steady state and dynamic)
  - Generation (steady state and dynamic)
  - Balance of plant
  - Protection of personnel
  - Frequency impacts/Dynamic Analysis
- Present results using graphical representation to visually show areas of impact and variations
- Provide % penetration limits report
- Provide user training on developed models and conversion process

Field Measurement Devices Provide Validation and Operational Data

- Field Validation Locations & Devices, Calibration & Select Customer Site Monitoring
- Gain insight on customer use and circuit level contribution of PV on grid

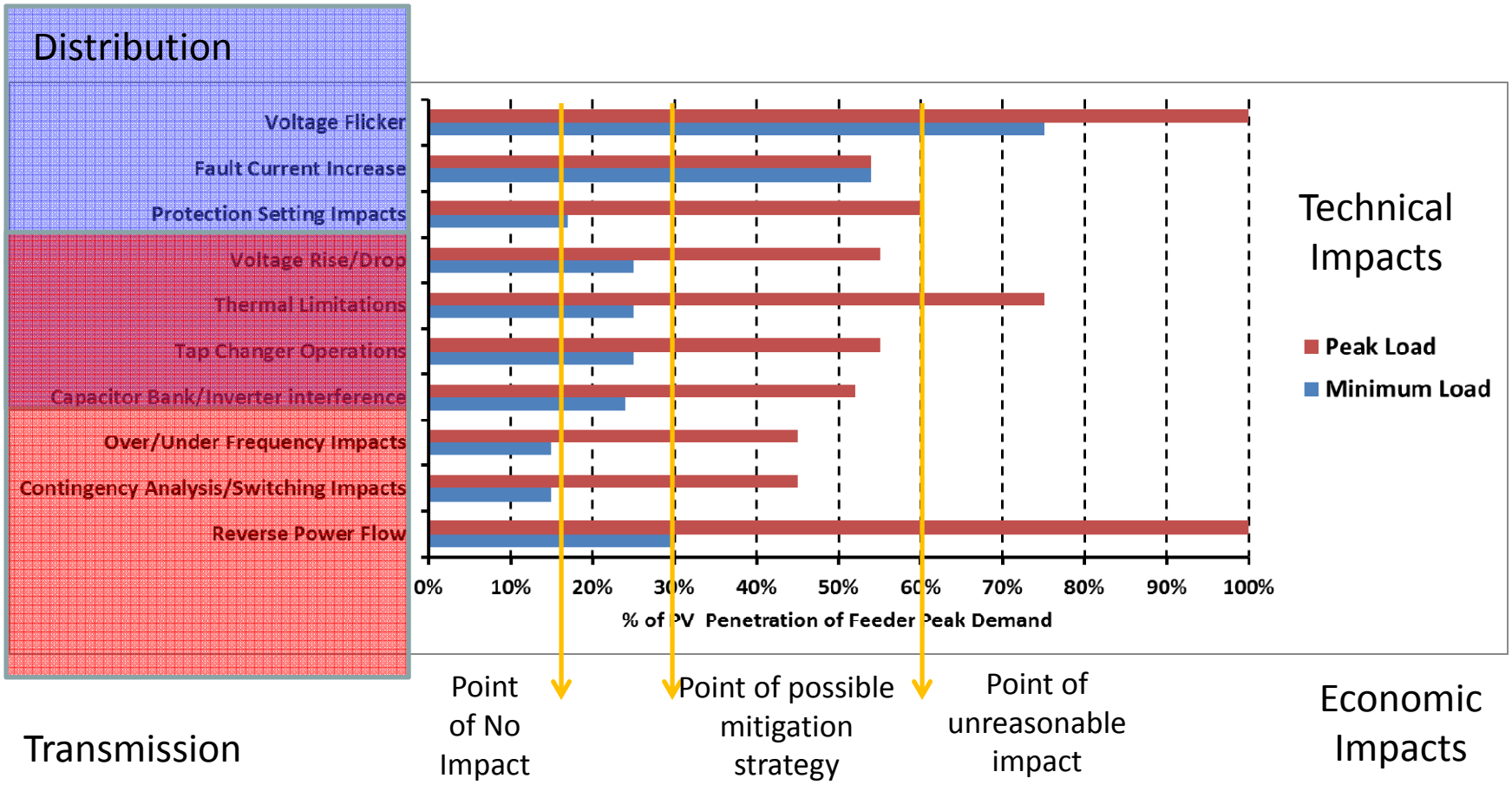


Rooftop calibration of LM-1 monitors

Customer site PV output monitoring

19

Using multiple reasons for determining impacts and limitations on a system wide basis



Transmission

Economic Impacts

Case Study 1: Oahu Feeder

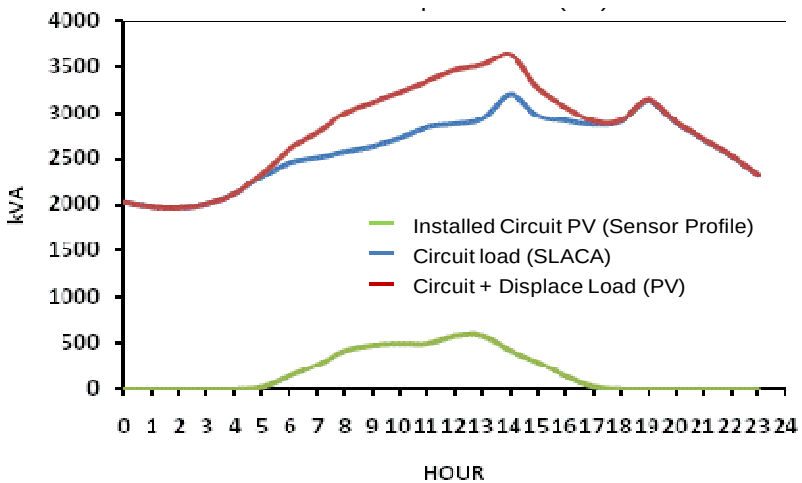
Existing high penetration, measured substation and PV data available, large commercial customers mixed with residential

