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ENG 505 - ENERGY SURETY AND SYSTEMS

Electricity Transmission Systems

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R&A: 5276068

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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Outline of Presentation

- About Me
- The Bulk Power System
- Power System Operations and Renewable Energy Integration
- Question & (hopefully) Answers

(Time Permitting)

ENG 505 - ENERGY SURETY & SYSTEMS

Transmission Systems

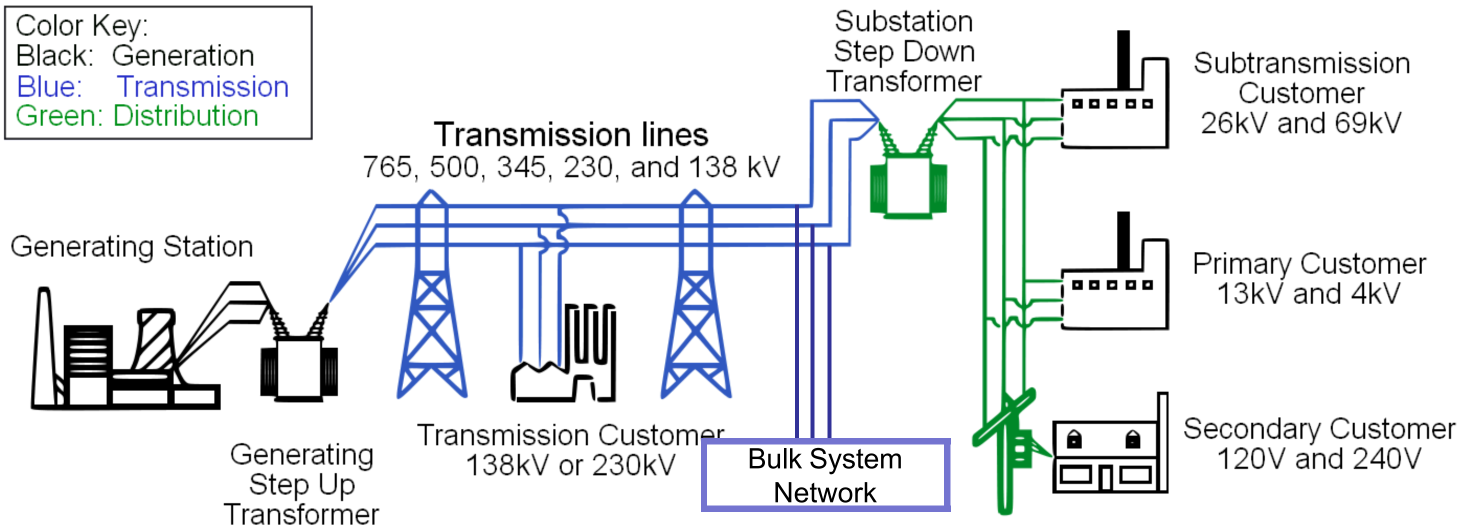
About Abe

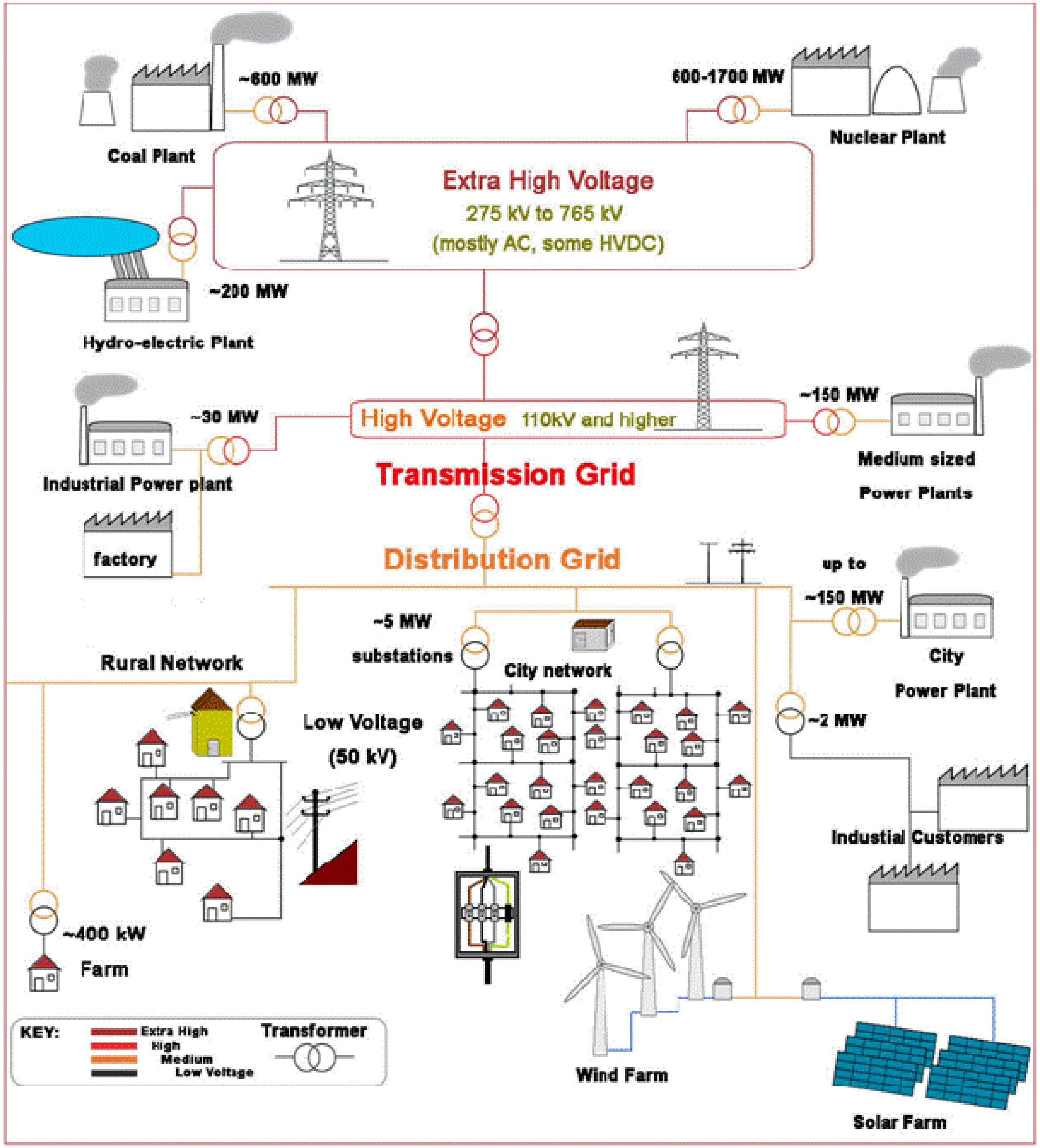
- Masters and Ph.D. in Power Systems, NMSU
- Work Experience
  - NMSU/SWTDI ('95 - '00): Off-grid PV/wind systems
  - PNM (00' - '08): Transmission Planning & Operations
  - Sandia ('08 -): Renewables Grid Integration
- Sandia Experience/Career Highlights Summary
  - Technical Lead for Distribution & Transmission PV Grid Integration ($3M/year)
  - Chairman/Convener for IEEE, NERC, WECC, IEC technical committees
  - RE/DER Conference Chair (www.4thintgrationconference.com, http://www.otti.de/en/events/id/5th-international-conference-on-integration-of-res-and-der.html)
  - Involved in several projects including PV, wind, hydro, energy storage, smart grid
  - Expertise in Grid Modeling, Technical Standards

