High-Penetration PV Integration Distribution System Modeling Challenges

PV Grid Integration Workshop

Tucson, AZ

Barry Mather Ph.D.

NREL- Distributed Energy Systems Integration Group

April 19th, 2012

Presentation Overview

- Background and update on the SCE High-Penetration PV Integration Project
- Introduction to the impacts of high-penetration PV integration on the distribution system
- Quasi-static time-series test feeder based evaluation of the impacts of PV variability
    - Distribution circuit voltage profile impacts
    - Line voltage regulator operational impacts

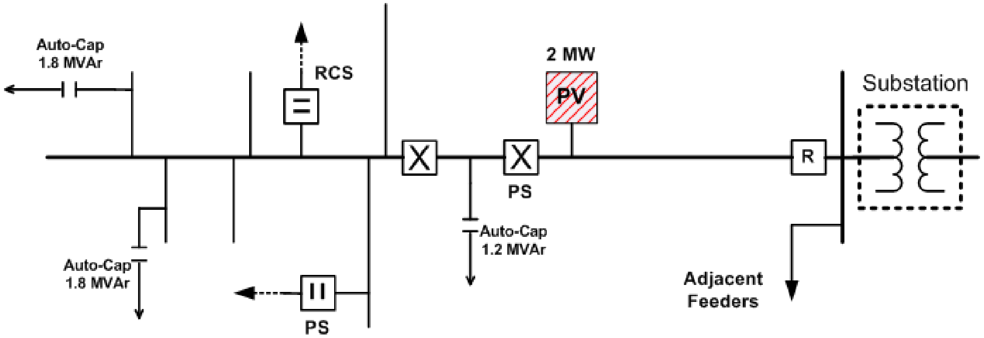
SCE Hi-Pen PV Integration Project

Project Overview:

- SCE is interconnecting 500MW of rooftop PV by 2015
- Three hi-pen PV feeders are being studied to develop a hi-pen interconnection handbook for utilities

Fontana, CA Study Circuit:

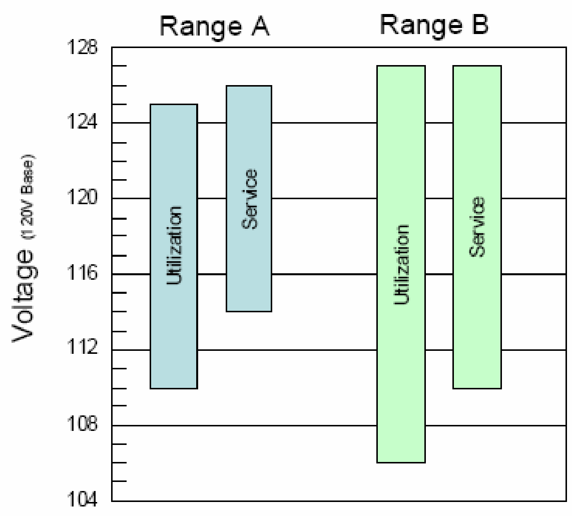
- 12.47 kV feeder, 7.8 miles
- Feeder rating: 12 MVA
- PV AC rating: 3.5 MW, 5.5 MW total in interconnection queue
- PV capacity penetration: 83%, 131% with 5.5 MW build out
- Voltage regulation via switched capacitor banks: 4.8 MVAr



Introduction: Hi-Pen PV Impacts

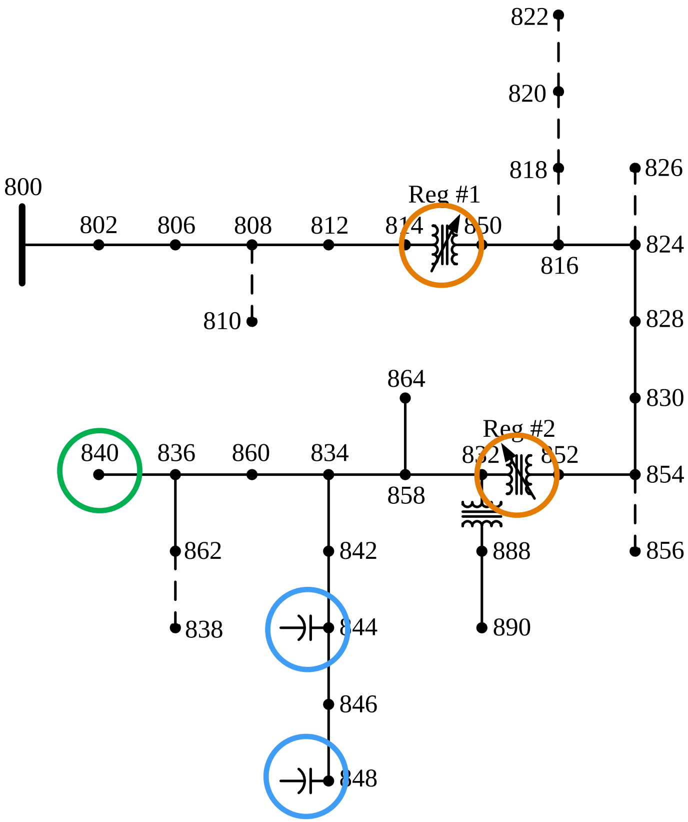
Distributed Generation Interconnection Technical Impacts:

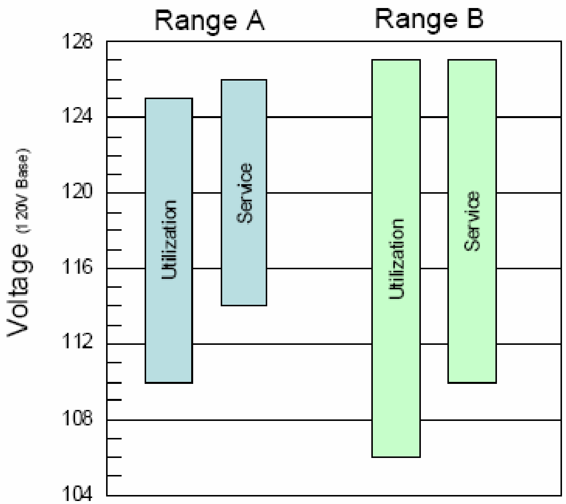
- Voltage regulation
  - Service voltage within acceptable range along the entire circuit
  - Regulation equipment (LTCs, line regulators, switched capacitors) frequency of operation / cycling
- Protection coordination
  - Relay desensitization
  - Increased fault current
- Power quality
  - Current harmonics
  - Flicker
- Unintentional islanding
  - Crew/public safety
  - Recloser operation



Model-Based PV Impact Study

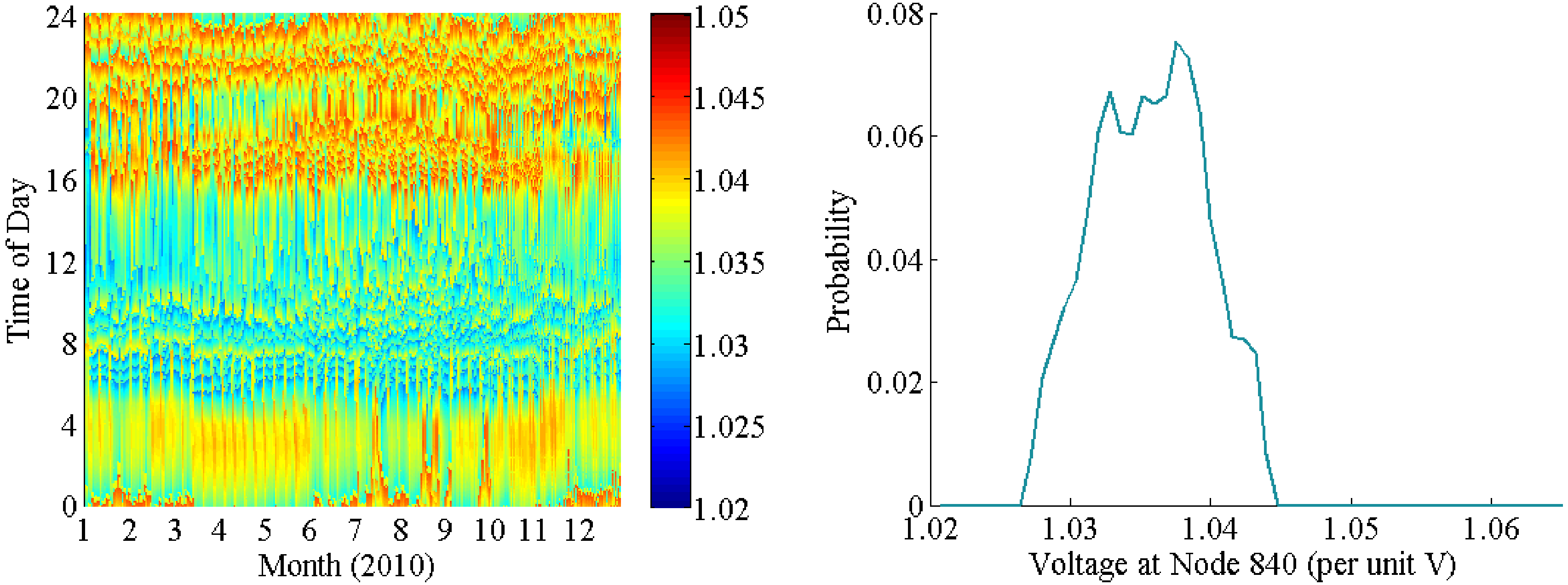
- Circuit based on the IEEE 34 Node Test Feeder
- PV resource based on NREL one resolution min data
- Load profiles based on load research statistics
- Line regulators have R+jX compensation and inherent one minute tap change lockouts





Baseline Dist. Circuit Operation

End of Circuit Voltage (840)

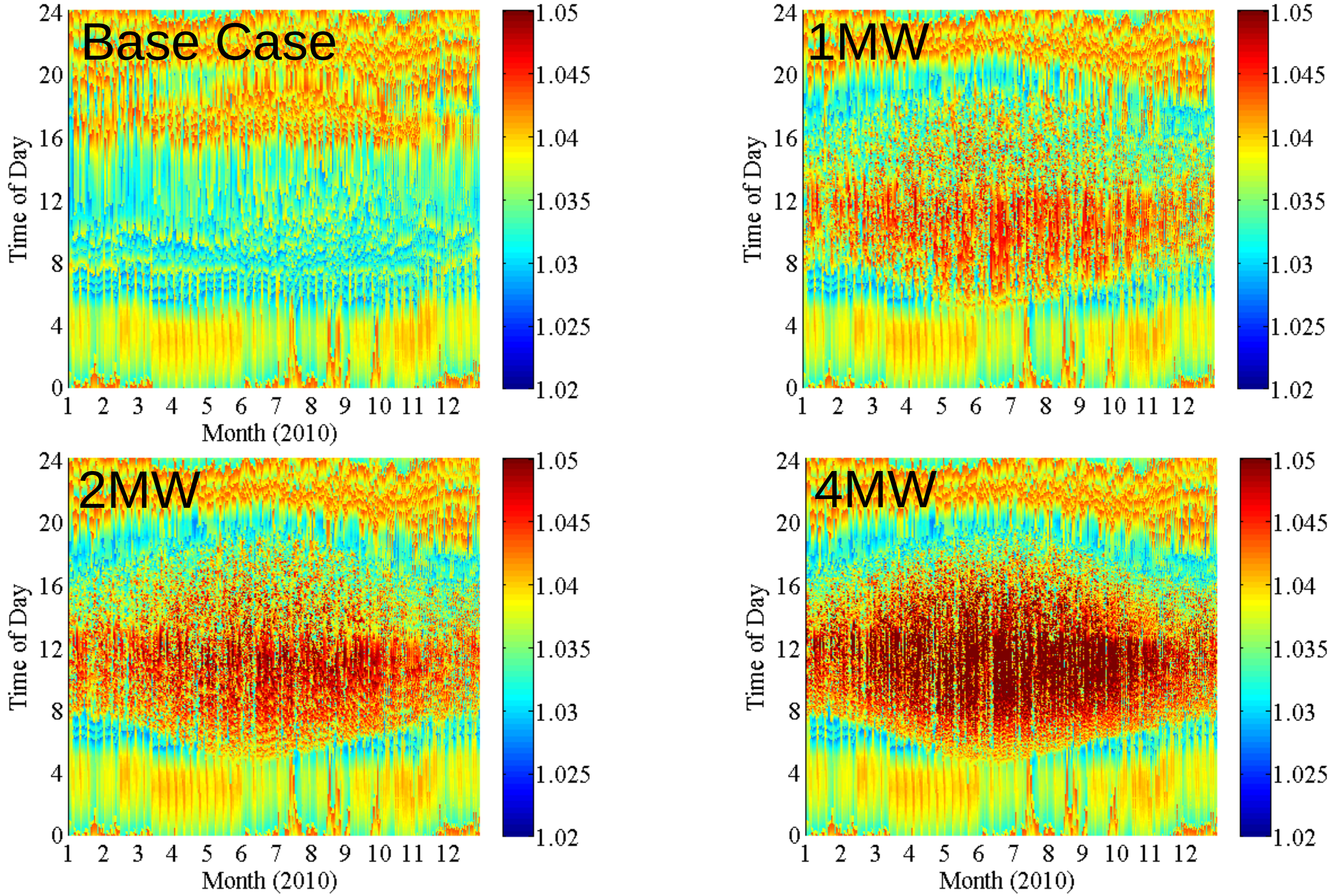


- High voltage in the night and evening, low voltage during the day
- About 8 line regulator tap changes per day

