Short Course

Renewable Energy Integration

Introduction to Power Systems

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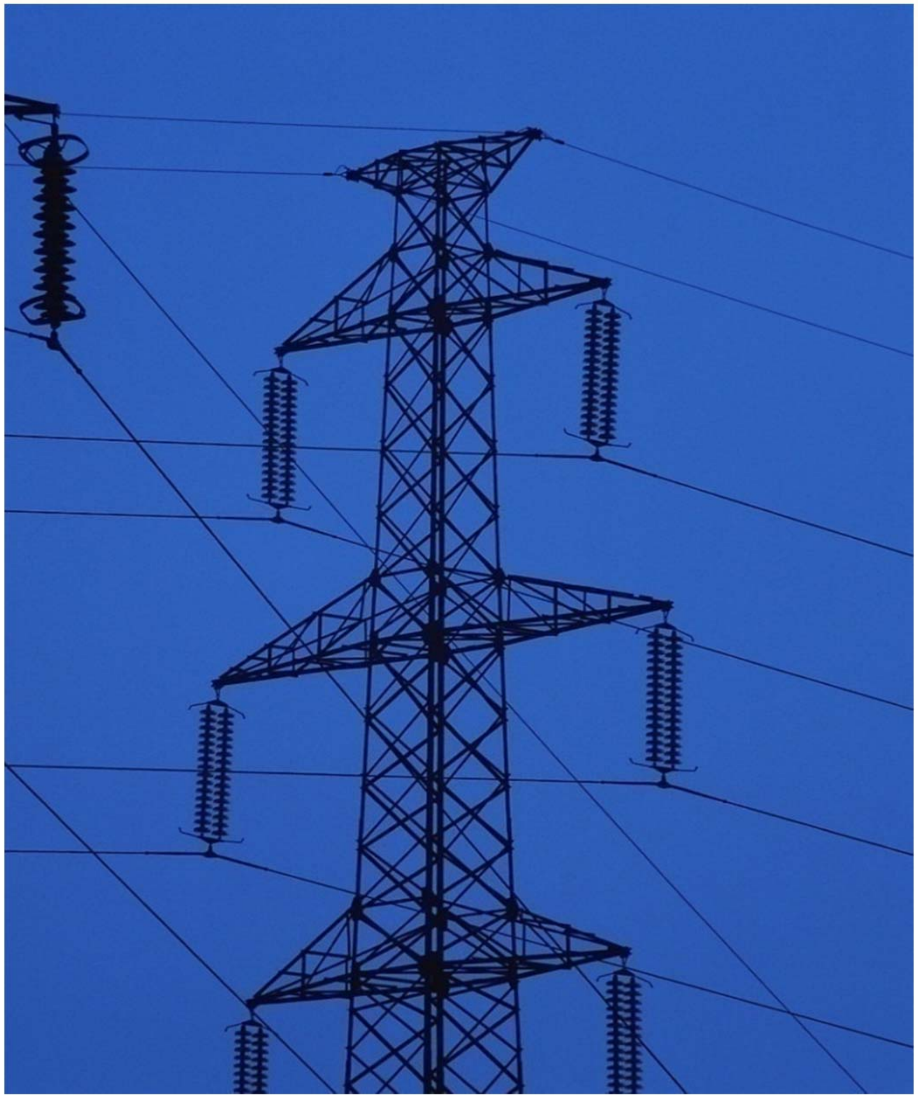
Topics



1. Power System Structure and Components
2. Power System Operations
3. Power System Planning
4. Variable Generation
5. High Penetration
6. Technical Issues

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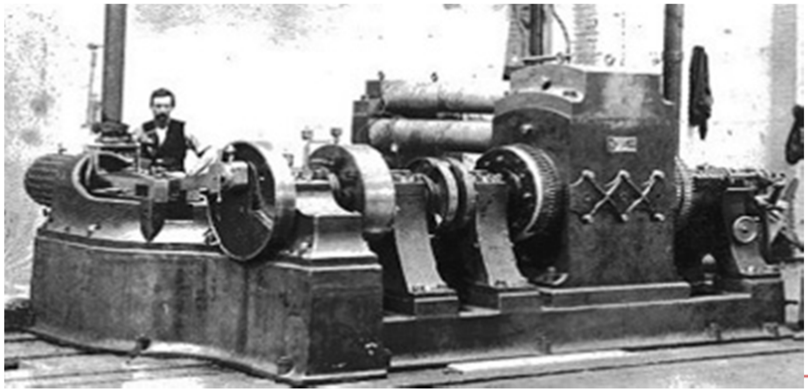
The Early Days

- 1882 – First power system Pearl Station, NY (Edison)
- 1884 – Introduction of AC transformer (Westinghouse)
- 1890's – Edison Vs Westinghouse: AC wins over DC
  - Ability to increase and decrease voltages
  - Simpler, lower cost motors and generators
- Frequency and voltage levels standardized
- 1950's HVDC became feasible (mercury arc valves)
- Few game changes since
  - Computers
  - Communications
  - Power Electronics
  - Distributed generation
  - Smart Grid?



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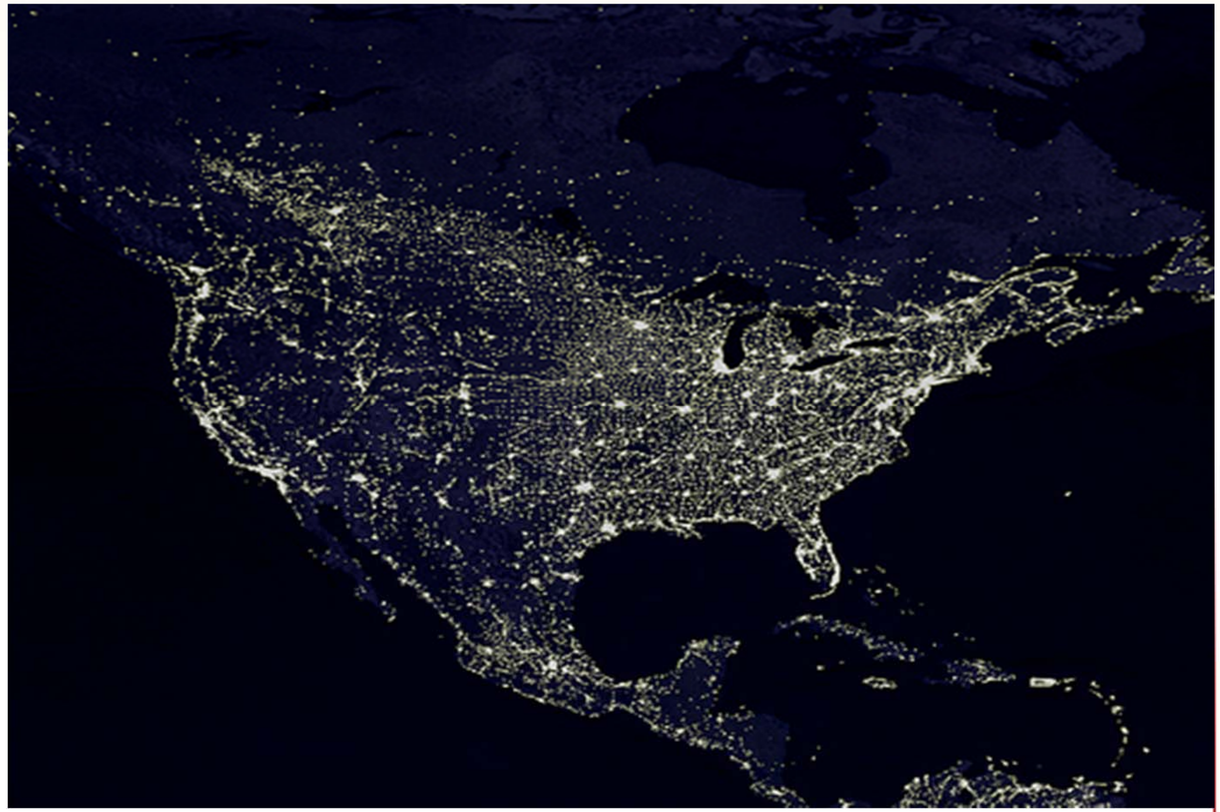
The Power System

- Extremely complex
  - **Physical**
  - **Market**
  - **Policy/Regulatory**
- Highly reliable
  - **Resilient to failure**
  - **1 day in 10 years or 99.97% reliability**
- Very expensive
- Critical Infrastructure



The North America Power System has 15,000 generators and hundreds of thousands of miles of transmission and distribution lines

A $4 Trillion infrastructure!

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Basic Concepts

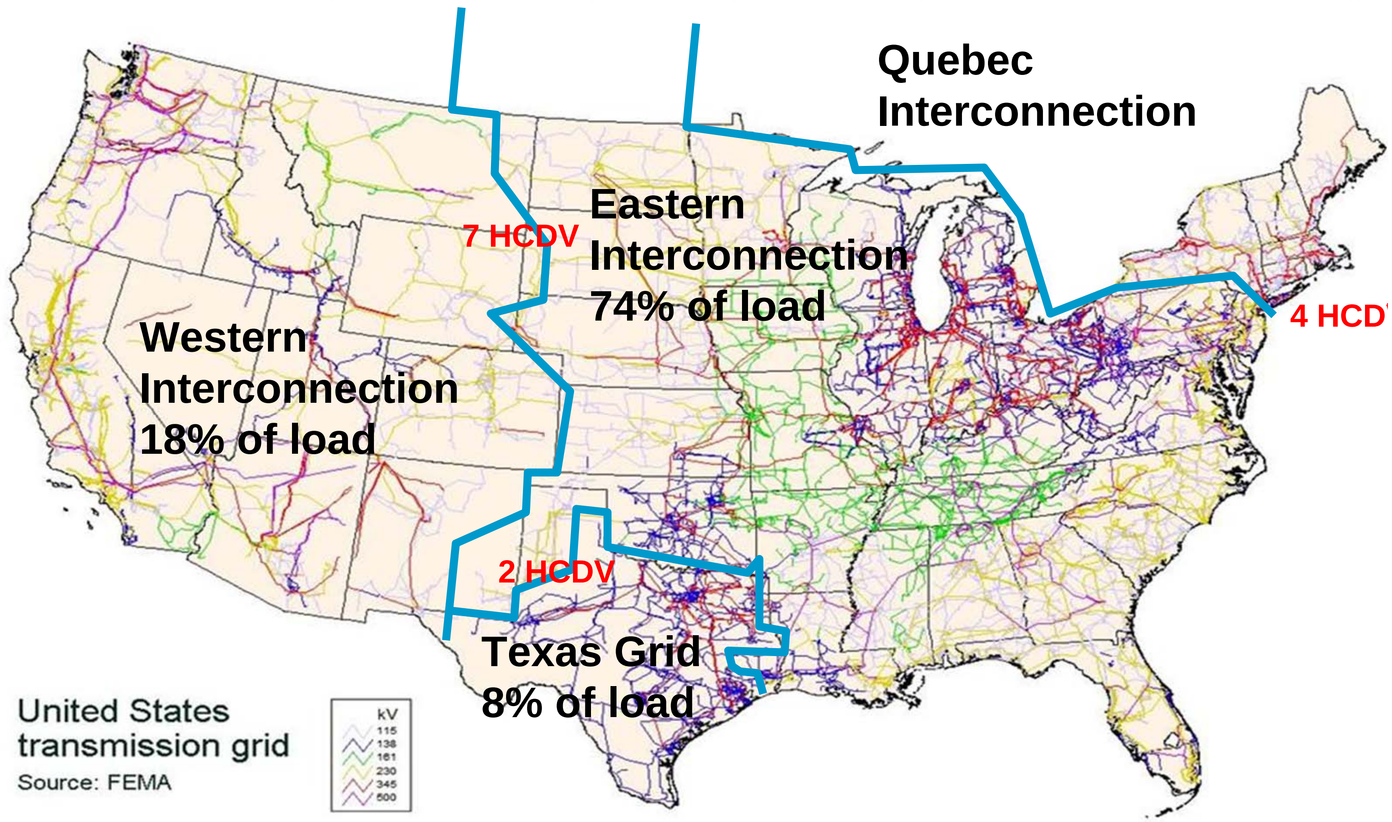
- Voltage and Current
  - Voltage [V] is equivalent to pressure
    - Excessive pressure, house could fail (“leak”)
    - Excessive voltage, insulators could fail (“fault”)
  - Current [A] is equivalent to flow
    - High flow heats the hose (friction)
    - High current heats the wires (resistance)