The Bulk Power System

Brief Introduction

- Transmission or Bulk System
  - Move bulk electricity from generation to load centers
  - Long distance (10s to 100s of miles), high capacity, high voltage, balanced 3-phase
  - Mostly network topology
- Distribution System
  - Distribute electricity to end users
  - Short distance (several miles), lower capacity, lower voltage, unbalanced 1-3 phase
  - Typically radial topology





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- Transmission
  - EHV: 345, 500, 765 kV
  - HV: 115, 138, 230 kV
  - Typically network
  - Long-distance
  - DC lines are used, too
- Sub-Transmission
  - 46, 69 kV
  - Network or long radial (e.g., rural feeders)
- Distribution
  - 4.16, 12.47 kV
  - Radial
  - Urban feeders

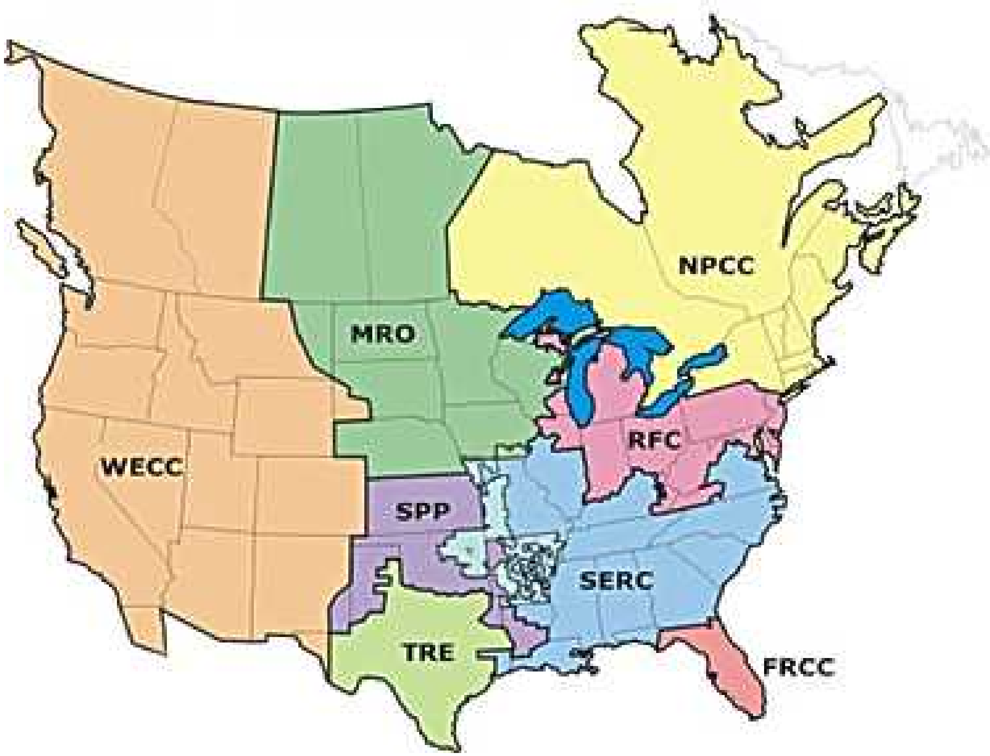
Brief Introduction

- 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 main driver (but not the only 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 standards
  - Must work within institutional constraints regulatory, policy, market, etc.

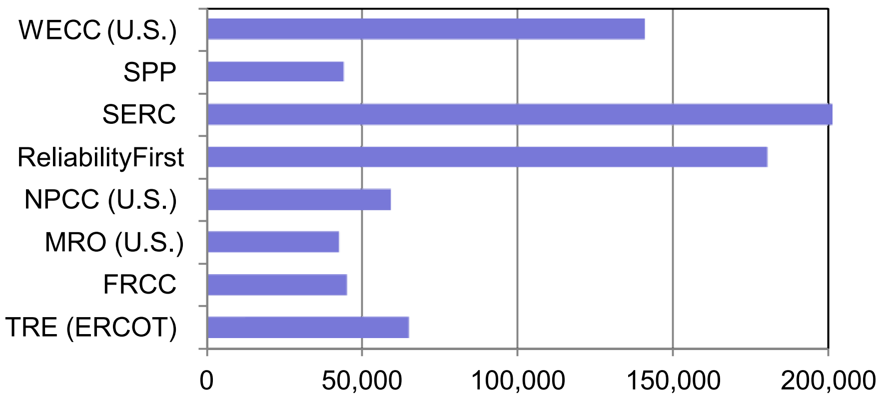
NERC and Regional Entities

NERC: North America Electricity Reliability Corporation

FRCC: Florida Reliability Coordinating Council
MRO: Midwest Reliability Organization
NPCC: Northeast Power Coordinating Council
RFC: Reliability First Corporation
SERC: SERC Reliability Corporation
SPP: Southwest Power Pool, RE
TRE: Texas Reliability Entity
WECC: Western Electricity Coordinating Council