Reg.	R+jX Comp.
1A	3009
1B	1499
1C	1719
2A	2978
2B	3009
2C	2907

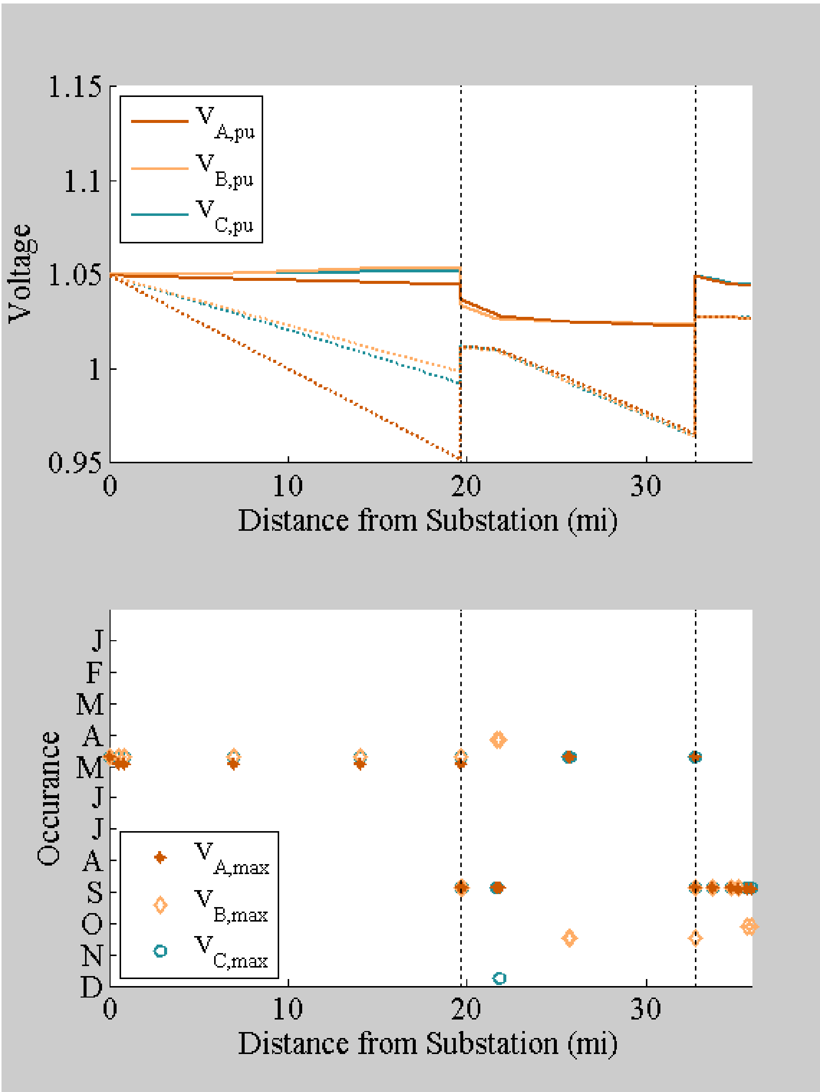
1- 4MW PV DG at End of Dist. Circuit

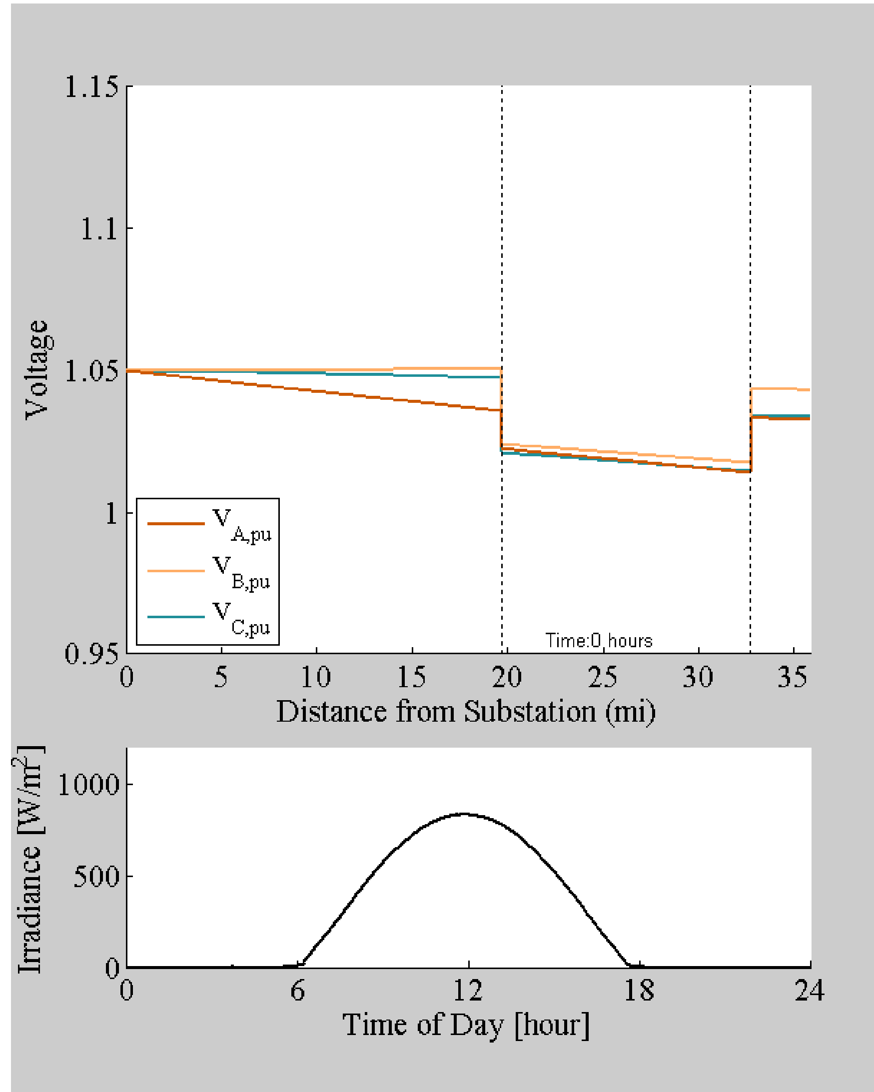
End of Circuit Voltage (840)



Base Case Circuit Operation

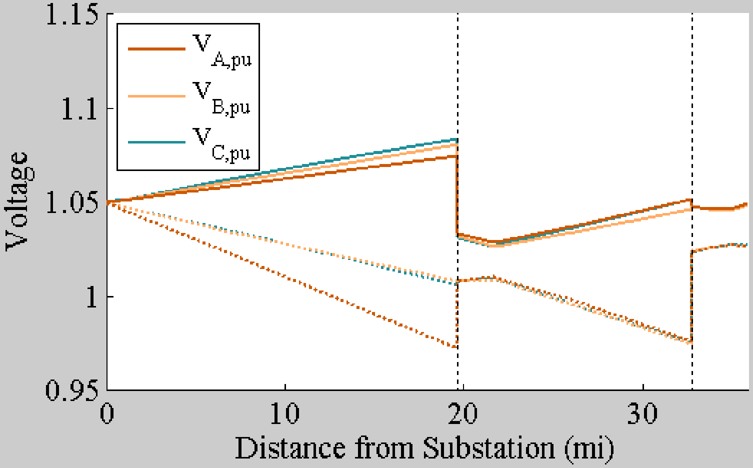
Sept. 26th, 2010

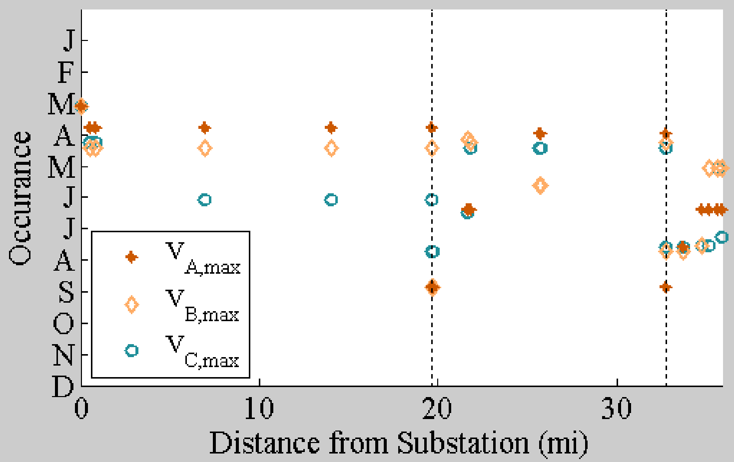


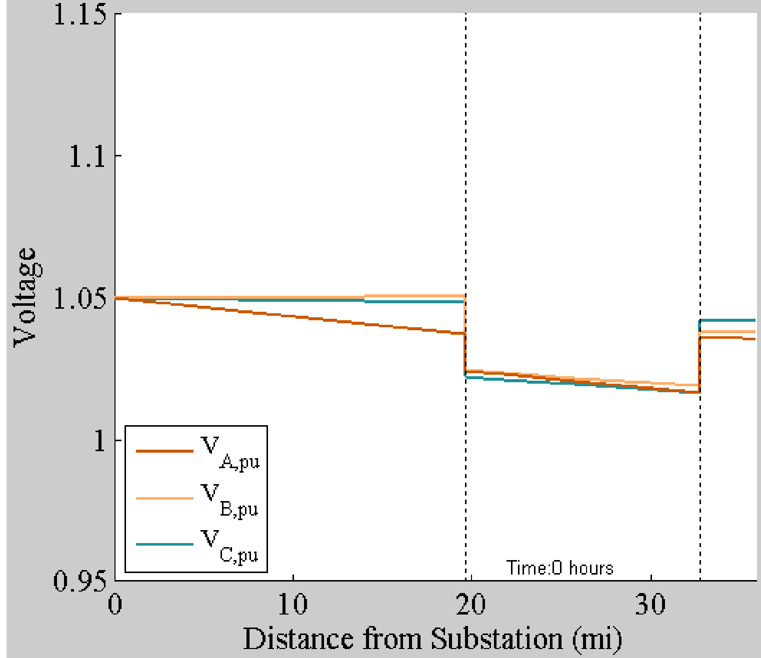


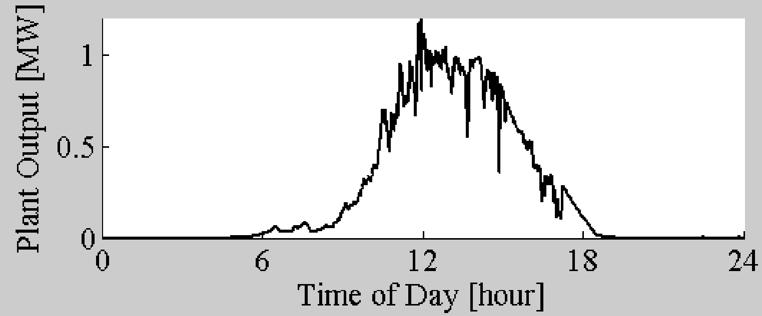
Circuit Operation: 1MW PV at Node 840

April 24th, 2010





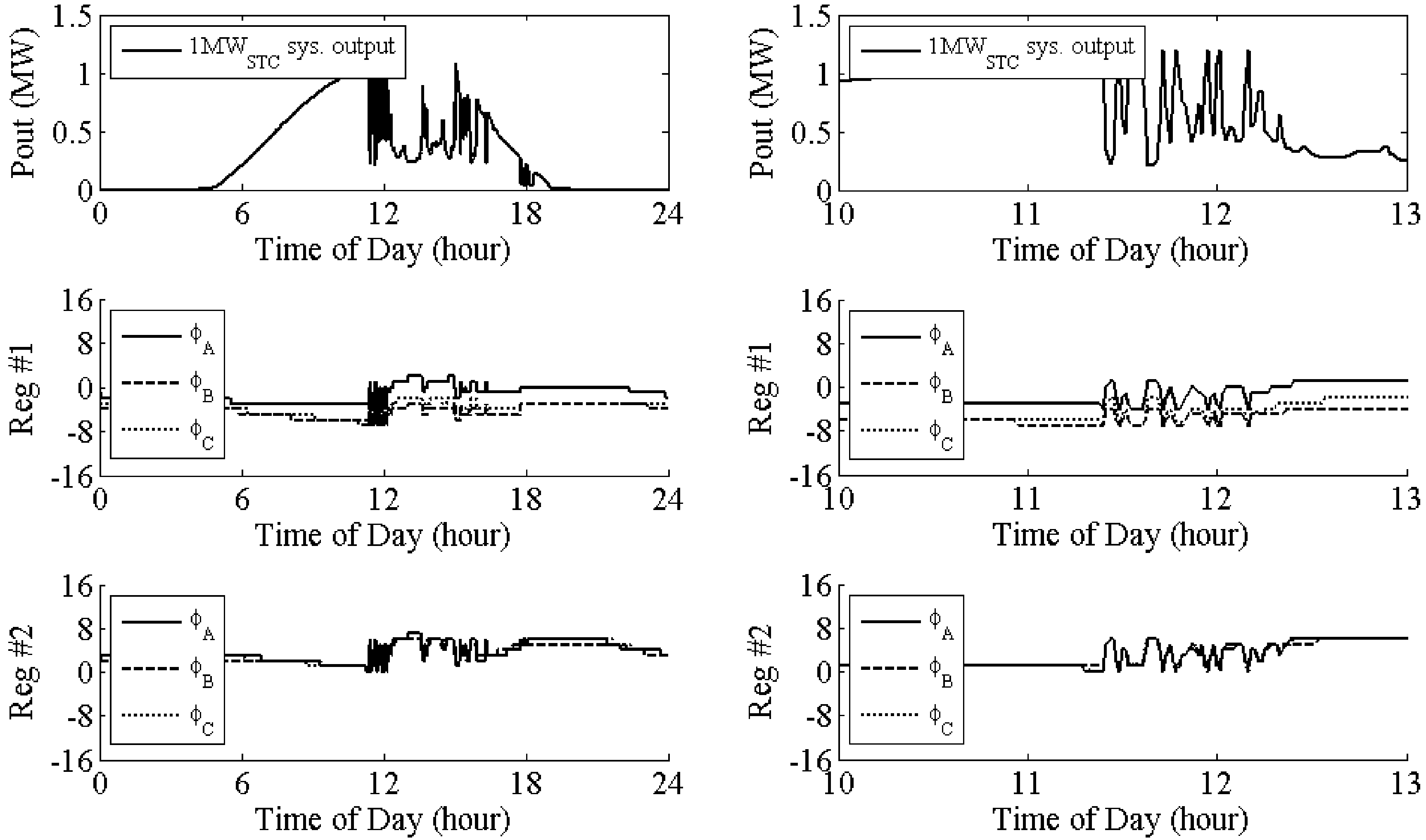




Line Regulator Operation (1MW)

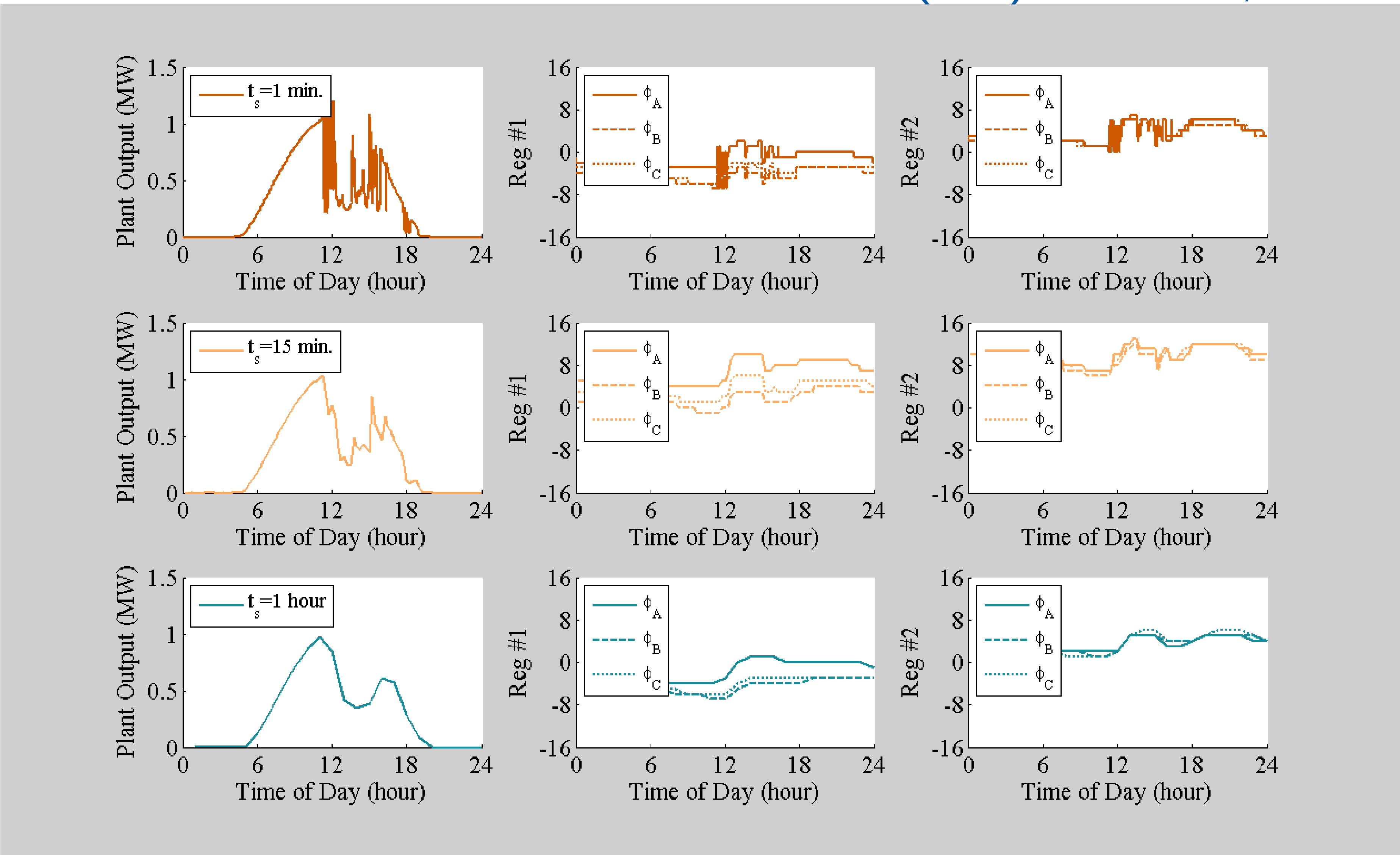
1MW PV at End of Circuit (840)