Analysis Process for Oahu 1

- 24 hour Load and PV profiles are added as customer zones to SynerGEE for feeders 1,2, 3 and 4, and for each of the PV locations
  - Profiles can be applied for each “day type” over 12 months
  - 1 hour data applied
- Voltage levels over 24 hours analyzed, at different potential PV levels
  - No PV
  - No PV + Spot Loads to account for displaced peak time load
  - Existing PV + Spot Loads
  - Existing PV + 1.5 MW potential PV at single location
- Minimum and average voltages are in general improved slightly by the addition PV Levels

Hi-Pen PV Impact on the Grid - Substation Circuit Monitoring & Analysis

Oahu Circuit



TJD-1 mobile solar irradiance sensors

LM-1 solar availability sensors

- Enabling, low-cost capability to separate PV production and actual system load per circuit
- Correlate sensitive grid conditions with solar variability (max load, light load, storm conditions, contingencies, reserve plans)
- Preliminary Results: Field sensor deployments and results are helping to increase visibility at the distribution level

23

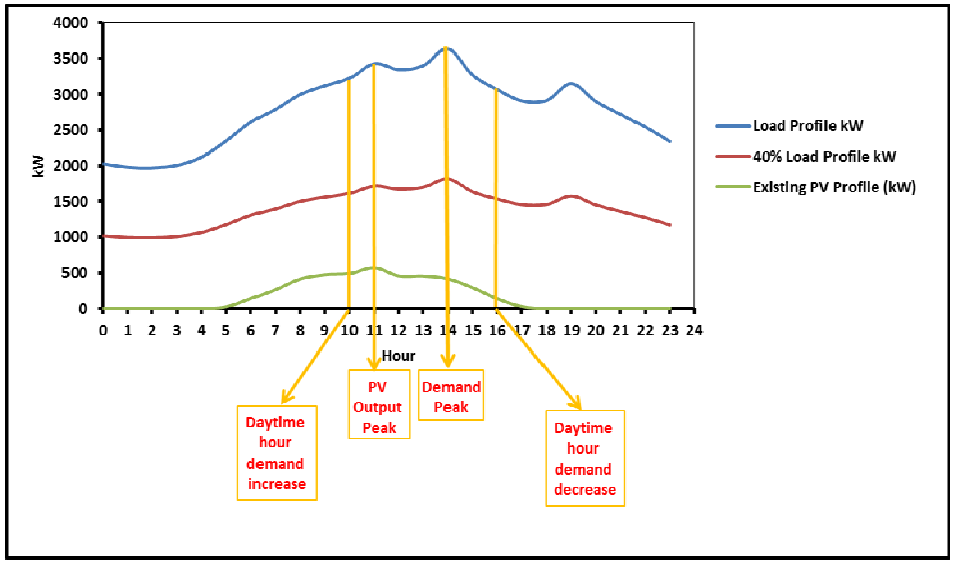
Determine Time Periods of Interest

(1) Demand daytime mid-peak begins around 10am

(2) PV Peak generation time, around 11 am

(3) Demand Super Peak time, approximately 2 pm and

(4) Demand decrease in the evening, around 5pm



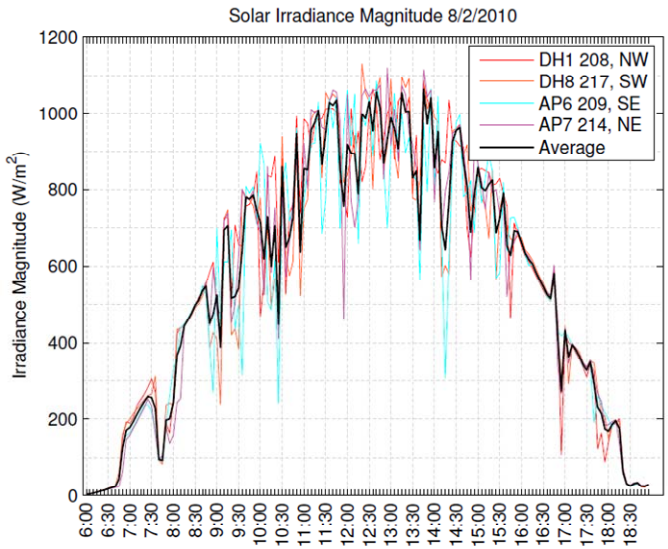
- Significant operational considerations for each time period.
- Minimum load conditions profile is either 40% of peak, with the same form as the peak curve for this example and demonstration
- Or available measured substation load data for a more accurate representation

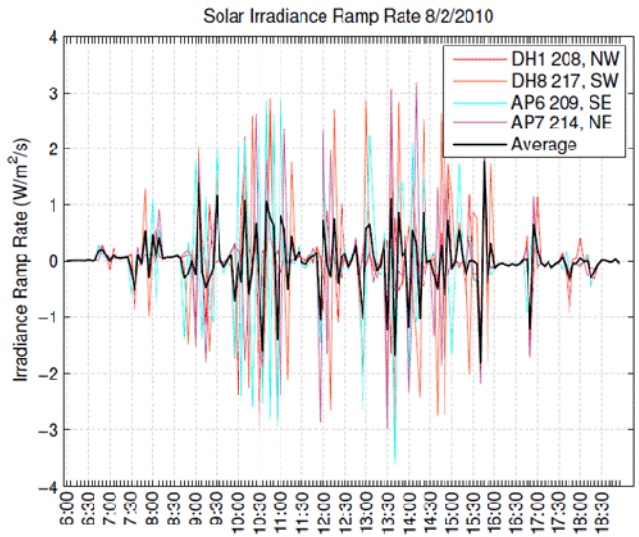
Load and PV penetration conditions resulting in back-feed to 46 kV

