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Grid Operations and High Penetration PV

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Outline

- How to measure "PV Penetration"
- What is "High PV Penetration"
- Thoughts about "Penetration Limits"
- System Operations with High Penetration
  - Distribution system issues
  - Bulk system issues
- Conclusions
- Definitions
  - DG = distributed generation; VG = variable generation

Definition of PV Penetration Level

- From the distribution system point of view
  - PV or DG Capacity / Peak Load of line section or feeder*
  - PV or DG Capacity / Minimum Load
  - PV or DG Capacity / Transformer or Station Rating
- From the bulk system point of view
  - Annual PV Energy / Annual Load Energy*
  - PV or VG Capacity / Peak Load or Minimum Load
- Often used in policy and procedures
  - E.g., RPS targets, interconnection screens

* Most commonly used

Definition of PV 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	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%

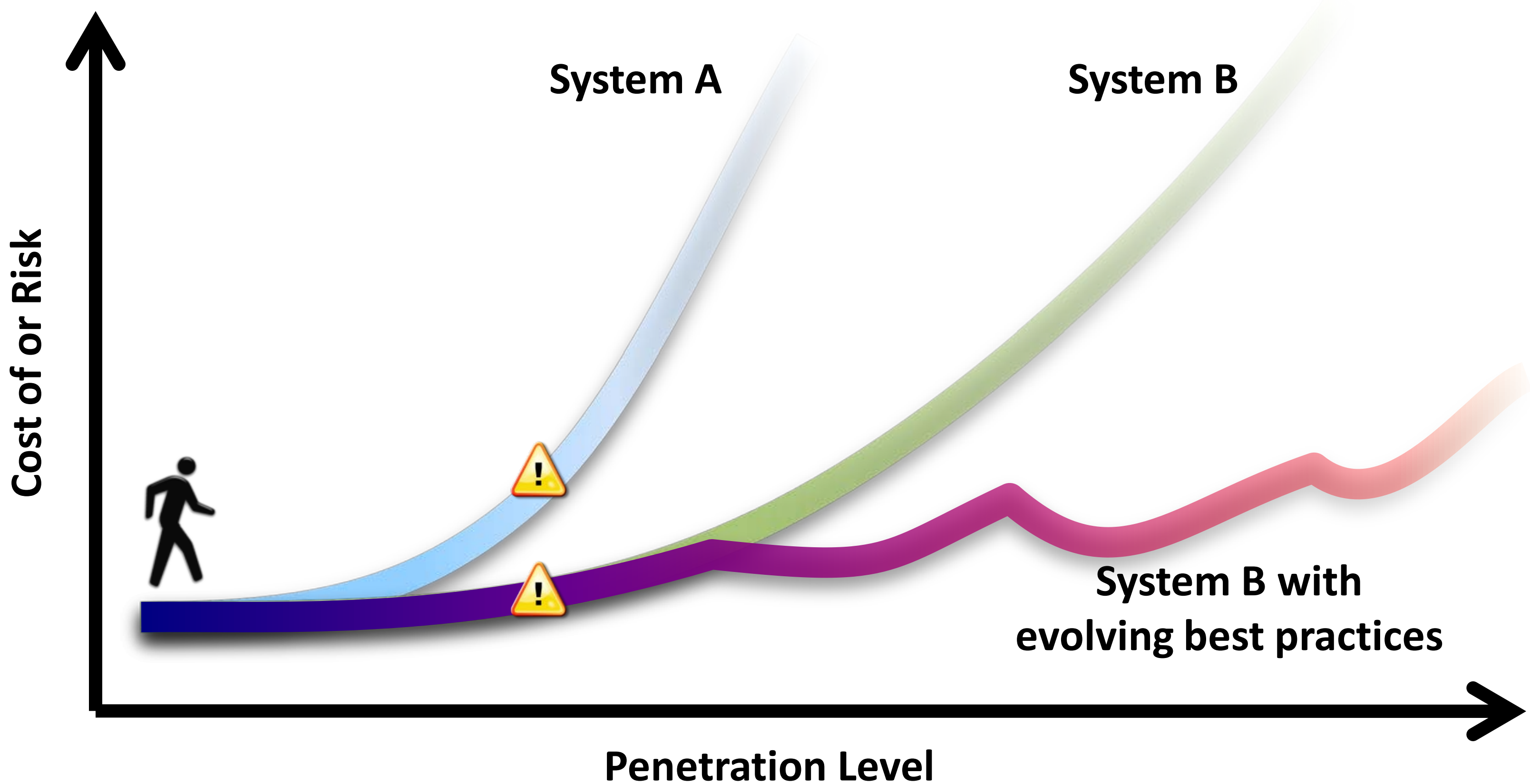
[1] e.g., SDGE, 2009 [2] e.g., CAISO, 2009 [3] Assumes 16% annual capacity factor

What is High PV 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…
  - There is a technical risk that system performance and reliability would be objectionable **and**
  - Cost of mitigation, allocation would be unreasonable

Are There Penetration Limits?