June 16th, 2010



Line Reg. Operations at Various Simulation Temporal Resolutions

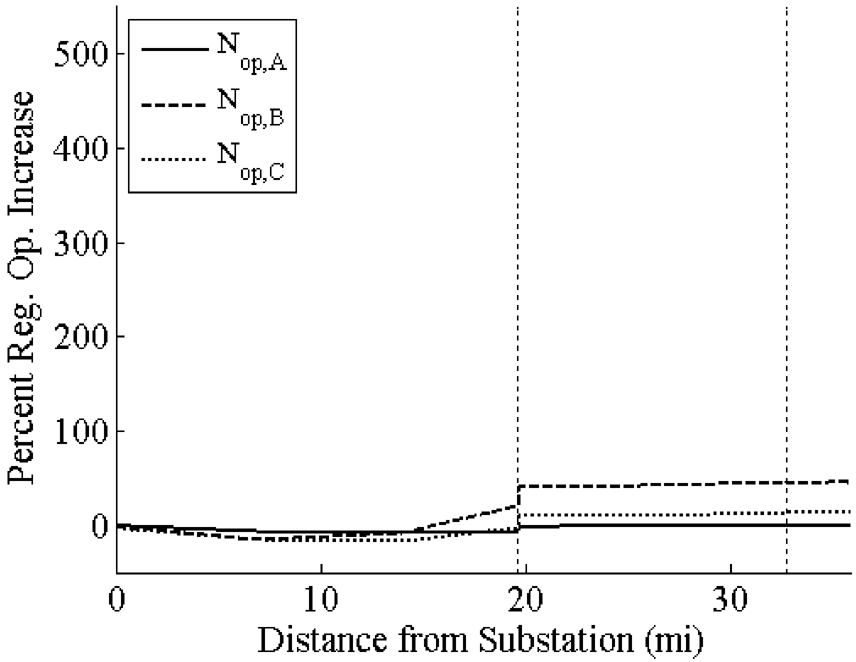
1MW PV at End of Circuit (840) June 16th, 2010



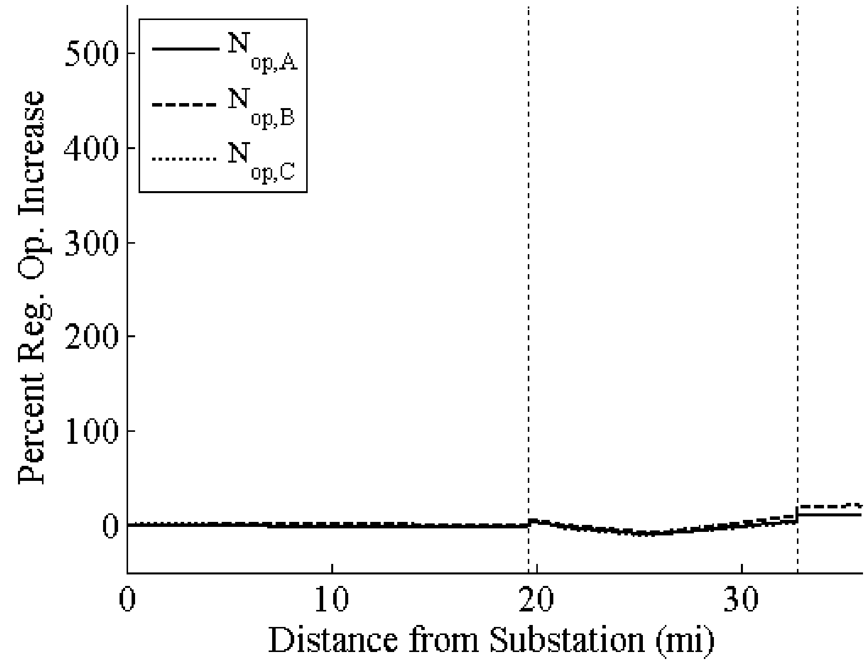
Developing Insight for PV Interconnections

1MW PV Interconnected at Any Point Along Circuit

Regulator #1



Regulator #2

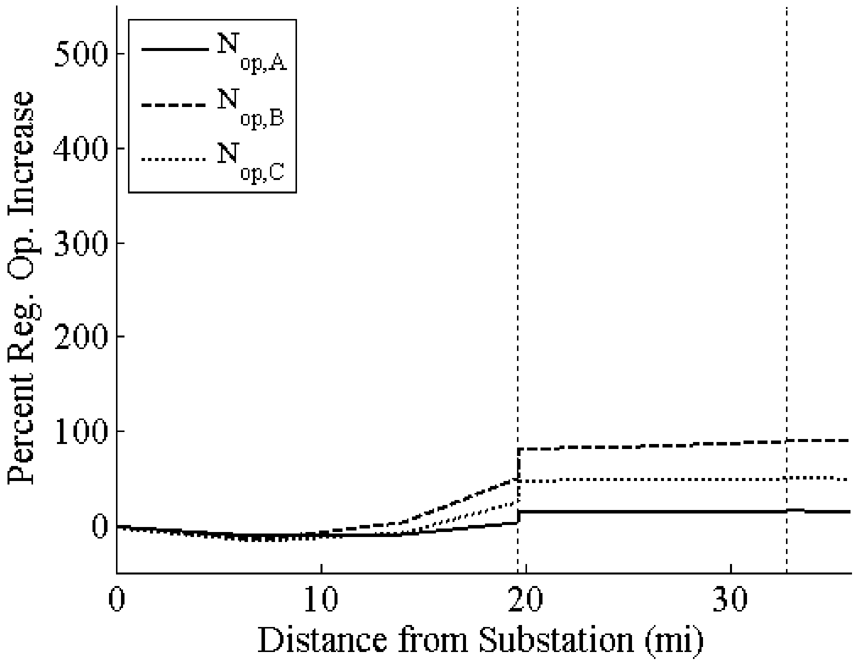


t_s = 1 hour

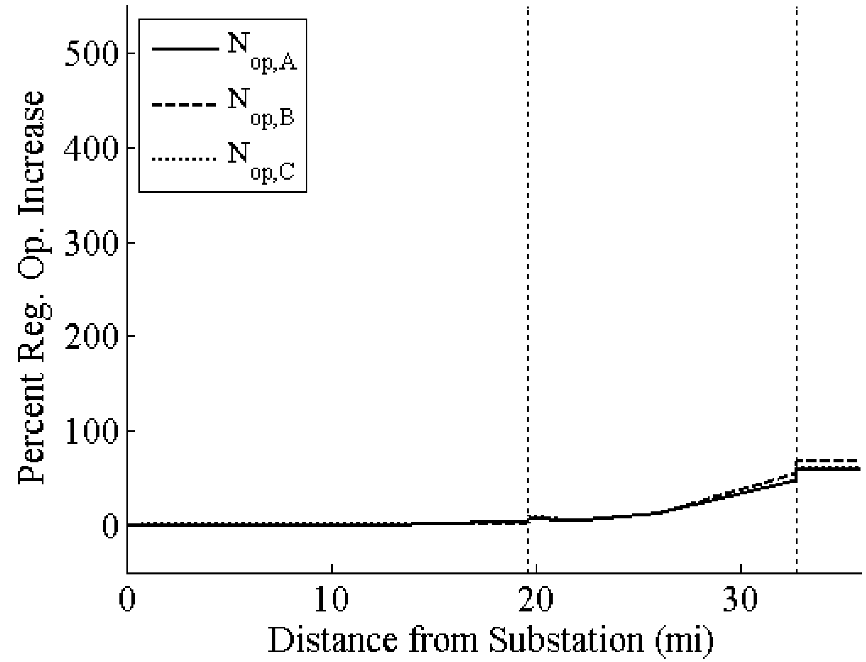
Developing Insight for PV Interconnections

1MW PV Interconnected at Any Point Along Circuit

Regulator #1



Regulator #2

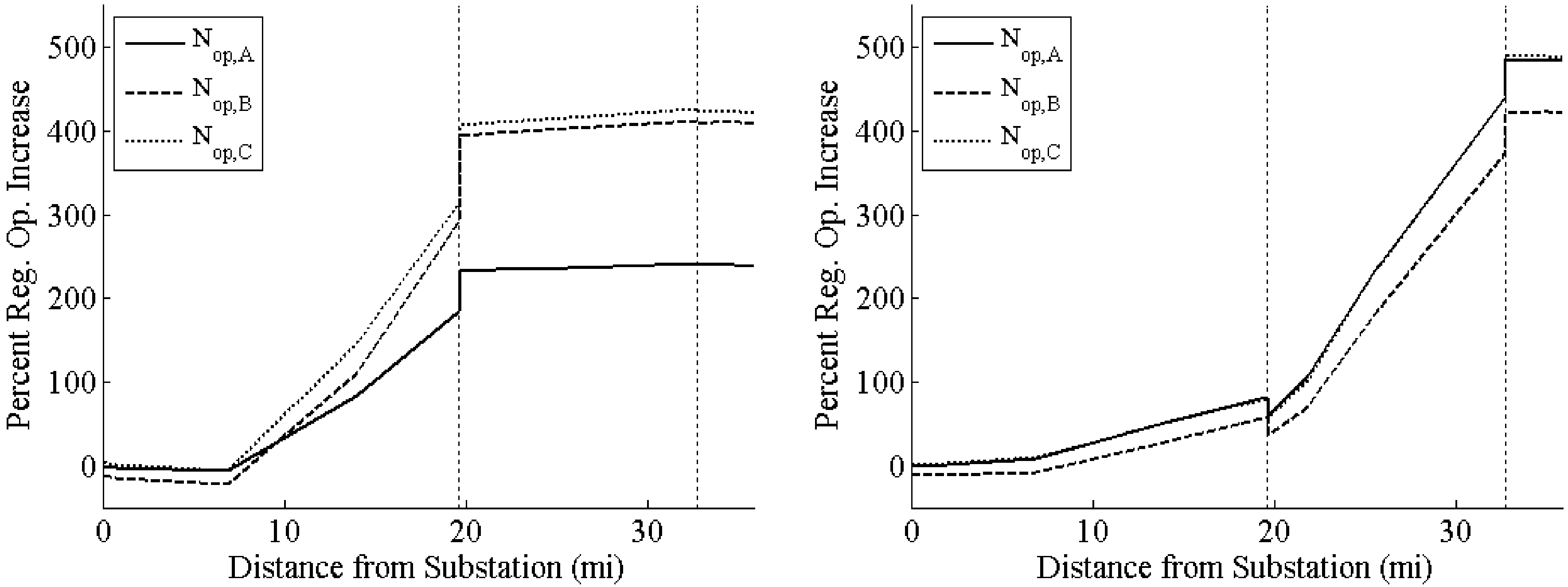


t_s = 15 min.

Developing Insight for PV Interconnections

1MW PV Interconnected at Any Point Along Circuit

Regulator #1 | Regulator #2



$t_s = 1$ min.

Thank you for your attention.

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EPRI Distributed PV (DPV) Feeder Impact Studies

Analysis and Case Study Results

Jeff Smith, Manager, Power System Studies

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PV Grid Integration Workshop

Tucson, AZ

April 19, 2012

Distributed PV (DPV) Feeder Impacts Analysis

- Objective
  - Determine practical circuit limits (hosting capacity) for high penetration PV
- Addressing
  - Feeder limitations and why
  - Different circuit topologies
- Approach
  - Detailed analysis of each feeder in OpenDSS
  - High-res solar data
- Breadth
  - 12 utilities
  - 40 feeders
  - Utility, EPRI, DOE, and CPUC funded projects

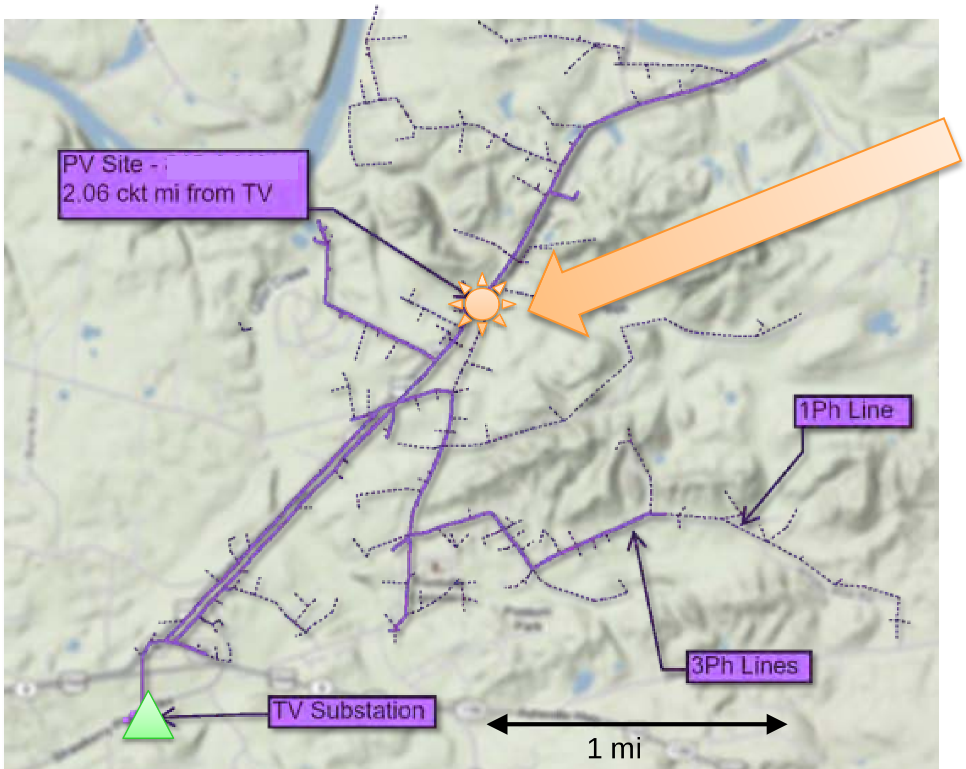
- Addressing
  - overvoltage
  - Voltage variations
  - Protection
  - Unintentional islanding
  - Demand “masking”
  - Power quality

Important Factors that Impact Hosting Capacity

- Size of PV
- Location of PV
- Feeder characteristics
- Utility requirements
- Electrical proximity to
  - Other PV on feeder
- Regulation equipment

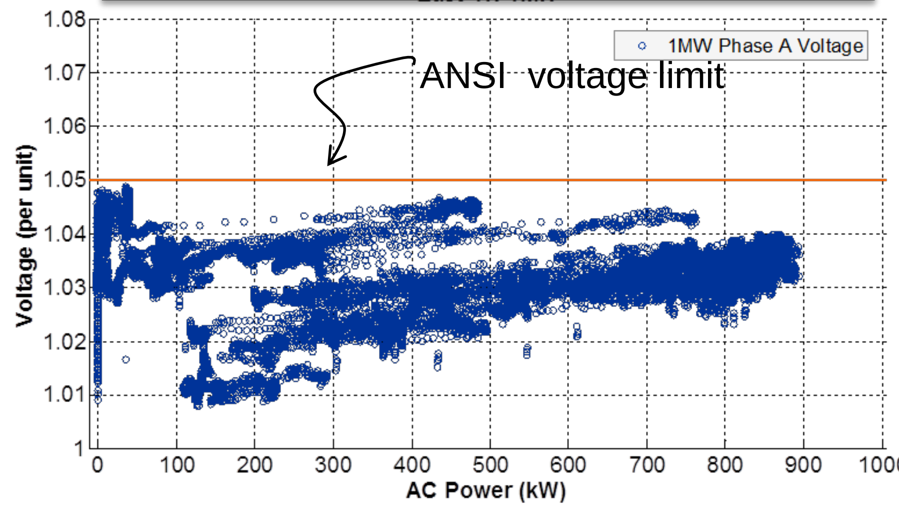
Location, Location, Location

Feeder 1: 1 MW PV 2 miles from Distribution Substation



Circuit Diagram

Measured Voltage as Function of PV Output



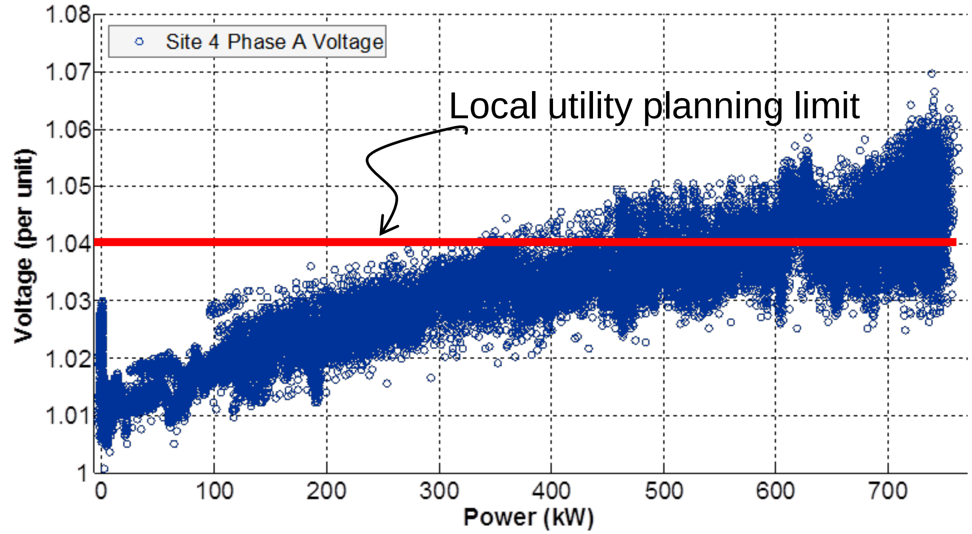
Feeder Characteristics	Value
Voltage (kV)	13.8
Peak Load	~ 6 MW
Existing PV (MW)	1.0
Substation LTC	Yes
Feeder Regulators	0
Capacitors	1 - fixed
Total Circuit Miles	28
Feeder "Footprint"	7mi^2

