SAND2013-4149P

Integration of High Penetration PV on Distribution Circuits

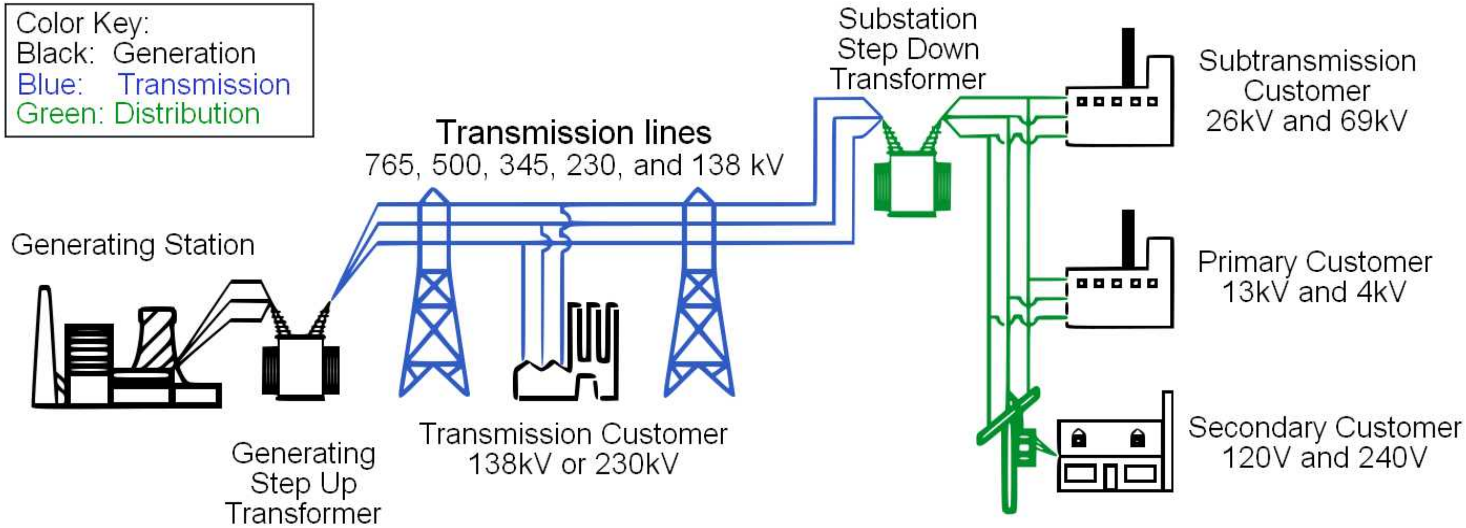
Abraham Ellis, PE, Ph.D.
Sandia National Laboratories

December, 2011

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Brief Introduction

- **Transmission**
  - Move bulk electricity from generation to load centers
  - Long distance (10s to 100s of miles), high capacity, high voltage
- **Distribution**
  - Distribute electricity to end users
  - Short distance (up to several miles), lower capacity, lower voltage



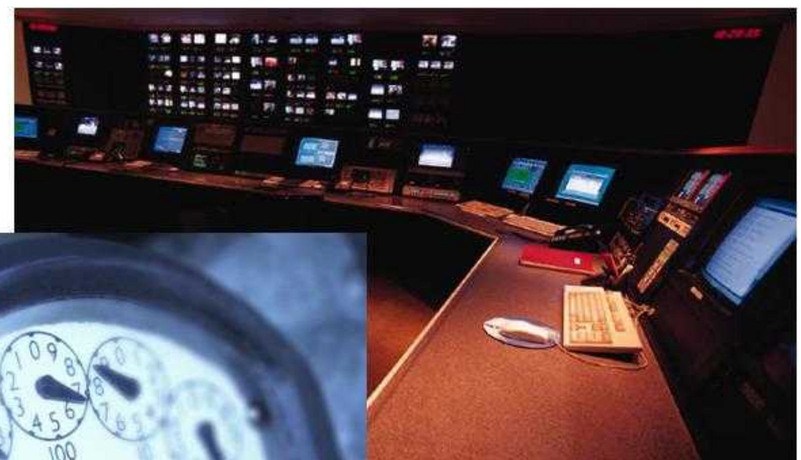
Sandia National Laboratories

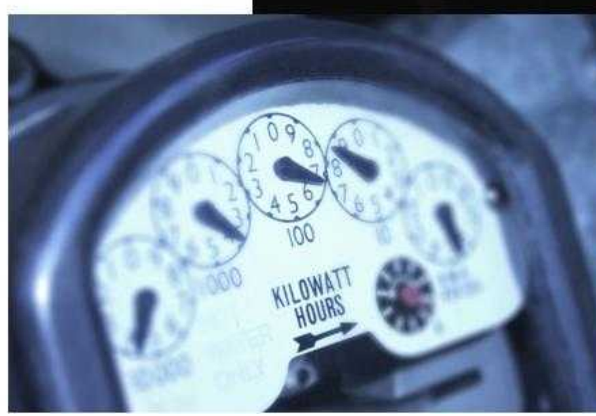
Brief Introduction

- **Transmission and Distribution Planning**
  - Identify future system upgrades system to cost-effectively meet future system needs
  - Project needs 1 to 10+ years ahead
  - Grid and resource (generation)
  - Load growth is the driver
- **Transmission and Distribution Operations**
  - Use existing system assets to meet load
  - Still have to “plan ahead” hours to weeks ahead in order to optimize operating cost and avoid exceeding equipment constraints
- **Rules**
  - Must meet performance, safety, reliability
  - Institutional: regulatory, policy, market rules, etc.

Grid Integration Challenge

- Are high penetration scenarios technically feasible?
- What are the impacts and mitigation? What is the cost?
- What performance standards are needed?
- How should we plan the grid to enable high penetration?
- What has to change?





Definition of VG Penetration Level

- **From the distribution system point of view**
  - VG Capacity / Peak Load of line section or feeder*
  - VG Capacity / Minimum Load
  - VG Capacity / Transformer or Station Rating
- **From the bulk system point of view**
  - Annual VG Energy / Annual Load Energy*
  - VG Capacity / Peak Load or Minimum Load

* Definition most commonly used

- **Often used in policy and procedures**
  - Penetration by energy used in State RPS targets
  - Penetration by capacity used in the context of interconnection procedures (screening)

Definition of VG Penetration Level

- **Example for distribution system**

	Peak / Min (MW)	Penetration for 1 MW PV
Feeder Load	3 / 0.9 [1]	33% / 111%
Station Load	10 / 3 [1]	10% / 33%
Station Rating	20 MVA	5%

[1] Minimum Load may be in the range of 20% to 40% of Peak Load

- **Example for bulk system**

	Load		Penetration for 1 GW PV	
	Peak/Min (GW)	Energy (GWh)	By Capacity	By Energy [3]
Utility (LSE)	5 /2 [1]	24,000 [1]	20% / 50%	6%
Balancing Area	50 / 20 [2]	240,000 [2]	2% / 5%	0.6%

[1] e.g., SDGE, 2009 [2] e.g., CAISO, 2009 [3] Assumes 16% annual capacity factor

What is High Penetration?