- There are no <u>absolute</u> technical limits
  – Cost and technical risk may increase

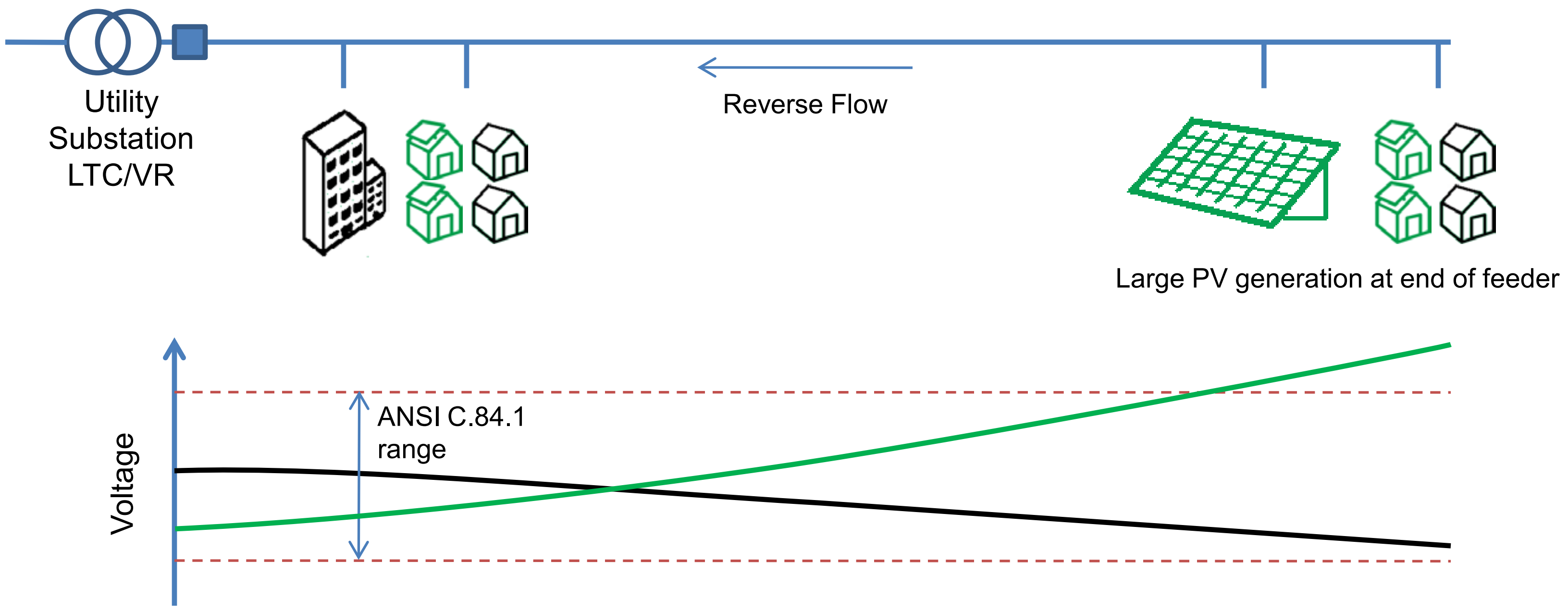


Distribution Operations Issues

- Possible impacts depend on factors including…
  - Feeder characteristics impedance
  - Penetration level, DG location on feeder
  - Type of voltage control and protection
  - Load characteristics
- Most common operations concerns include…
  - Customer voltage regulation, power quality
  - Excessive operation of voltage control equipment
  - Protection

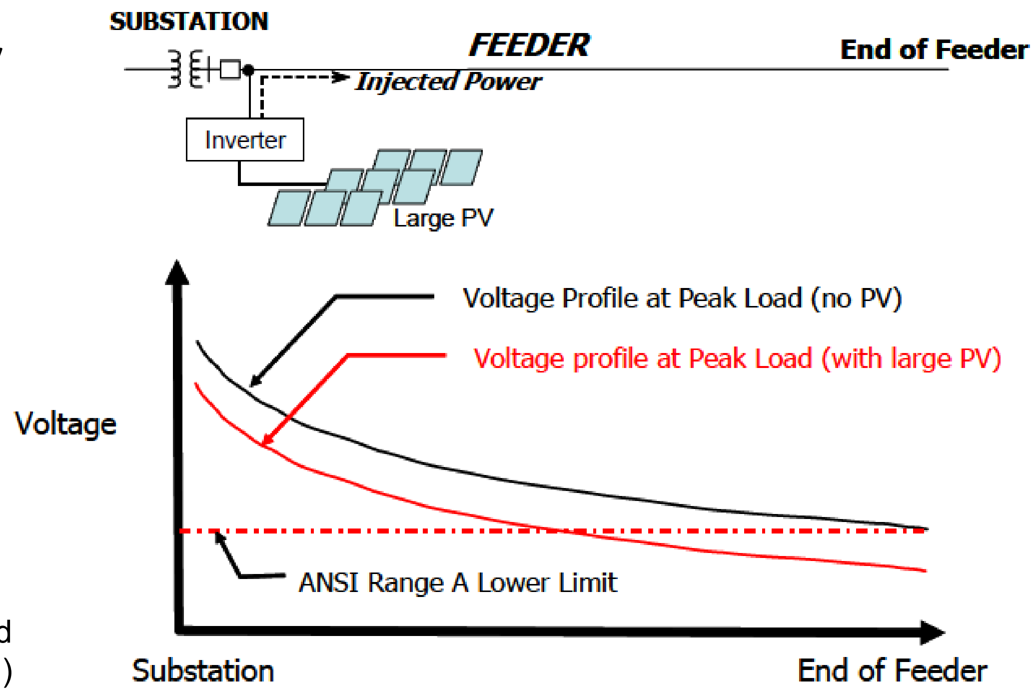
Voltage Control

- High voltage at end of feeder with high PV generation at the end of a long feeder
  - Operate PV generators at lower power factor
  - Adjust LTC/VR settings; adjust capacitor schedule