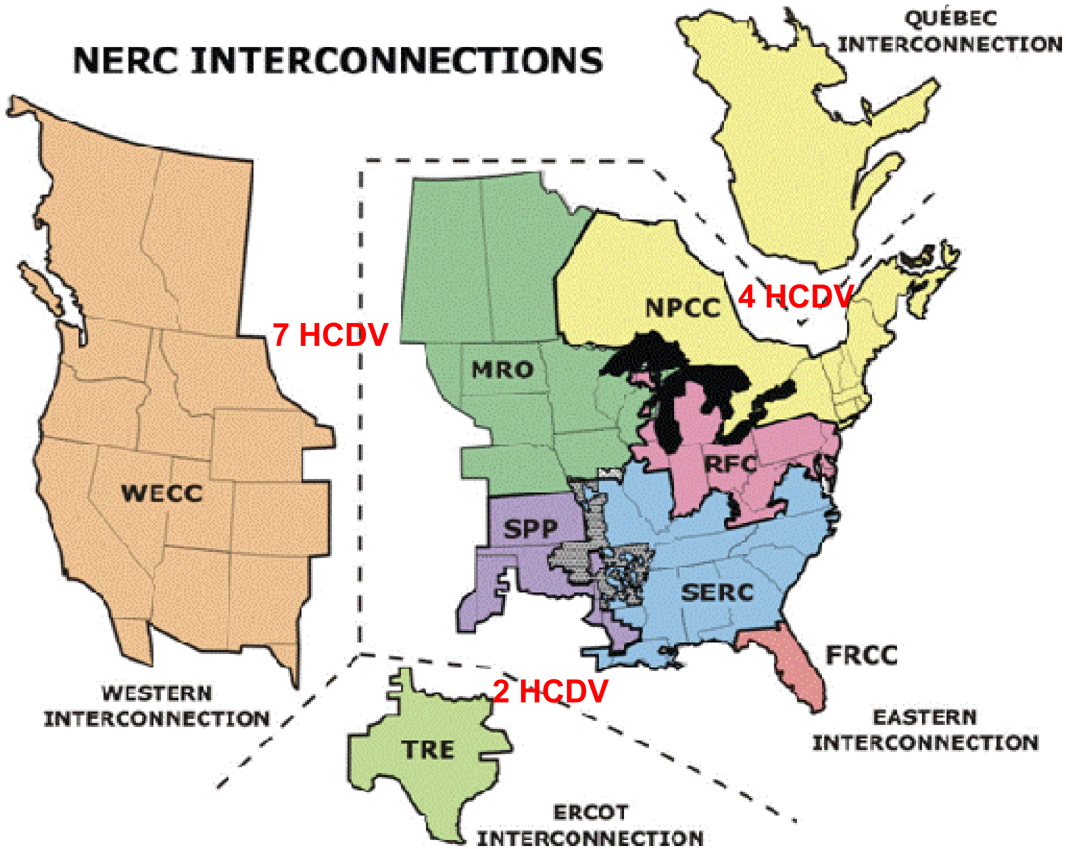
Net Demand (MW) – Summer 2008



Contiguous US: 780,068 MW
Capacity Resources: 929,338 MW
Capacity Margin: 16.1
Source: NERC

Major North America Interconnections

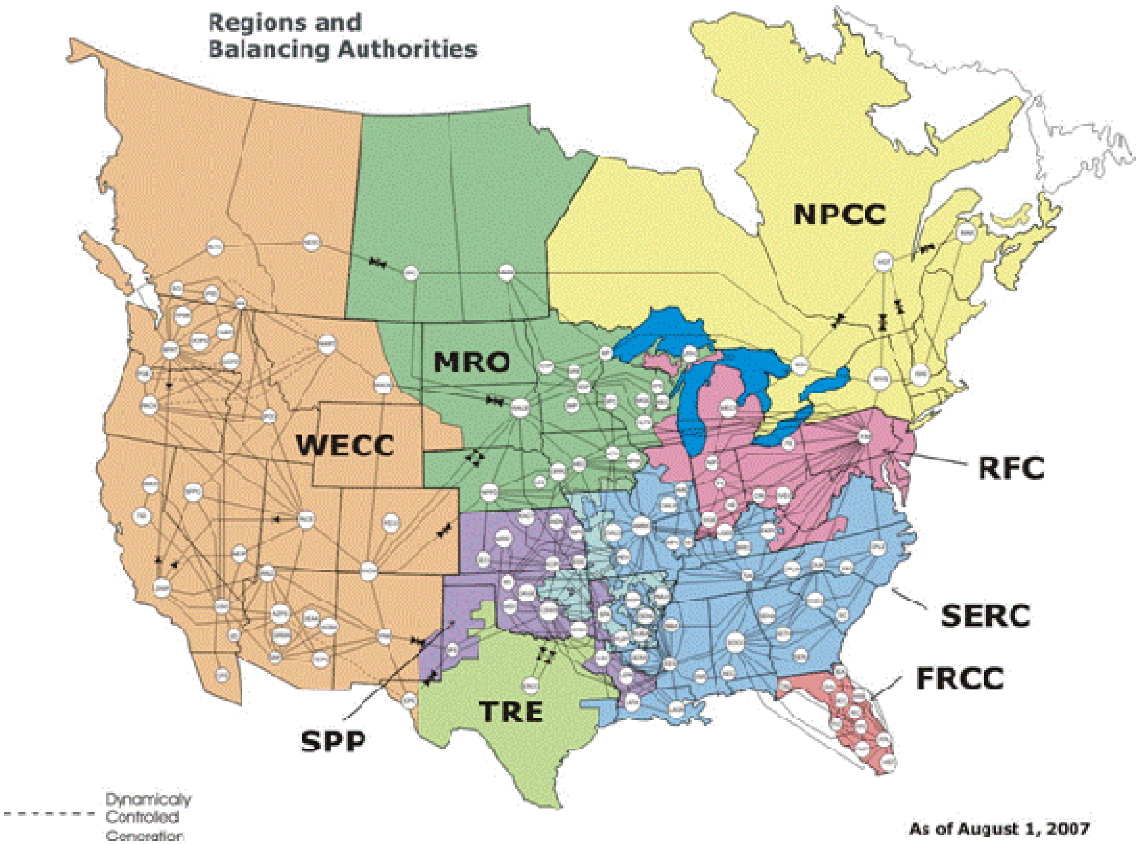
- NA Grid is actually 4 major Interconnections, limited connectivity between!
- An interconnection…
  - Is frequency-synchronized
  - Shares system assets
- DC lines or back-to-back HVDC can be used to tie interconnections
- An electrical disturbance in one interconnection does propagate to other interconnections