Water hose analogy

- Power and Energy
  - Power [W] is equivalent to pressure x flow
    - How much electricity is used at any one time
  - Energy [W-hr] is equivalent to pressure x flow x time
    - Total amount of electricity used over some time

Power System Structure

Contiguous 48 States



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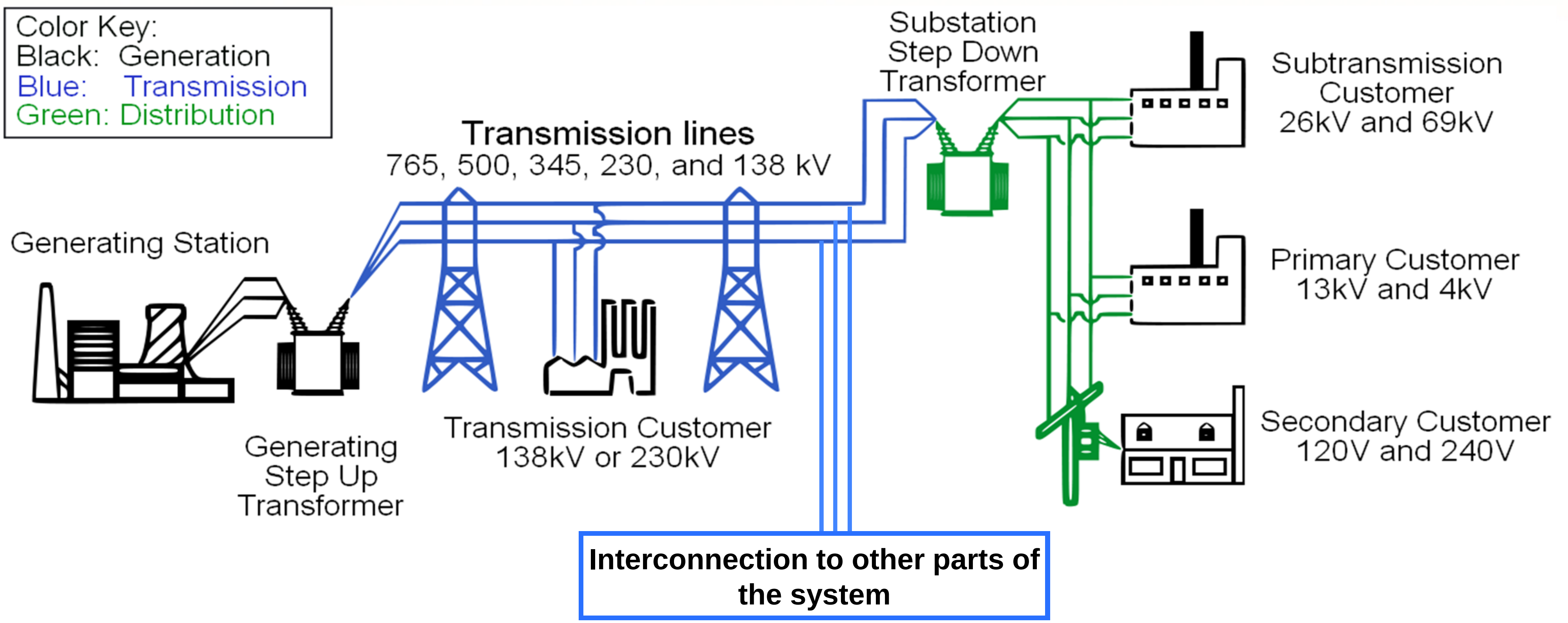
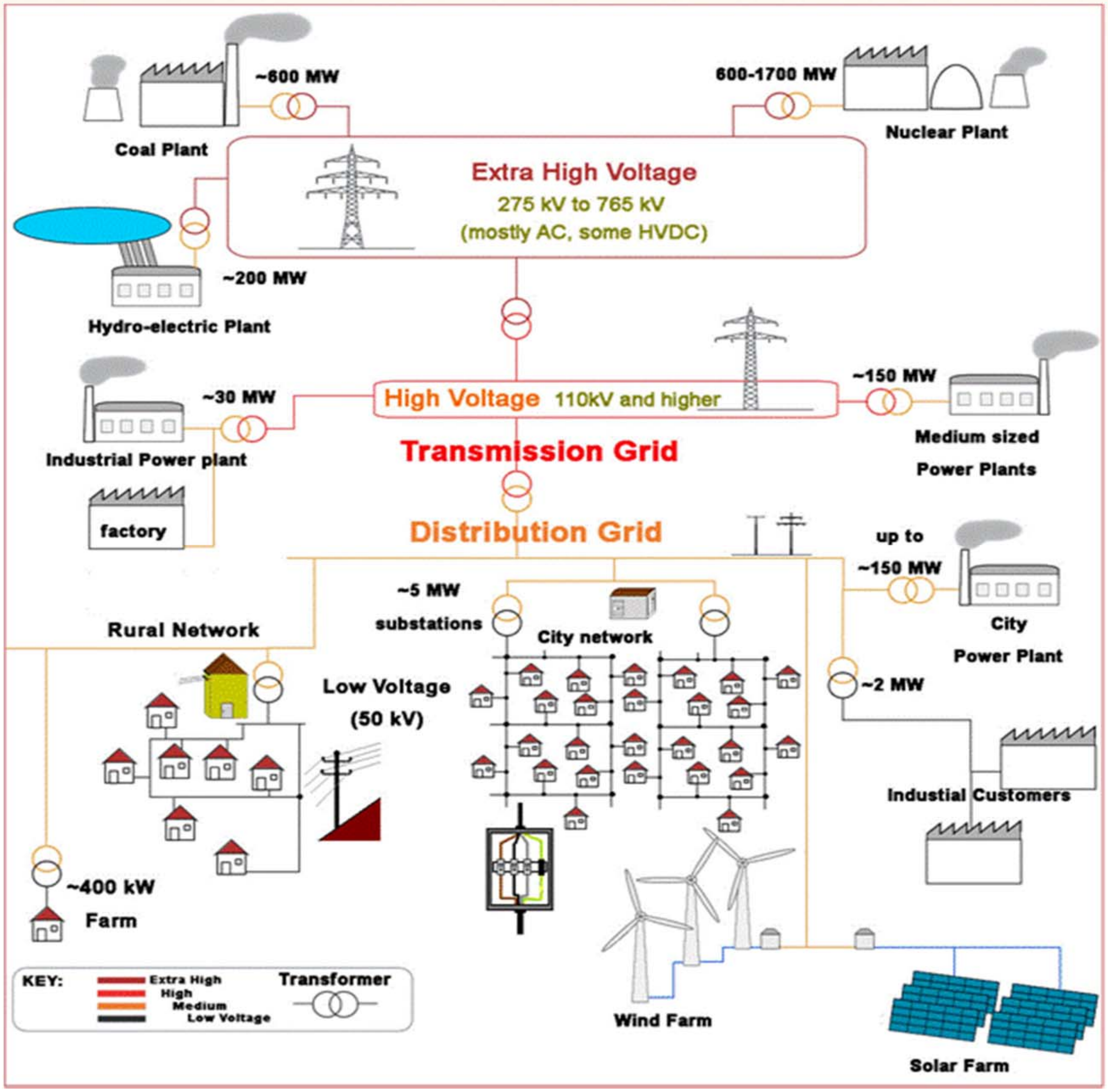
Power System Structure



Power System Structure



- Bulk system
  - Transmission lines and other transmission assets
  - Large generators
- Distribution system
  - Distribution lines and other distribution assets
  - Distributed Generation (DG) and other Distributed Energy Resources (DER)

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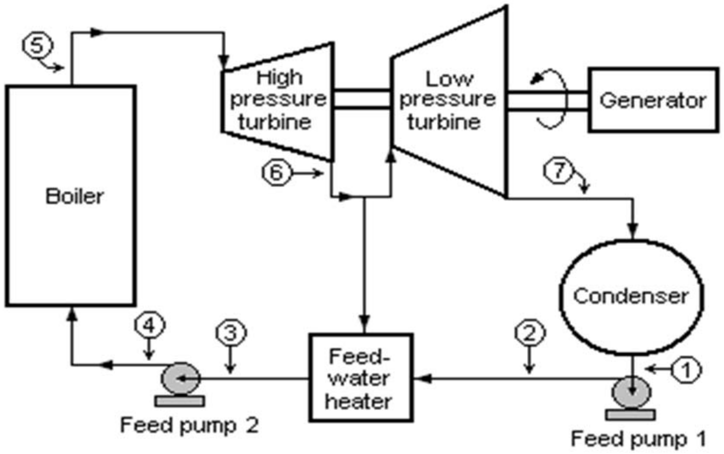
Power System Components

- Thermal Power Plants
  - Hot gas (steam or air) spins a turbine
  - Turbine powers a generator
  - Generator produces electricity

Siemens Steam Turbine
Photo: Christian Kuhna, Siemens Germany

Mohave 1,580 MW coal-fired power Plant near Laughlin, Nevada (out of service since 2005). Photo is in the Public Domain (GFDL)



Power System Components

- **Other types of power plants**

Solar-thermal Generation at Sandia's NSTTF

Three Gorges Hydroelectric Plant, China. Photo: Christoph Filnkößl (GFDL)

Geothermal Power Plant in Iceland. Photo: Gretar Ívarsson (GFDL)

Green Mountain Energy Wind Farm, TX. Photo: Leaflet (GFDL)

Nellis AFB PV Plant, NV. Photo: Nadine Y. Barclay (GFDL)

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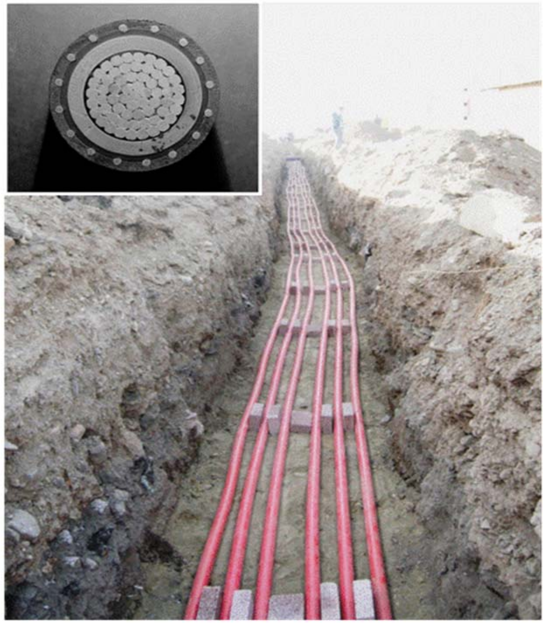
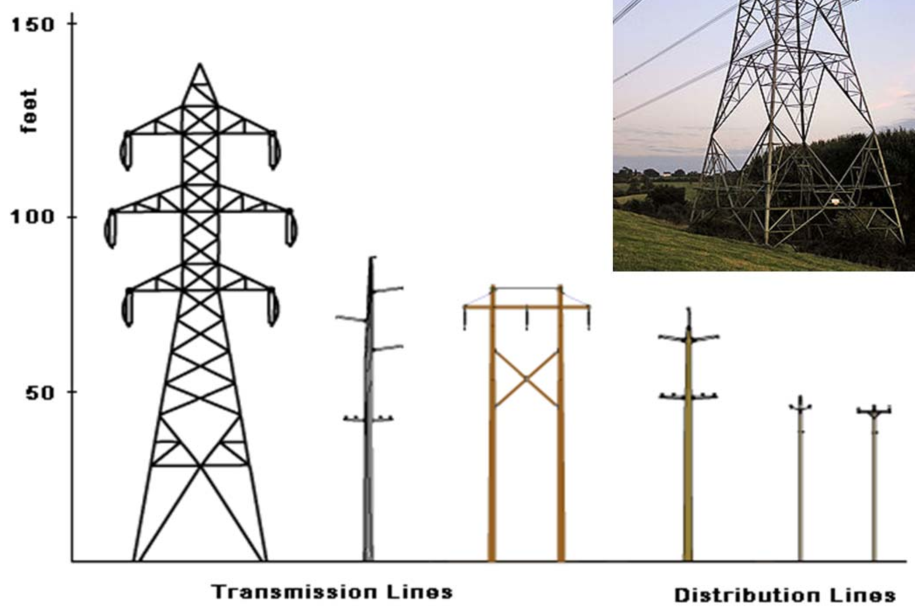
Power System Components