- **It depends!**
  - With respect to what part of the system?
    - Feeder or Local Grid?   >50% by capacity?
    - BA/Market?   Interconnection?   >5% by energy?
  - Assuming Business-As-Usual or Best Practices?
    - Technology, Standards, Procedures, Market, Regulatory…

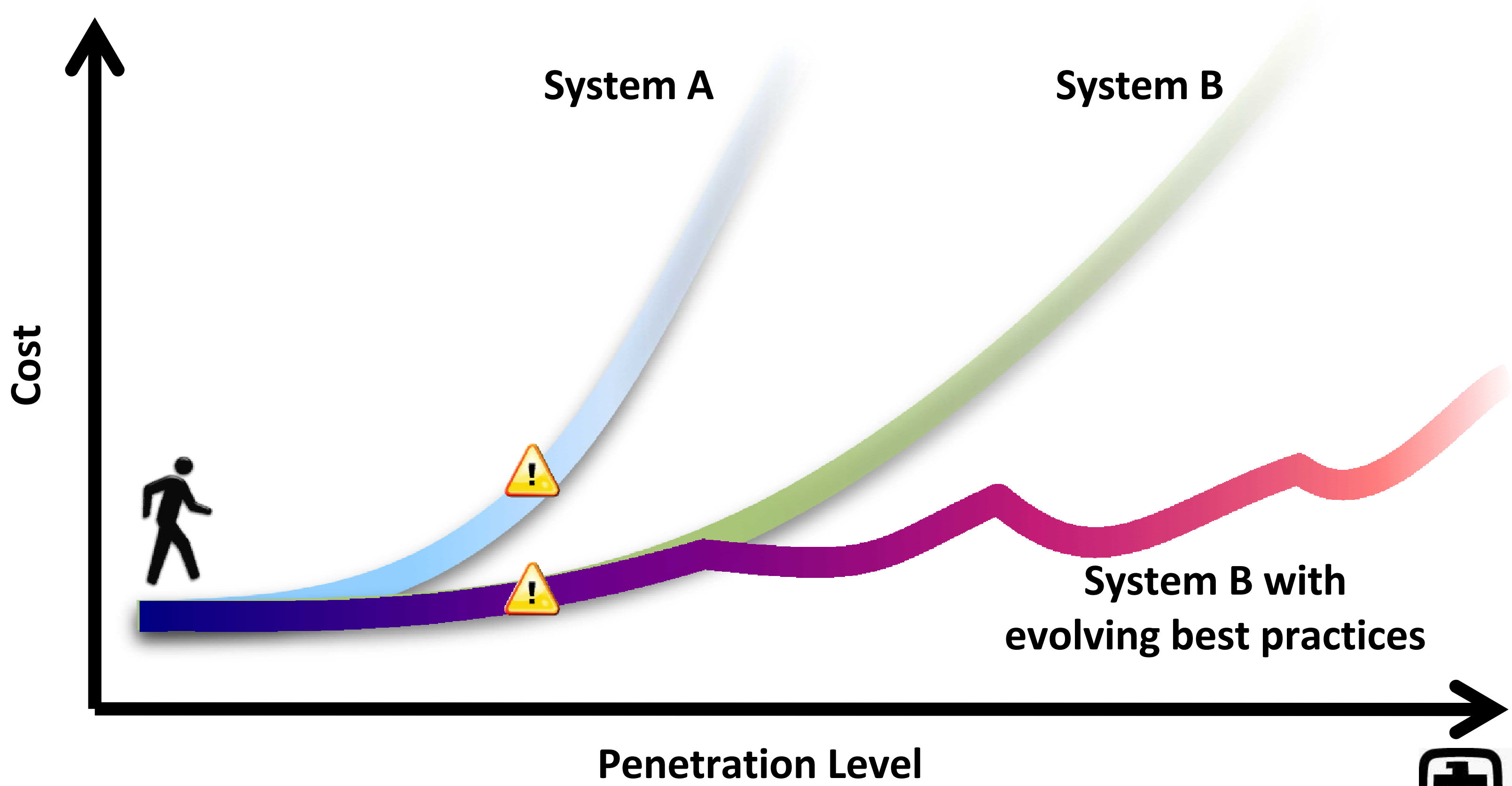
- **High penetration is a concern when…**
  - Performance & reliability would be materially impacted

AND

  - Cost of mitigation and cost allocation are unacceptable to stakeholders

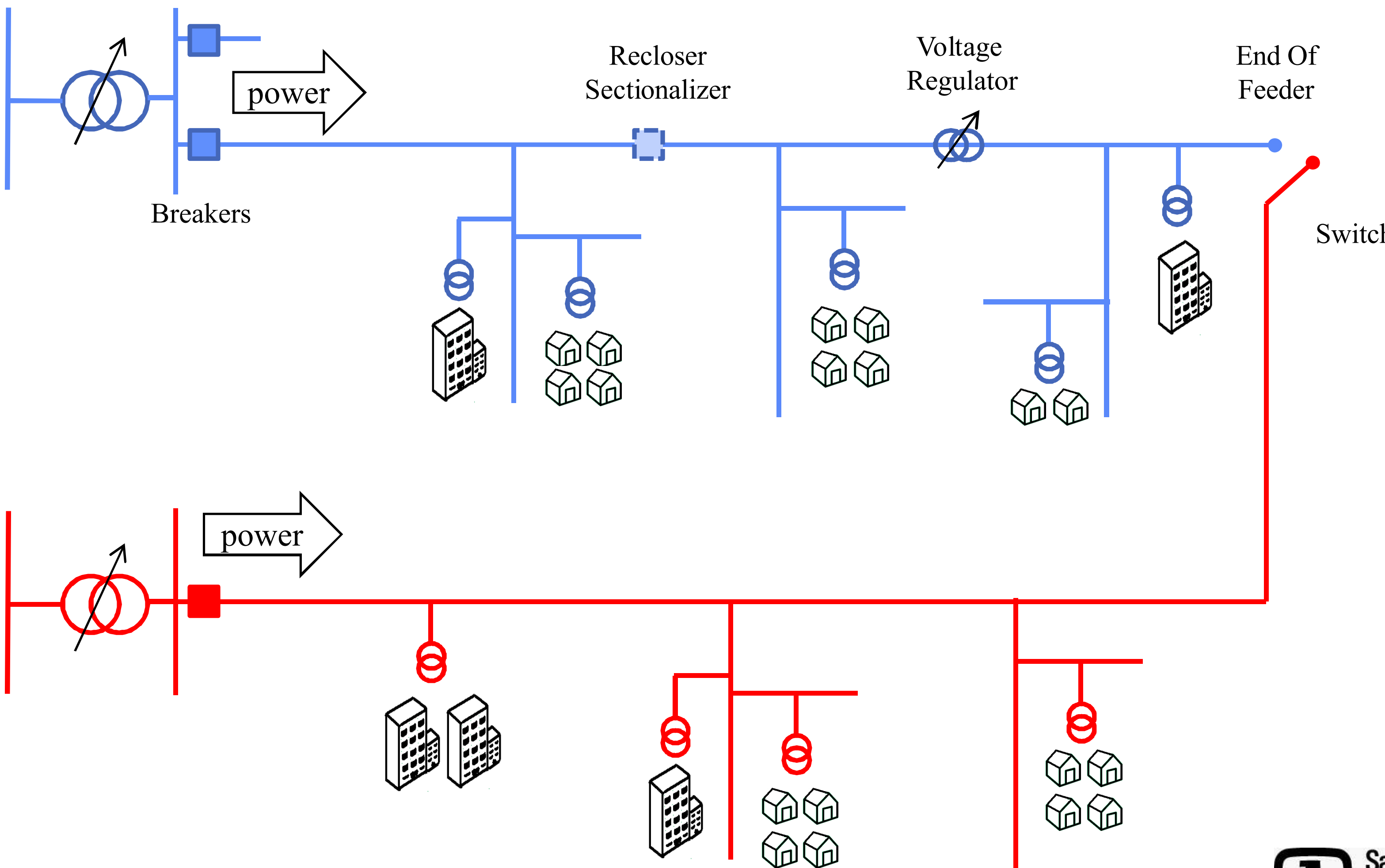
Are There Penetration Limits?