Source: NERC

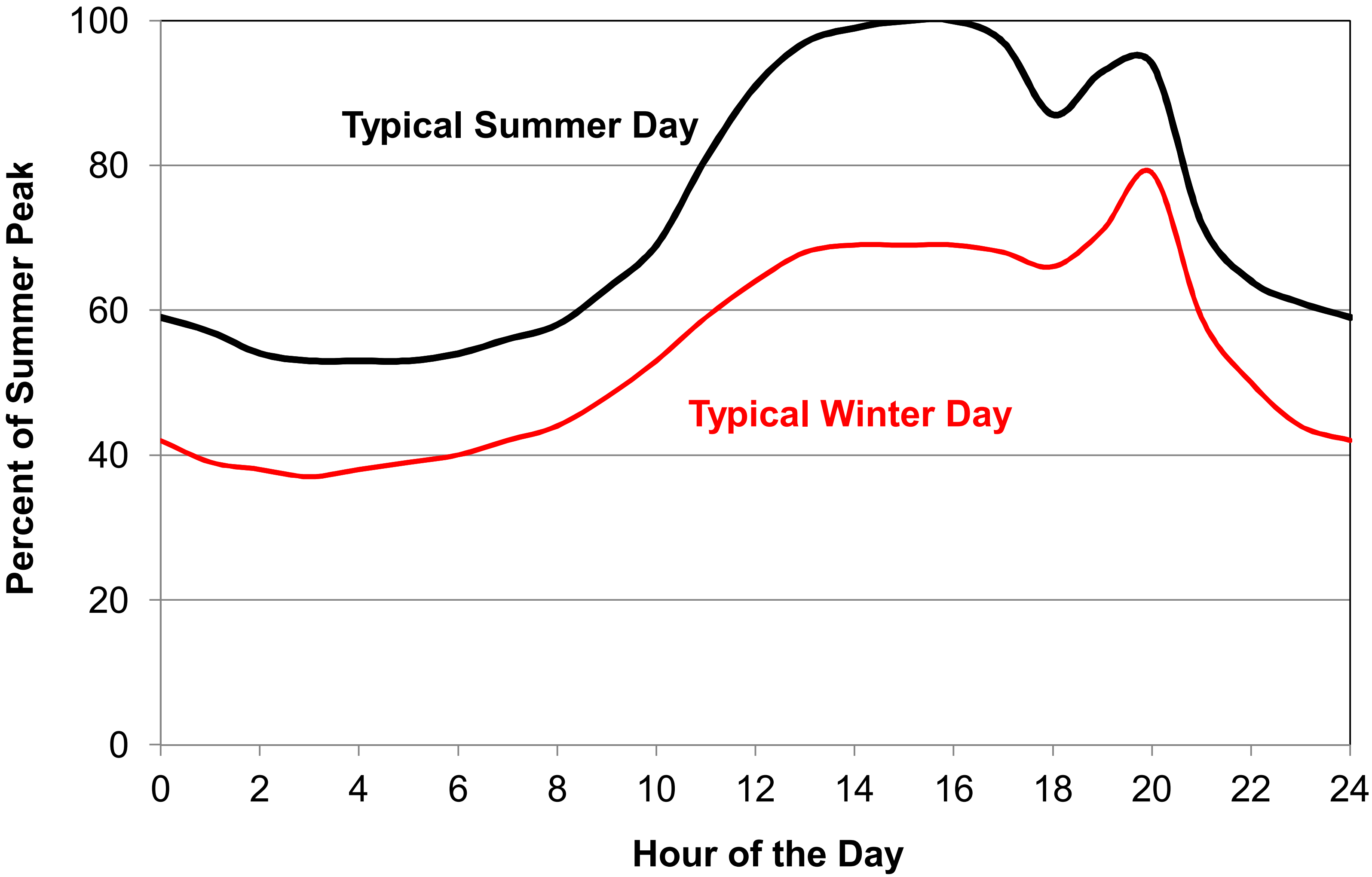
NERC Balancing Authorities

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

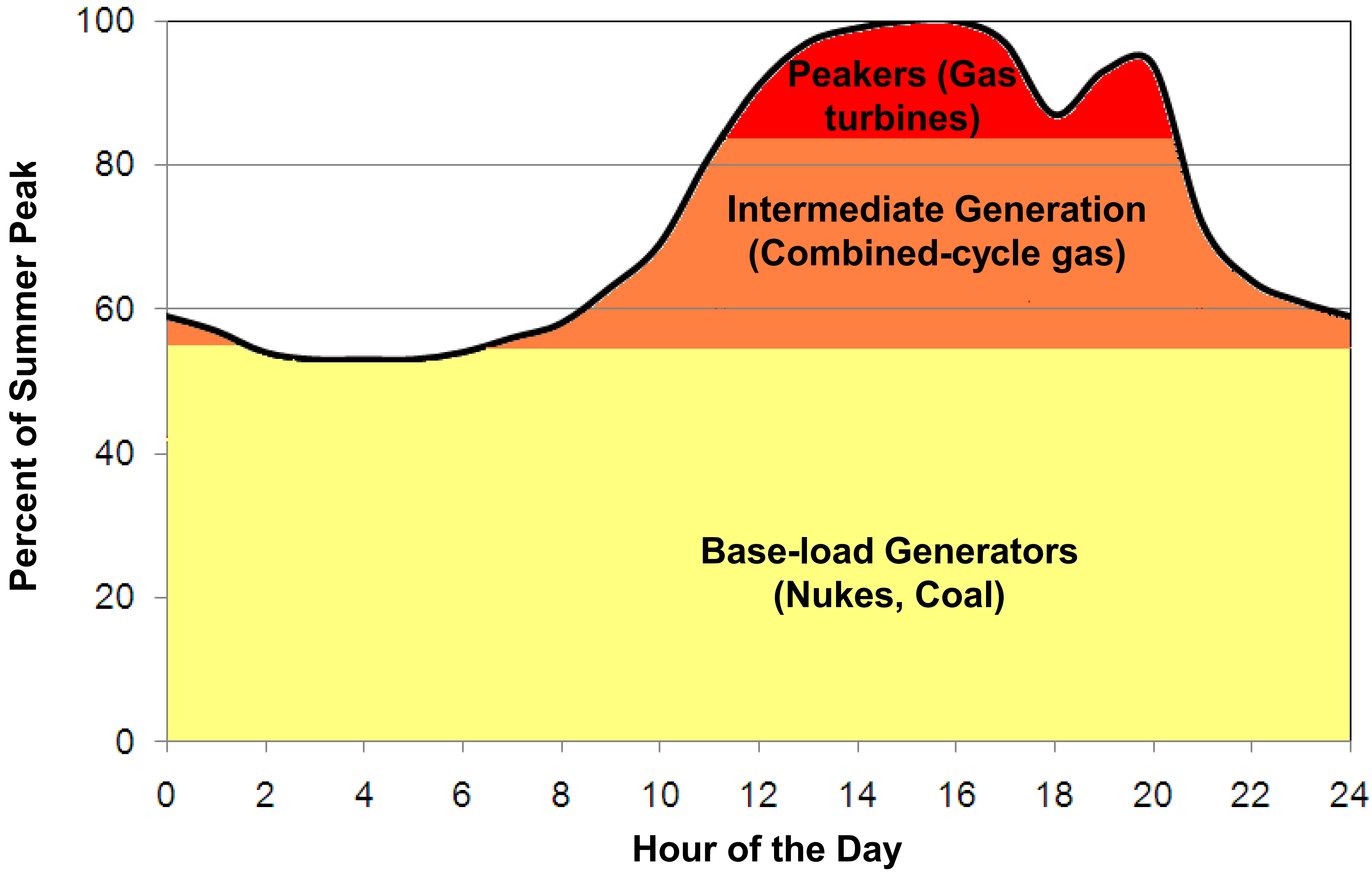