- **Transmission and Distribution Lines**
  - **Transmission, Sub-transmission, Distribution**
    - **500 kV, 345 kV, 138 kV, 115 kV**
    - **69 kV, 46 kV**
    - **4.16 kV, 12.47 kV, 24 kV**
  - **Overhead or Underground**





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Power System Components

- Other Power Components
  - Transformers
    - Steps voltage to another class
  - Capacitors and reactors
    - Help adjust voltage up or down
  - Breakers and switches
    - Connect/disconnect elements
  - Protection Equipment
  - Communications and Measurement
    - System Control and Data Acquisition (SCADA)

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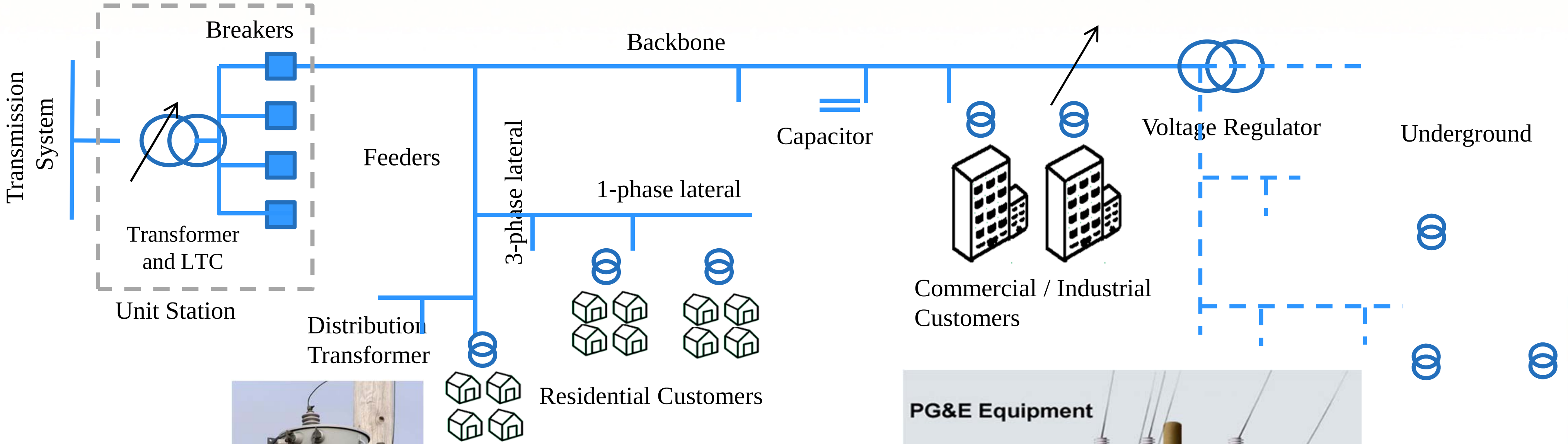
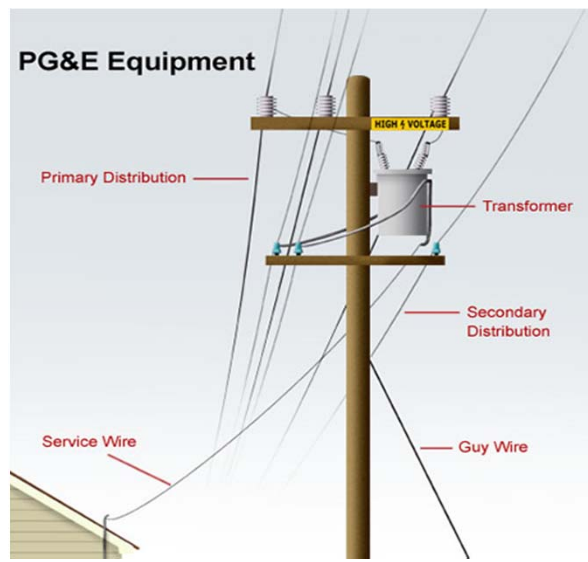
Power System Components

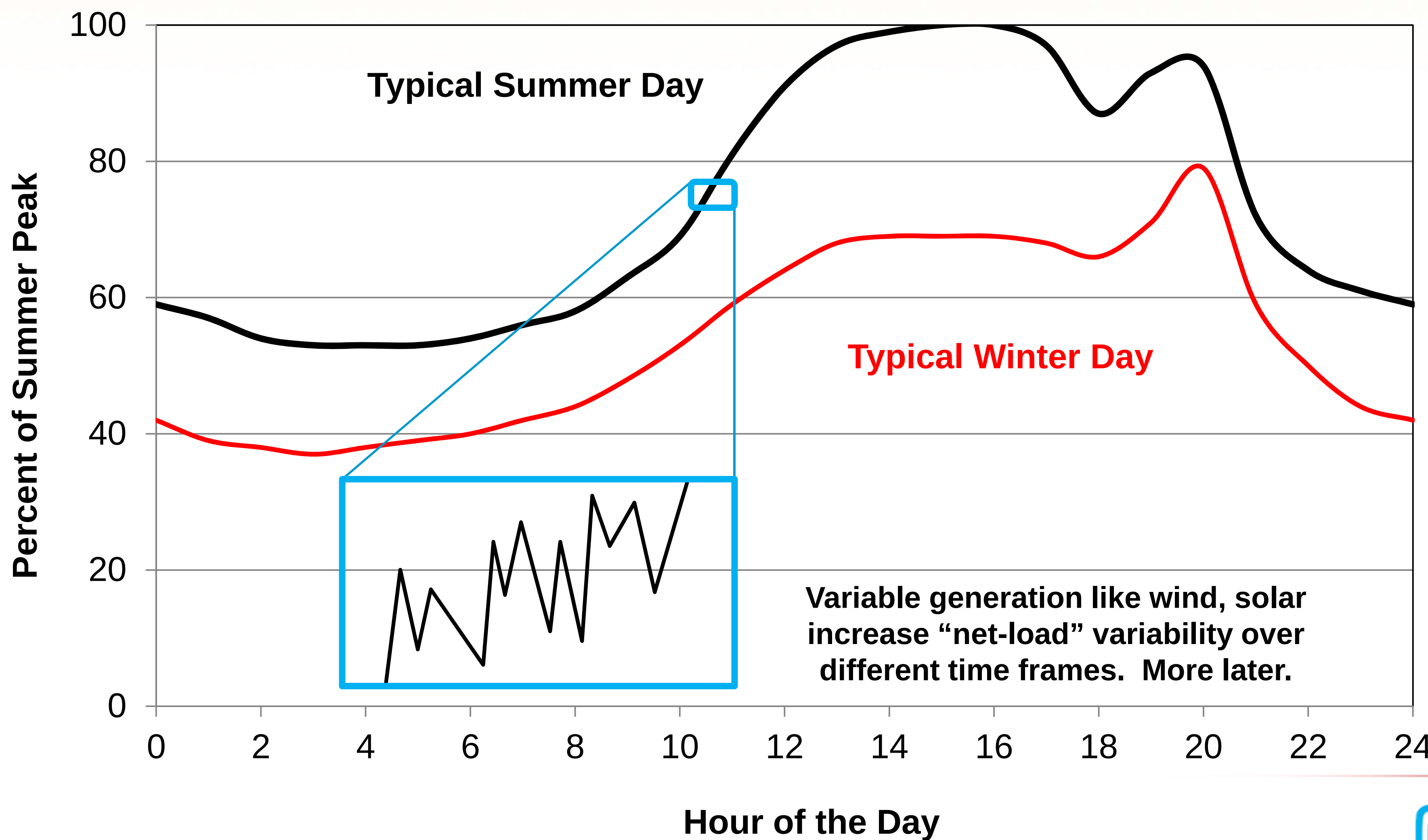
- **Distribution System Structure and Components**



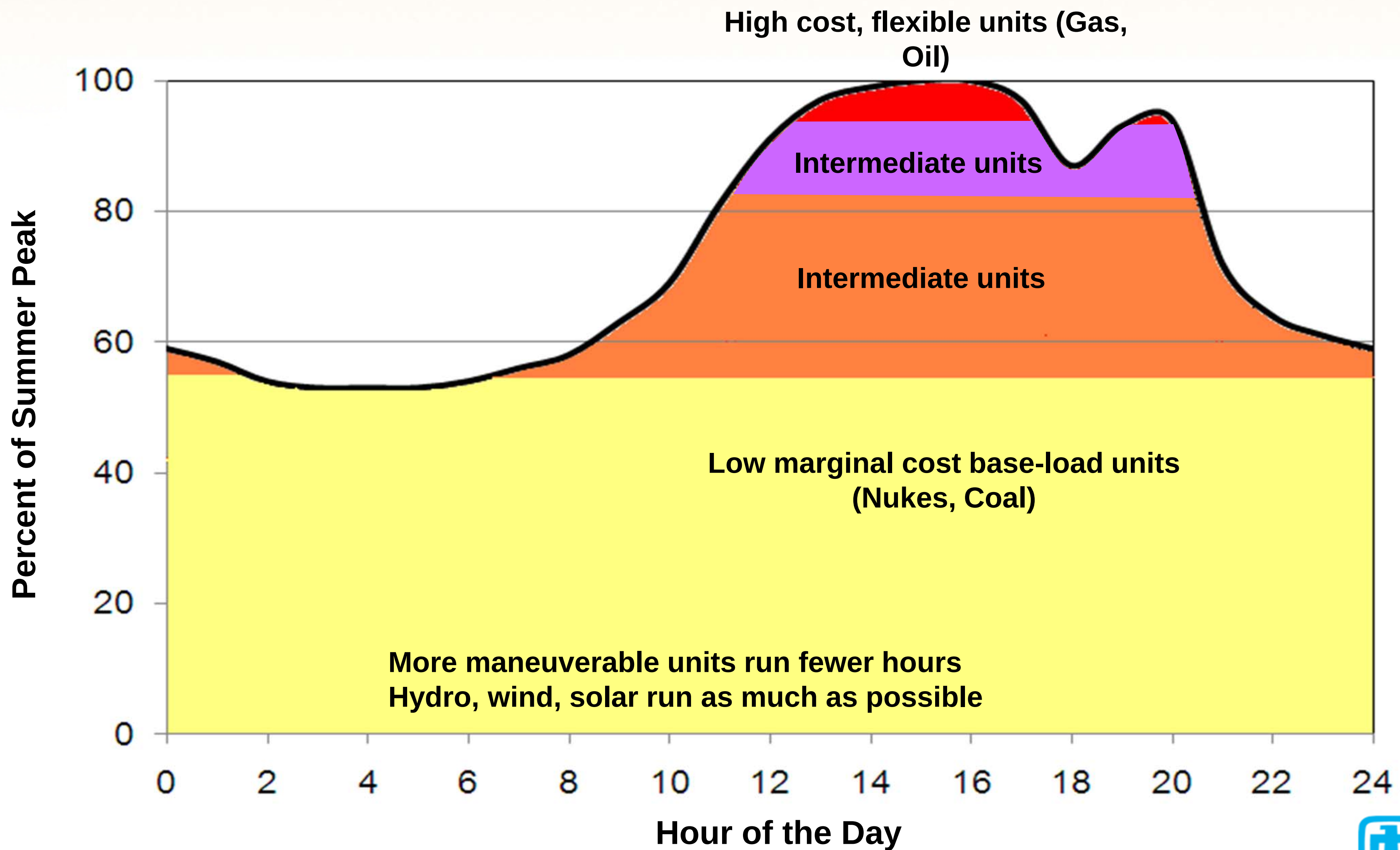


From PG&E FAQ (http://www.pge.com/mybusiness/customerservice/otherrequests/treetrimming/customerresources/faq/index.shtml)