- **There are no <u>absolute</u> technical limits to PV penetration**
  - Cost is the issue, and this is system-specific

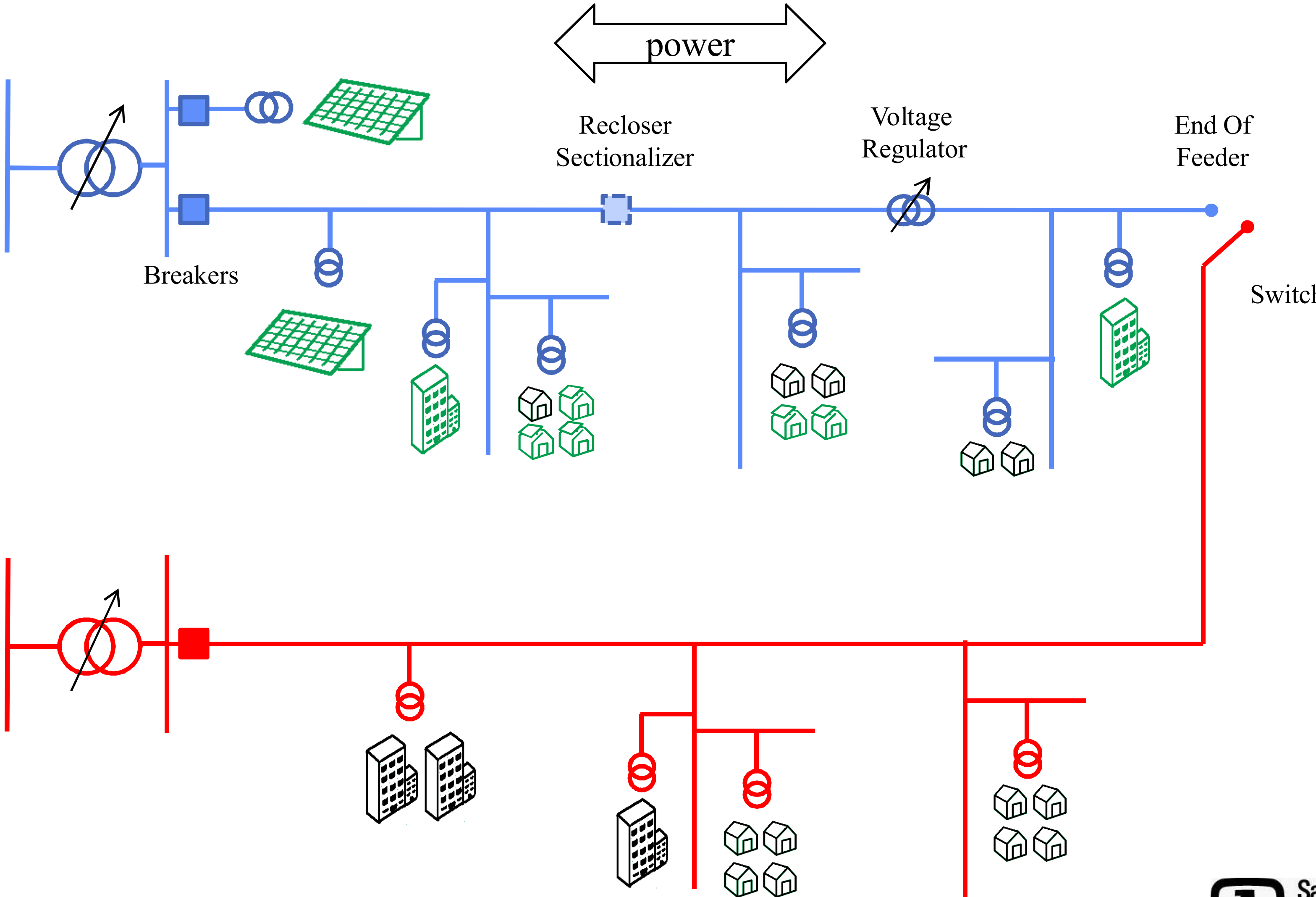


Sandia National Laboratories

Distribution System



Distribution System with High Penetration PV



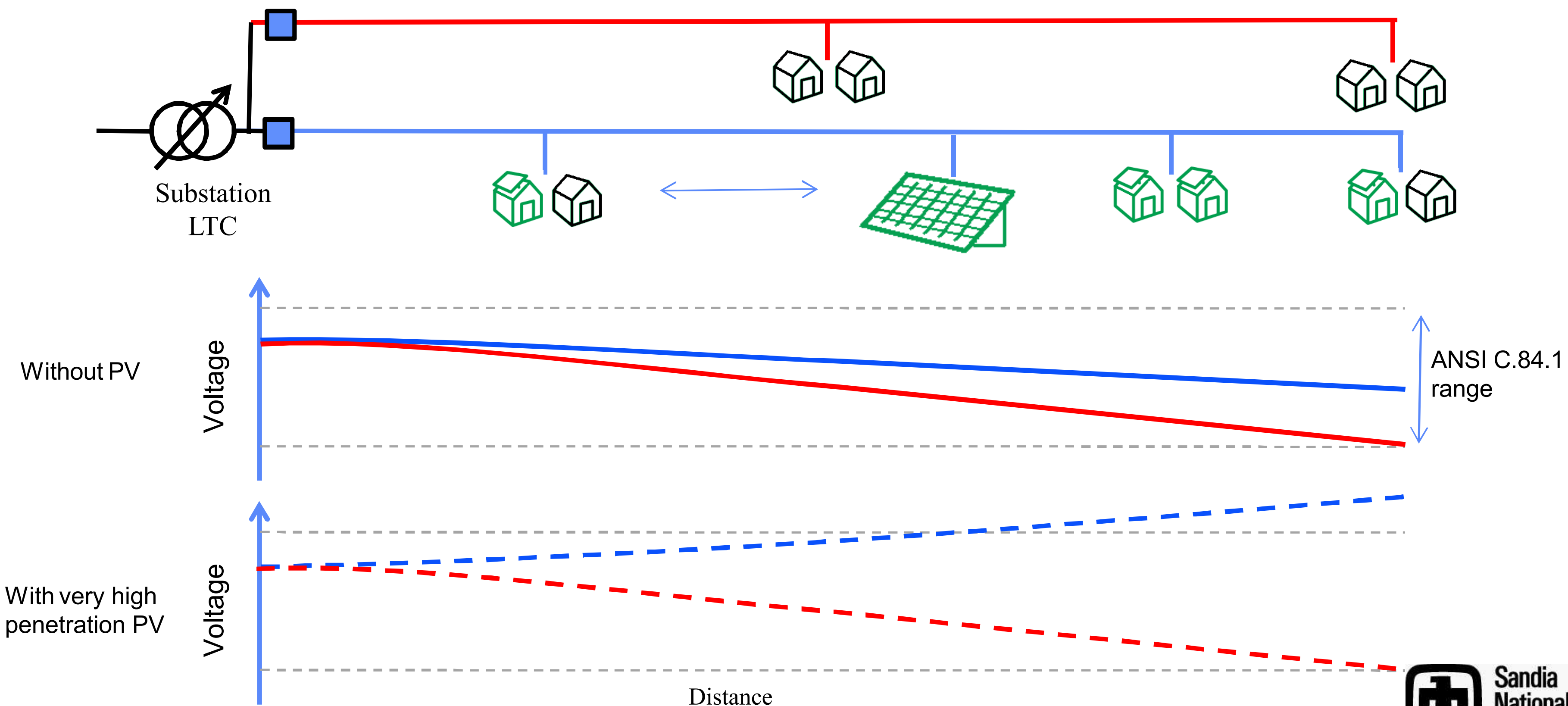
Distribution System Integration

- **Voltage Regulation**
  - Ability to maintain customer voltage within range
  - Wear-and-tear on voltage control equipment (e.g., tap operations) due to variable output
- **Power Quality**
  - Flicker, harmonics
- **Protection**
  - Performance of relays and other protection equipment
  - Risk of unintentional islanding