Source: NERC

Electricity Demand



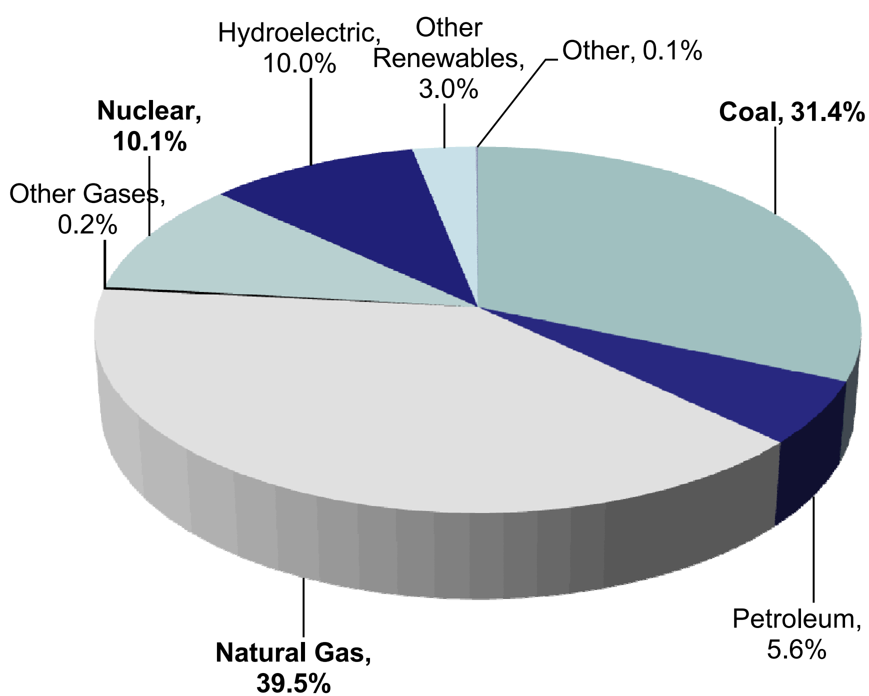
Electricity Supply



US Generation Stats (2007)

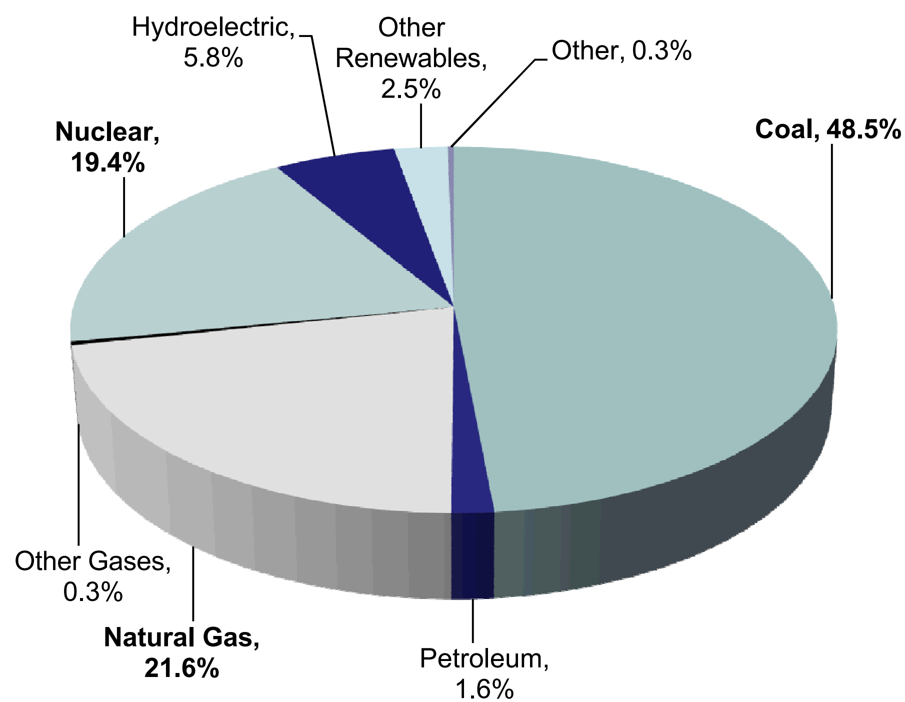
By Capacity (Summer)