Maintaining Generation – Load Balance



Maintaining Generation – Load Balance



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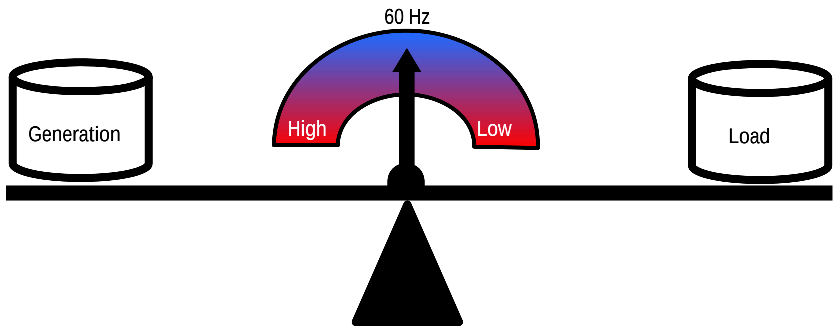
Power System Operations

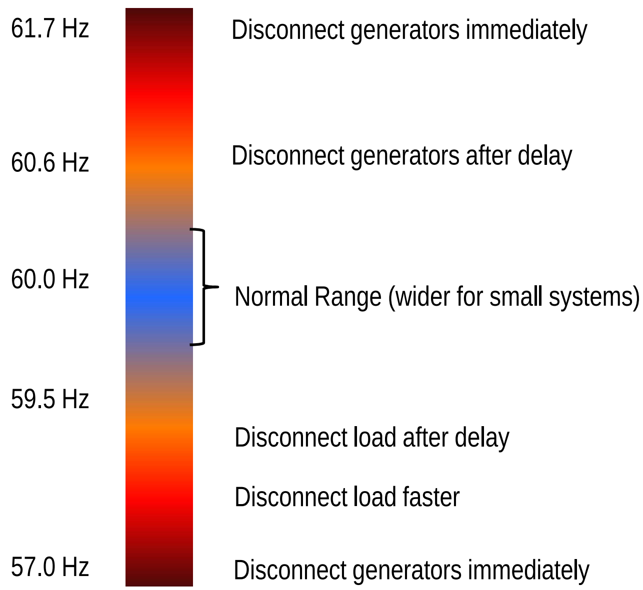
- Work with available/accessible system assets
- Operate within physical limits
  - Maintain voltage and current within equipment specifications
  - Balance overall load and generation to maintain system frequency



- Optimize operating cost subject to many constraints
  - System security (able to withstand a credible contingency)
  - Contracts, regulations, market rules

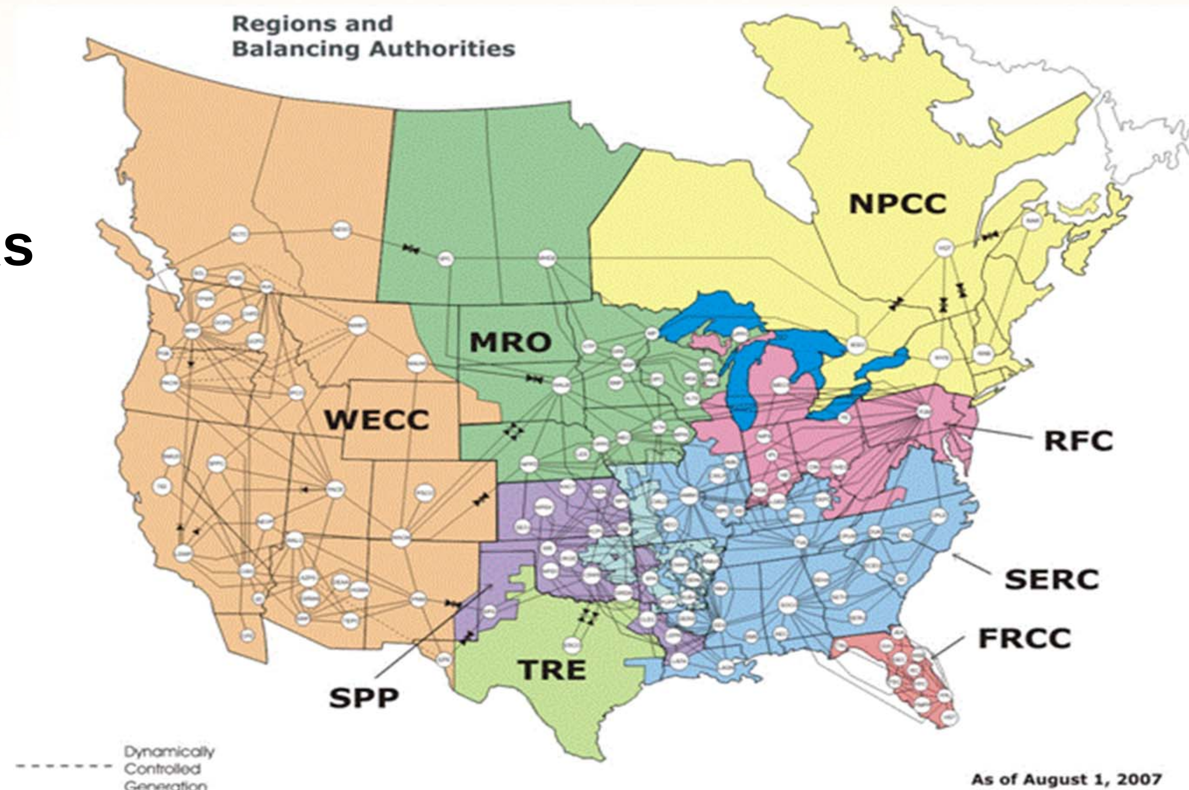
Maintaining Generation – Load Balance

- **Frequency tolerance**
  - **Normal <u>sustained</u> frequency should be within ~1% of nominal (60 Hz)**
  - **Manual and automatic controls**
    - **Generator response (inertia, AGC)**
    - **Protection schemes (e.g., load shedding)**



Maintaining Generation – Load Balance

- BA functions
  - Maintain desired level of interchange with other BAs
  - Balance demand (load) & supply (generation)
  - Support interconnection frequency
- Larger BAs are generally more efficient
  - More generation flexibility
  - BA consolidation being explored in some areas



Source: NERC

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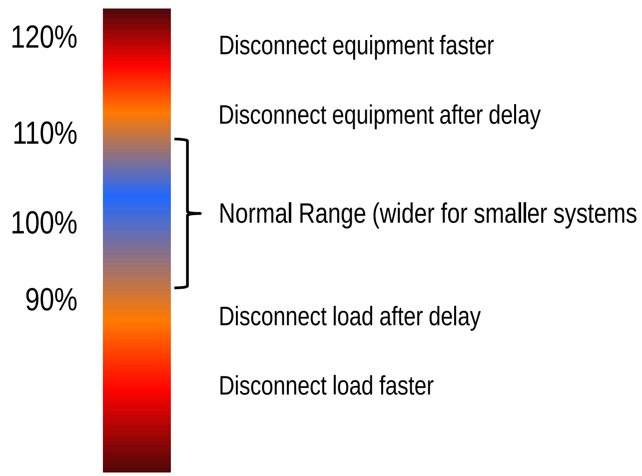
Maintaining System Voltage

- Voltage tolerance
  - Normal sustained voltage should be within ~ 10% of nominal
  - Larger deviations can occur temporarily
  - Manual and automatic controls
    - Capacitor, reactor switching
    - Generator, transformer controls
    - Protection schemes (e.g., load shedding)



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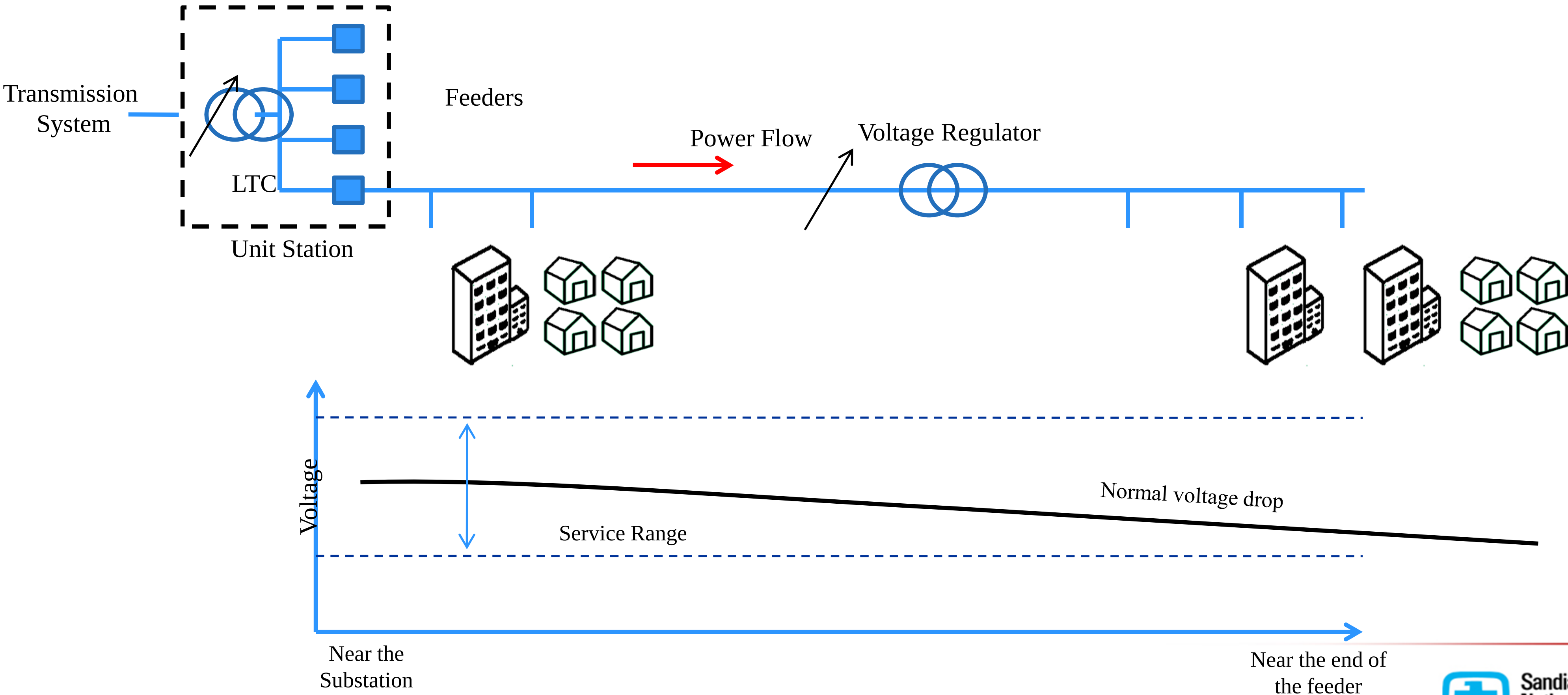
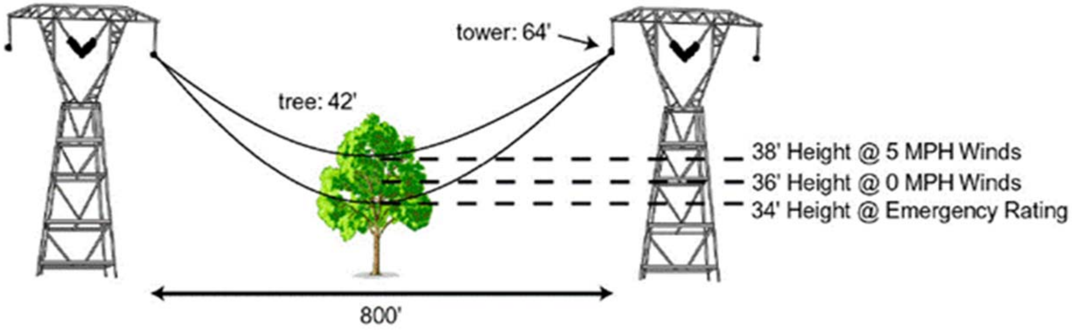
Maintaining System Voltage

- **Distribution System – Feeder**



System Contingencies

- Possible causes
  - Nature (e.g., winds, lightning, fires, ice)
  - Equipment malfunction
  - Operation outside equipment specs
  - Human error
- Consequences
  - Temporary and limited to prolonged and widespread loss of service