Voltage Control

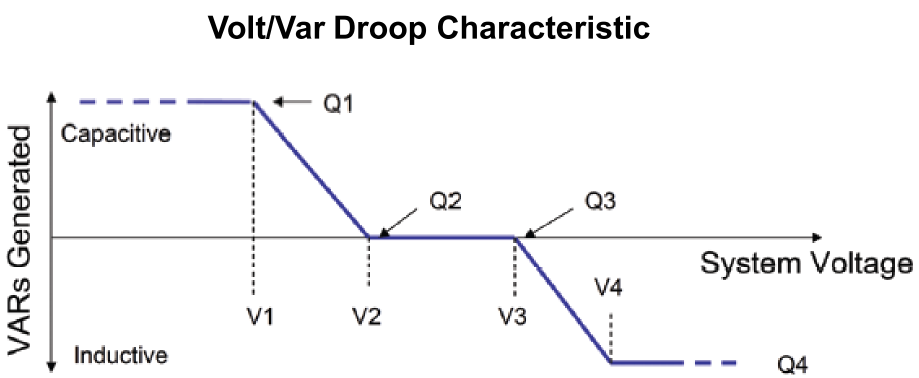
- Low voltage at end of long feeder due to large PV ahead of load
  - Account for PV injection in LTC/VR control logic
  - PV on dedicated feeder
  - Install VR ahead of PV



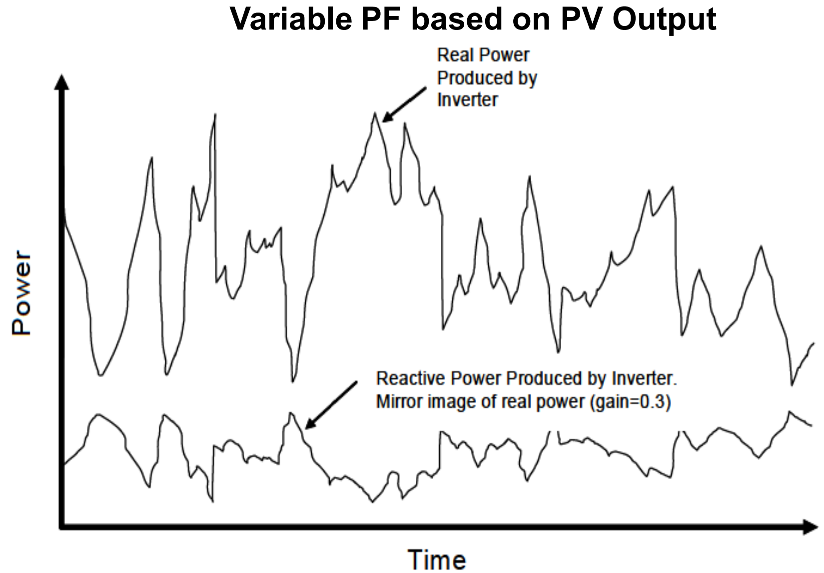
Source: DOE RSI study, “Advanced Grid Planning and Operations” (EPRI)

Voltage Control

- Excessive LTC/VR tap activity or flicker due to PV variability (centralized PV, long feeder)
  - Review and adjust VR/LTC settings (dead band, timer)
  - Enable PV inverters to provide dynamic var support, passively or actively



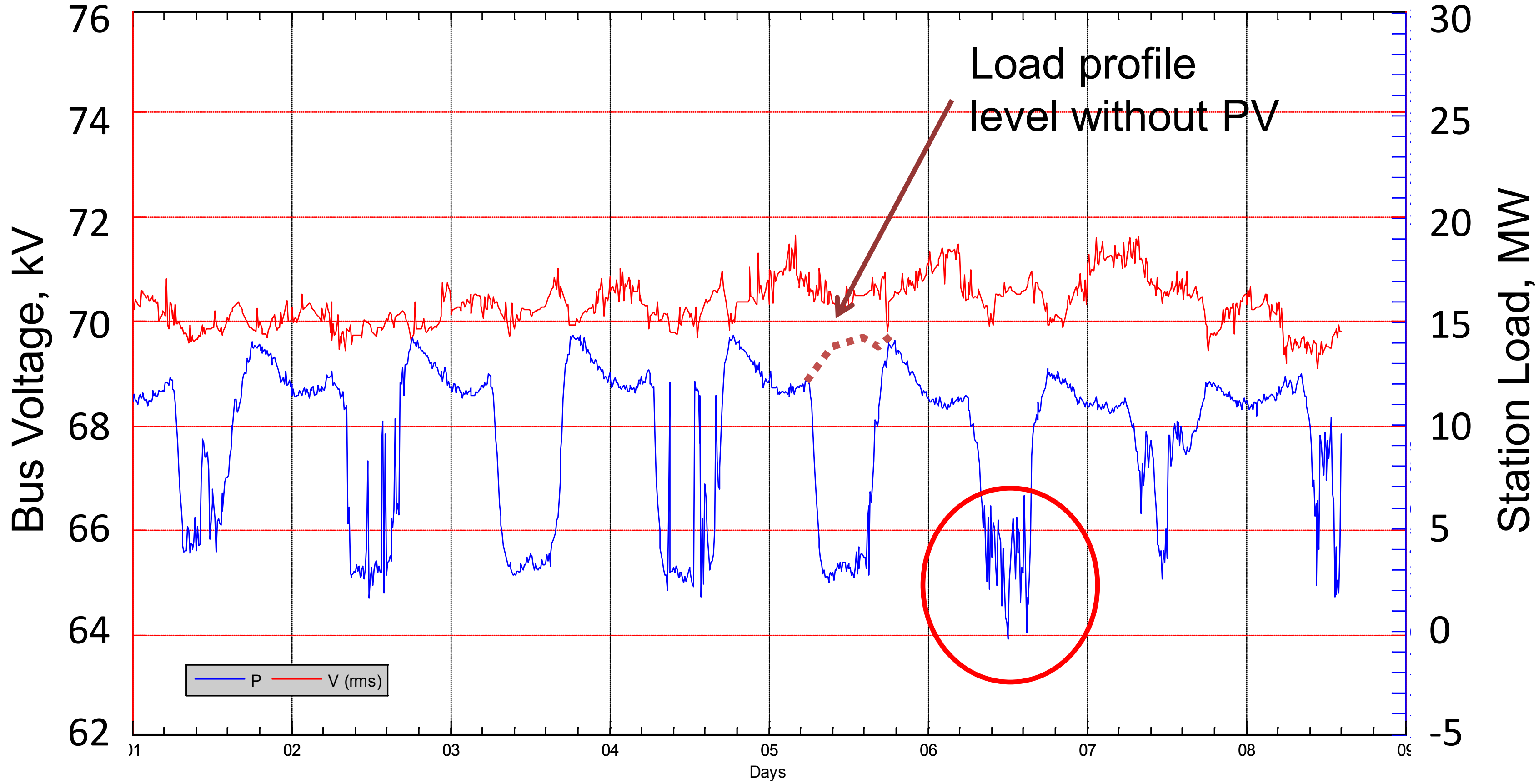
Source: EPRI/Sandia Inverter Interoperability Project