- **System planning and operations**
  - Feeder load switching, maintenance, outage management
  - Controllability and visibility of distributed resources
  - Possible impact on bulk system

Sandia National Laboratories

Voltage Regulation Issue

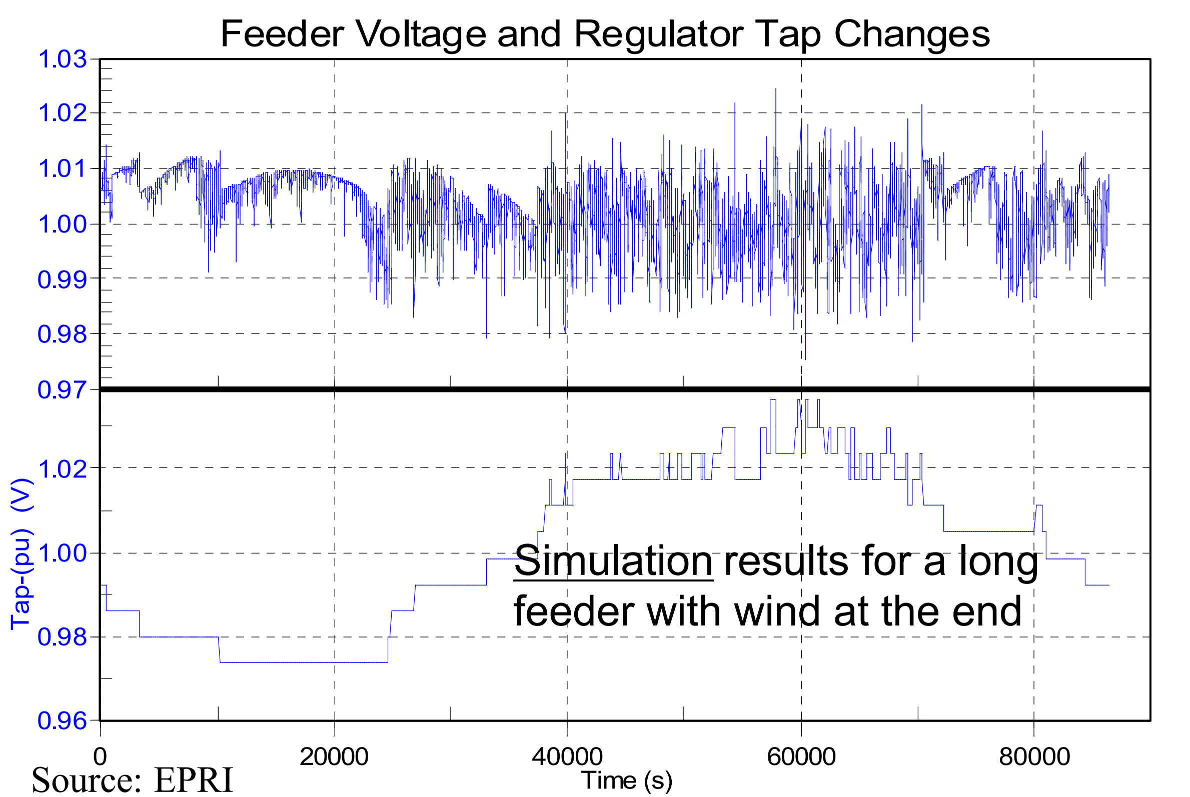
- **High voltage at end of feeder**
  - Most commonly encountered issue for high penetration PV
  - Worse on long feeders with PV at the end



Sandia National Laboratories

Voltage Regulation Issue

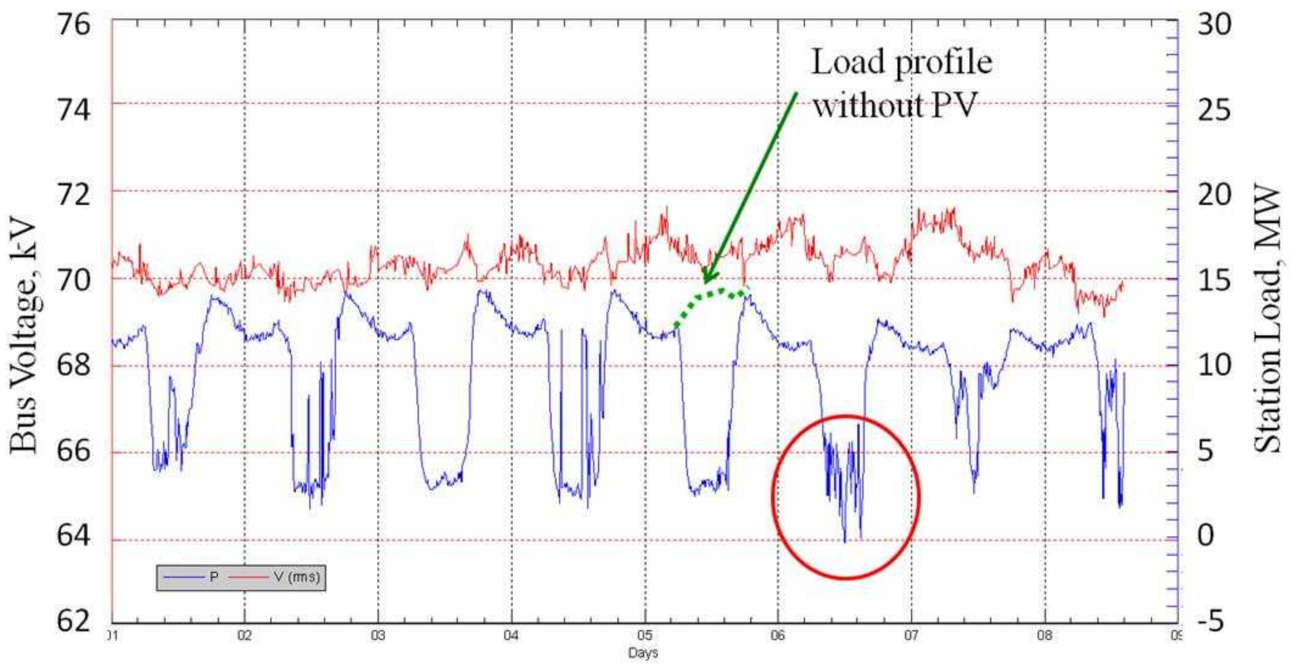
- **Possible increase in LTC/VR activity, voltage flicker**
  - Worse on long feeders with PV at the end