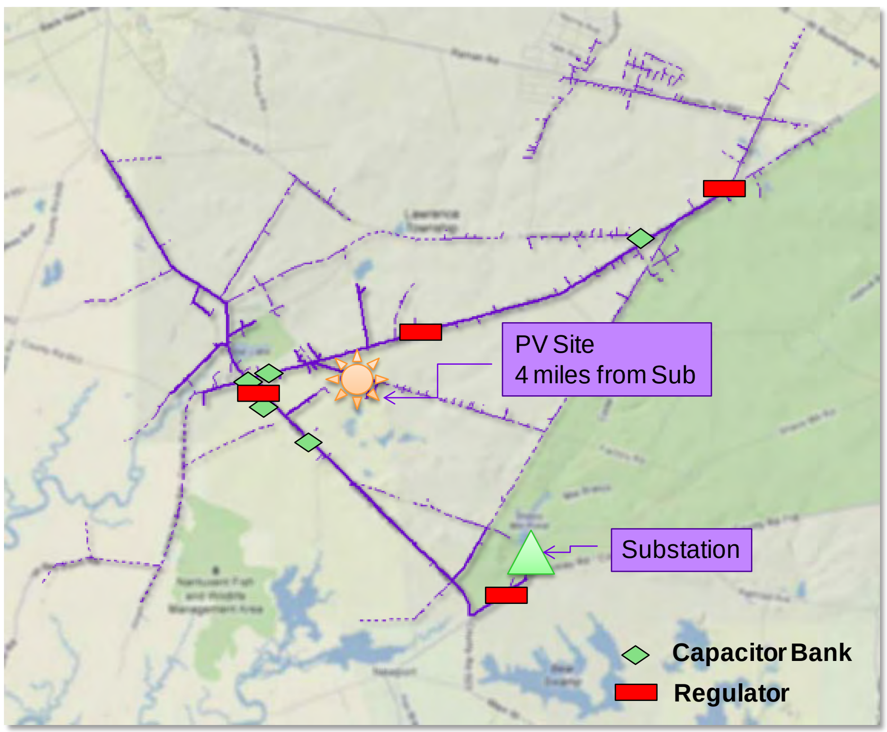
PV has <u>minimal</u> impact on feeder voltage

Location, Location, Location

Feeder 2: 1.7MW PV, 4 miles from Distribution Substation

Measured Voltage as Function of PV Output





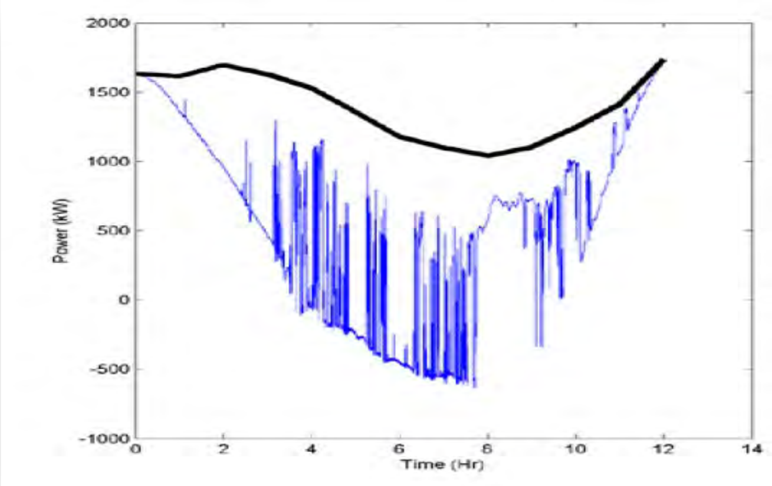
Circuit Diagram

Feeder Characteristics	Value
Voltage (kV)	12.47
Peak Load	~ 6 MW
Existing PV (MW)	1.7
Substation LTC	Yes
Feeder Regulators	3
Capacitors	2 – fixed 3 - voltage controlled
Total Circuit Miles	58
Feeder “Footprint”	35mi^2

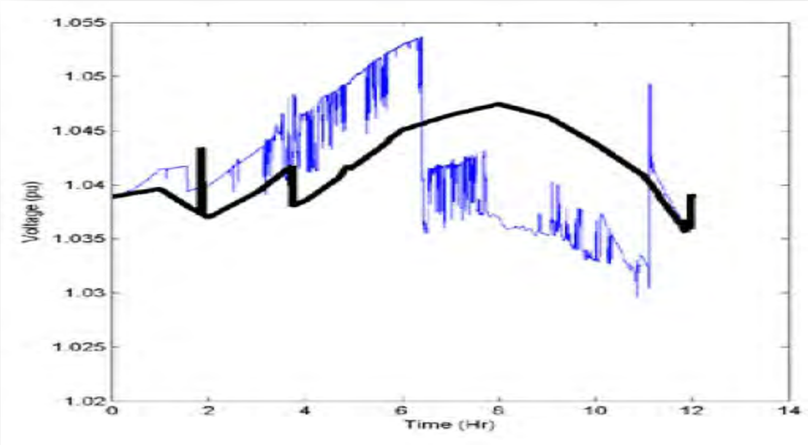
PV has <u>significant</u> impact on feeder voltage

Feeder 2 -
OpenDSS Simulation Results using Field Measurement Data

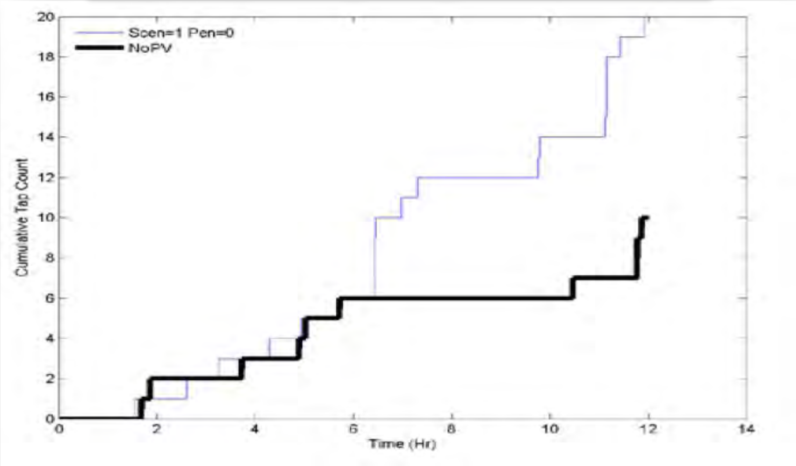
Total Demand (Feeder Head)



Maximum Feeder Voltage



Regulator Tap Operations



Existing PV increased regulator operation by 100%

- No PV
- With PV

Example 1 – "Small" Feeder

Key Characteristics

Voltage class: 15kV

Peak Load: 7.5 MVA

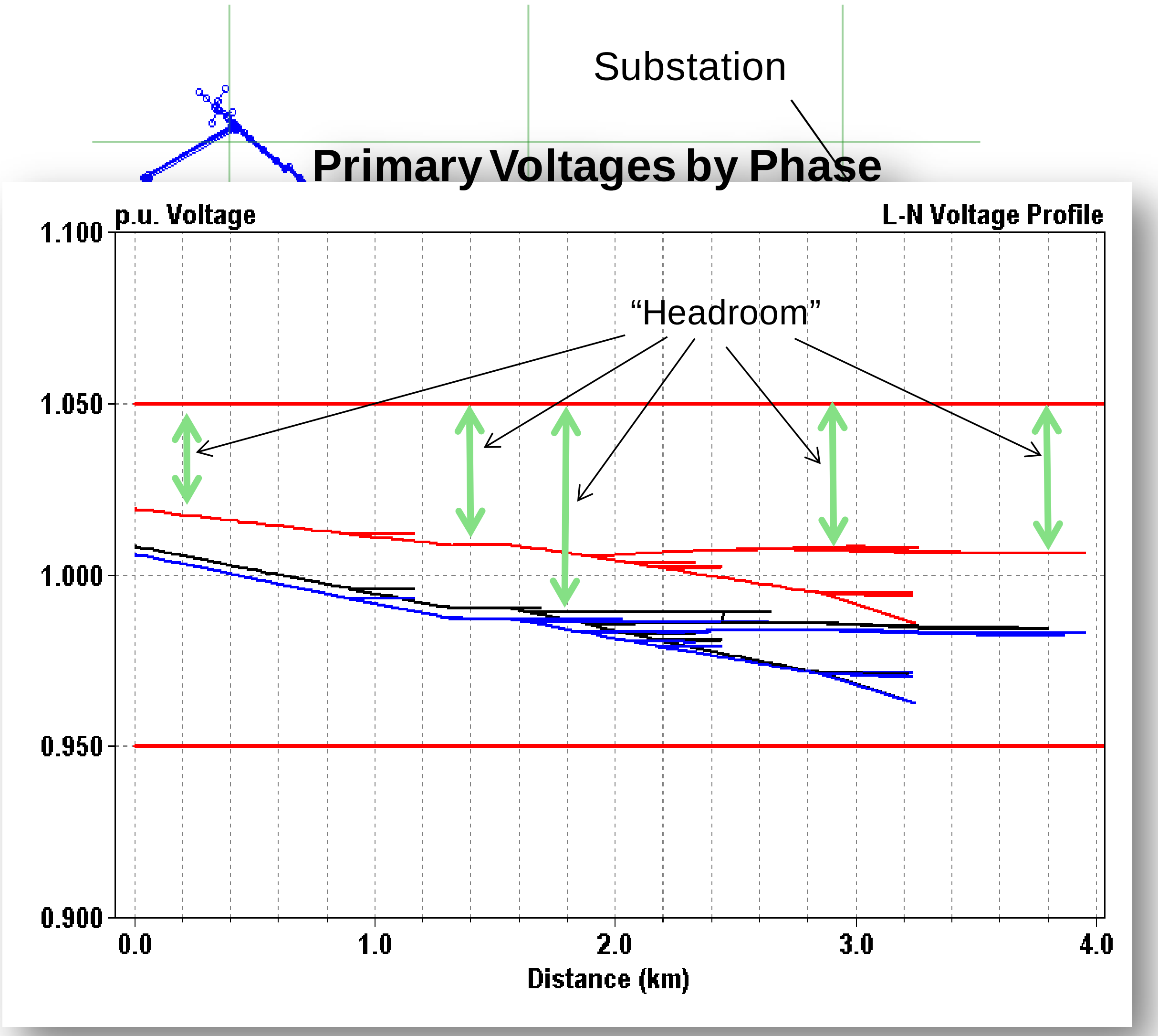
Total 3Phase Miles: 6

Total 1-2Phase Miles: 6

Feeder Regulation:
- Substation LTC
- No feeder regulation
- Fixed cap banks

Total Customers: 600

Small "footprint"



Example 2 – "Large" Feeder

Key Characteristics

Voltage Class: 15kV

Peak Load: 11 MVA

Total 3Phase Miles: 60

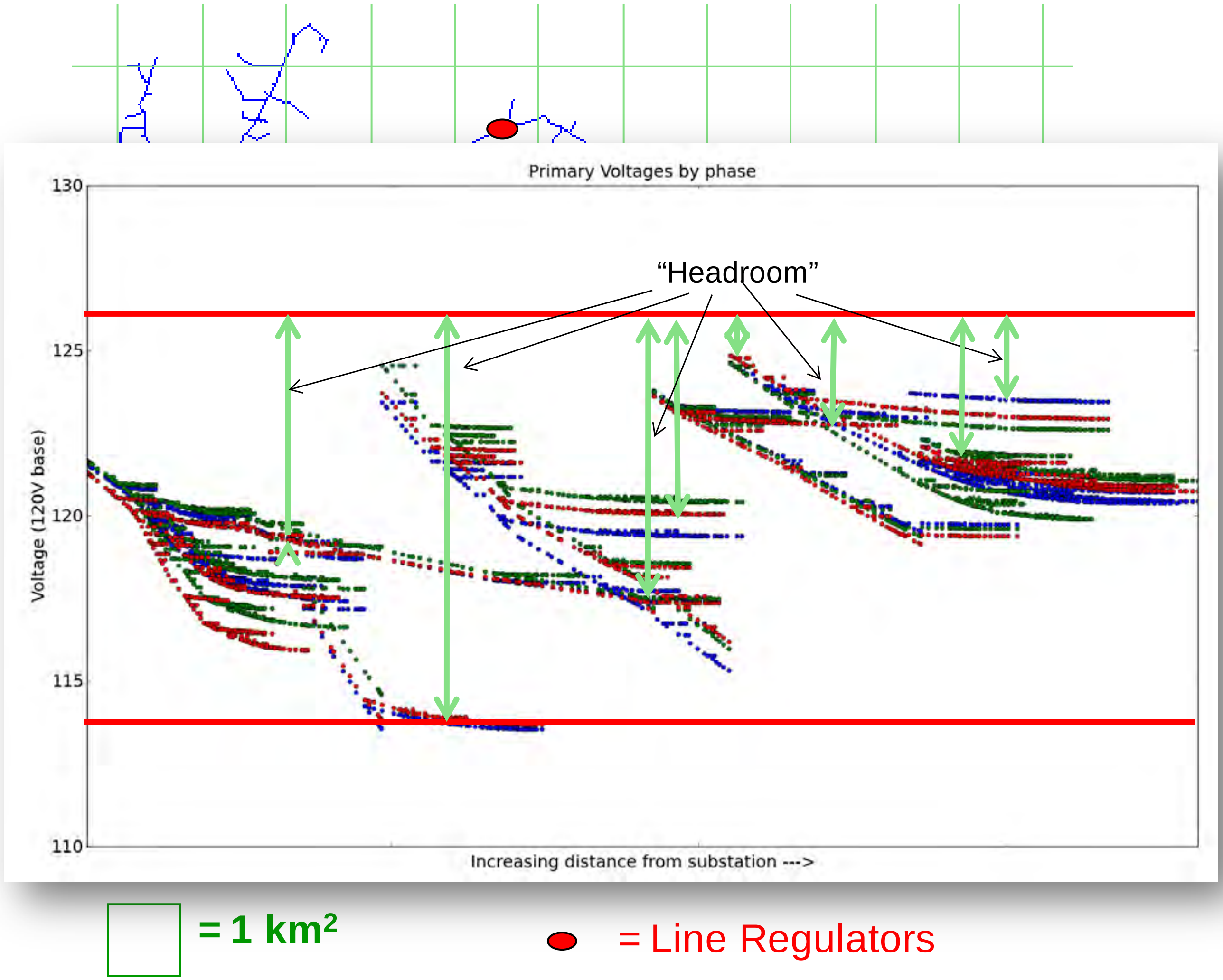
Total 1-2Phase Miles: 50

Longest Distance: 11 miles

Feeder Regulation
- Substation LTC
- 6 feeder regulators
- switched capacitor banks

Total Customers: 6700

Large "footprint"