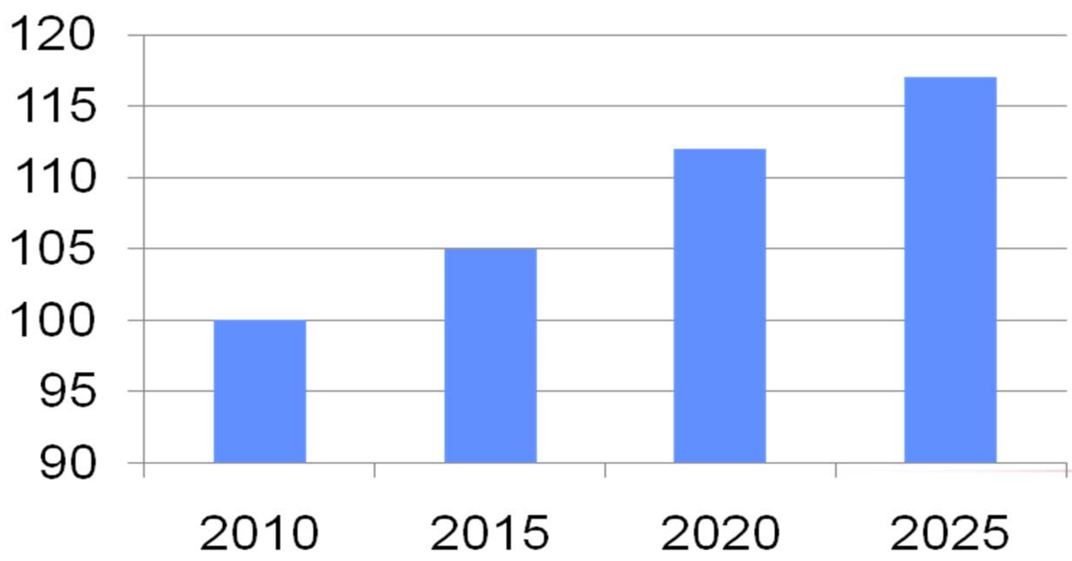


Power System Planning

- Ensure that future power system infrastructure is adequate for reliable supply
- Scope and Drivers
  - Main driver is load growth
  - Resource Planning (generation) and Transmission Planning
  - Fiduciary responsibility to avoid over-building
  - High uncertainty and complicated rules and regulations
    - State and Federal policies and procedures (e.g., Transmission Open Access, RPS, Carbon, etc.)
    - Multiple stakeholders
  - Reliability metrics established by NERC (for bulk power system) and by State Regulatory requirements

Generation Planning

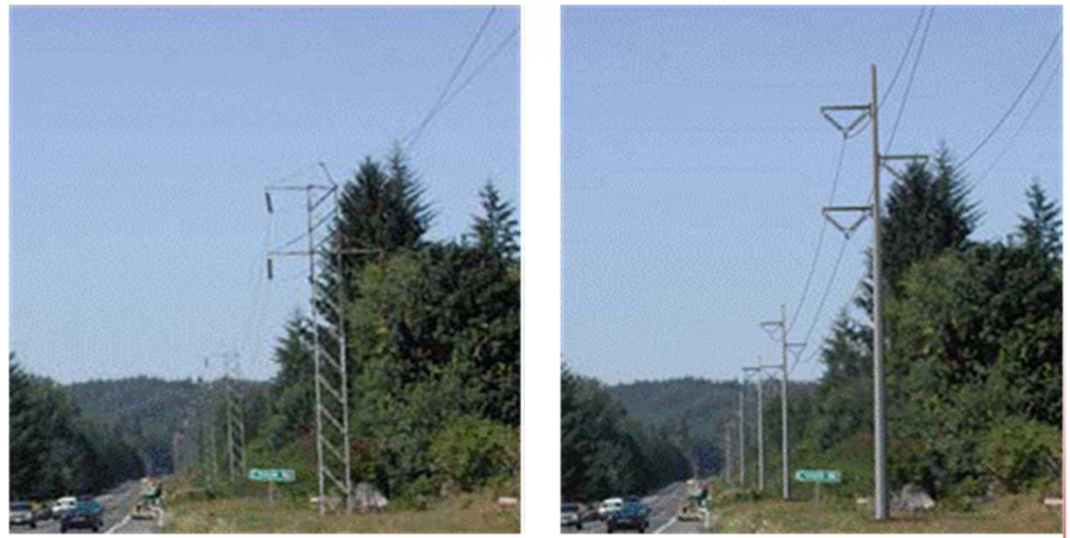
- **Key considerations**
  - **Forecasted load growth**
  - **Generation reserve requirements**
  - **Unit retirements**
  - **Policy guidelines (e.g., energy efficiency, RPS)**
  - **Availability/feasibility of transmission**
  - **Many others**



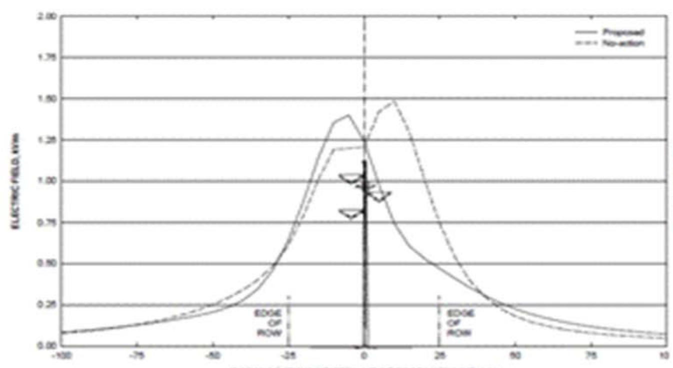
Transmission Development

- **Environmental Impact Study**
  - Land Use
  - Geology and Soil
  - Water quality
  - Air quality
  - Visual quality
  - Vegetation
  - Wildlife
  - Wetlands
  - Flood plains
  - Cultural resources
  - Health and safety
  - Socioeconomics
  - Noise

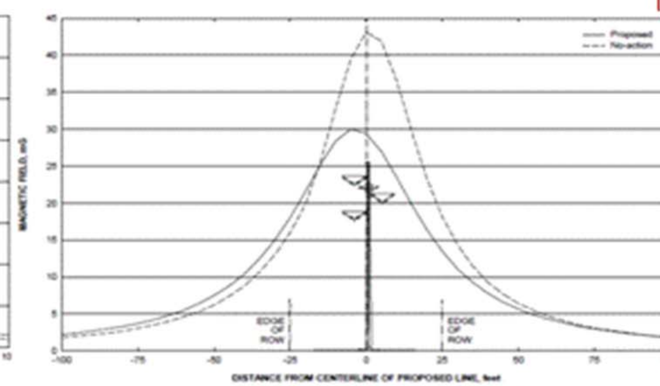
Sample 115 kV line rebuild project



Electric Field



Magnetic Field



Source: BPA

Transmission Development

- **Slow, risky, expensive**
  - **Planning**
  - **Permitting**
  - **Financing**
  - **ROW acquisition**
  - **Engineering design**
  - **Construction**

Typical OH Transmission Line Cost

Voltage (kV)	$/Mile	Capacity (MW)	$/MW-Mile
230	$2,076.50	500	$5,460.00
345	$2,539.40	967	$2,850.00
500	$4,328.20	2,040	$1,450.00
765	$6,577.60	5,000	$1,320.00

2008 Dollars. Source: EEI

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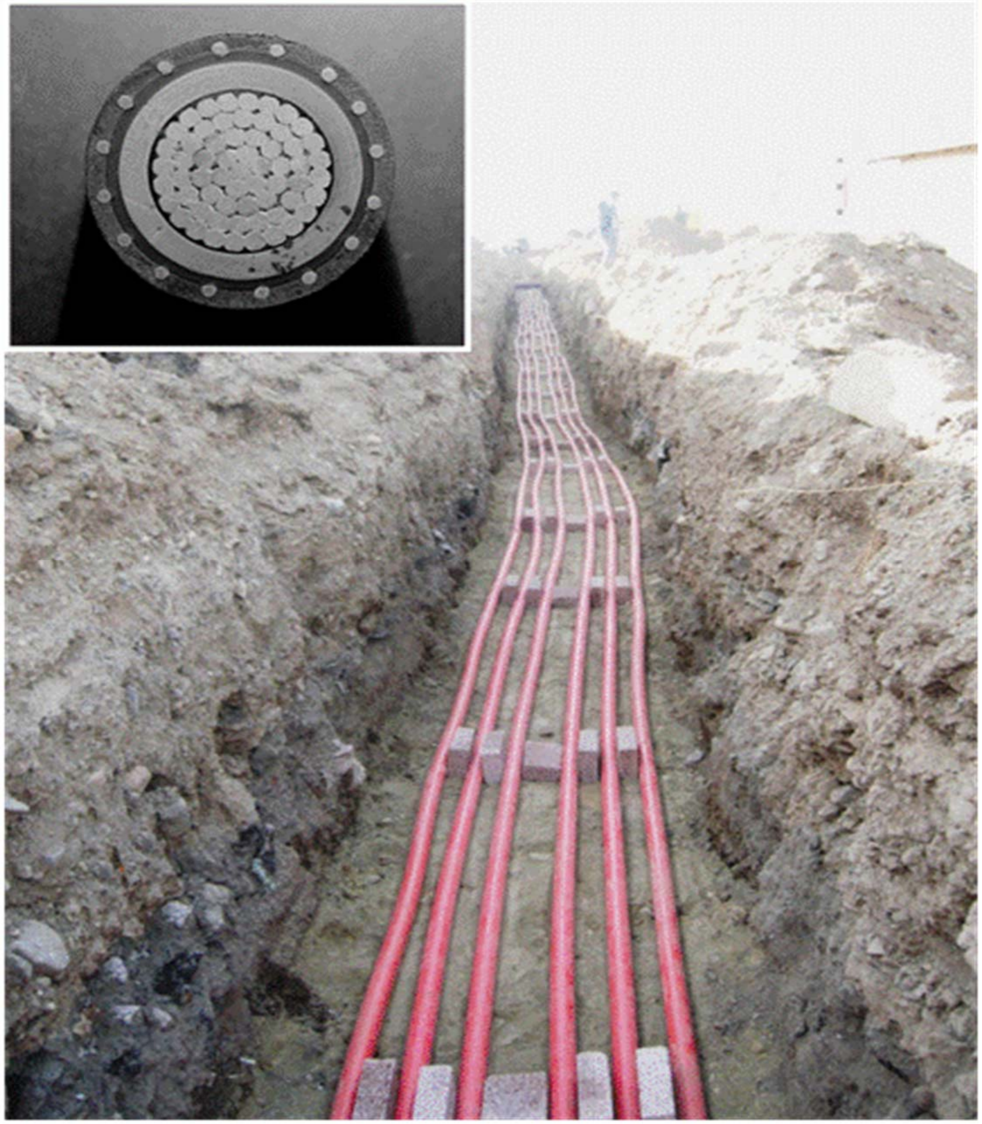
Underground Vs. Overhead Lines

- Benefits
  - Reduced visual impact
  - Reduced exposure to weather, vehicles, …
- Drawbacks
  - Cost (5x to 10x compared to overhead lines)
  - Longer outage duration
  - Complex protection
  - Trenching