Source: EPRI

Voltage Regulation Issue

- **High penetration does not always lead to voltage issues**
  - Short urban feeder
  - PV connected close to the feeder head
- **Example below: PV is connected next to strong urban feeder head, station voltage does not change**

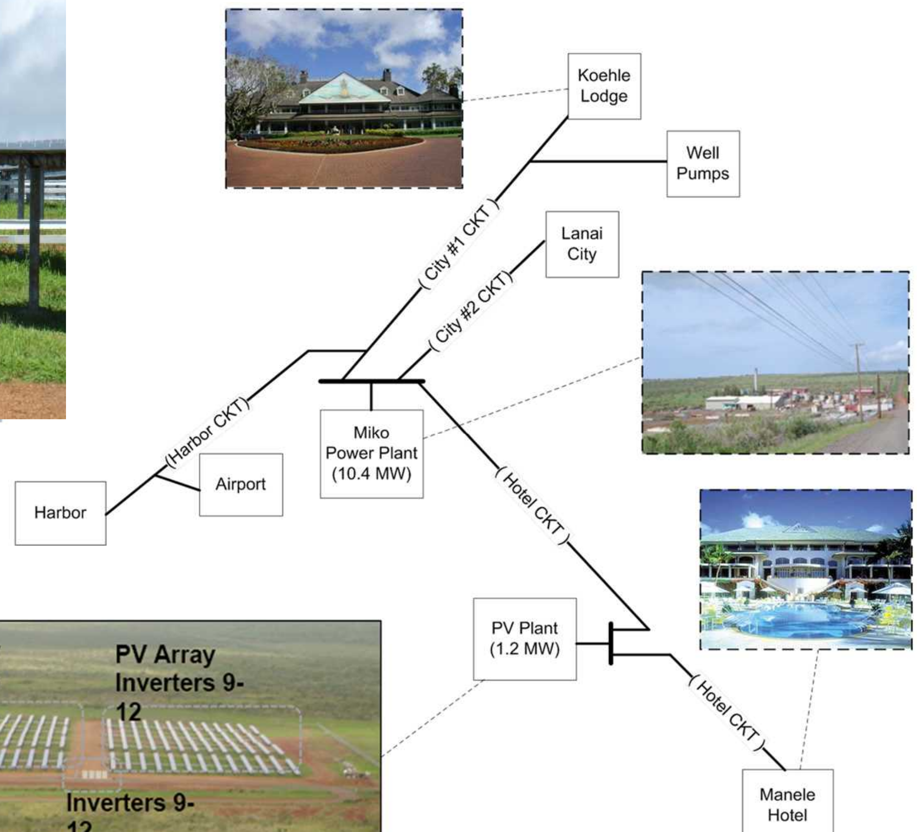


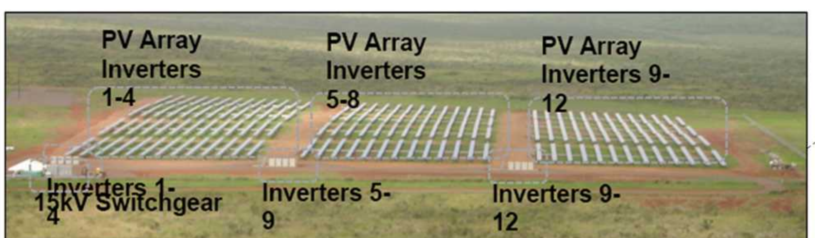
Sandia National Laboratories

Examples of High PV Penetration

Lanai , Hawaii

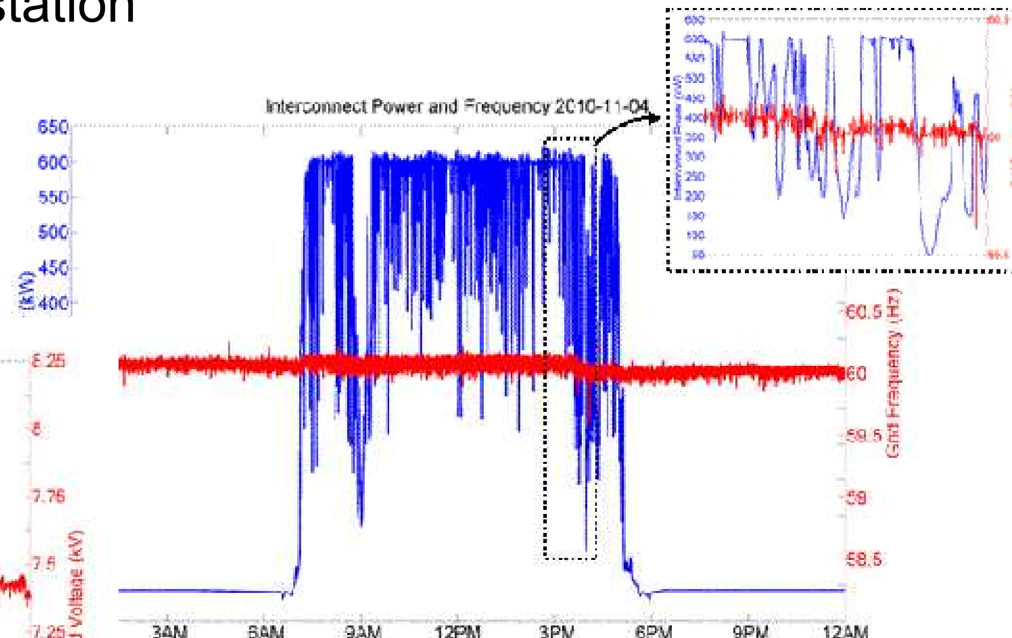
1.2 MW PV system on 5 MW peak island grid supplied by set of diesel generators