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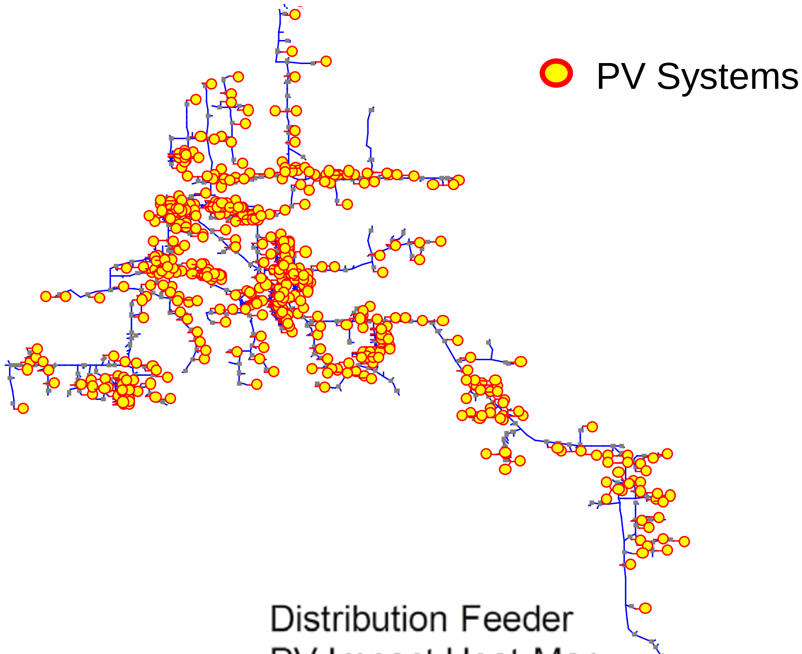
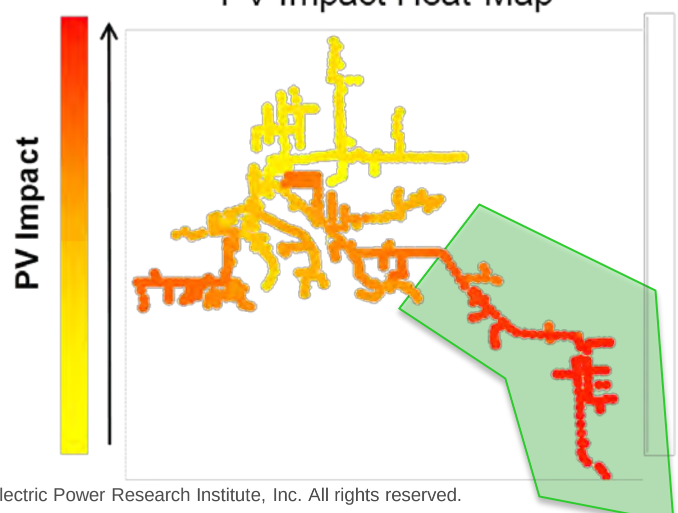
Analyze Multiple Scenarios and Penetration Levels (Stochastic)



Distribution Feeder
PV Impact Heat Map



- Baseline – No PV
- 20% PV
- 30% PV
- 50% PV
- Beyond…

Increase Penetration Levels Until Violations Occur

Evaluation Criteria

Voltage
- Overvoltage
- Voltage deviations @ regulation equipment

Protection
- Increased fault current contribution
- Unintentional islanding
- Sympathetic tripping + fuse saving
- Reduction of reach

Power Quality
- Total harmonic distortion
- Individual harmonics

Loading
- Thermal overloads
- Demand masking
- Power factor reduction

Operational
- Load tap changers
- Regulators
- Capacitor banks

Stochastic Analysis

Time Series Analysis

Combination of stochastic and time series analysis

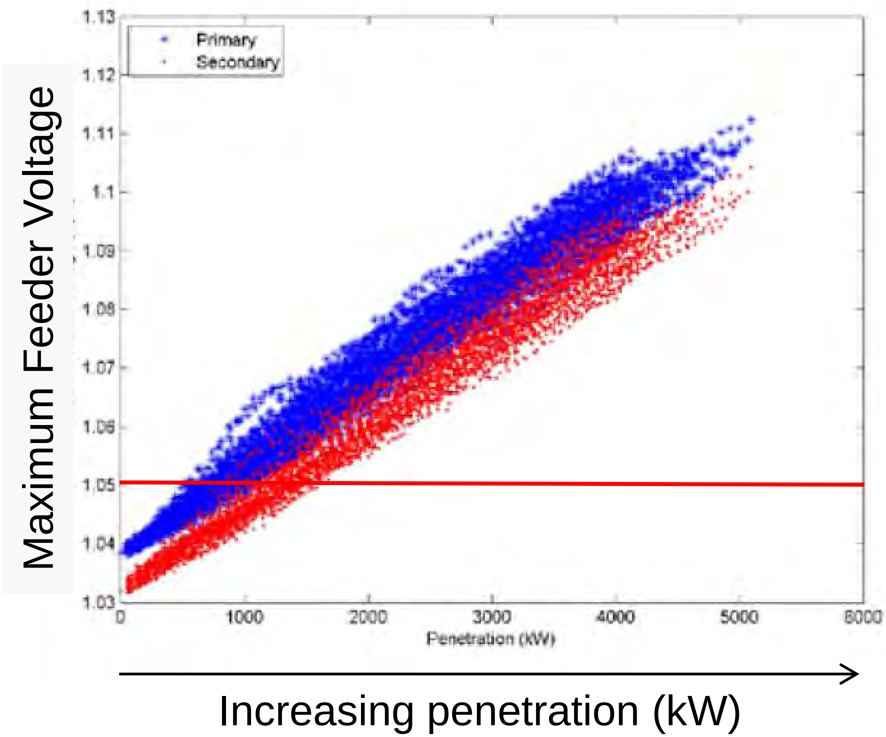
-Location specific impacts

-Time-varying impacts

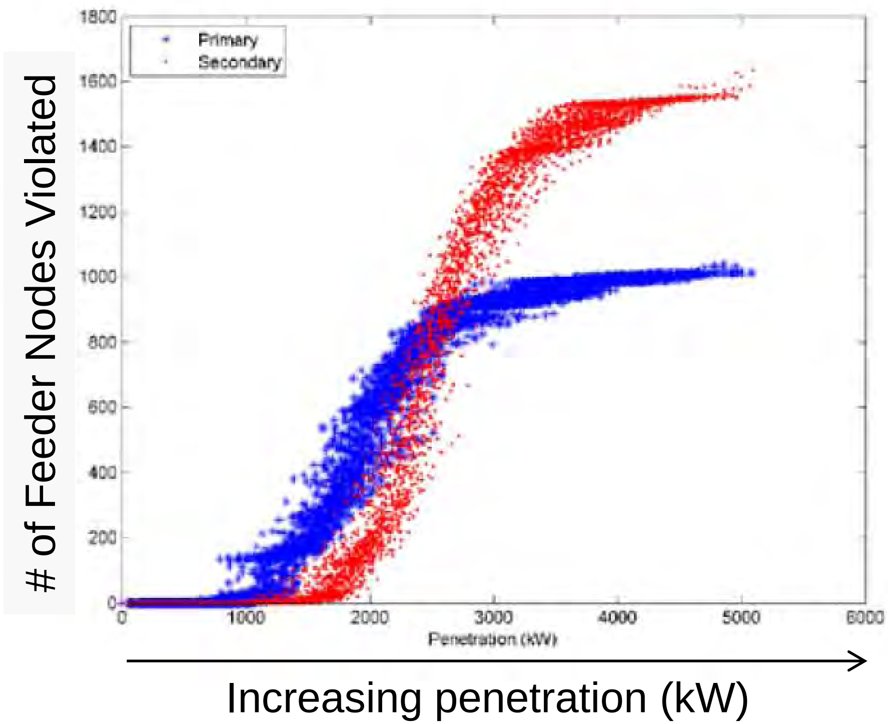
Sample Feeder Results – Overvoltage Violations

Maximum Voltage Observed for Each Case

Penetration level when violations occur



Feeder exposure to violations



- Each point represents the worst-case violation for a single case
- 5000 cases shown

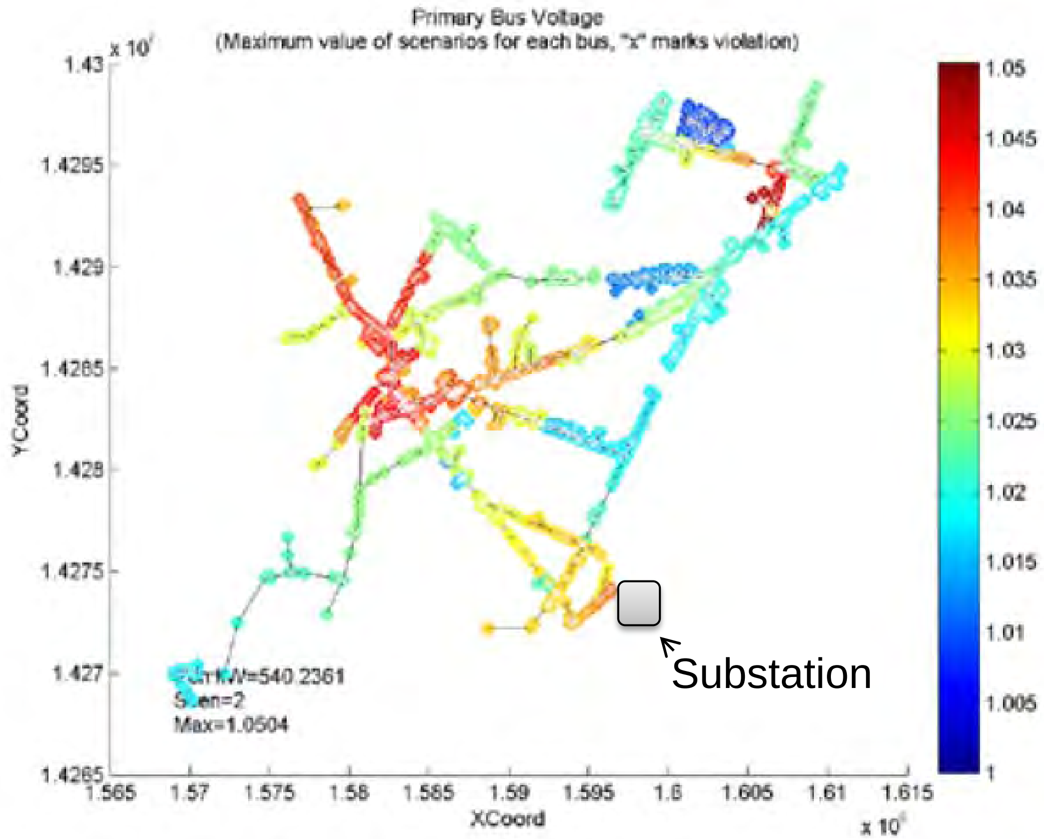
Blue – primary voltage

Red – secondary voltage

Sample Feeder Results – Overvoltage Violations

Maximum Voltage Observed for Single Case (540kW distributed)

Where violations occur within the feeder



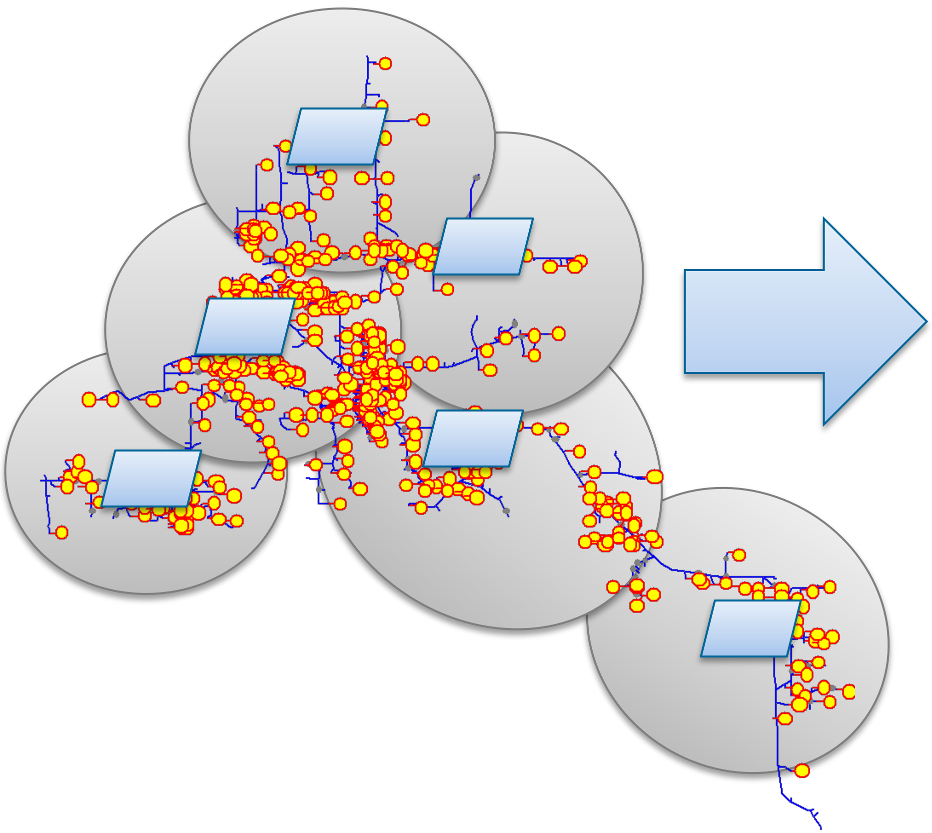
Sample Results from Stochastic Analysis
Voltage Impacts

Feeder	A	B	C	D
Voltage Level	12.47	12.47	12.47	12.47
Total Ckt Miles	12	6	8.5	**58**
Peak Load (MW)	8	4.6	4.5	6
Voltage Regulation	1	1,2	1	1,2,3
Results				
Max PV* (MW)	>5	3.2	>4	0.3

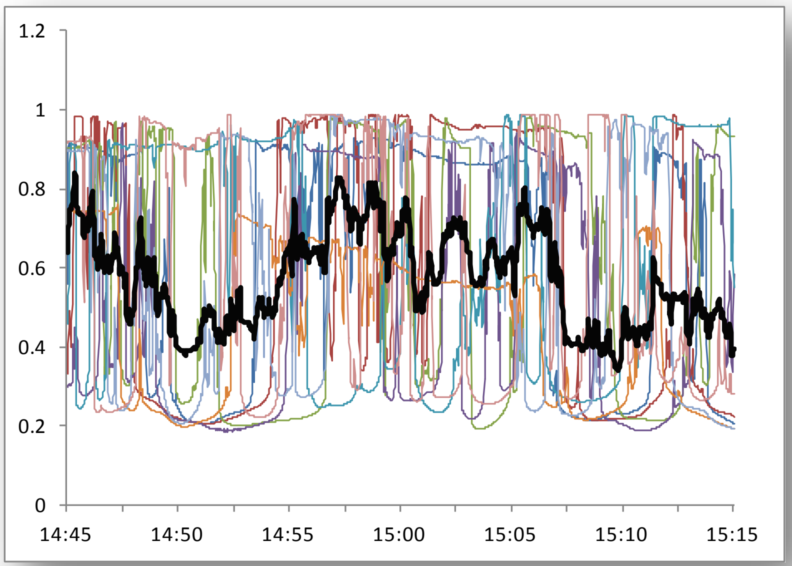
*First occurrence of overvoltage/voltage deviation violations – small scale PV results shown