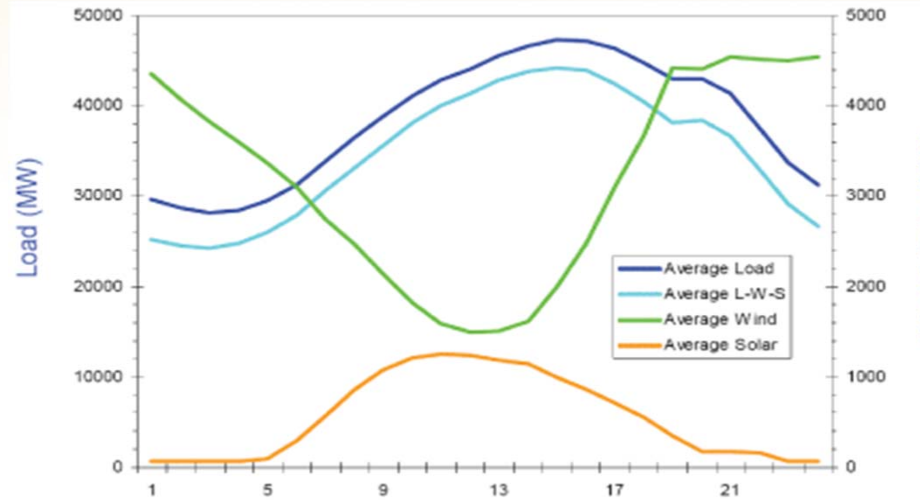


Impact of High Penetration Variable Generation on the Grid

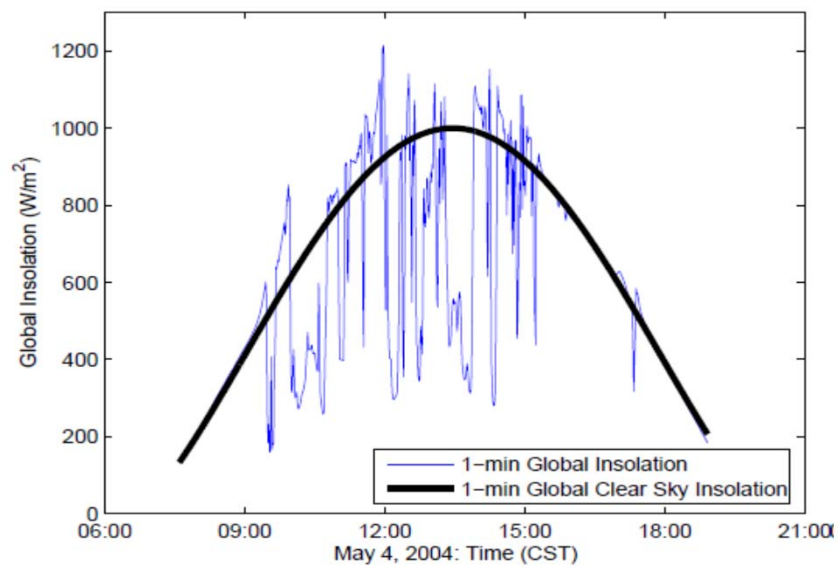
- Basic Concepts
  - Definition of Variable Generation (VG)
  - What determines variability?
- Integration of VG on the Grid
  - How to measure “Penetration Level”
  - What is “High Penetration”?
  - Thoughts about “Penetration Limits”
- System Operations with High Penetration
  - Bulk system challenges
  - Local system challenges
- Conclusions

What is Variable Generation?

- **Typically refers to Solar (PV) and Wind**
- **Variable**
  - **Long-term and short-term patterns**
  - **<u>Limited</u> ability to control**
- **Uncertain**
  - **Ability to forecast**
  - **Accuracy depends on how far ahead the forecast covers**



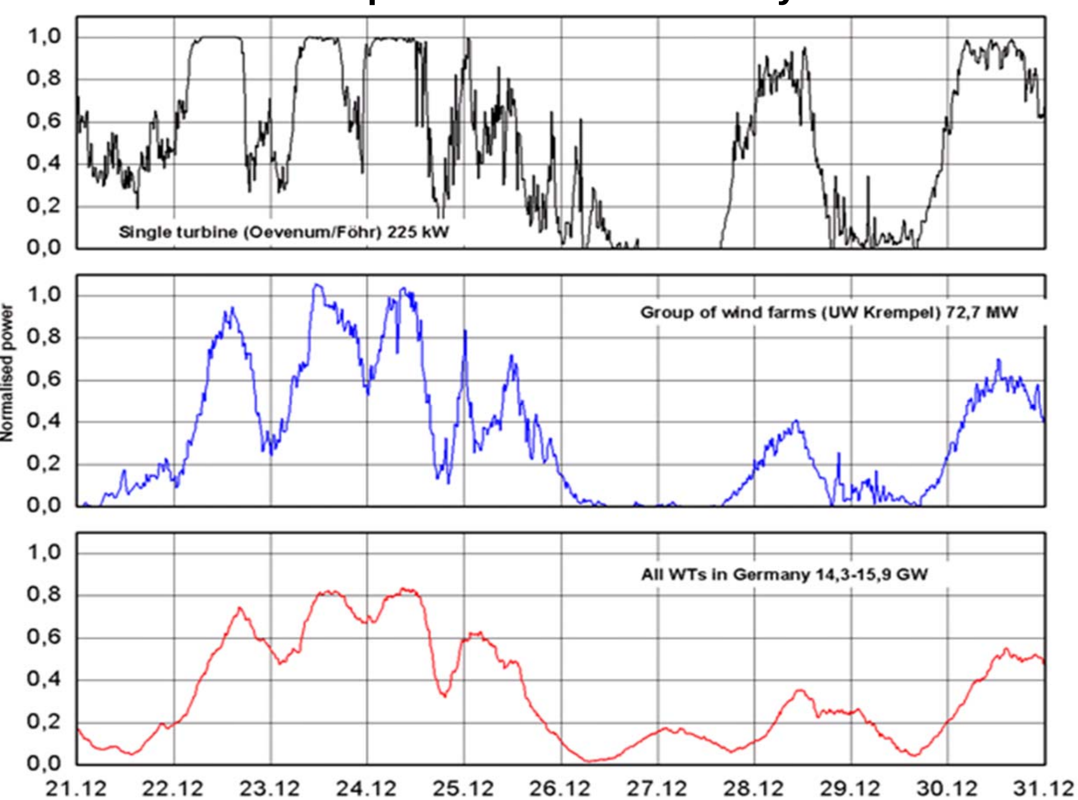
Average PV and wind output patterns in CA



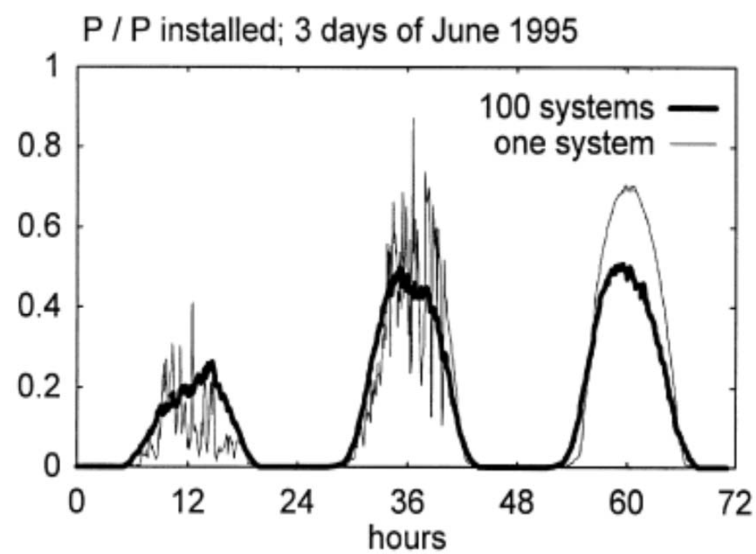
Variable Generation

- **Geographic separation helps mitigate variability**
  - **Variability does increase at the same rate as generation capacity**
  - **At the system level, aggregated variability is what matters**

Example for Wind in Germany



Example for Solar PV in Germany



Large PV Plants

Olmedilla Park Solar Power Plant (60 MW)

Waldpolenz Solar Park (40 MW)

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**

* Most commonly used definition

- **Often used in policy and procedures**
  - **Penetration by energy used in State RPS targets**
  - **Penetration by capacity used in interconnection screens & procedures**

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	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

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

What are the Technical Challenges?

- **Bulk System Issues**
  - **How to handle added variability and uncertainty**
    - **Can the system handle? What is the cost?**
  - **How to accommodate more VG**
    - **Technology (grid and VG)**
      - How will the Smart Grid help?
      - Can VG contribute to voltage control?
      - Can VG output be controlled for reliability reasons?
    - **Performance standards**
    - **Planning and operations best practices**

Increase in Operating Cost

- System with high penetration VG looks different
  - More difficult to "follow" net variability over all time frames
  - It can be done, but cost of operation is higher
  - Generation flexibility is key to allow for High Penetration scenarios

"Easy" Week

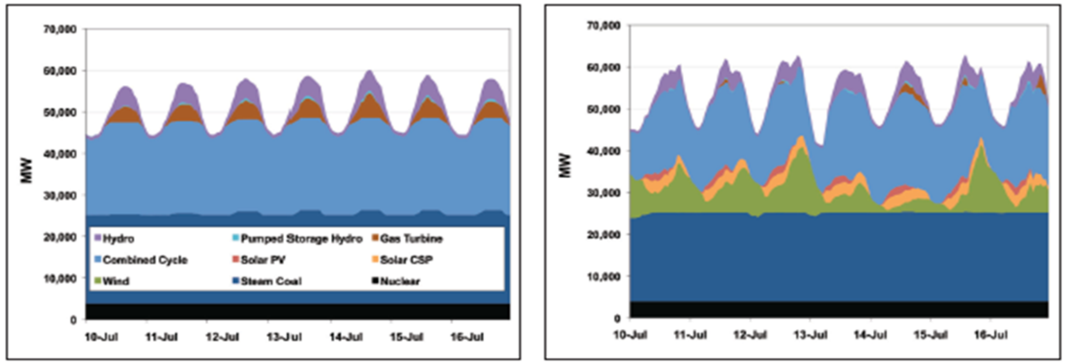

Figure 3 – 35% renewables have a minor impact on other generators during an easy week in July, 2006. WestConnect dispatch - no renewables (left) and 30% case (right)

"Hard" Week

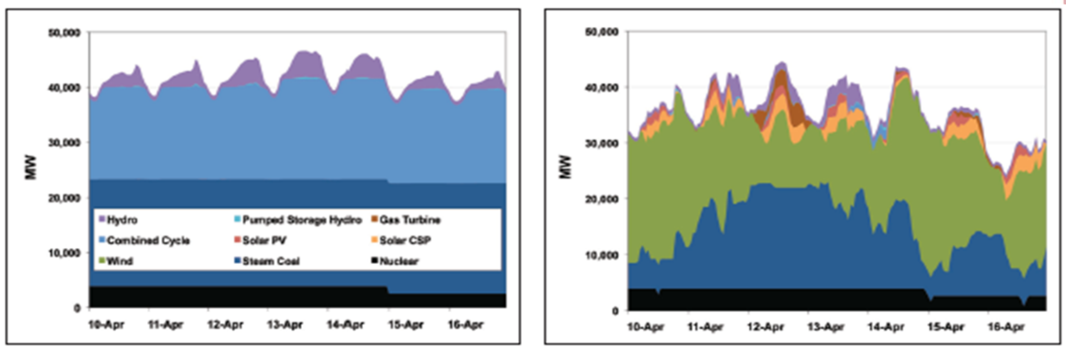

Figure 4 – 35% renewables have a significant impact on other generation during the hardest week of the three years (mid-April 2006). WestConnect dispatch - no renewables (left) and 30% case (right)