Total = 995 MW



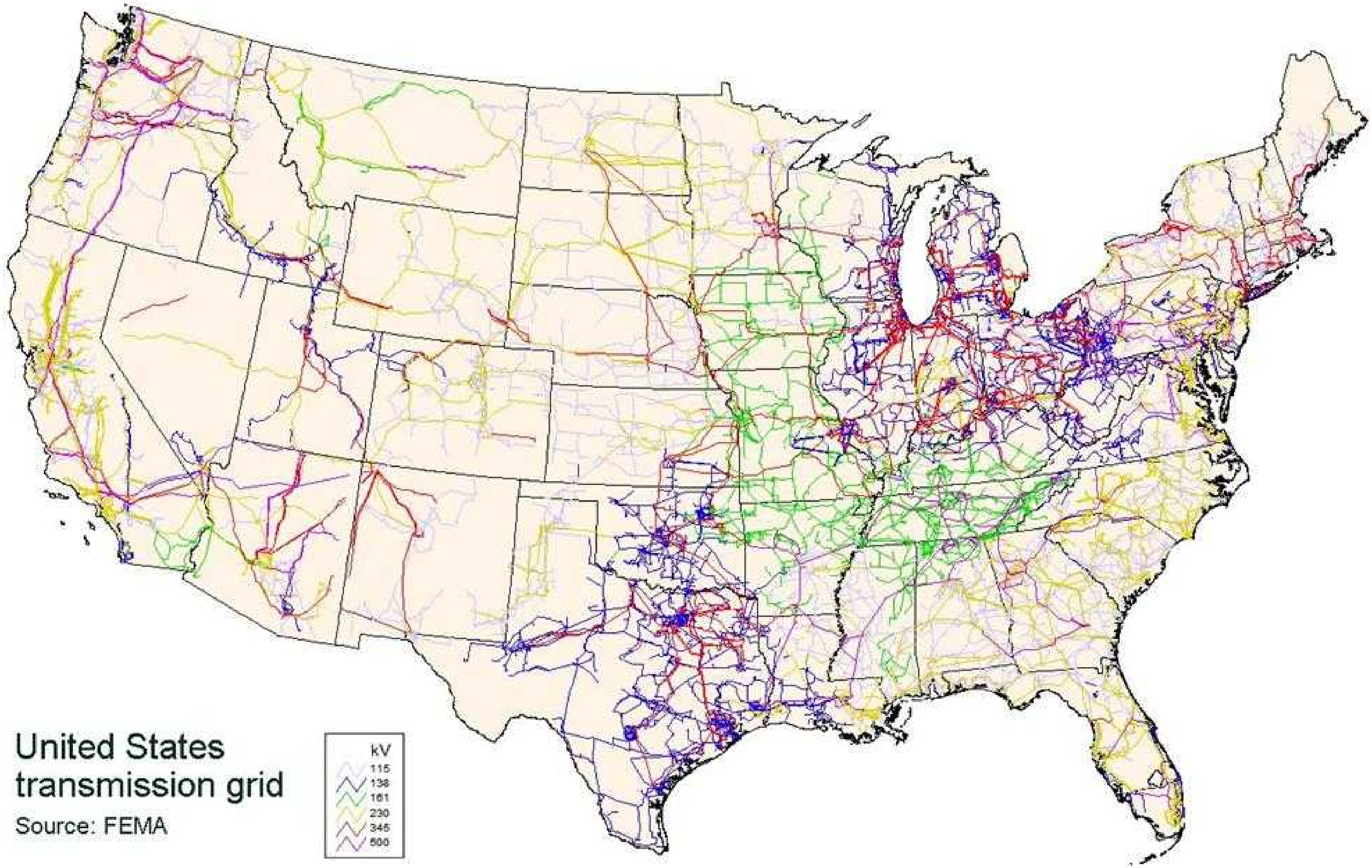
By Energy Produced

Total = 4.157 Million MW-h



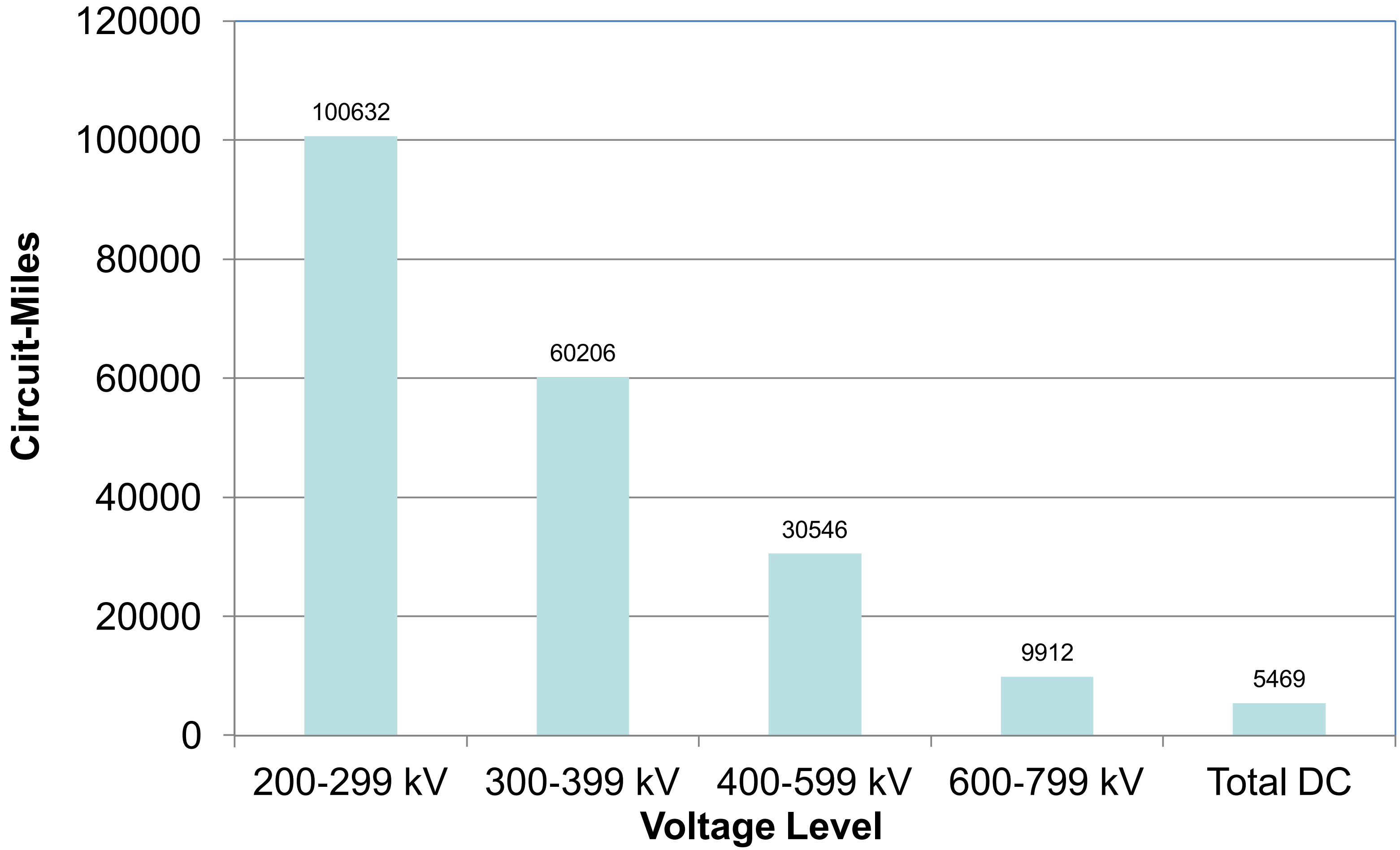
Source: Energy Information Administration, Form EIA-923, "Power Plant Operations Report" and predecessor form(s) including Energy Information Administration, Form EIA-906, "Power Plant Report;" and Form EIA-920, "Combined Heat and Power Plant Report."

US Transmission System



NOTE: Not Up to date

US Transmission Lines



Source: EIA – Transmission Availability Data System - 1st Quarter 2008 Phase I Metrics and Data Report

Who Owns Transmission?

- Investor-owned utilities (IOUs)
- Federally-owned utilities
  - BPA, WAPA, SWPA, TVA
- Other public entities
  - State agencies
  - Municipalities, public power districts, irrigation districts
- Cooperatively-owned utilities
- Independent transmission companies