Voltage Regulation
1 – LTC
2 – switched caps
3 – feeder regulator

Solar Measurement Data for Time Series Analysis



Measured Solar Data from Pole-Mounted PV Modules



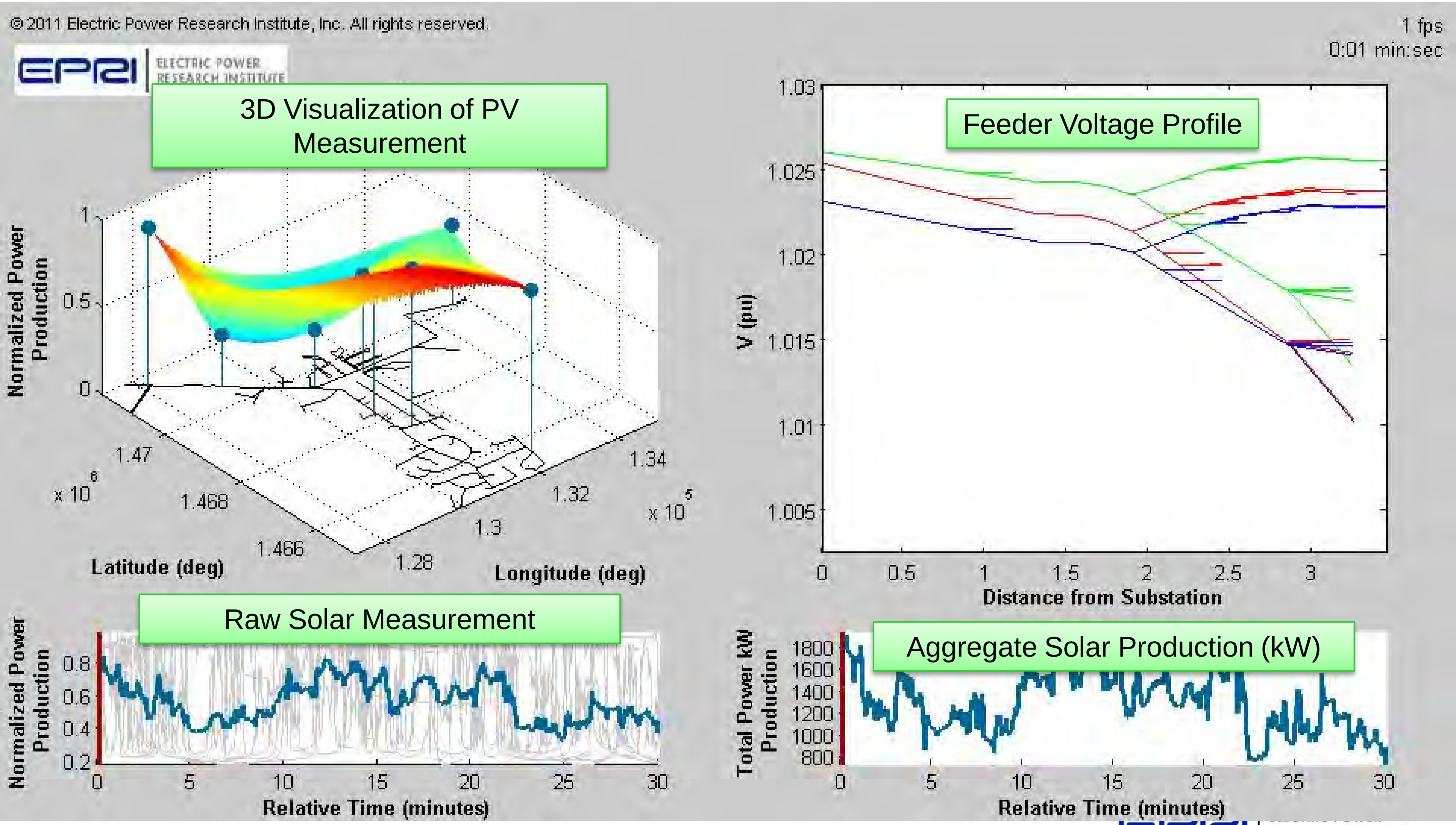
(color) – individual solar measurement points

(black) – average of all measurements

Modeled PV Systems

Pole-Mounted PV Modules

Voltage Variations with PV Intermittency



Summary

- PV hosting capacity strongly dependent upon
  - Feeder characteristics
  - Location of PV
  - Utility planning criteria
- Integration of high-penetration PV into Dx system can be a challenge
  - Voltage
  - Protection
  - Lack of visibility (demand masking)
- Feeder impact analysis is ongoing
- Challenges can be overcome
  - Developers working with the utility
  - Utilization of advanced inverter functions (Standards!!!)
  - Communication/control

High Penetration Case Studies

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4 / 19 / 12

aps

Agenda

- Overview of APS
- Renewable Energy Context
- Renewable Generation Integration
- Case Studies

APS – Arizona's Largest Utility

Service Territory

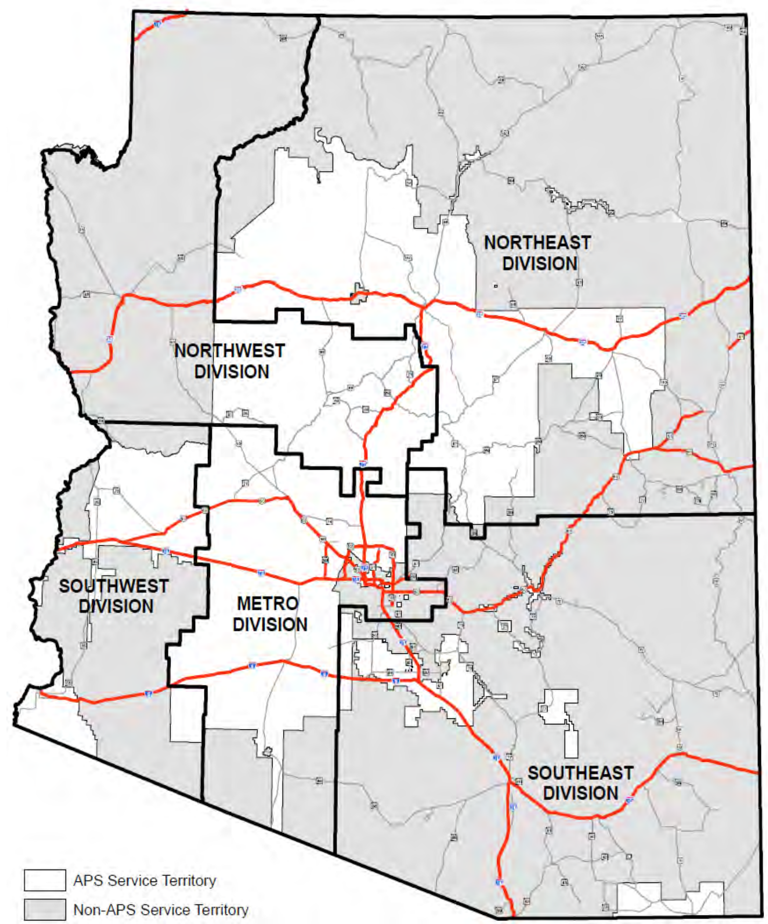
- 1.1 million customer accounts
- 34,646 square miles

Scope of Energy Delivery

- 28,000 distribution miles
- 5,300 transmission miles
- 1200 distribution feeders
- 410 substations

Resources

- 8,600 MW total capacity
- Peak Demand – 7,100 MW
- Over 1,000 MWs of renewables owned or in development



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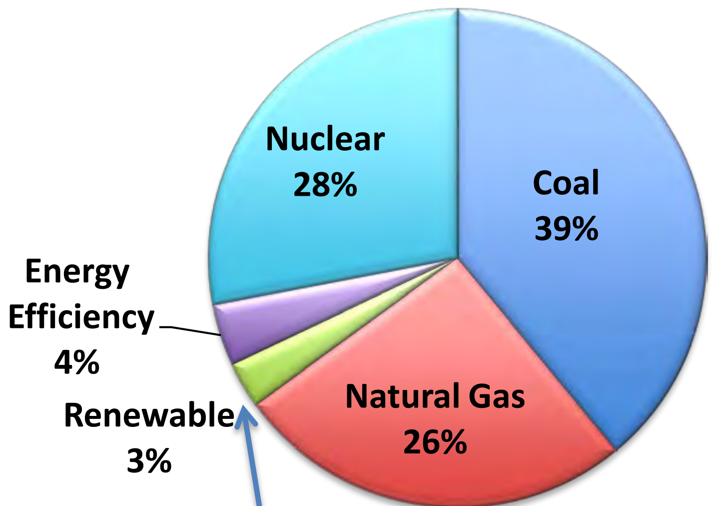
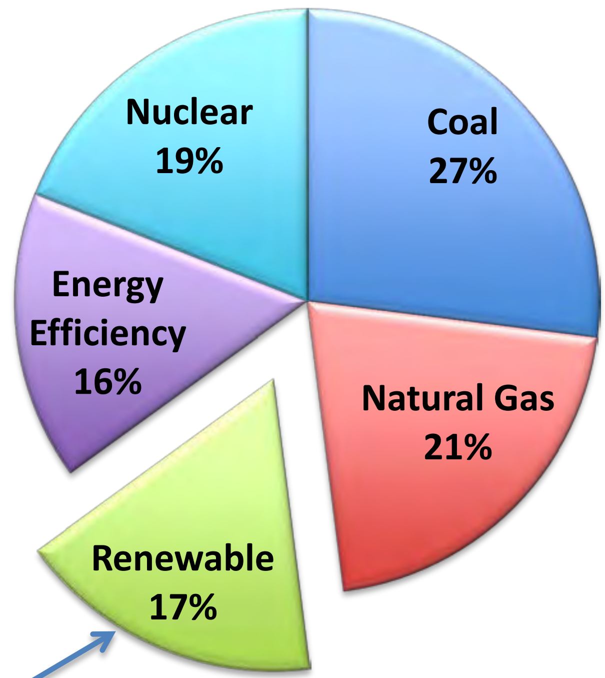
APS Energy Sources 2011 vs. 2025

Focused on a diversified portfolio of generation resources for our customers

2011



2025



End of 2010
288 MW in service

State Renewable
Requirement
15% of electricity by 2025
~2,500MW

Renewable Energy Standard (RES)

- 15% of Retail Sales by 2025
  - < 70% from Utility Scale
  - > 30% from Distributed Energy
    - 50% from Residential
    - 50% from Non-Residential
- Within next year, 200 MWs of DE
- Over 400 MWs of DE in next 5 Years
- Utility Scale PV - 200 MWs Approved
- 280 MWs of Concentrating Solar
- Schools & Governmental Program – 15 MWs

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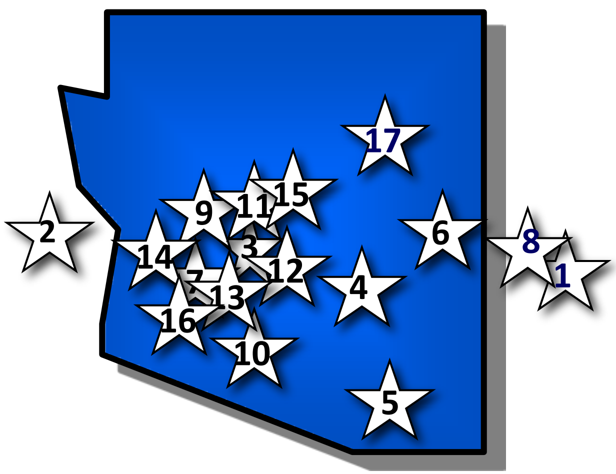
APS Renewable Generation Portfolio



Projects	Net Capacity	Type	Status
2. Salton Sea **(CA)**	10 MW	Geothermal	In operation
5. Saguaro	1 MW	CSP	In operation
6. Snowflake White Mt.	15 MW	Biomass	In operation
11. City of Glendale Landfill	3 MW	Landfill	In operation
7. Solana	250 MW	CSP	Under development
			~280 MW
1. Aragonne Mesa **(NM)**	90 MW	Wind	In operation
2. High Lonesome **(NM)**	100 MW	Wind	In operation
3. Perrin Ranch	99 MW	Wind	In operation
			~ 290 MW
9. Agreement 1	4.5MW	Solar – PV	In operation
10. Agreement 2	10 MW	Solar – PV	In operation
11. Agreement 3	15 MW	Solar – PV	In operation
12. Agreement 4	15 MW	Solar – PV	Under development
13. Agreement 5	15 MW	Solar – PV	Under development
3. Prescott Airport	3.6 MW	Solar - PV	In operation
4. Distributed PV (STAR)	1.0 MW	Solar - PV	In operation
5. Paloma	17 MW	Solar – PV	In operation
9. Cotton Center	17 MW	Solar – PV	In operation
10. Hyder	16 MW	Solar – PV	In operation
9. AZ Sun Additional	100 MW	Solar – PV	ACC approved 1/18/12
10. Chino Valley (69kV)	19 MW	Solar – PV	Under development
11. Hyder II	14 MW	Solar – PV	RFP Meeting March 21
			~ 265 MW
9. Distributed, Customer	120 MW	Solar – PV	In operation
10. Distributed, Customer	80 MW	Solar – PV	expected within 1 yr
11. Distributed, Customer	200 MW	Solar – PV	expected within 5 yrs
			~ 400 MW

~ 1200 MW Renewable generation within 3-5 yrs

Segmented Renewable Strategy

Renewables allow more flexible deployment than traditional generation

Distributed Energy	Small Utility-Scale	Large Utility-Scale
3kW – 10MW Customer Sited	1 – 20MW Distribution Level	21 – 250MW Central Station
• Solar Incentive Programs • Flagstaff Community Power Project • Schools and Government Program	• Paloma Solar Facility • Hyder Solar Facility • Cotton Center Solar Facility • Chino Valley Solar Facility	• 250MW Solana Power Plant • Aragonne Wind Farm • High Lonesome Wind Farm • Perrin Ranch Wind Farm

Study and Demonstration Roadmap for Examining Renewable Integration

Distributed Generation Integration Studies

Beck Study

- Solar Variability
- DOE HPSD
- Energy Storage

Smart Grid

- Community Power
- Flagstaff Smart Grid Demo

Forecasting Planning

- Solar Water Heating
- Distributed Solar/Wind Forecast

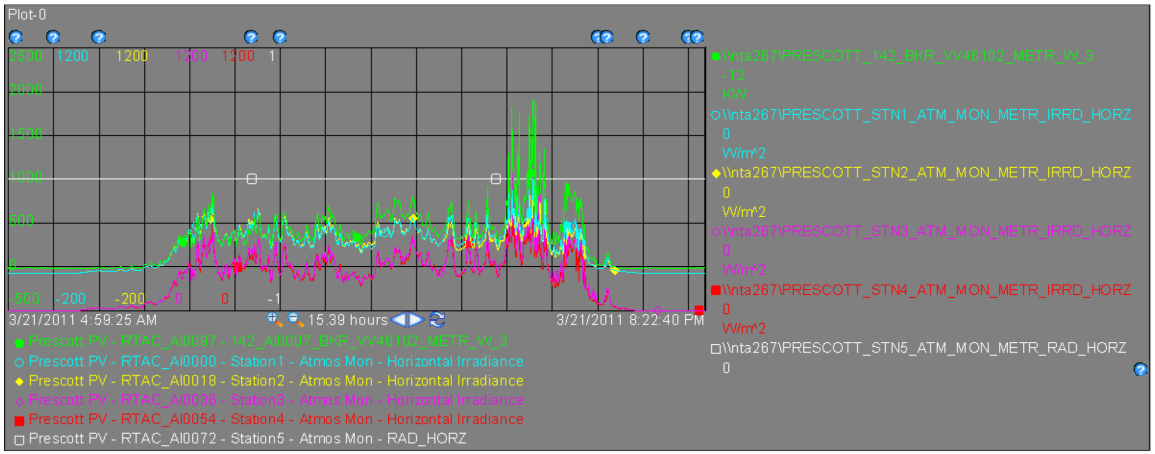
Prescott Variability Study

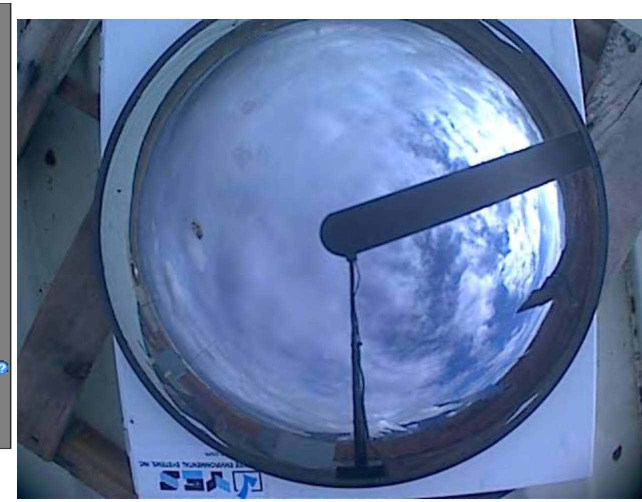
- Evaluate different techniques for analyzing variability
- Experience with analytic instrumentation and tools
- Correlations with irradiance to overall output
- Effects of variability on distribution system voltage
- Provide raw data for additional studies (think Solar Integration Cost Study)
- Determine any further issues to study in the Flagstaff Community Project
- Provide opportunity for comparisons of solar forecasts to actual performance