Figures from Western Wind and Solar Integration Study, 2010

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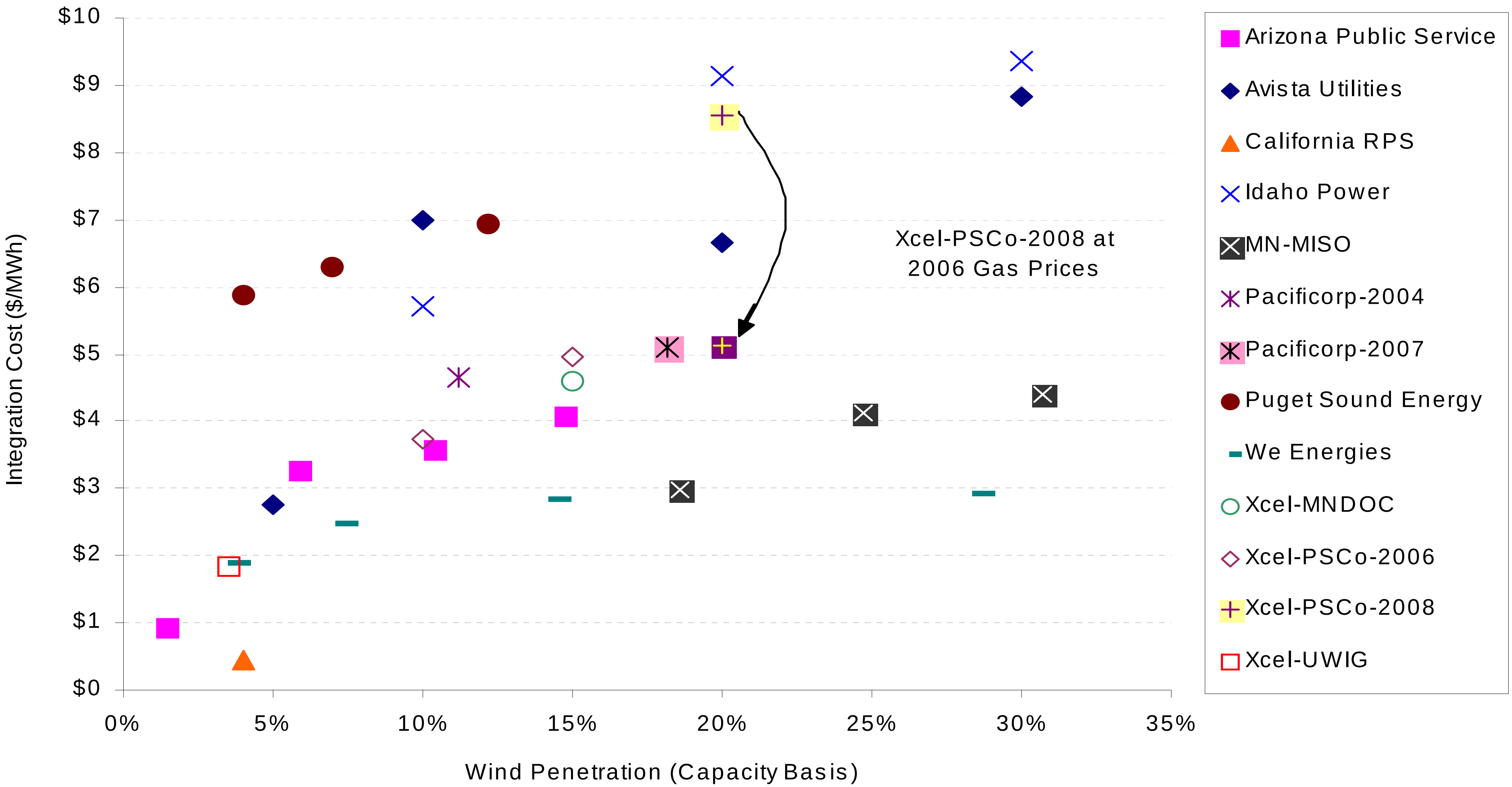
Increase in Operating Cost



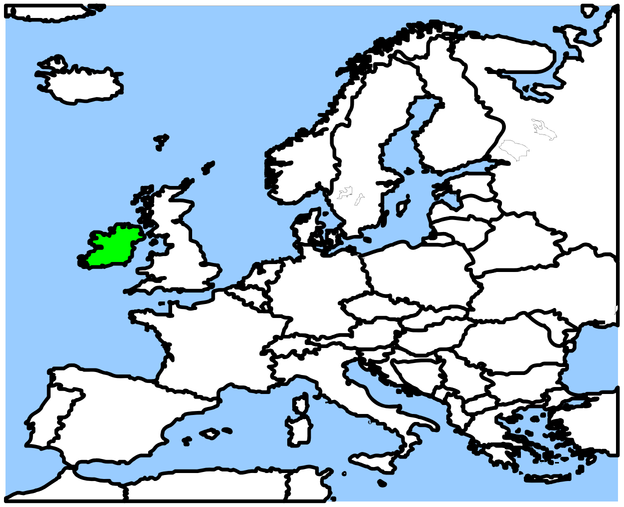
Source: LBL

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

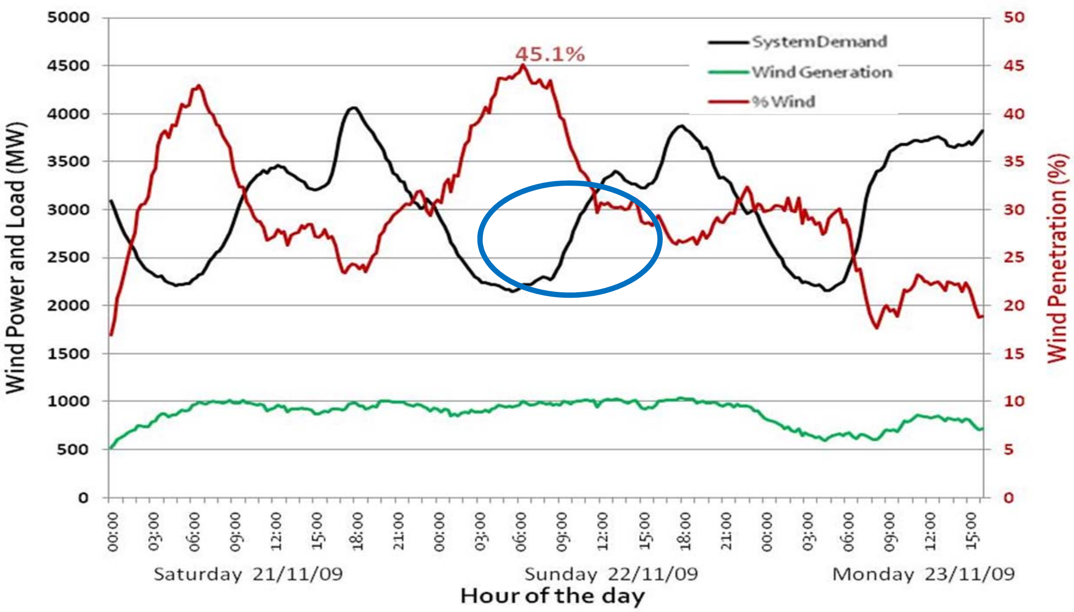
Examples of Very High Penetration

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



Ireland Example

- **Penetration by energy approaching 15%**
- **Instantaneous penetration reaches 50%**



Source: Mark O'Malley

Similar high penetration levels in Hawaii

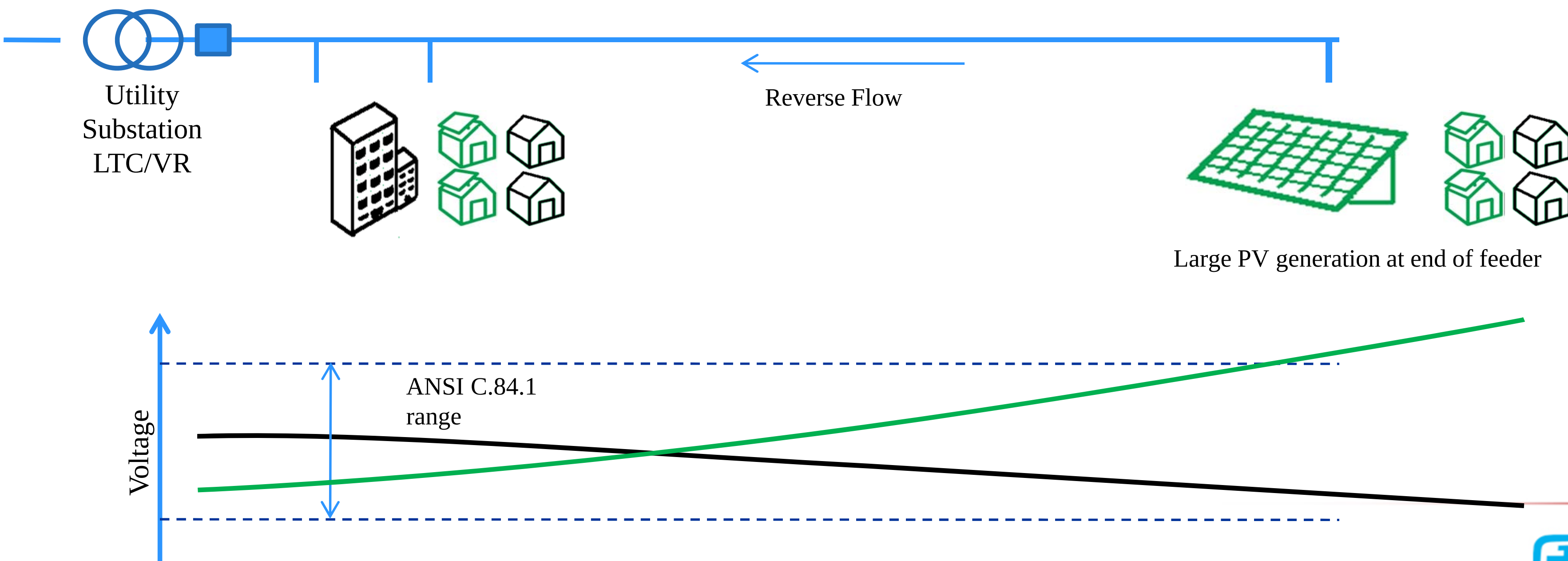
Distribution Operations Issues

- 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**



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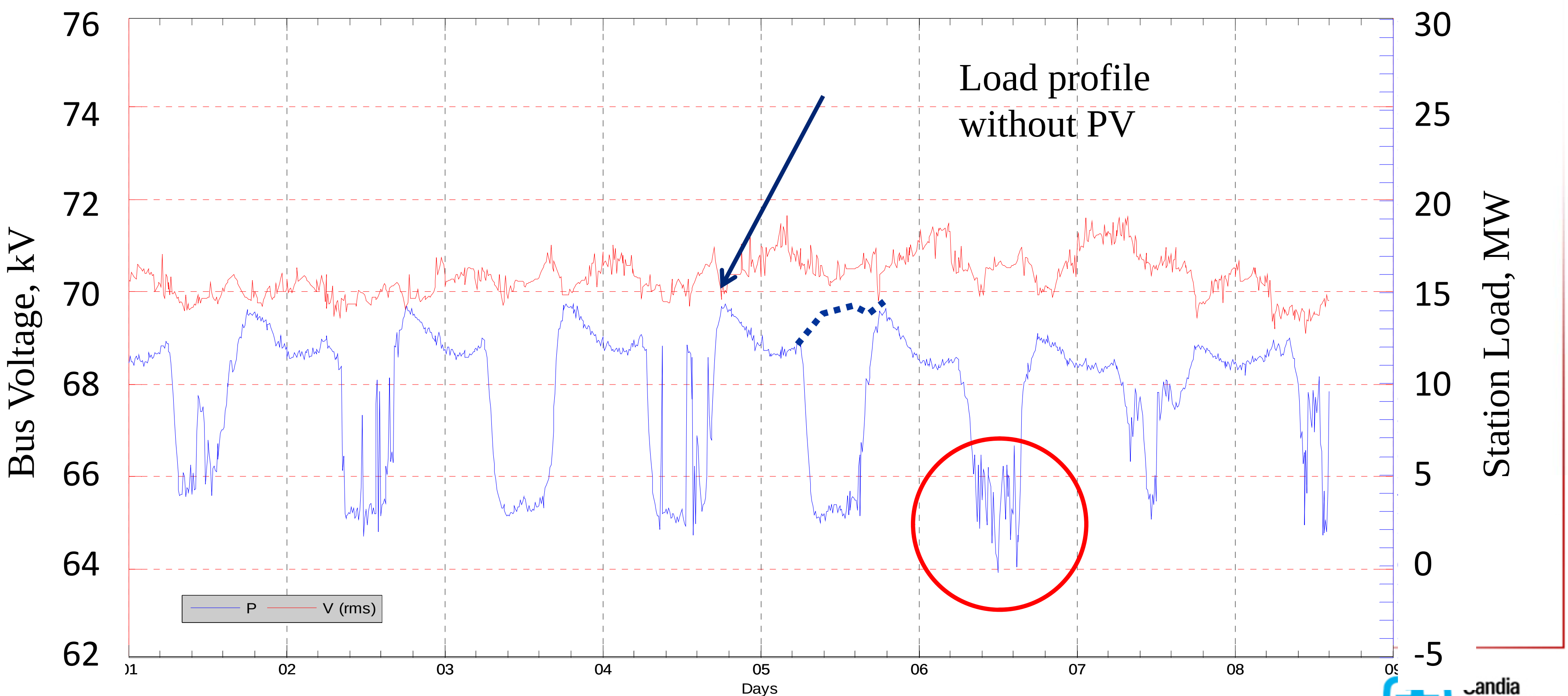
Voltage Control