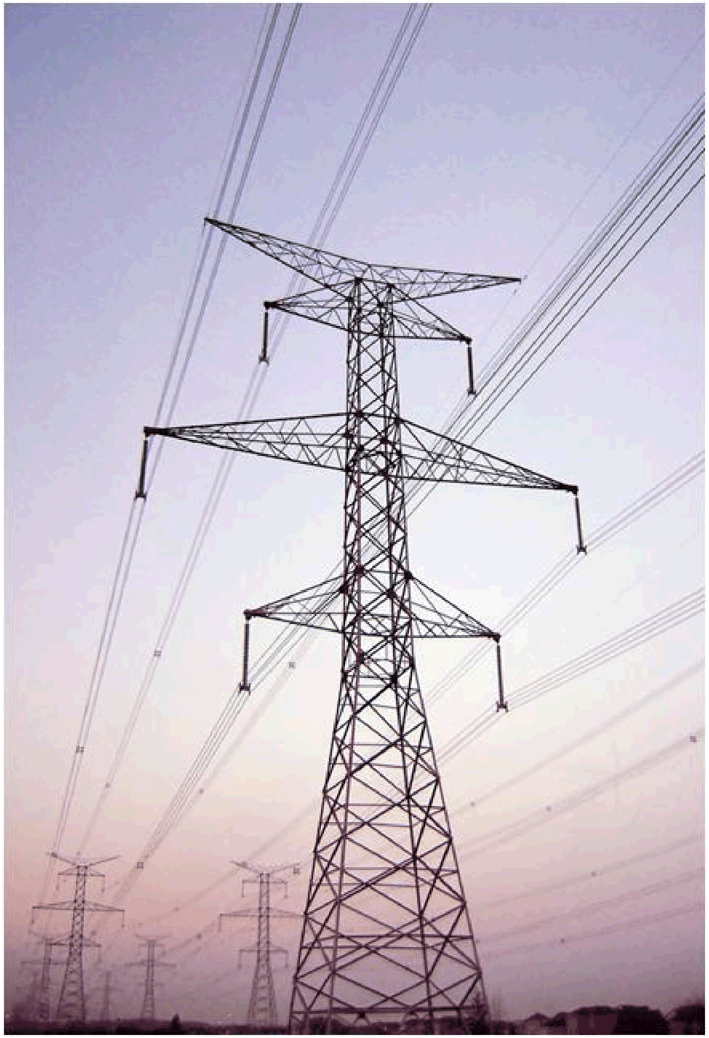
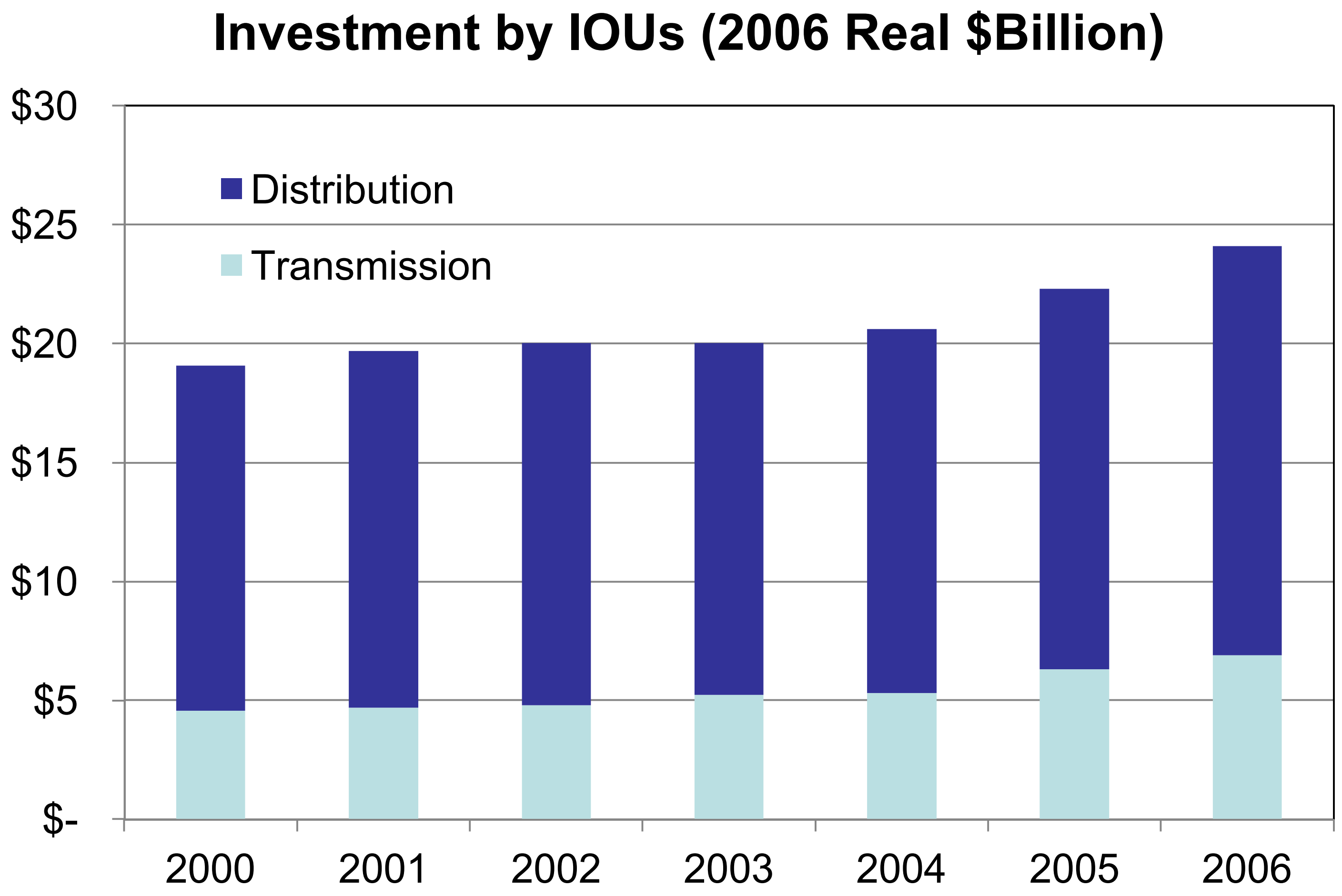


Photo credit Ian Muttoo. http://www.flickr.com/photos/imuttoo/2423929597/

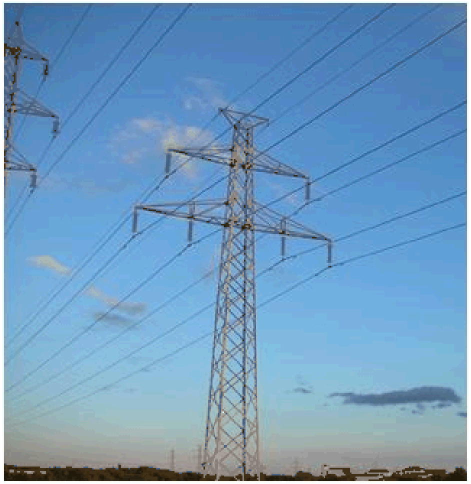
T&D Investment in the US

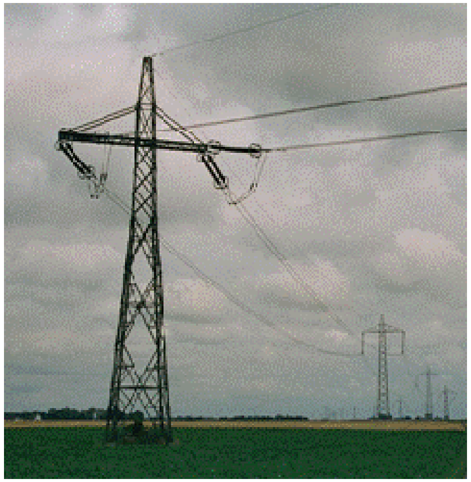


Source: EEI – Transforming America's Power Industry: The Investment Challenge 2010-2030

Transmission Network Infrastructure

- Transmission lines
  - AC, DC
- Switching stations
- Transformers
  - Voltage, phase shifting