DOE RSI study, "Advanced Grid Planning and Operations"

Voltage Control

- Voltage issues are much less problematic in short urban feeders, even at very high penetration!

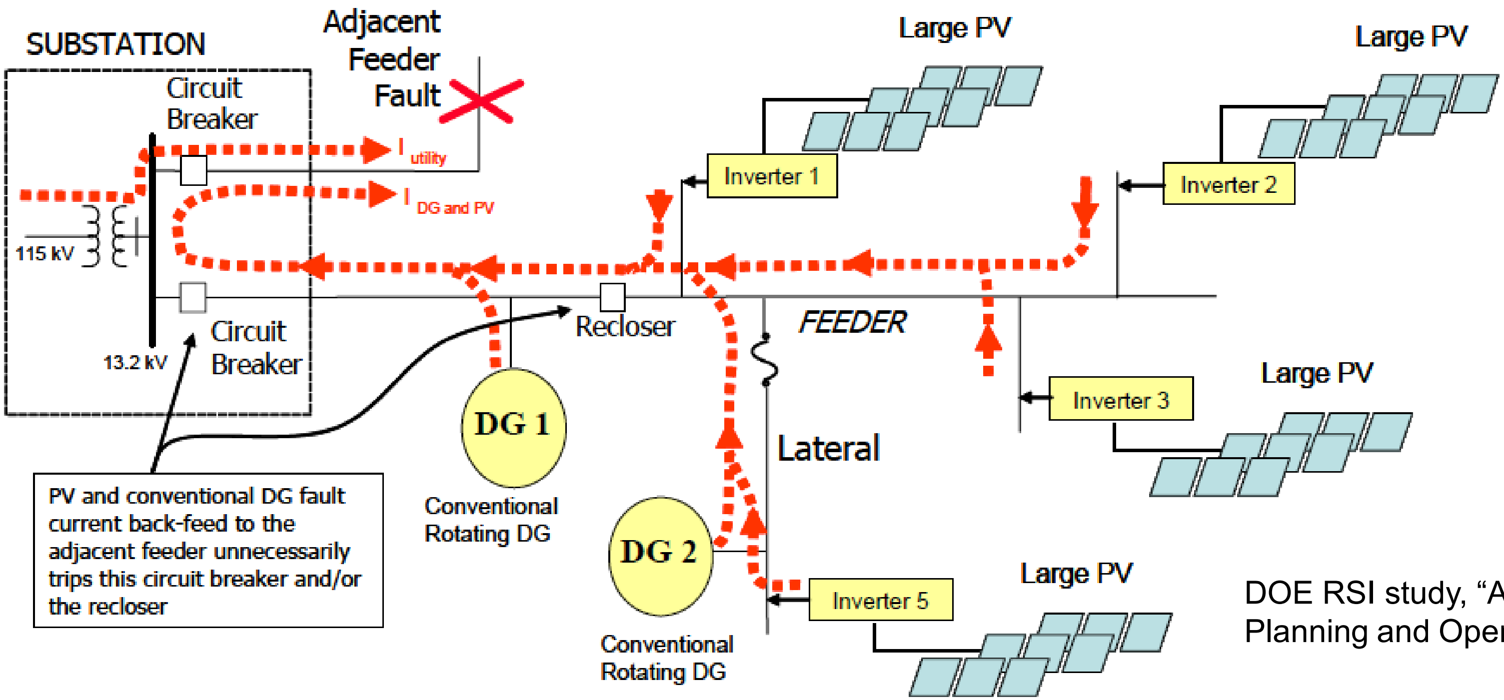


Other Distribution Operations Issues

- Other power quality
- Protection and islanding
  - Relay desensitization, nuisance tripping
    - Reduction in fault current from utility source, reverse flow
  - Risk of islanding
    - Customer exposure to high voltages (ferro-resonance)
    - Recloser coordination
- Management and control
  - Visibility and controllability of distributed PV
  - Interoperability, Cyber-security