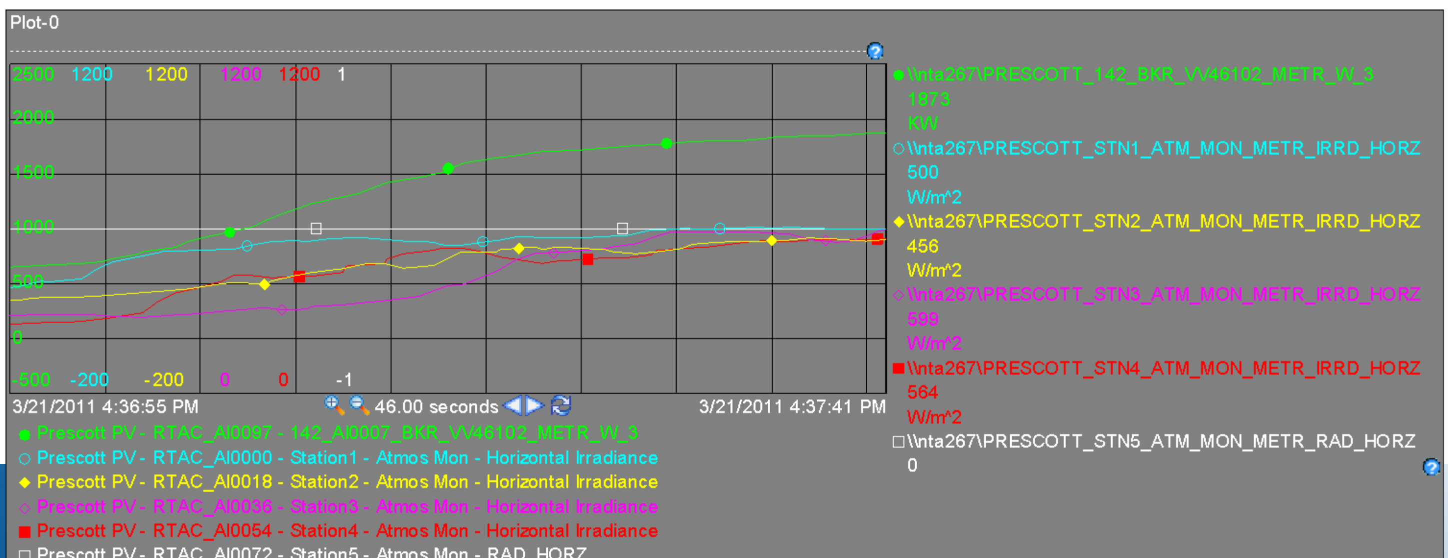
Preliminary Prescott Findings

- Penetration was about 23% on feeder
- Learned how to manage large quantities of data into PI database and transfer to analytic tools (applications transferable to additional studies)
- Raw 1 second data used in setting up Energy Storage control simulations
- Demonstrated smoothing of power output even with a smaller solar facility
- No voltage events with variability outside the regulation requirements of the feeder or substation
- Analyses on variability provided some categorization that may assist in establishing methods for Solar Forecasting application (both utility scale and large scale distributed)
- These and other preliminary findings being evaluated for further study within Flagstaff Community Power Project analyses

Example of Smoothing
March 21, 2011 Rainy







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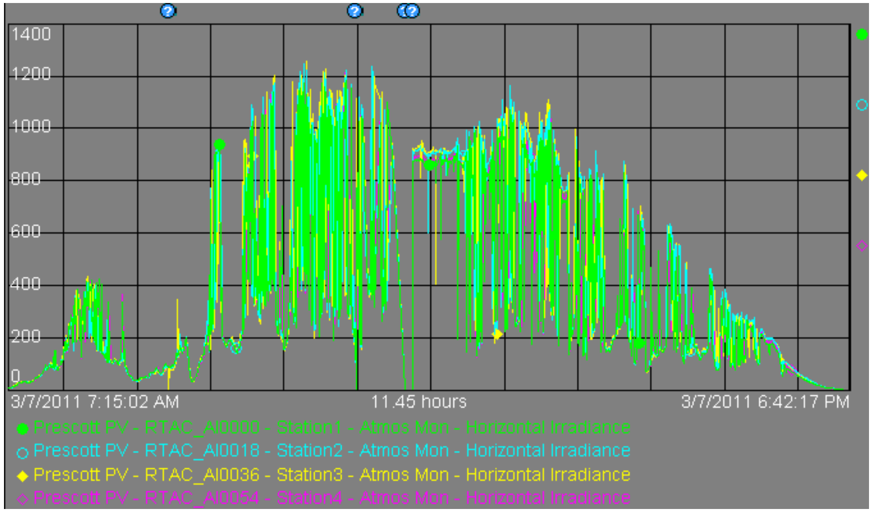
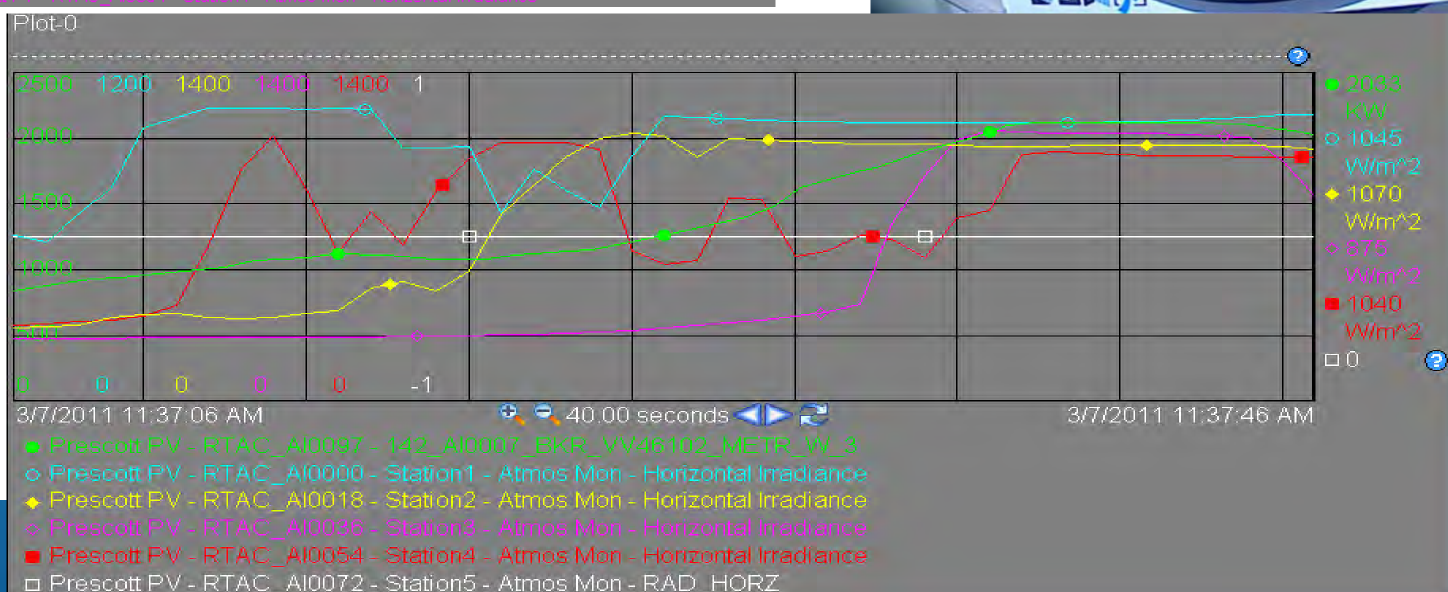
Example of Smoothing
March 7, 2011 Partially Cloudy

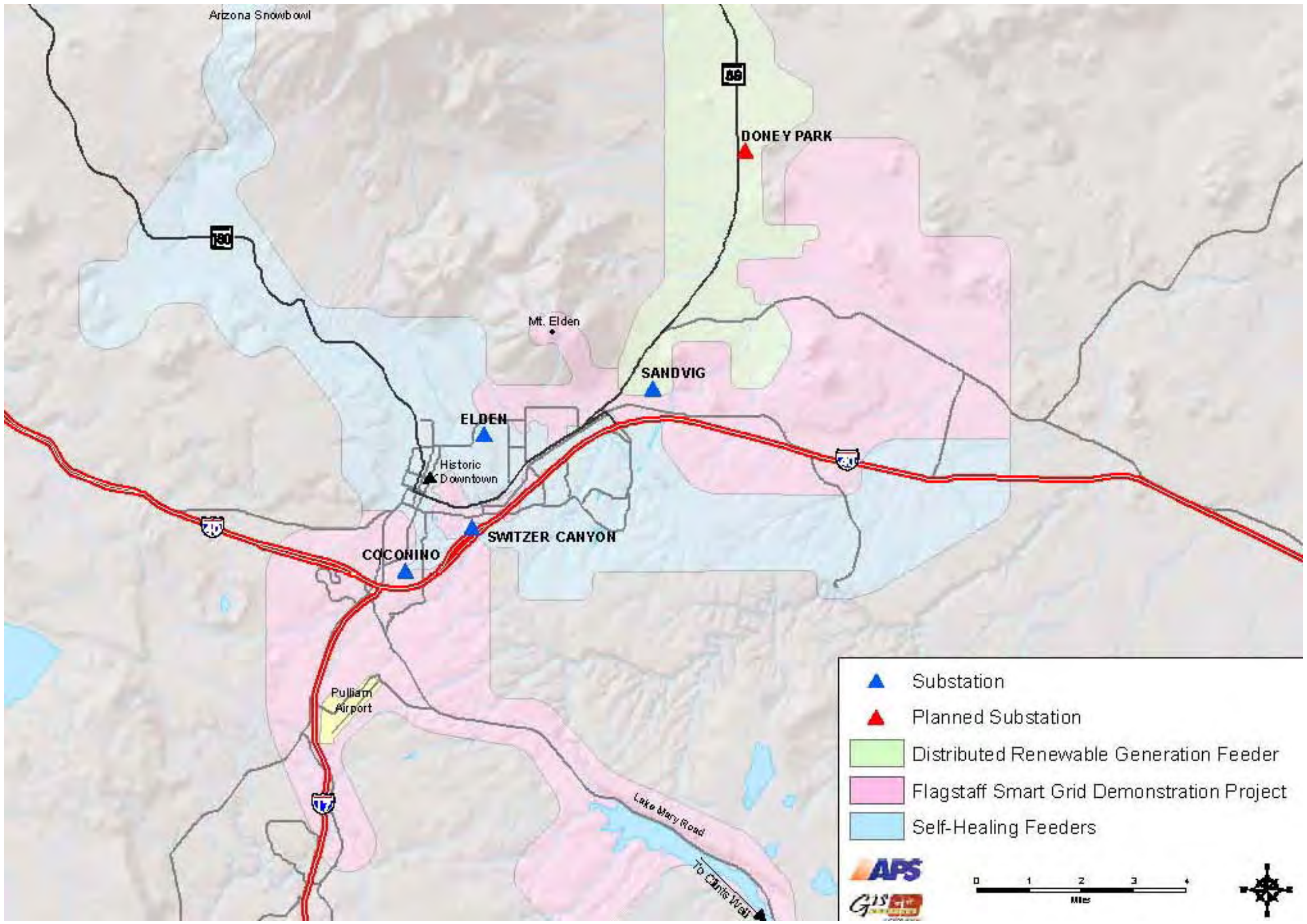




Flagstaff High Penetration Solar Study

- High penetration of distributed variable generation on a small feeder. (reach or exceed 30% of feeder capacity)
- Evaluate the effects
  - The substation transformer
  - The feeder
  - Any of the loads (customers)
  - Analyze the effects on other distribution system devices (cap banks, reclosers)
- Deployments completed, Modeling and Data collection in progress

Flagstaff Demonstration Projects



Flagstaff provides a living, safe and reliable laboratory for data collection and demonstration of technologies.

Provide insight on how to assure continued reliability and value to the customer and the APS system.

Community Power Project – Flagstaff

Customer Value Proposition:

20 year program
APS owns & maintains systems
Interconnected on APS side of meter
Customer eligible for Solar Rate in exchange for easement
Experienced solar installers contracted for installation and maintenance

Residential Requirements:

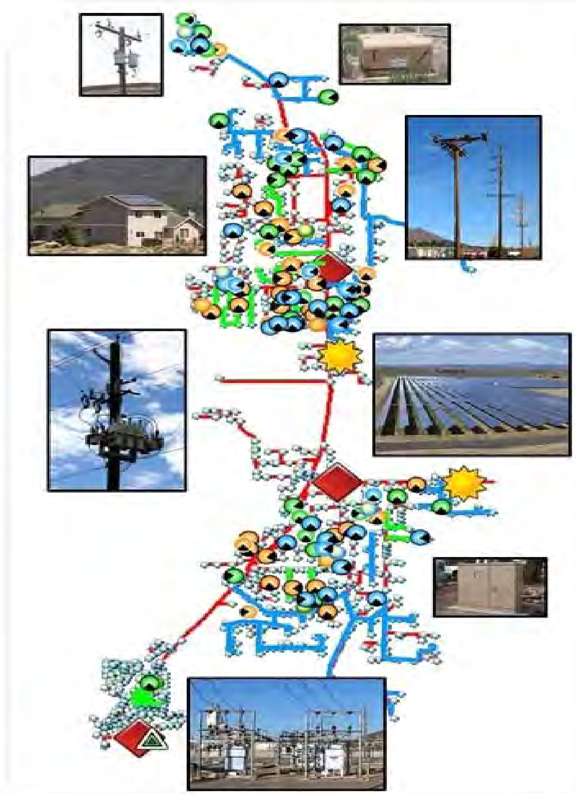
Minimum 4,800kWh annual average usage
Minimum 10 years roof life remaining
Single family, detached homes
Eligible for 2, 3 or 4kW system, based on average annual usage
Full-time resident

High Penetration Study – DOE Funded

Primary Objective & Deliverables
Determine how high penetration of PV affects a working utility distribution feeder

- Validated feeder, PV inverter and load models
- High penetration PV data acquisitions methodology and field deployment
- High penetration PV paired with grid-support inverter, energy storage

Phase 1 results available soon



U.S. DOE

ASU

ViaSol ENERGY SOLUTIONS

NREL

Jan 2010 — Dec 2014

2011 | 2012 | 2013 | 2014

Jan 2010 - Jun 2011 Phase 1	Jan 2011 - Jun 2012 Phase 2	Jul 2012 - Mar 2013 Phase 3	Apr 2013 - Dec 2013 Phase 4	Jan 2014 - Sep 2014 Phase 5
Models of fdr baseline, PV & cust. loads Data acquisition system prototypes (DAS) GE smart inverter – initial evaluation	HiPV model DAS & PV Deployment	Theoretical PV limits Field data validation	Final HiPV models Model Extensions	Final report Cost/benefit Recommendations

aps

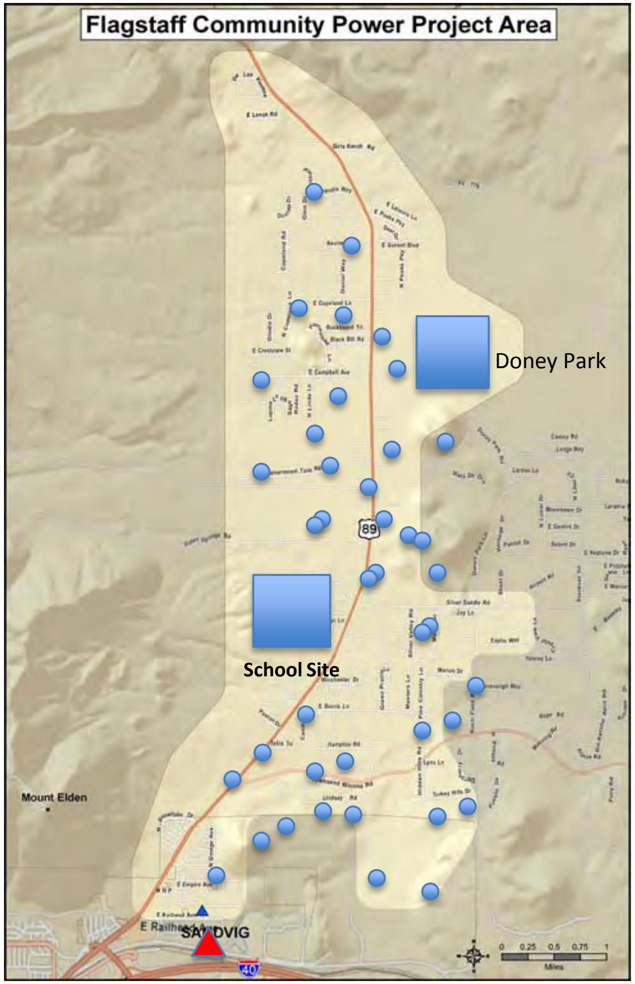
Energy Storage Study

- **Partners- Electrovaya, ABB, ASU**
  - Lithium-Ion battery technology/ABB grid interface
  - 500 kW, 1.5 MWh (3 hour) storage capacity