- Increase PV penetration incrementally at different locations on the feeder
- Monitor changes in voltage regulation and tap changer positions
- Note point at which PV feeds back to the 46 kV and at which loading condition

- Conditions
  1. Normal peak time, with spot loads replacing load displaced by PV
  2. Minimum demand time on peak day
  3. Assumed minimum peak time load of 40% on a Sunday at 1pm
     - Assume large customer is still at peak here but other industrial loads are at minimum

Averaging effect of multiple sensors/multiple PV panels

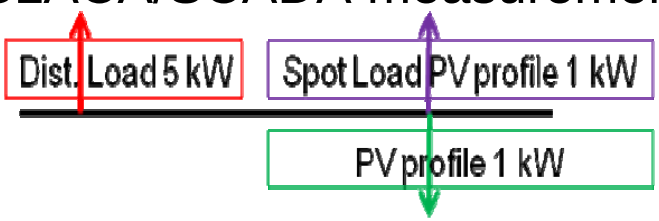




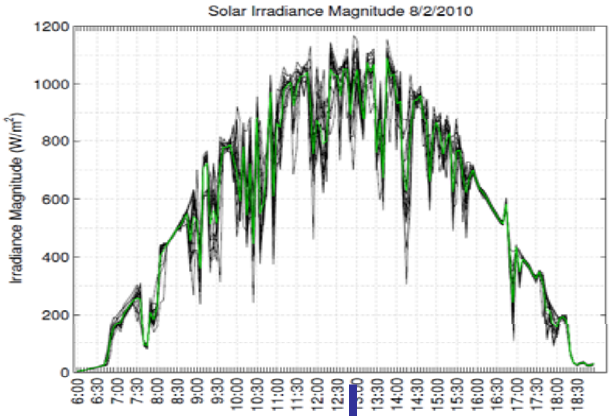
- All sensor output raw data is 1-second timestep, here averaged to a 5-minute time-step
- Compared to the individual sensors outputs, the average exhibits reduced peaks and valleys
  - Still seems to have similarly frequent output swings
  - Right hand side shows the ramping, or change in irradiance, for the same timestamp as the irradiance output
    - The magnitude of change in irradiance is significantly reduced when averaged

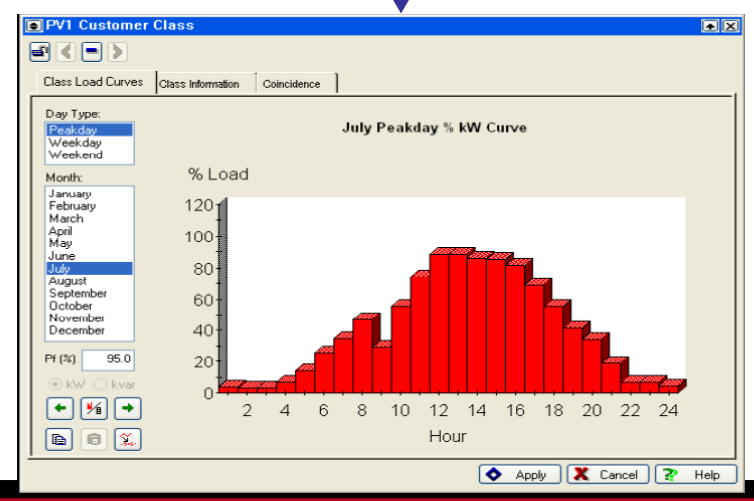
Preliminary PV Modeling

- Conversion of PV data to model format
  - Applied to SynerGEE Electric Dataset
- Model loads to replace existing PV not accounted for in SLACA/SCADA measurements



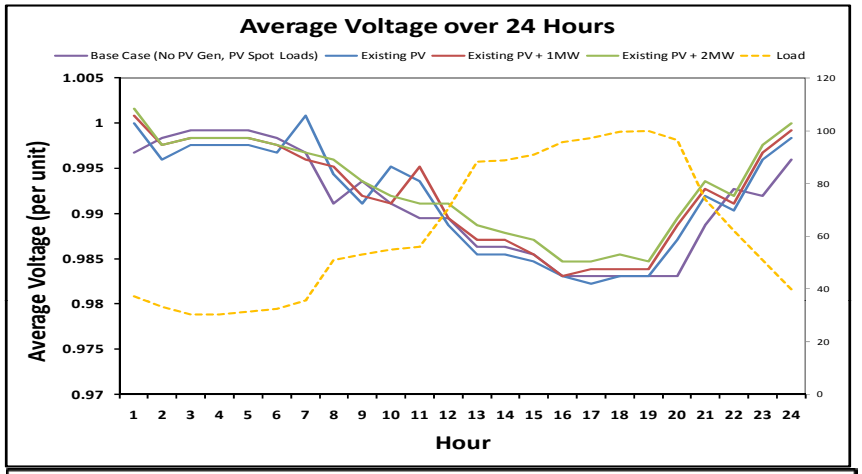
$$P_{gen}(t) = \frac{0.001G(t)A\eta_{module}\eta_{inverter}}{P_{rated}}$$