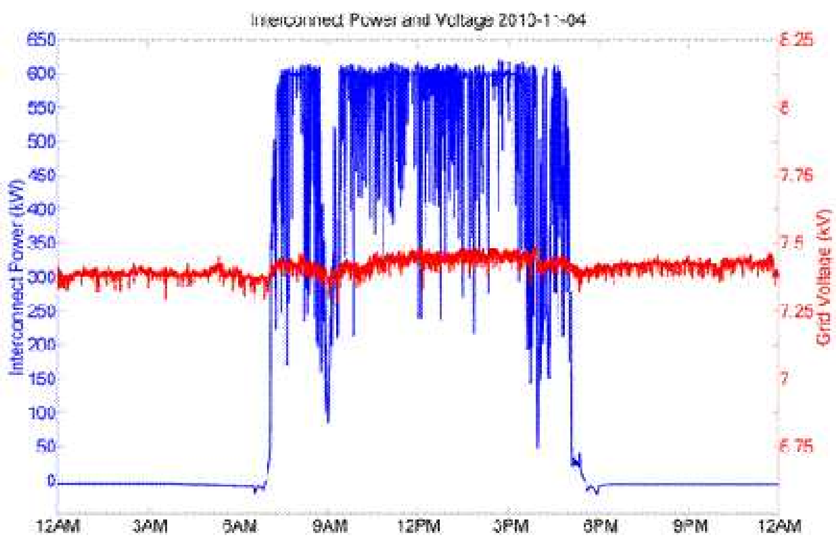




Examples of High PV Penetration

- **High penetration at feeder and system level**
- **Data shows minor impact on voltage and frequency**
  - PV close to generating station





Source: Sandia Report “Initial Operating Experience of the La Ola 1.2-MW Photovoltaic System”, SAND2011-8848, October 2011.