Nuisance Tripping

- Inverter fault contribution is relatively small, but could cause unnecessary relay operation
  - Review reverse current protection scheme



DOE RSI study, "Advanced Grid Planning and Operations"

DG Connection Standards

- IEEE 1547 Voltage and Frequency Tolerance

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

- Additional disconnection requirements
  - Cease to energize for faults on the Area EPS circuit
  - Cease to energize prior to circuit reclosure
  - Detect island condition and cease to energize within 2 seconds of the formation of an island (“anti-islanding”)

DG Connection Standards

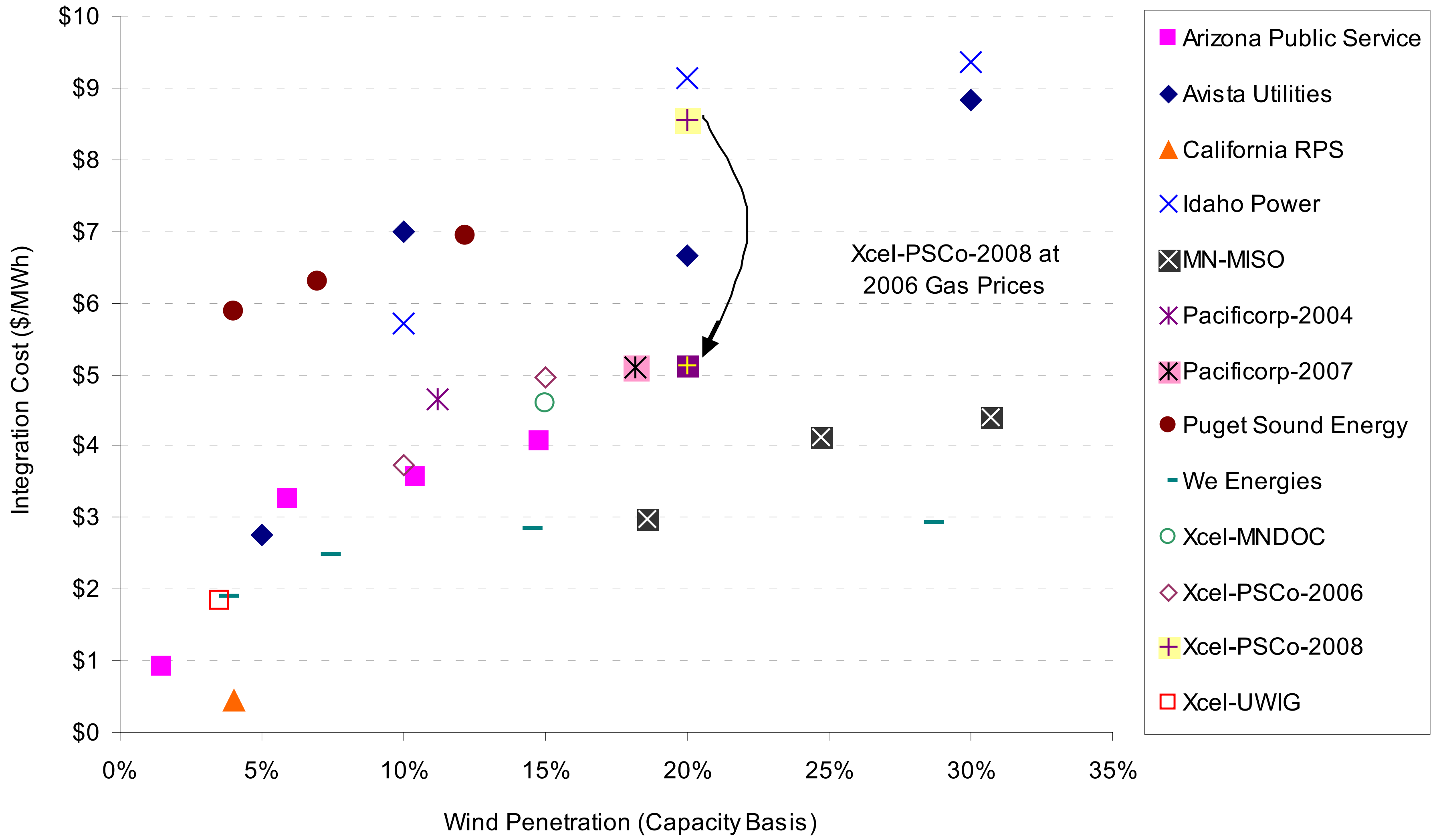
- Other applicable codes and standards

	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

Impact on Bulk System Operations

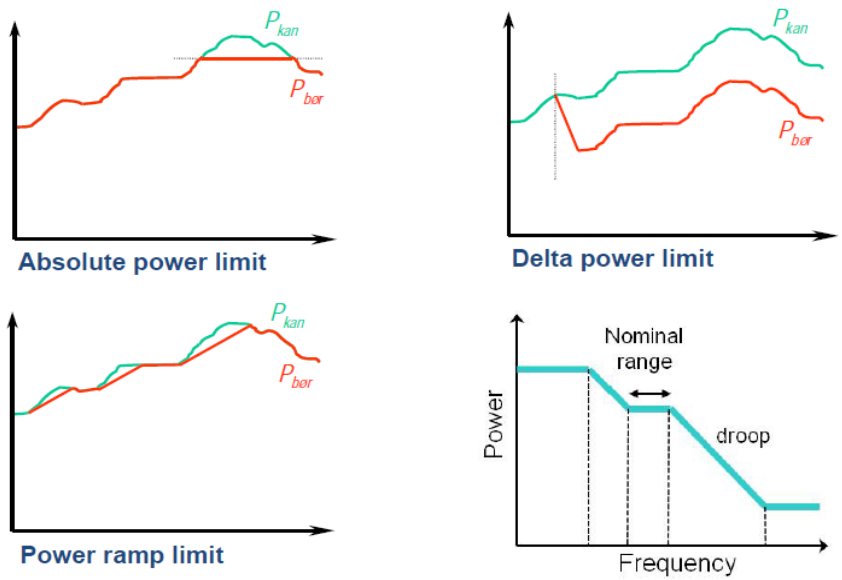
- Impacts depend on factors such as…
  - Penetration level