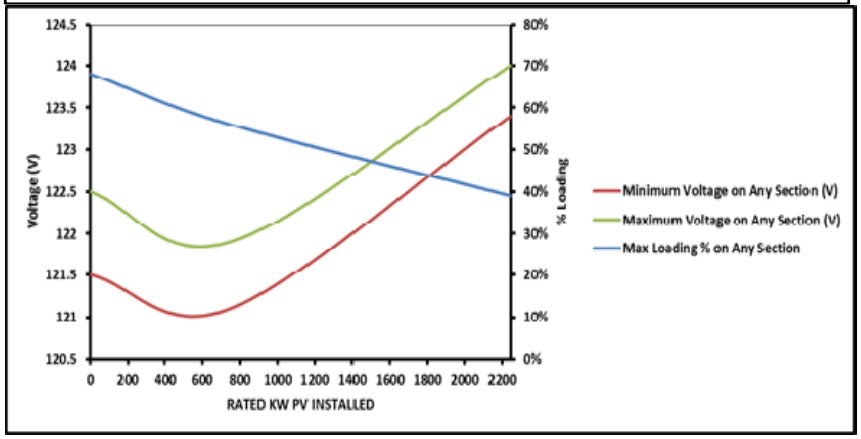




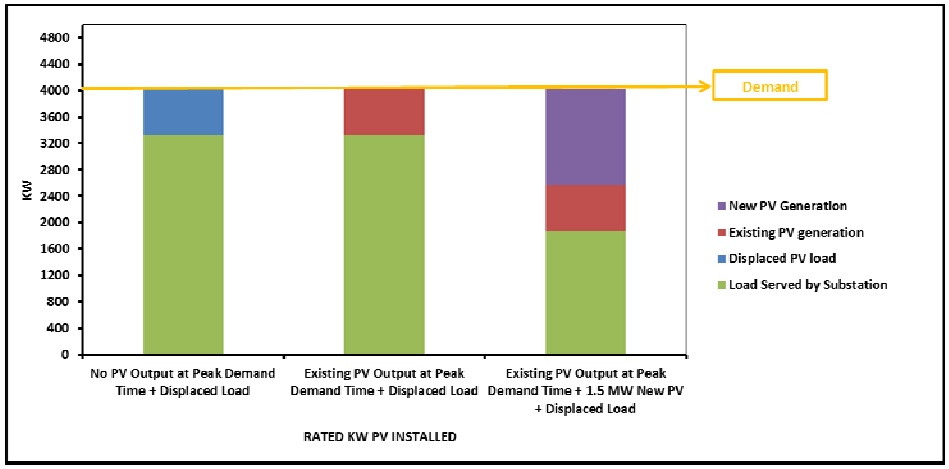
Steady State and Time Sequential Analysis

- Consider the full 24 hour demand and PV profile to determine effects at non-peak periods not previously considered
  - Determine the difference between control operations, such as the KVAR flow when capacitors are on and off, or voltage across the whole time period
- 24 hour time step analysis is the precursor to building dynamic studies
  - Determining times dynamic contingencies are of particular interest, a different analysis framework to be started in the second year of work
- Determine reliable methods of quantification impact based on maximum and minimum voltage plots against kW PV installed



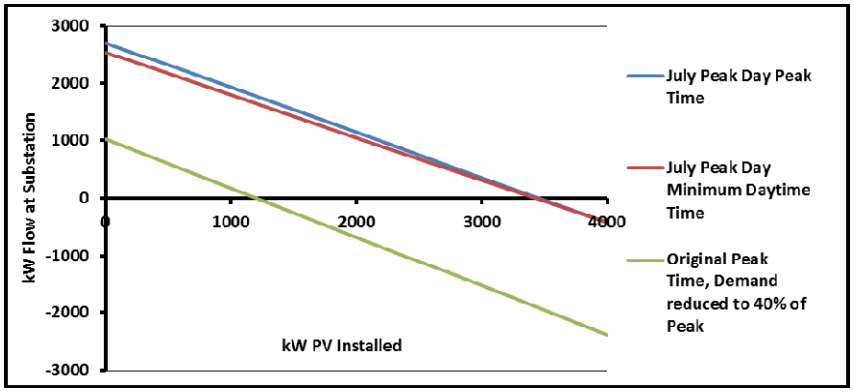


Quantify impacts on the feeder, substation and higher voltages



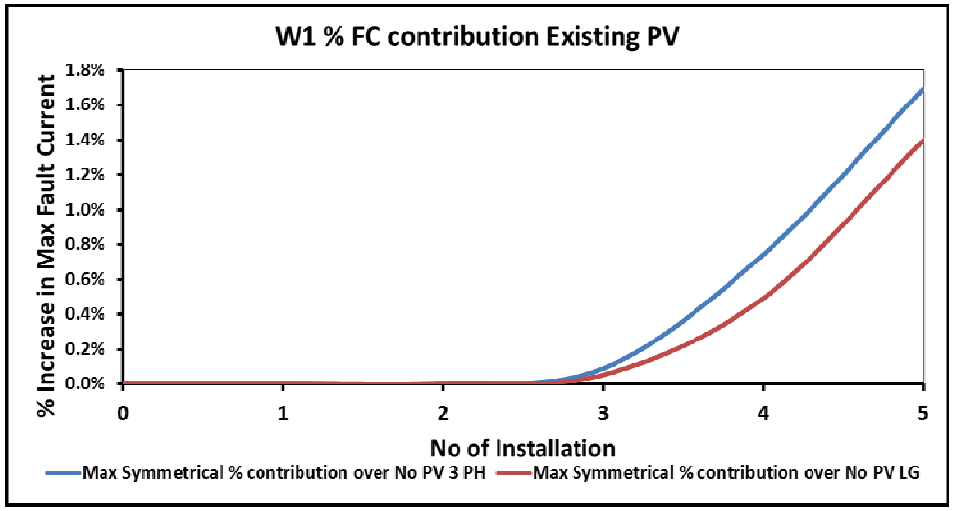
- As variable renewable technologies increase, at what point must spinning reserve be considered?