Sandia National Laboratories

Examples of High PV Penetration

Ota City, Japan

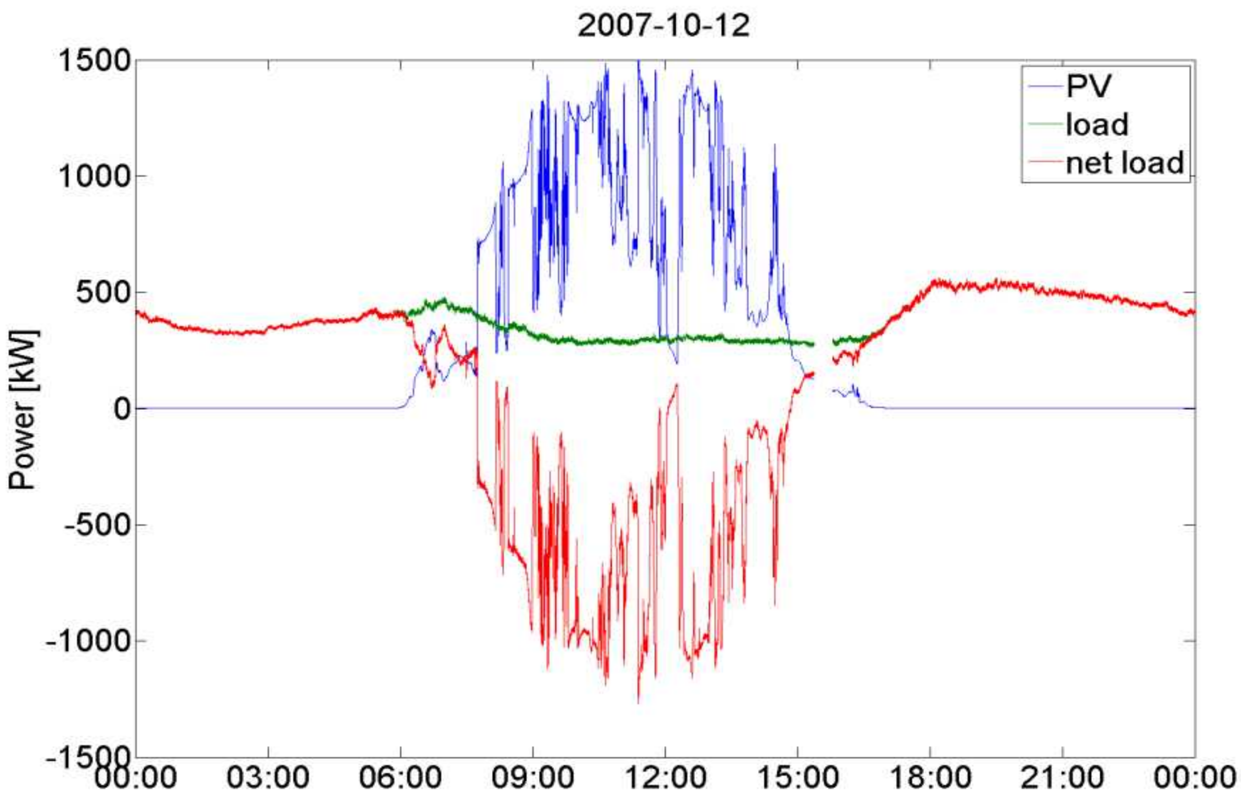
2 MW PV on single feeder

553 homes, 3.85 kW average PV system

Sandia National Laboratories

Examples of High PV Penetration

- **Reverse power flow, but no major voltage problems**

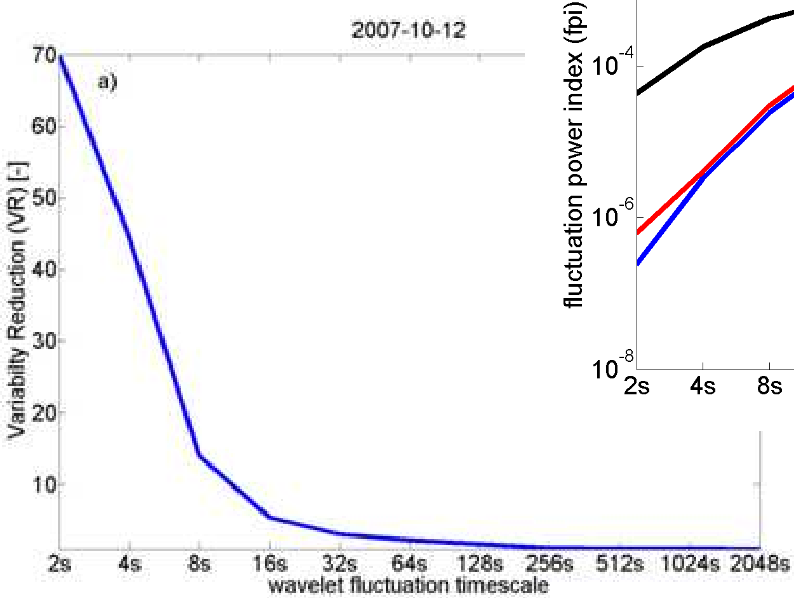


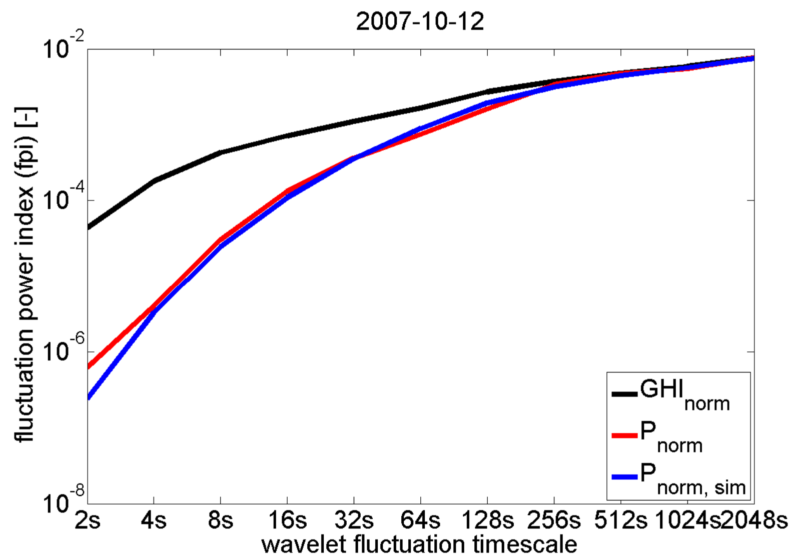
Source: Sandia Report "Ota City: Characterizing Output Variability from 553 Homes with Residential PV Systems on a Distribution Feeder", December 2011

Sandia National Laboratories

PV Output Variability Compared to Irradiance Variability at a Given Location

- **Depends on the plant footprint, time frame of interest**
  - Larger the footprint = less variability compared to irradiance
  - Shorter time frame = less variability compared to irradiance
  - Output characteristics can be estimated based on irradiance





Source: Sandia Report "Ota City: Characterizing Output Variability from 553 Homes with Residential PV Systems on a Distribution Feeder", December 2011

Sandia National Laboratories

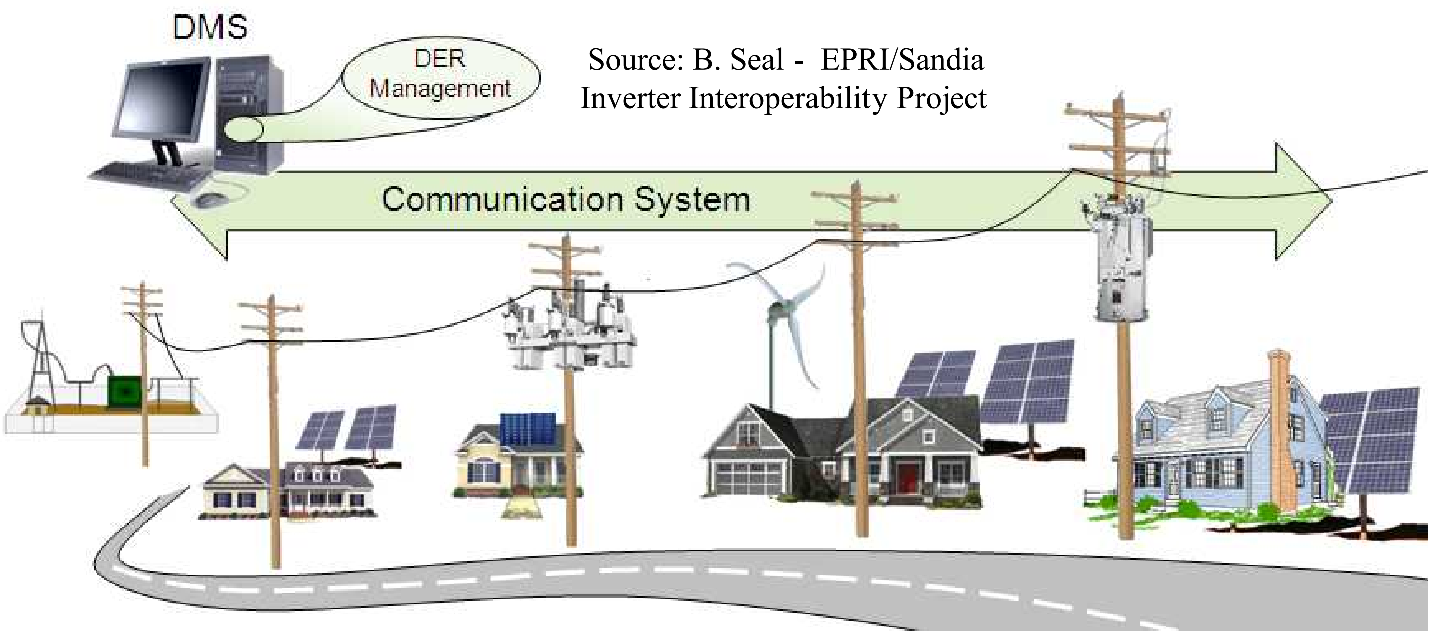
Distribution Operations Issues

- **While previous examples show no problems, high penetration PV could have impacts depending on factors**
  - Feeder characteristics (impedance)
  - Amount of PV, location, deployment (centralized vs. distributed)
  - Type of voltage control and protection
  - Load characteristics

- **What can be done to address possible voltage issues?**
  - Adjust existing voltage control equipment
  - Reduce PV power factor
  - Consider express feeder where possible
  - Allow PV to manage voltage

Evolution of Performance Standards

- **PV 'could' help manage voltage**
  - Emerging commercial availability (e.g., SEGIS)
  - Emerging performance and communications standards (e.g., EPRI/Sandia PV Inverter Interoperability Project)
  - High interest, but still low market demand