  - <u>Aggregated</u> output characteristics (short-term, daily, seasonal variability)
  - System characteristics (size, maneuverability of generation resources, market flexibility)
- Most common operations concerns include…
  - Increase in cost (regulation, ramping, scheduling, UC)
  - Degradation of Balancing Area performance
  - Wear-and-tear on regulating units

Increase in Operating Cost



Possible Increase in Operating Cost

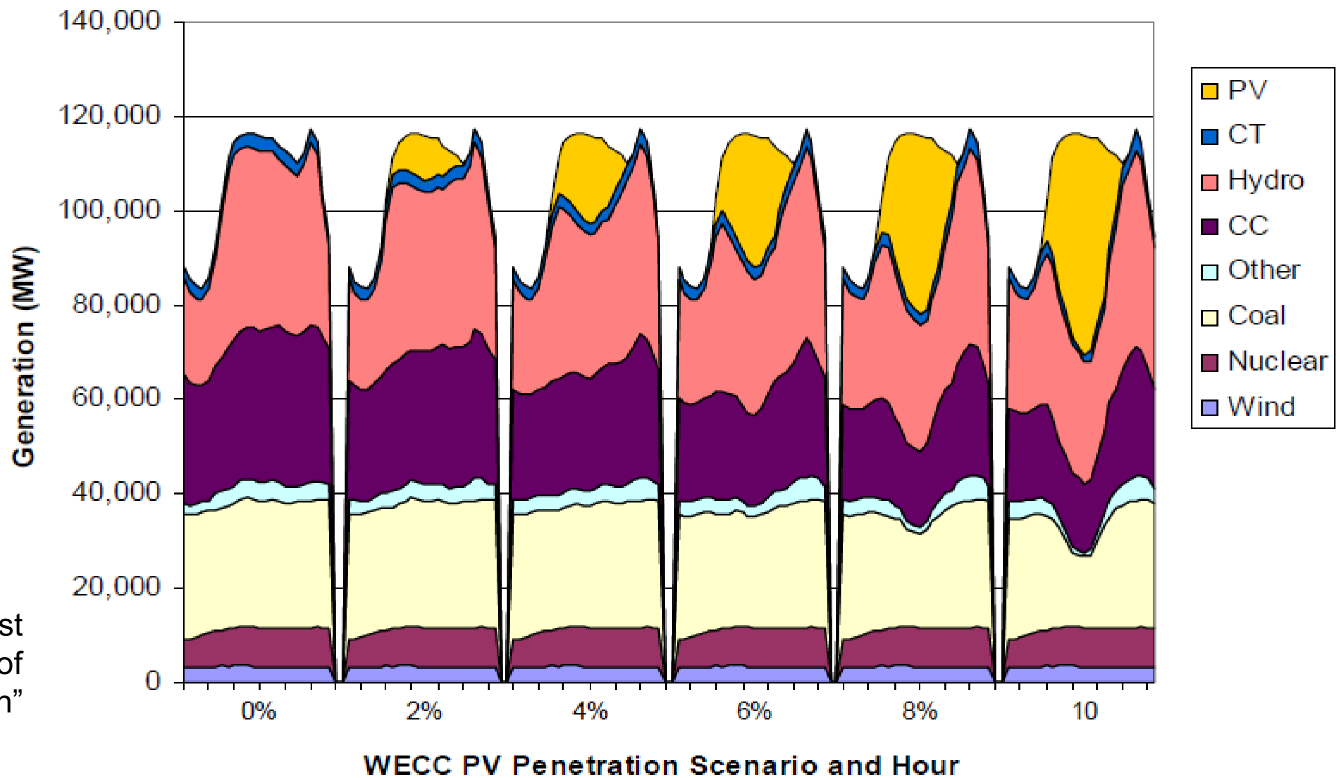
- There are many effective strategies to mitigate additional variability; some
  - Larger BA footprint, better cooperation among BAs
  - Access to formal and flexible markets
  - Application of forecasting
  - Active power controls
  - Plan for flexibility
  - Energy storage
  - …



Source: Energinet.dk

Possible Increase in Operating Cost

- System with high penetration PV looks different
  - Daytime output makes issues less problematic
  - Generation flexibility is key for High Penetration