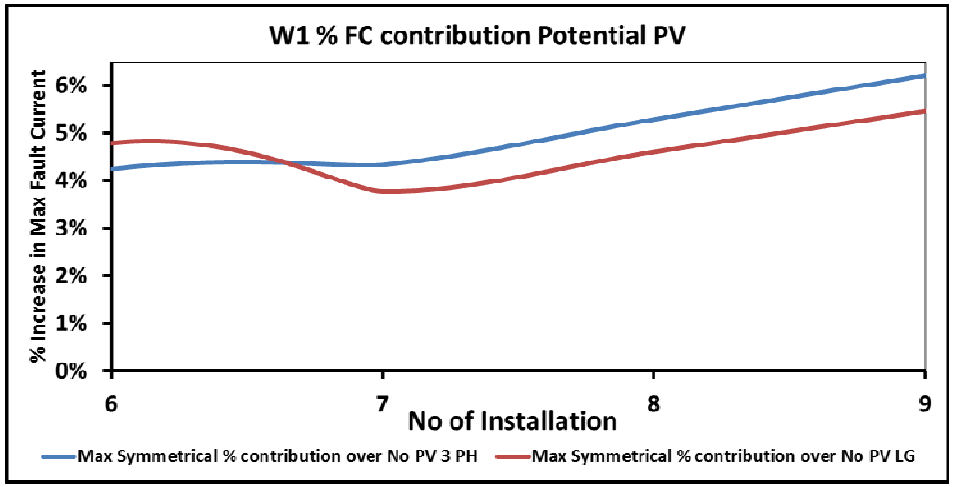
- Minimum load with high PV conditions often result in back-feed conditions at high penetration levels
  - Impact on substation equipment
  - Impact on transmission and generation



Fault Current Results

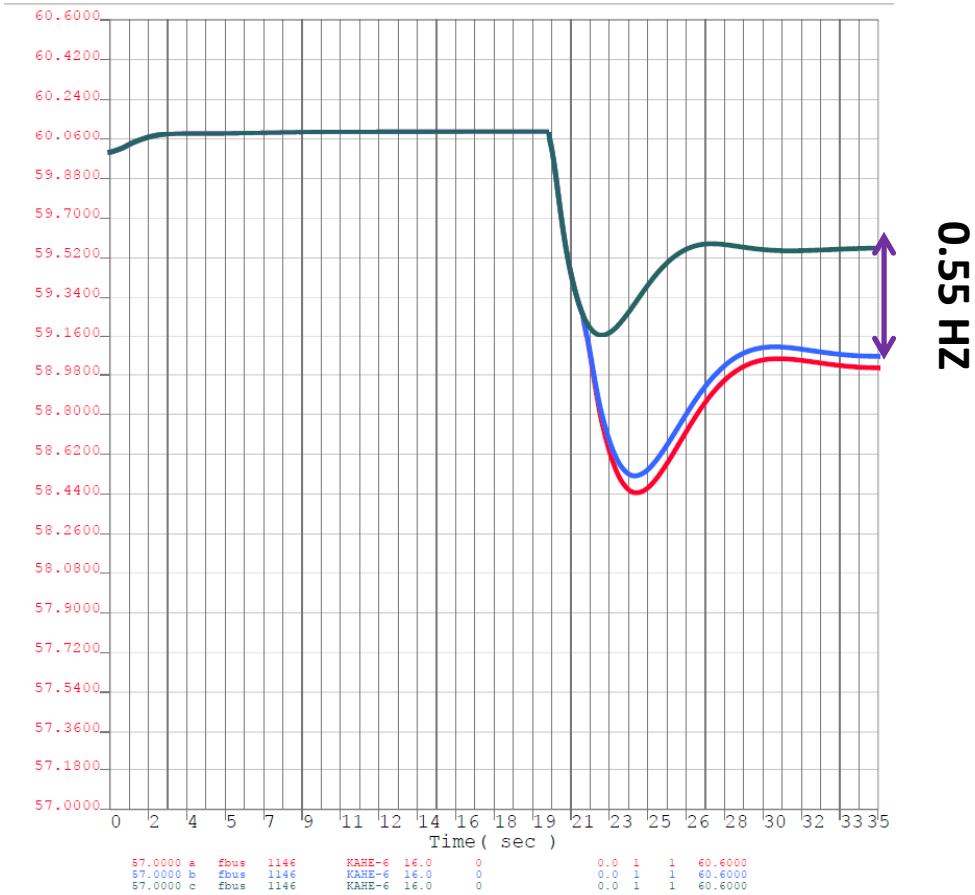
- Equivalent inverter modeling for steady state
- Dynamic inverter modeling for transient analysis
- Results presented are steady state
- Fault current reflected from low voltage units into the distribution system from each installed, and potential units
- Assumed a large installation in the large commercial customer area of 1.5 MW on top of existing 0.5 MW
  - Total penetration is 70% of peak in this case





Example of Dynamic Analysis: Comparing Inverter Settings for 3-phase and 1-Phase

- Generator commitment scenario 1 at HECO
- 1% change in frequency by allowing inverters to ride through the fault at 58 Hz
- At the existing level, little difference in recovery level as very small number of 3 phase generators
- The more that ride through the fault by MW the better the system recovery



Summary

- Validation of modeling and analysis against metered power data is essential
  - Data is collected, discuss how to obtain and validation procedure
- Continue baseline analysis and scaling of PV after recommendations
  - Verify models when sensor data is available
- In future, model detailed inverters using next upgrade of SynerGEE
- Completed preliminary survey of data for Oahu substation
  - Require some further data
    - Continued download and analysis of PV monitors
    - Circuit loading profiles and minimum load day case (Sunday afternoon)
- Analysis of equivalency of generators and loads for transient stability
- Data conversion tool concept is being considered