- **Phase I: Substation Application (Elden)**
  (bulk storage, smoothing, peak shaving, control)
  - Communications infrastructure
  - Location & site layout
  - Smart Grid substation

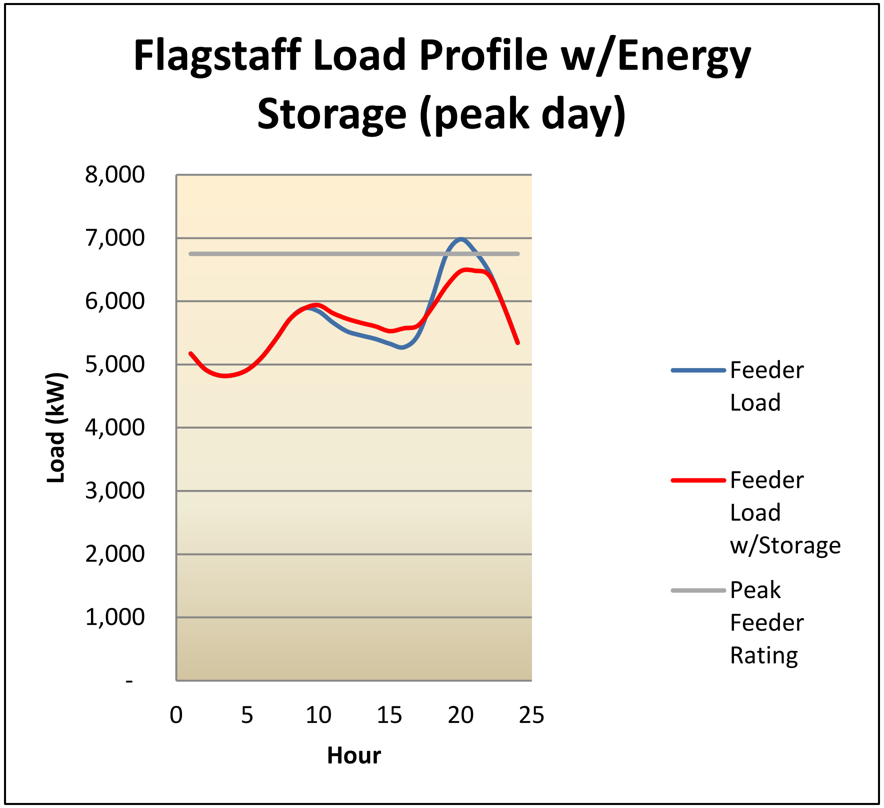
  Currently in commissioning

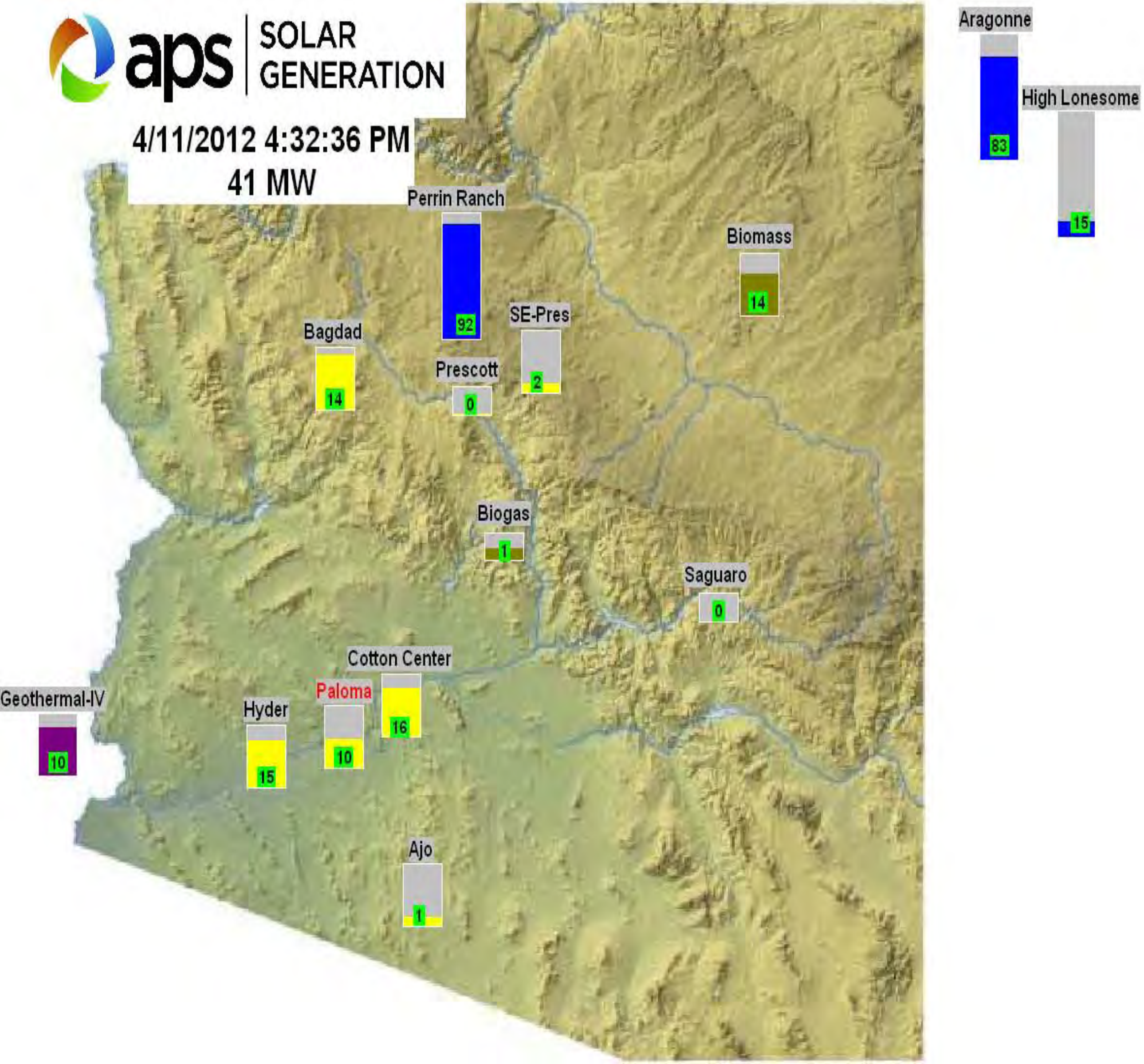
- **Phase II: PV Site Application (DPRES)**
  - Part of High Penetration Solar Deployment
  - Opportunity for PV Variability mitigation
  - Opportunity for “down-the-feeder” operation



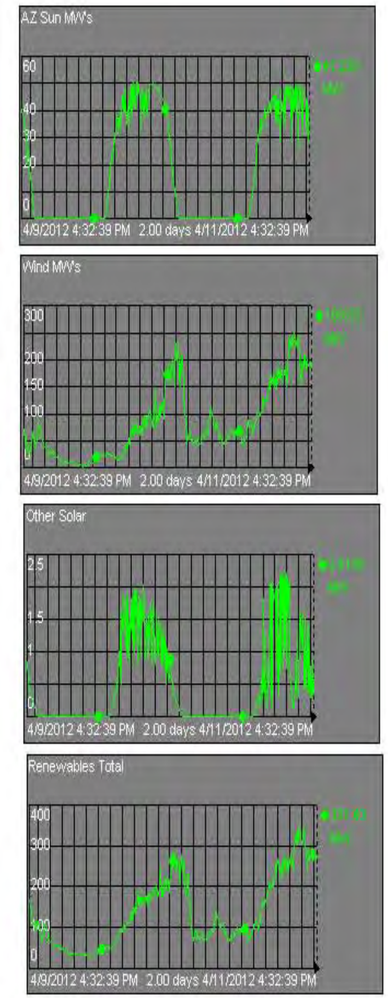
Phase I Operation- Peak Shaving

- Function- off peak storage, peak dispatch
- Why test this? Potential benefits:
  - Asset utilization, reduce stress
  - Levelize load, improve feeder load predictibility
  - Potential to defer asset upgrades
  - Dispatchable energy
- Control Modes
  - Scheduled dispatch
  - Remote dispatch (non AGC)
  - Grid monitoring (setpoint)
- Schedule
  - Q1 2012 – Q4 2012

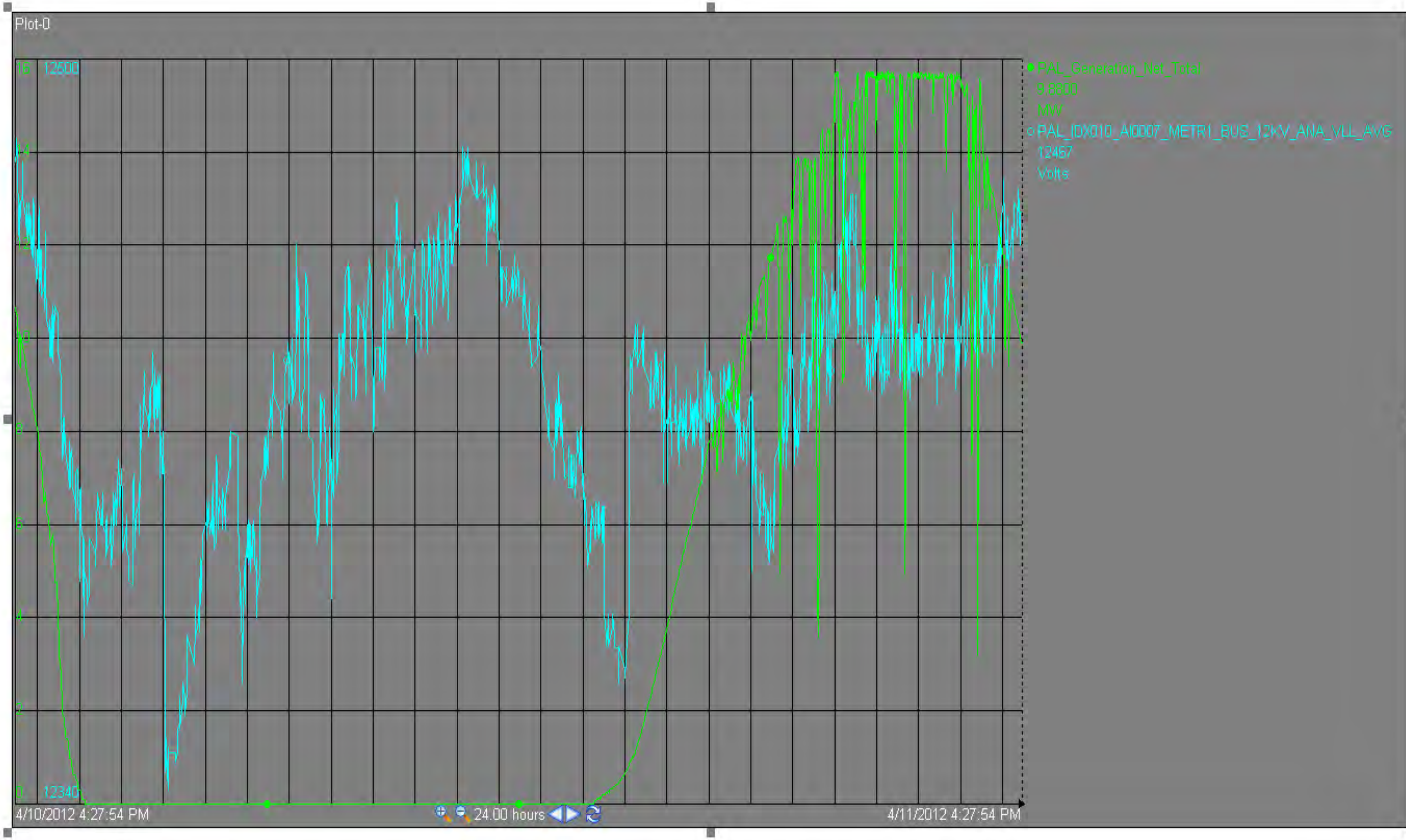




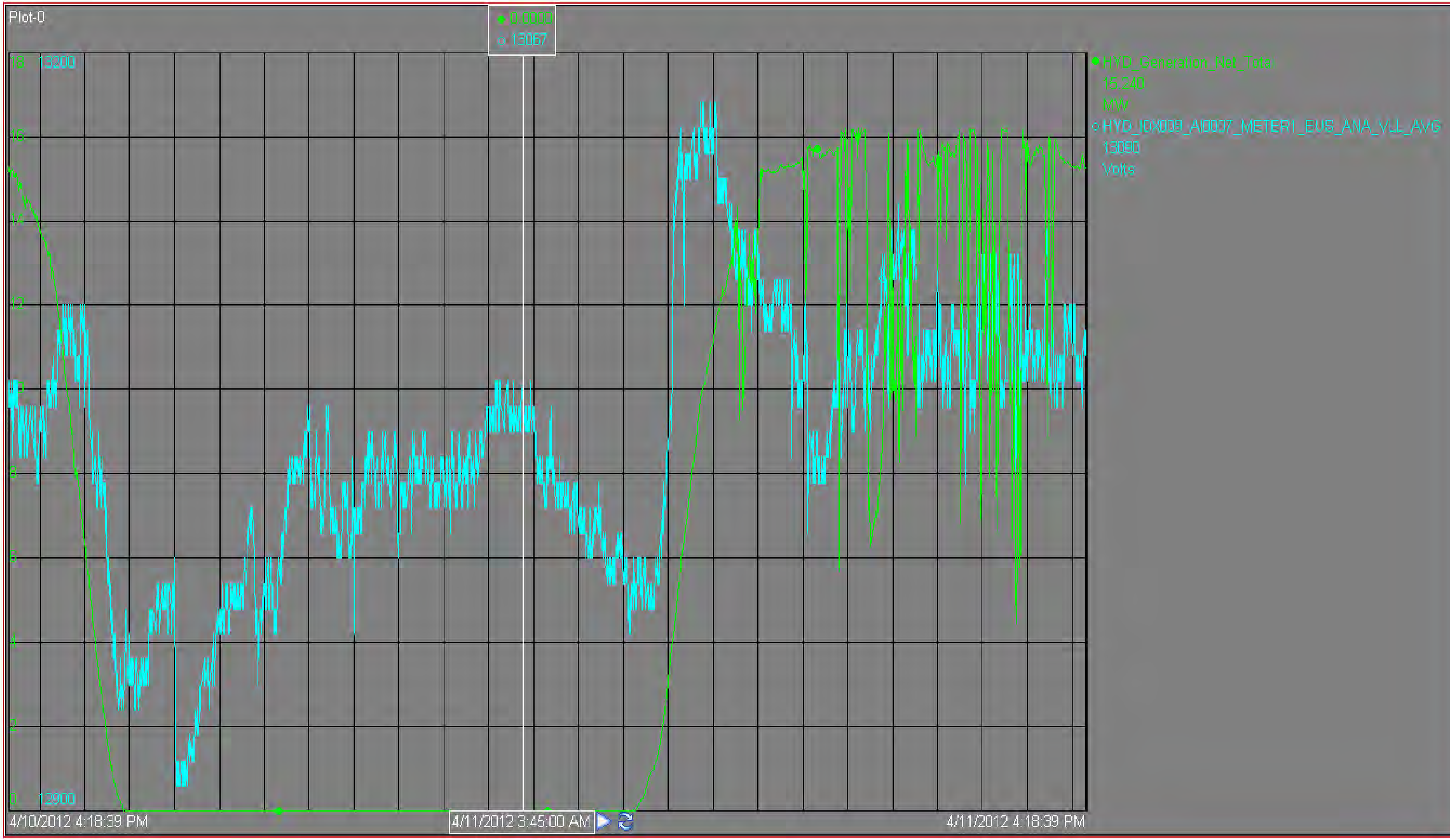
Two Day Trends



Paloma PV Plant (17 MW)



Hyder PV Plant (16 MW)



Thank you for your time!

More Information:

APS High PV Penetration:
http://www.aps.com/main/green/choice/solar/highpenetration.html

U.S. Department of Energy Solar High Penetration Portal
https://solarhighpen.energy.gov/

APS YouTube Channel (Energy Storage featured):
http://www.youtube.com/user/arizonapublicservice

APS Energy Storage- How it Works:
http://www.flickr.com/photos/apspics/6921479361/in/set-72157629066368860/

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