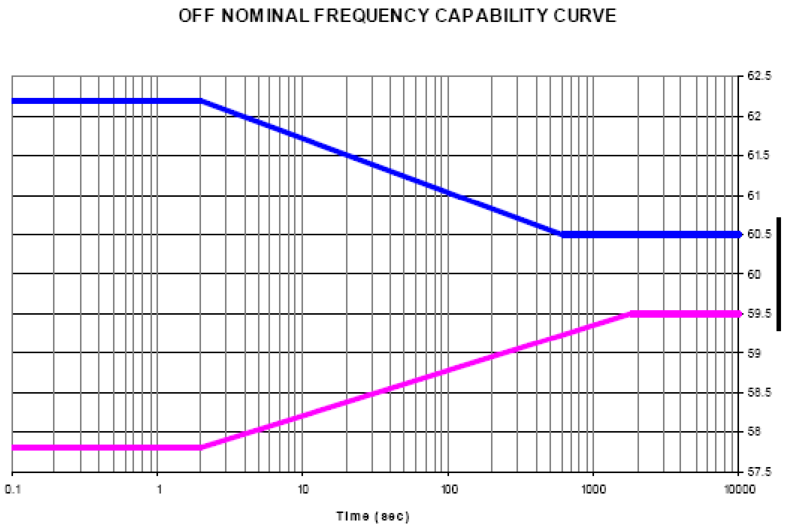
DOE RSI study, “Production Cost Modeling with High Levels of Photovoltaics Penetration”

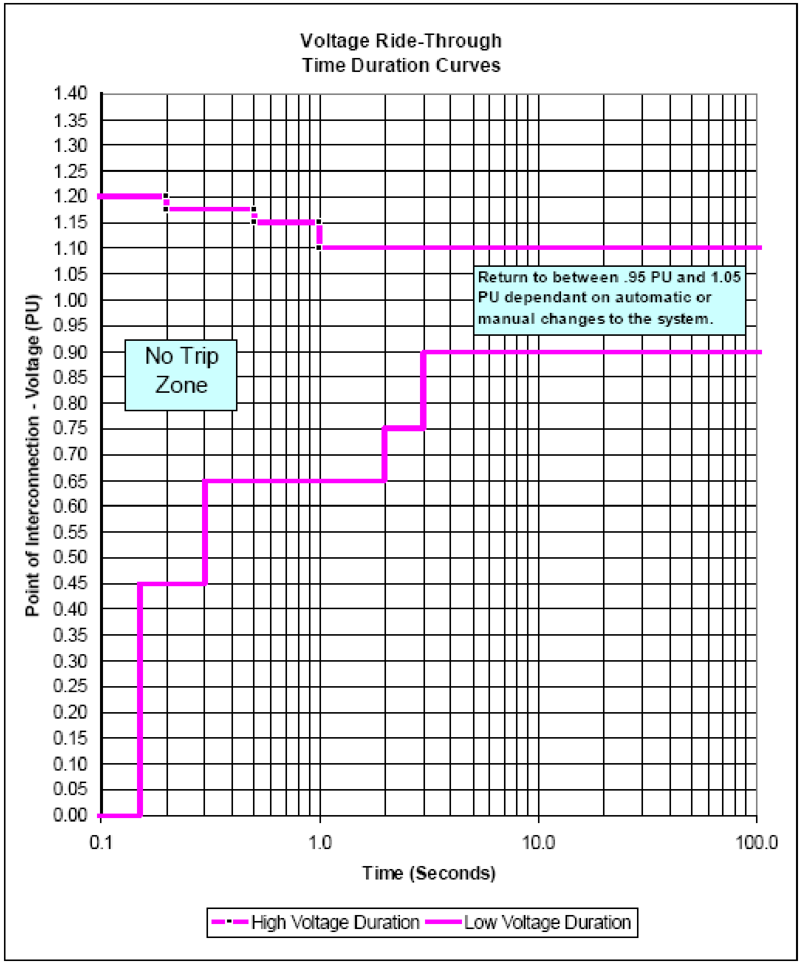
Other Bulk System Operation Issues

- Sympathetic tripping of PV generation due to transmission disturbances
  - Voltage and frequency tolerance standards
- Voltage stability (locally)
  - Reactive power standards
- Frequency performance due to displacement of inertia (with very high penetration of inverters)
  - Active power controls—market-based incentives?
  - Synthetic inertia