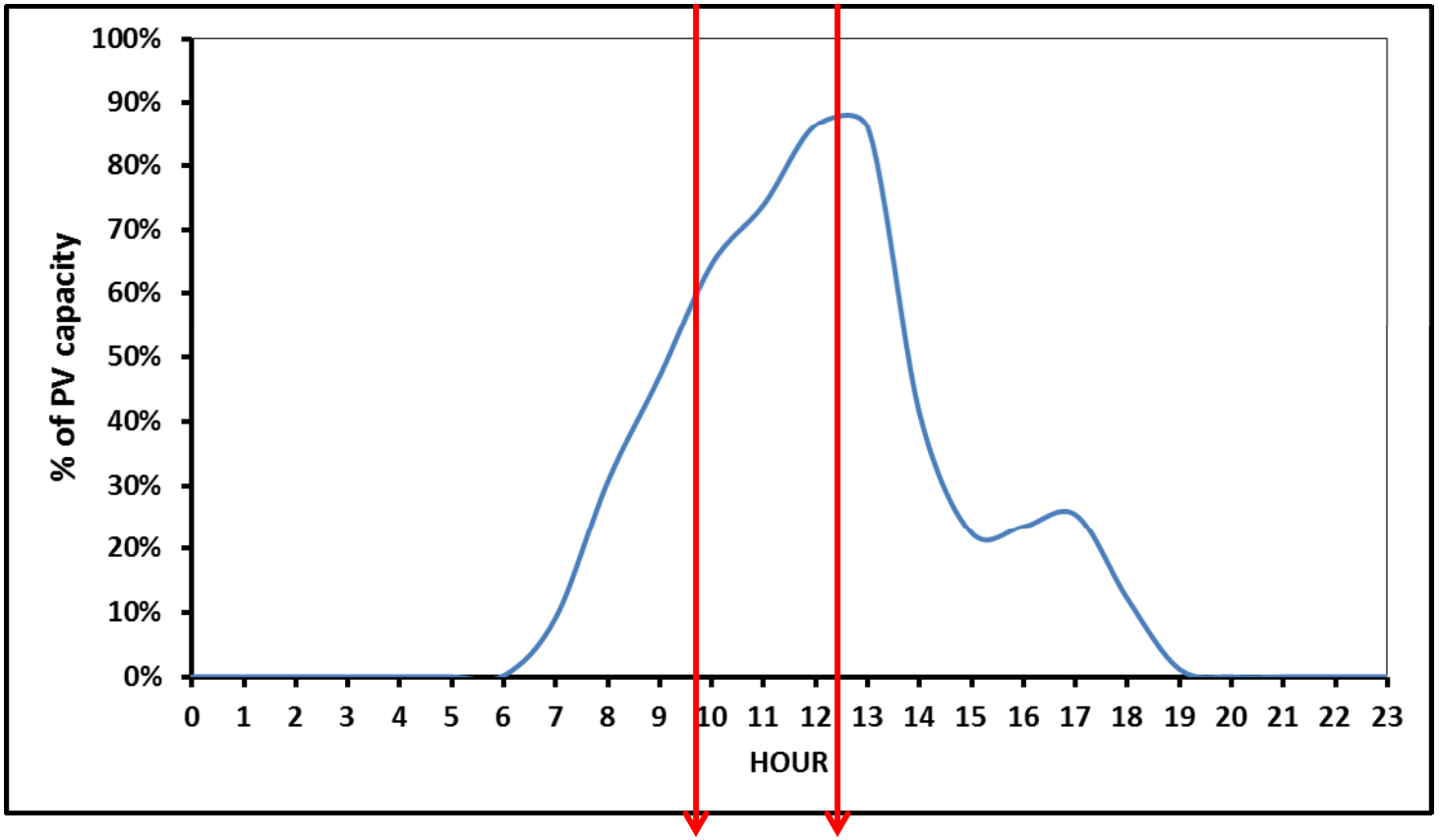
Case Study 2:SMUD Feeder

Impact of proposed PV site on rural feeder with existing DG

April Minimum Day – Measured Demand Data

- On April 4th 2011, the minimum daytime load of all measured data was observed
- Using Residential Feeder 1 PV data as a proxy on this day profiles are developed in SynerGEE Electric
- There is a dairy digester on Rural Feeder 1 – 225 kW also being measured
  - Generally the dairy digester is either ON or OFF
- 1 to 3 MW of PV is proposed on Rural Feeder 1
- Load flow and voltage analysis is completed to determine the impact of the proposed PV on this minimum daytime (i.e. when PV is generating) day

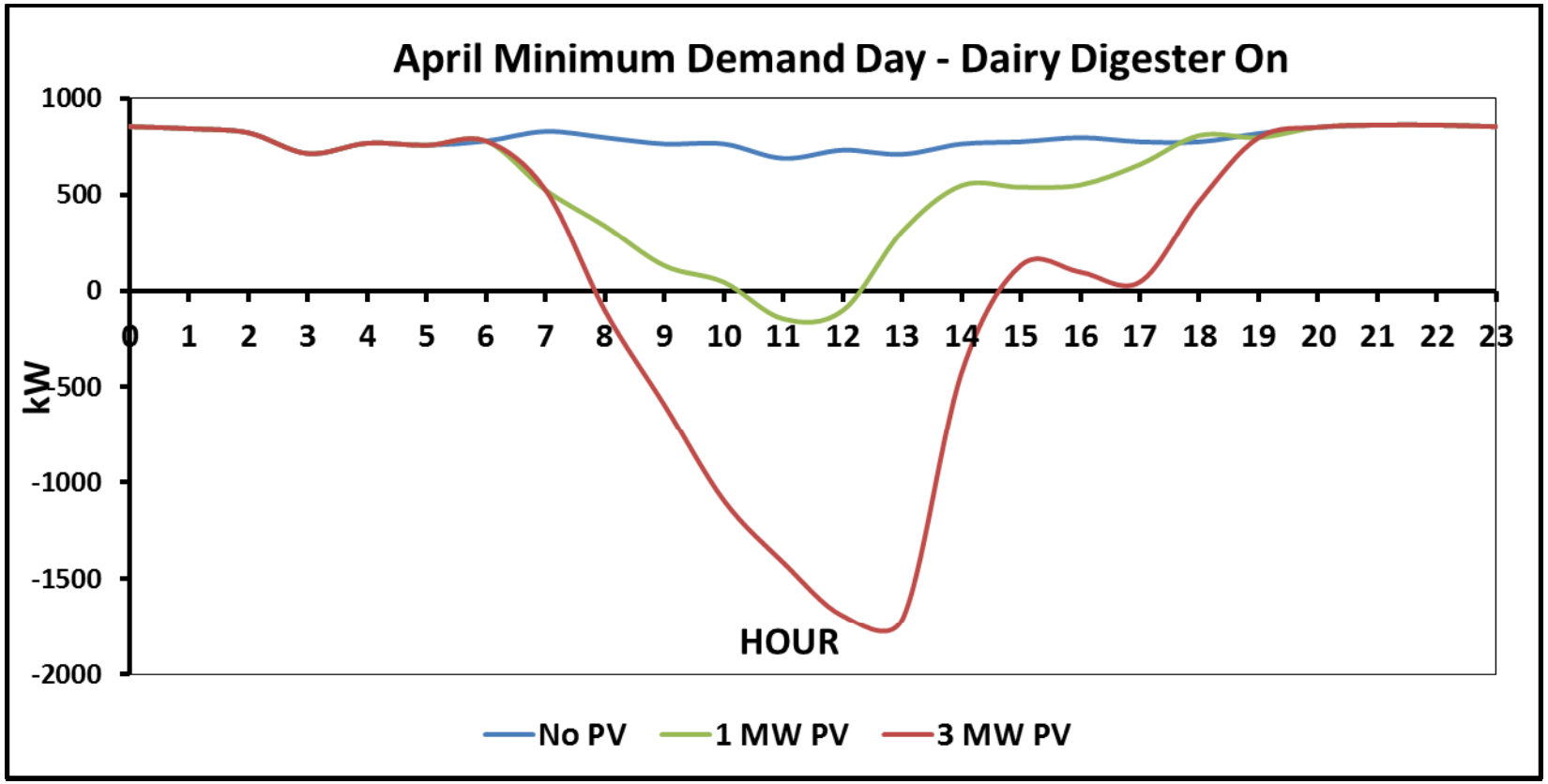
PV Gen profile April 4th 2011 (Geographically Similar Site)