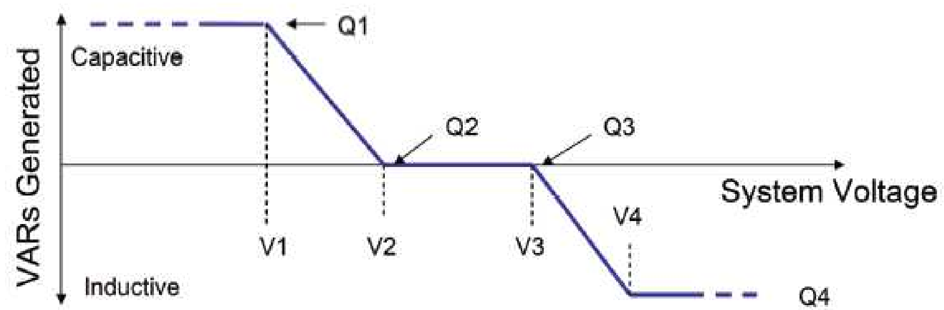


Source: B. Seal - EPRI/Sandia Inverter Interoperability Project

Evolution of Performance Standards

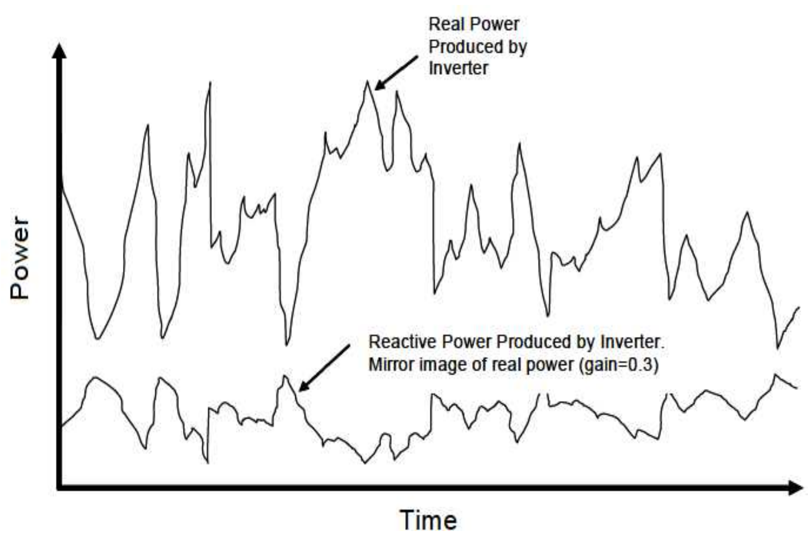
- **Options for feeder-level 'open loop' voltage support**
  - May not require communications

Volt/Var Droop Characteristic



Source: EPRI/Sandia PV Inverter Interoperability Project

Variable power based on PV Output



DOE RSI study, "Advanced Grid Planning and Operations"

Sandia National Laboratories

DG Connection Standards

- Other applicable codes and standards

	Requirement
Voltage Regulation	Maintain service voltage within ANSI C84 Range A (+/-5%)
Voltage control	Not permitted (IEEE 1547)
Flicker	Maximum Borderline of Irritation Curve (IEEE 1453)
Harmonics	<5% THD; <4% below 11^{th}; <2% for 11^{th} – 15^{th}, <1.5% for 17^{th} – 21^{st}; 0.6% for 23^{rd} – 33^{rd}; <0.3% for 33^{rd} and up (IEEE 519)
Power Factor	Output power factor 0.85 lead/lag or higher (equipment typically designed for unity power factor)
Direct Current Injection	<0.5% current of full rated RMS output current (IEEE 1547)
Synchronization and Protection	Dedicated protection & synchronization equipment required, except smaller systems with utility-interactive inverters

DG Connection Standards

- **Voltage and frequency thresholds in existing standard create an exposure for high penetration scenarios**

Voltage Range (% Nominal)	Max. Clearing Time (sec) *
V < 50%	0.16
50% ≤ V < 88%	2.0
110% < V < 120%	1.0
V ≥ 120%	0.16

(*) Maximum clearing times for DER ≤ 30 kW; Default clearing times for DER > 30 kW

Frequency Range (Hz)	Max. Clearing Time (sec)
f > 60.5	0.16
f < 57.0 *	0.16
59.8 < f < 57.0 **	Adjustable (0.16 and 300)

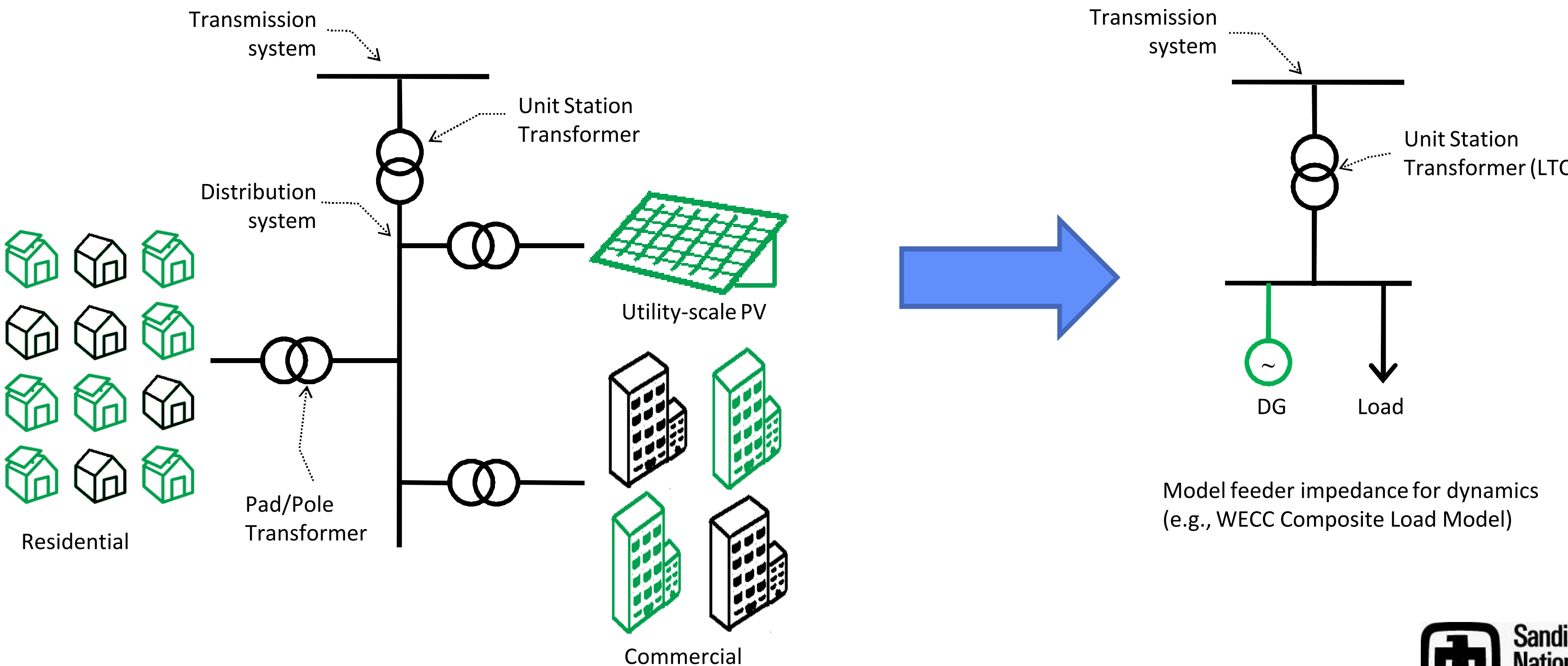
(*) 59.3 Hz if DER ≤ 30 kW

(**) For DER > 30 KW

- NOTE: Different thresholds adopted in Hawaii
- Could conceivably affect bulk system stability if penetration scenarios are high enough

Possible Impact on Bulk Systems

- **Need to capture behavior of PV (and other DG) in bulk system planning studies**
  - Most importantly, voltage and frequency tripping
  - WECC REMTF making some progress on PV modeling



Sandia National Laboratories

Conclusions

- **There are many examples of high penetration PV in Hawaii and elsewhere, where impacts have been minor**

- **However, high penetration in distribution circuits could cause problems**
  - Local voltage management is the most common issues or concern
  - System level impacts are possible if penetration levels are high enough
  - Impacts are a function of penetration levels and system characteristics; it is very difficult to make generalizations
  - Technical solutions are possible and emerging
  - Institutional barriers such as established practices, standards and procedures tend to be more difficult to change

Questions and Discussion