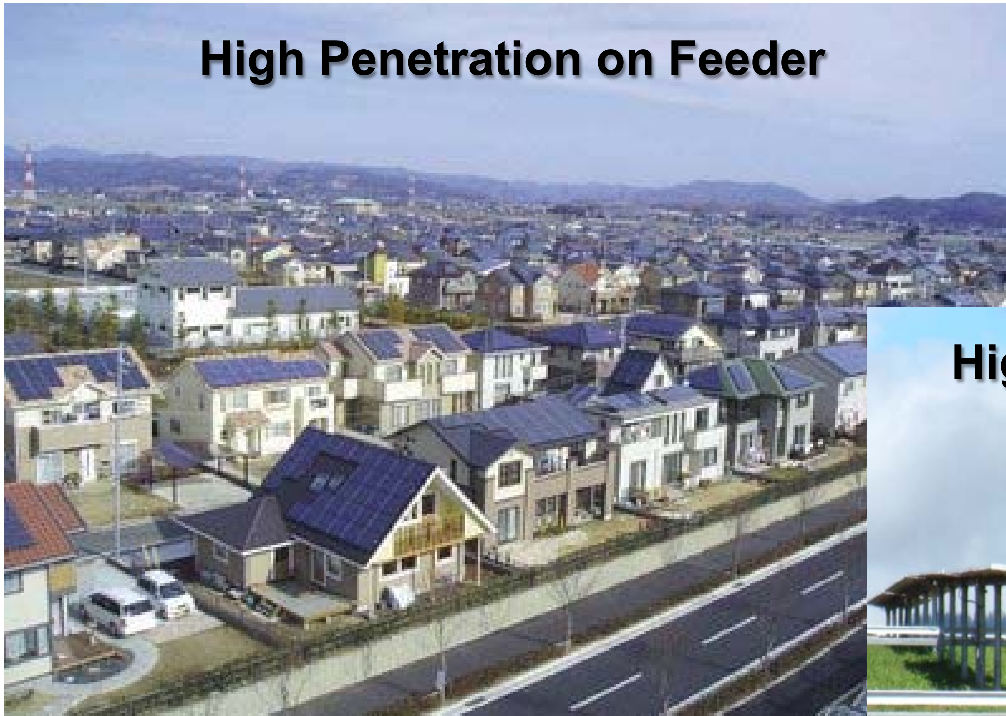
Sympathetic PV Generation Tripping

- Voltage and Fre2quency ride-through standards
  - Proposed NERC PRC-024
  - Technology-neutral (applies to all generators)
  - What about DG?





Examples of Very High PV Penetration

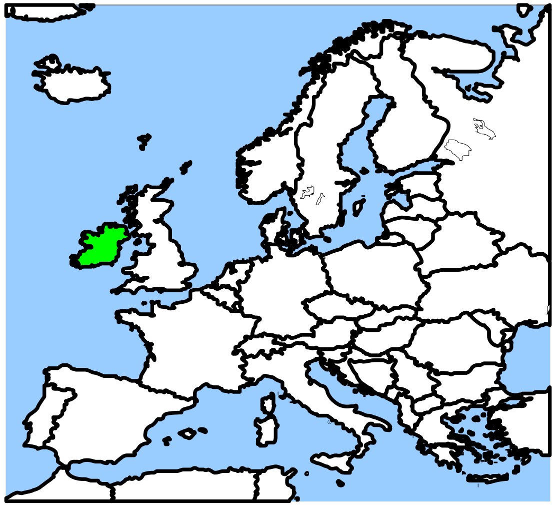


Ota City, Japan: 2 MW PV on single feeder (553 homes, 3.85 kW average PV system)

Lanai , Hawaii: 1.2 MW PV system on 4.5 MW island grid supplied by old diesel generators

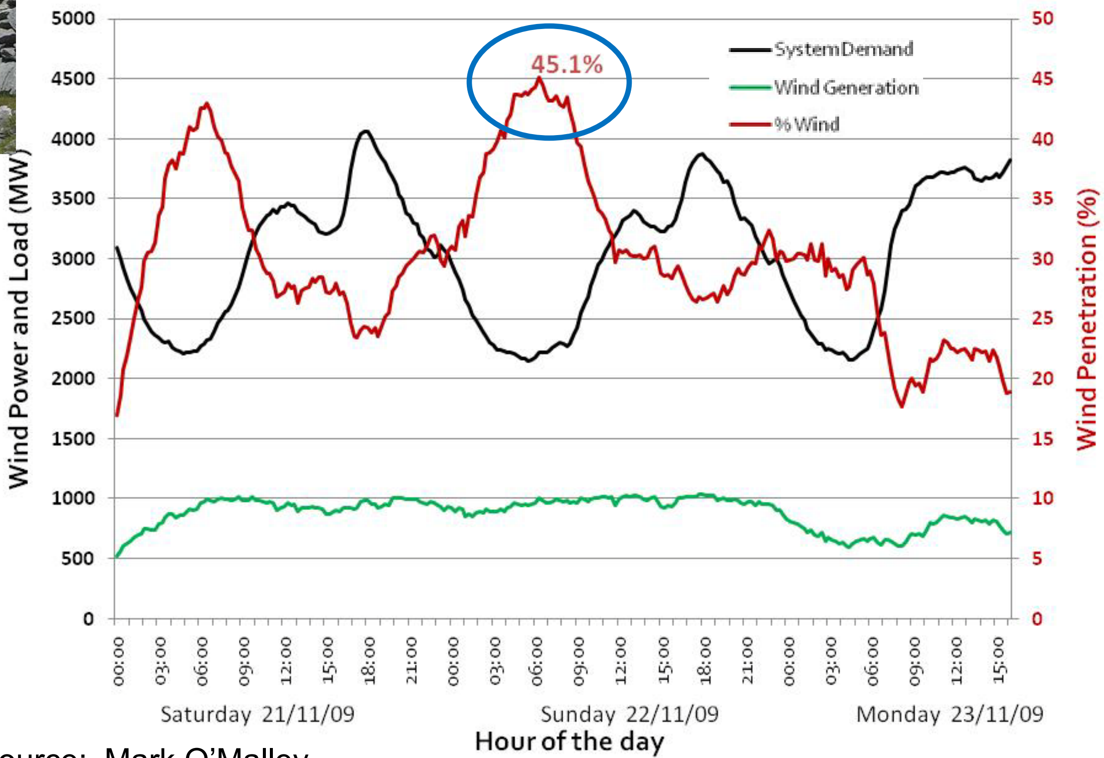
Examples of Very High Penetration

Ireland: >1 GW wind capacity in 7 GW peak load island system



Penetration level by energy approaching 15%

Instantaneous penetration level reaches 50%



Source: Mark O'Malley

Conclusions

- Penetration Levels
  - Different definitions for different purposes
- There are no absolute "penetration limits"
  - Issues boil down to cost and risk
- Technical and process challenges are real
  - Embracing best practices and change is the key
  - Technology and standards need to evolve constructively
  - Procedures and policies should keep up!