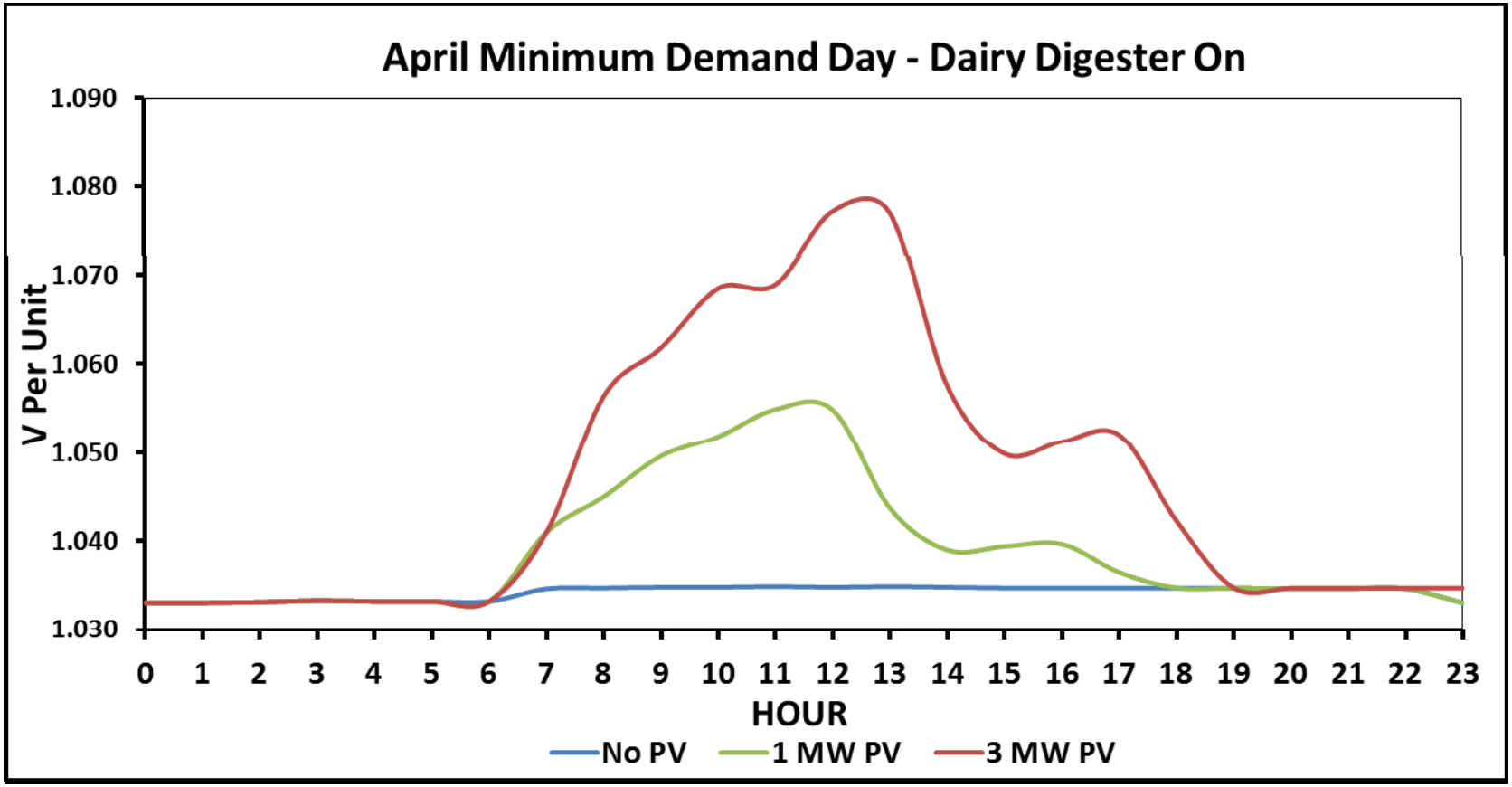
Min Daytime Demand time

Peak PV Generation Time

Load Flow Results 0 to 3 MW PV (dairy digester on)