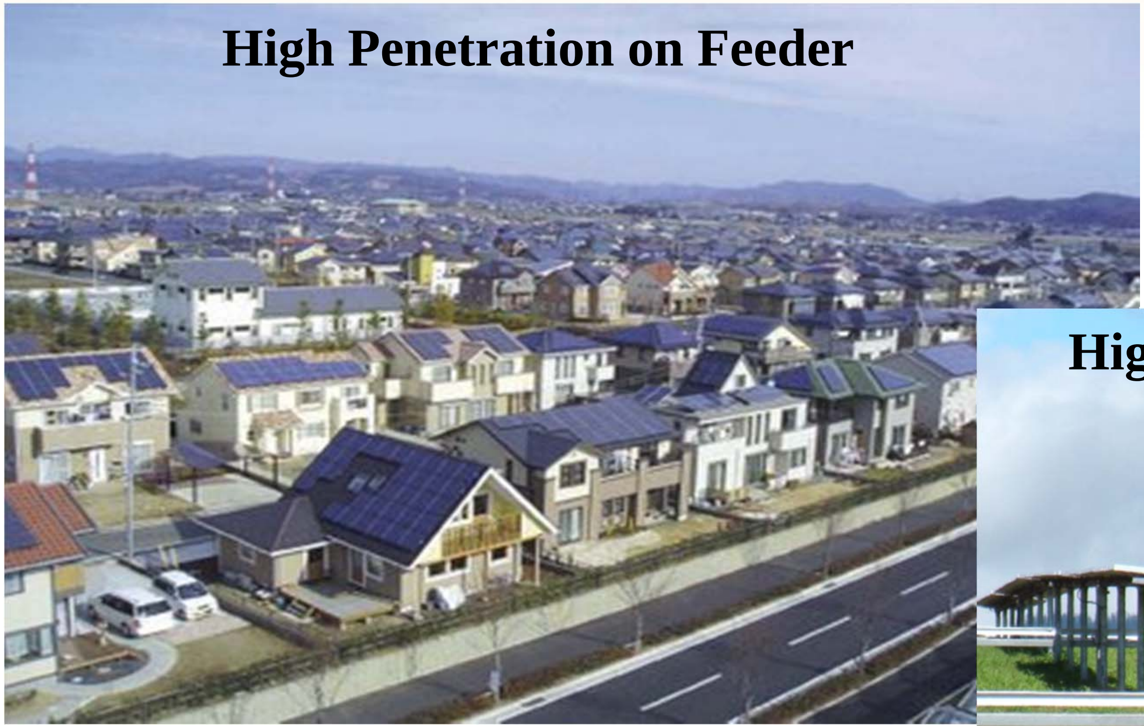
- **Voltage issues are much less problematic in short urban feeders, even at very high penetration!**



Other Distribution Operations Issues

- Protection and safety
  - Relay desensitization, nuisance tripping
    - Reduction in fault current from utility source, reverse flow
  - Risk of islanding
    - Customer exposure to high voltages (ferro-resonance)
    - Coordination with protection systems
- Management and control
  - Visibility and controllability of distributed DG
  - Interoperability, Cyber-security

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

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Current Research on Grid Integration

- Some Examples of Sandia Work
  - Prediction of solar and wind profiles
  - Wind/solar Forecasting
  - Refinement of simulation models and tools
  - Technology Development
  - Evolution of Standards

Modeling of PV Systems

- Need to model effects of distributed PV on bulk grid
- Implement as addition to WECC composite load model

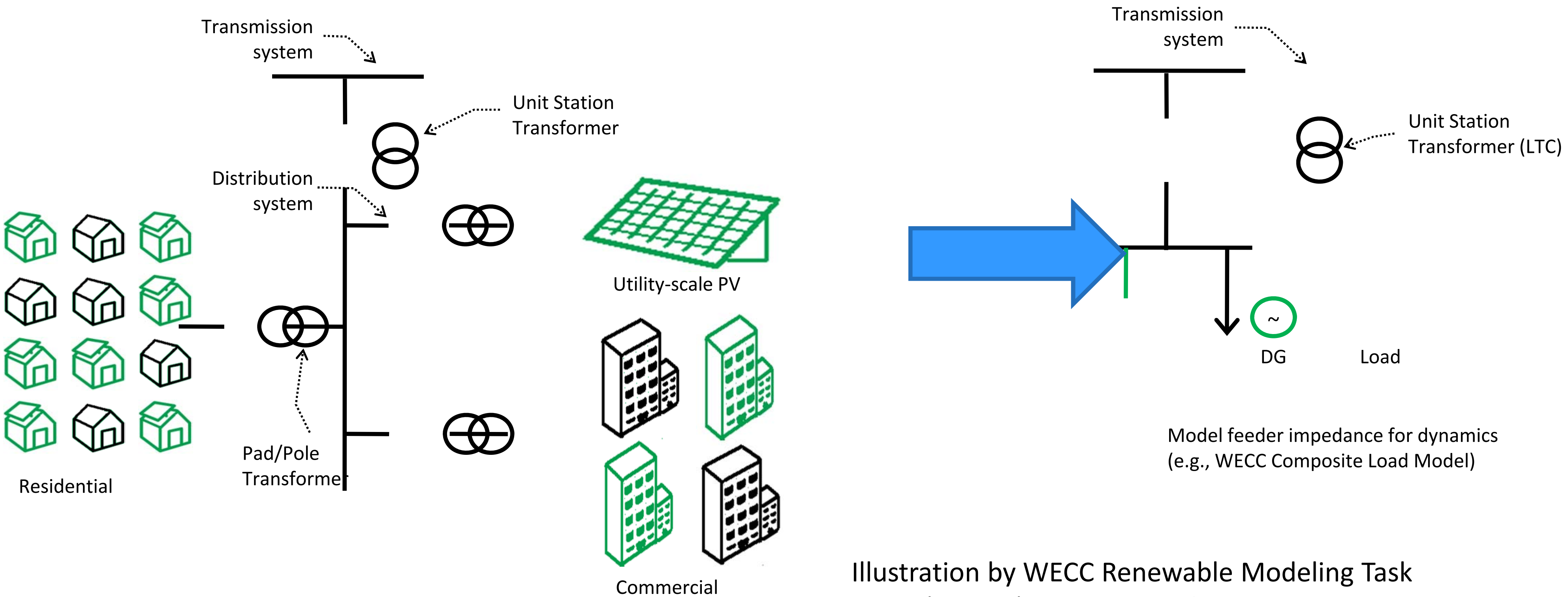

Illustration by WECC Renewable Modeling Task Force (REMTF), coordinated by Sandia

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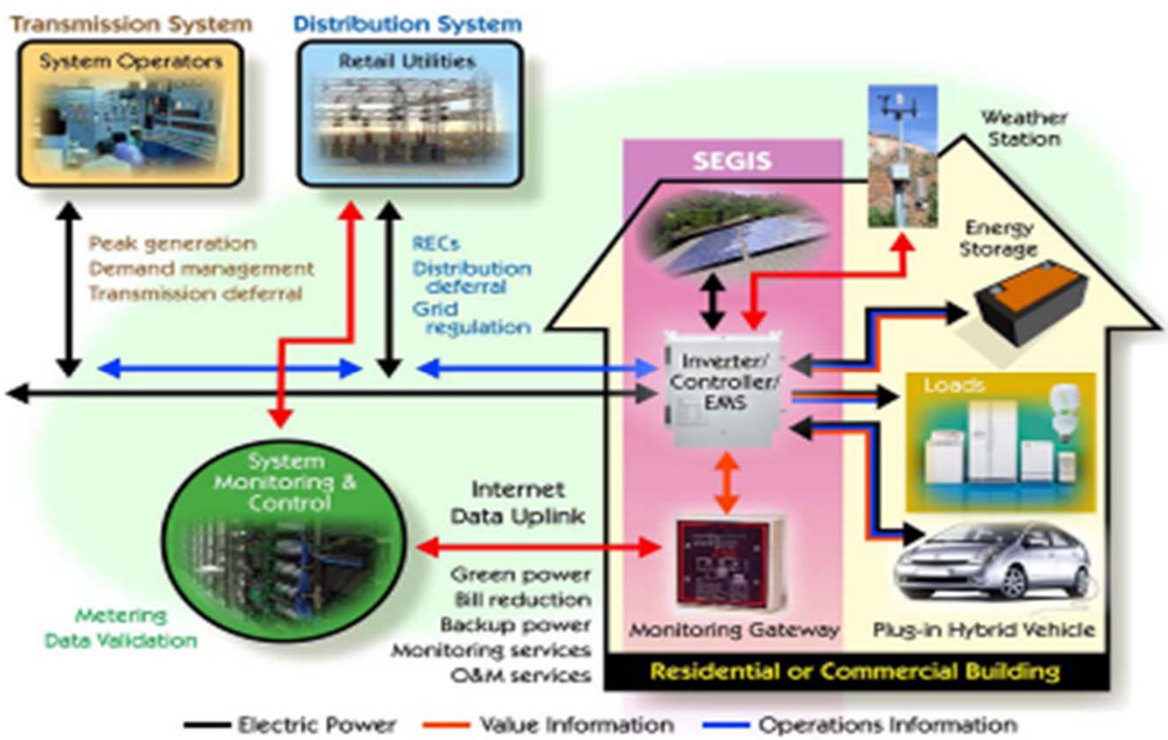
Technology Development

- PV inverter technology advances are required to enable future high penetration PV
  - Increase value of PV systems to customers and to the grid



DOE/Sandia Solar Grid Integration Systems (SEGIS)

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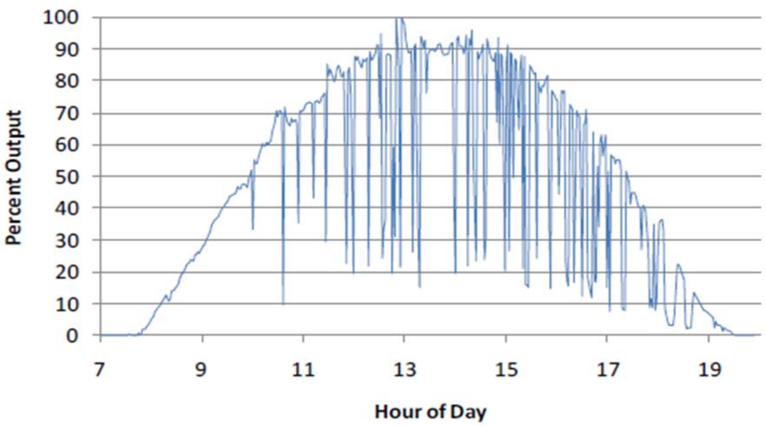
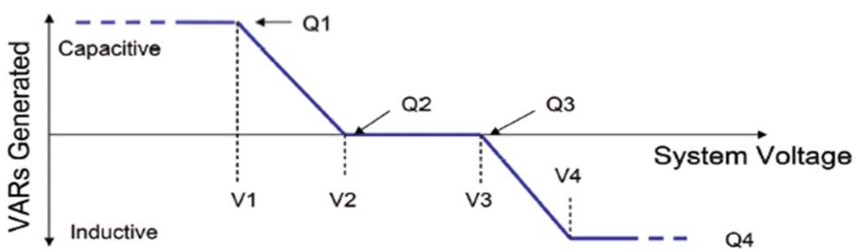
Codes and Standards Development

- **Future codes and standards need to allow distributed systems to provide more grid support functions**
  - **Existing standards not designed for high penetration scenarios**

Variable PV Output could cause voltage control issues at the feeder local level



One solution could be to allow inverters to help control voltage using reactive power (VARs)



Existing IEEE 547 standards for distributed generation

	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 11th; <2% for 11th – 15th, <1.5% for 17th – 21st; 0.6% for 23rd – 33rd; <0.3% for 33rd 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

Source: EPRI/Sandia Inverter Interoperability Project

Sandia National Laboratories

Conclusions

- Penetration Levels
  - Different definitions for different purposes
- High penetration impacts
  - Impacts are system specific
  - Flexibility is the key to reduce cost and integrate more variable generation
- There are no absolute “penetration limits”
  - Issues boil down to cost
- 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!

Questions and Discussion