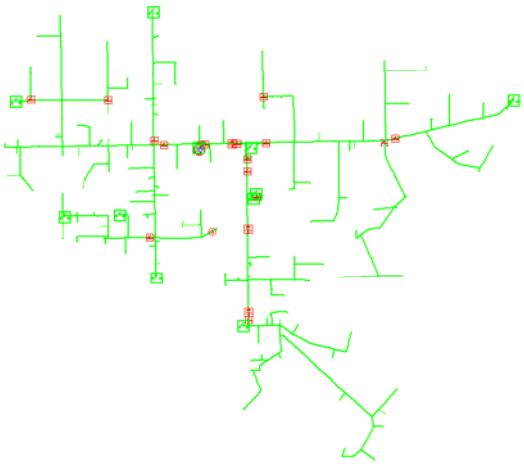


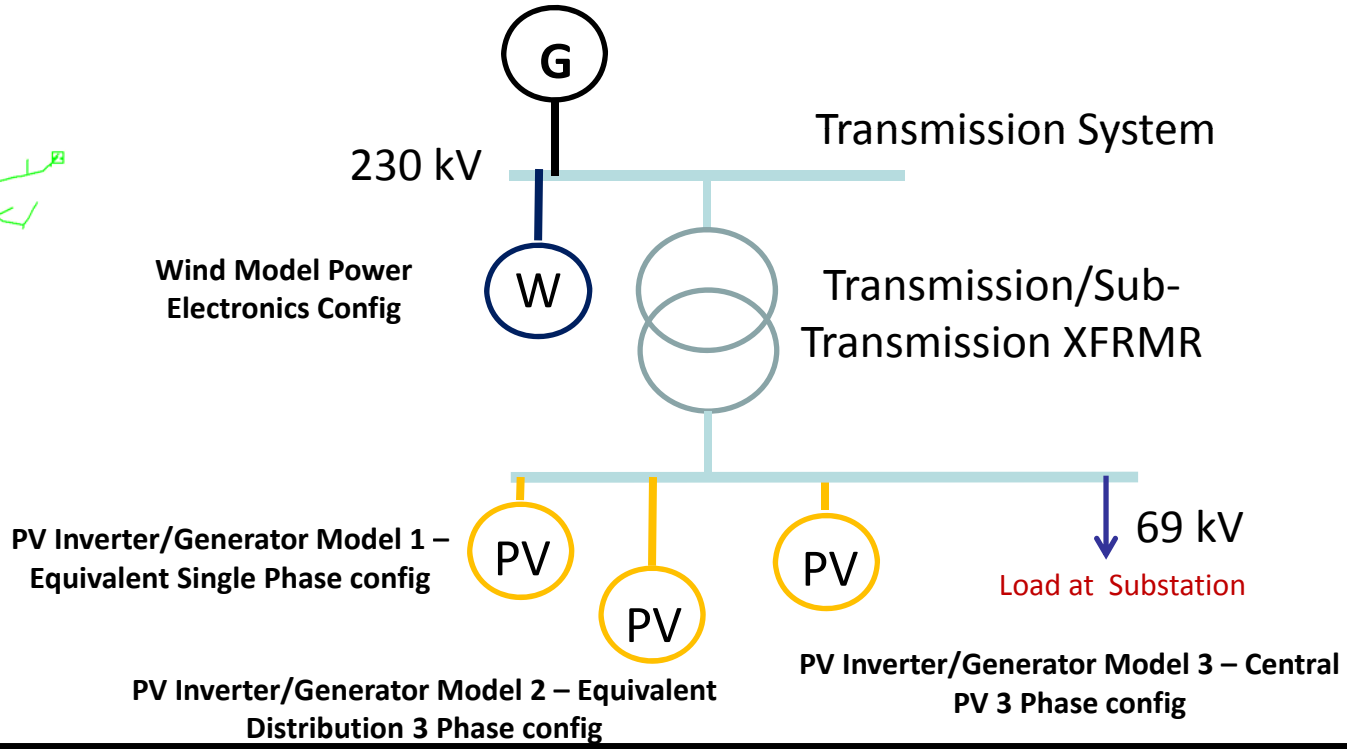
Maximum Voltage Results – combined (dairy digester on)



Rural Feeder 1 Nodal Approach

- Large amount of PV being proposed/Installed on distribution and sub-transmission levels





Preliminary Generalized Feeder Findings

- Fault current rise is significant in high-penetration scenarios going above 40% PV
  - Protection co-ordination studies will be necessary and possibly result in large scale changes
- Detailed PV data is essential to quantify short time scale effects like flicker
- Voltage rise can occur regularly on light load, high penetration feeders
  - Customer impacts (flicker, loss of service, damage to sensitive equipment)
  - Mitigation strategy (regulators, control schemes for cap banks, inverter control strategy)
  - Voltage rise could be due to many things – capacitor banks control system, or fixed on-off settings, line impedances,
- Interaction between capacitor banks/inverters/tap changers could significantly impact reliability

Biggest Challenges/Conclusion

- Availability of measured data is essential for validation and lacking in many cases
- Highly variable PV systems must be analyzed in a detailed dynamic and steady state simulation
- Feeders can be characterized in terms of load type, geo location, voltage, and PV penetration
- Commercially available tools must be integrated and used for different tasks
- As more detailed inverter control schemes become widely available to customers the impact must be justifiable and proven through simulation
- Partnerships between utilities sharing results and funds allow focused and economically viable measurement and analysis to be completed

CONTACT DETAILS

EMMA STEWART emma.stewart@bewengineering.com
RON DAVIS (BEW) ron.davis@bewengineering.com
ELAINE SISON-LEBRILLA (SMUD) ESison@smud.org
DORA NAKAFUJI (HECO) dora.nakafuji@heco.com