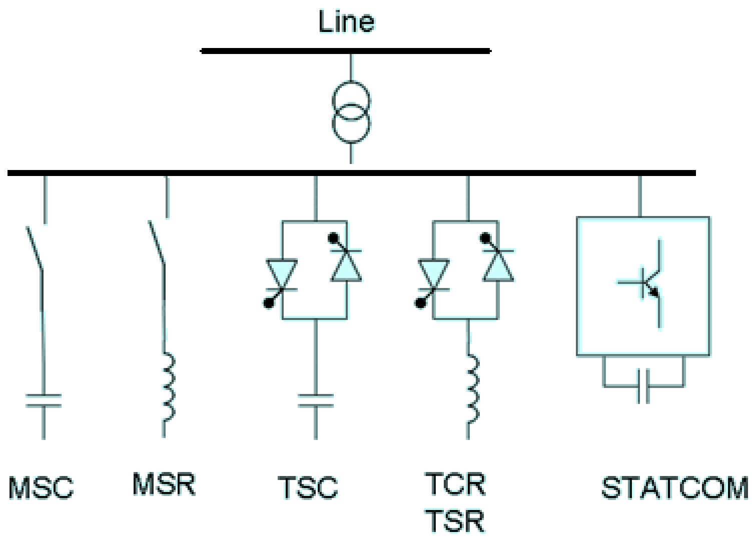


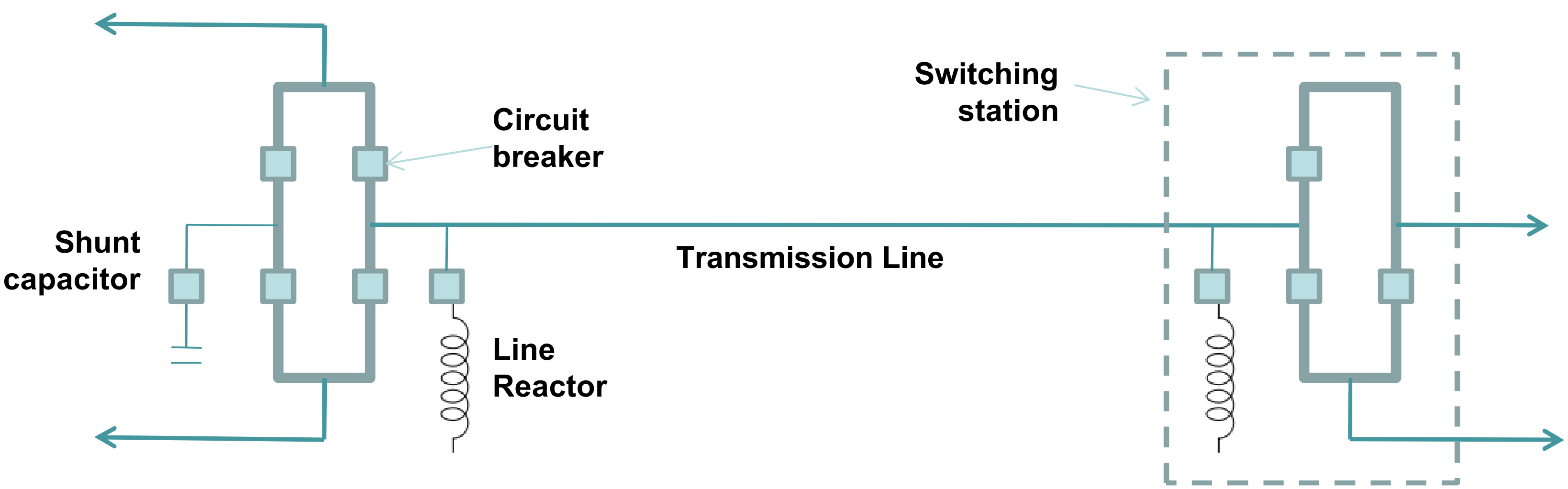


http://www.ansaldovei.ru/eng/3/

Transmission Components

- Voltage support devices
  - Mechanically-switched shunt capacitors, reactors
  - Series capacitor
  - SVC (TSR, TSR, TSC, MSC, MSR)
  - STATCOM





Transmission Development

- Costly, Slow, Difficult
  - 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

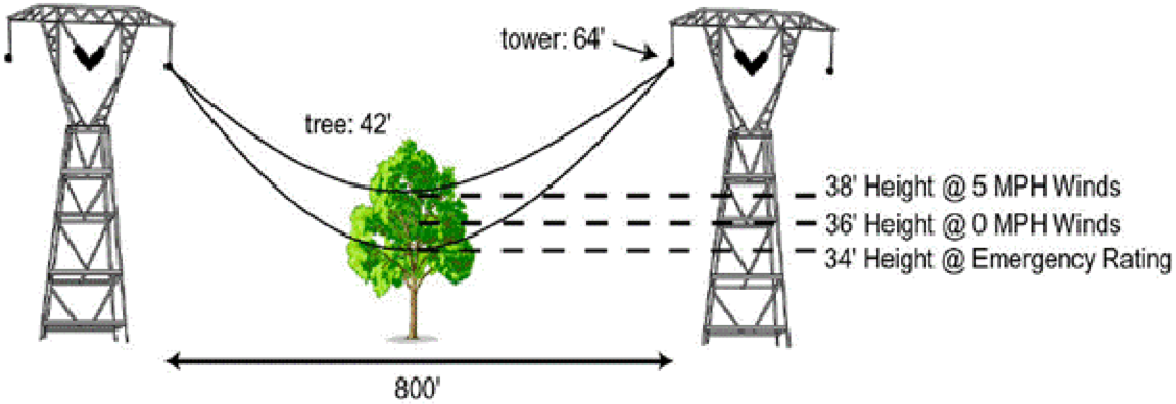
2008 Dollars. Source: EEI

Transmission System Limits

- Thermal/Current Limit
  - Higher loading = higher wire temp. due to electrical losses I^2R
  - Actual conductor temperature depends on factors such as wind speed/direction, solar gain, and ambient temperature
  - Limiting condition is either maximum conductor temperature (~75C for ACSR) or ground clearance (more common)
  - Larger conductor = higher line rating (higher ampacity, lower R)

Typical OH Transmission Line Thermal Rating

Voltage (kV)	Thermal Capacity (MW)
230	500
345	967
500	2,040
765	5,000



Transmission System Limits

- Voltage/reactive power constraints
  - Voltage needs to be within +/-10% of nominal (station equipment limit)
  - AC transmission lines consume *[produce]* reactive power when power transfer is higher *[lower]* the Surge Impedance Loading (SIL)
    - This reactive power imbalance tends to make voltage too high or too low
    - Need to add reactive support (capacitors, reactors) to compensate

$$SIL = \frac{V^2_{rated}}{Z_c}$$

SIL is in MW if V_{rated} is in kV

$$Z_c \approx \sqrt{L / C}$$

Characteristic impedance (lossless line)

L and *C* are inductance and capacitance of the line, respectively (function of line geometry)

Typical OH Transmission Line Rating and SIL

Voltage (kV)	Thermal Capacity (MW)	Surge Impedance Loading (MW)
230	500	140
345	967	420
500	2,040	1,000
765	5,000	2,280

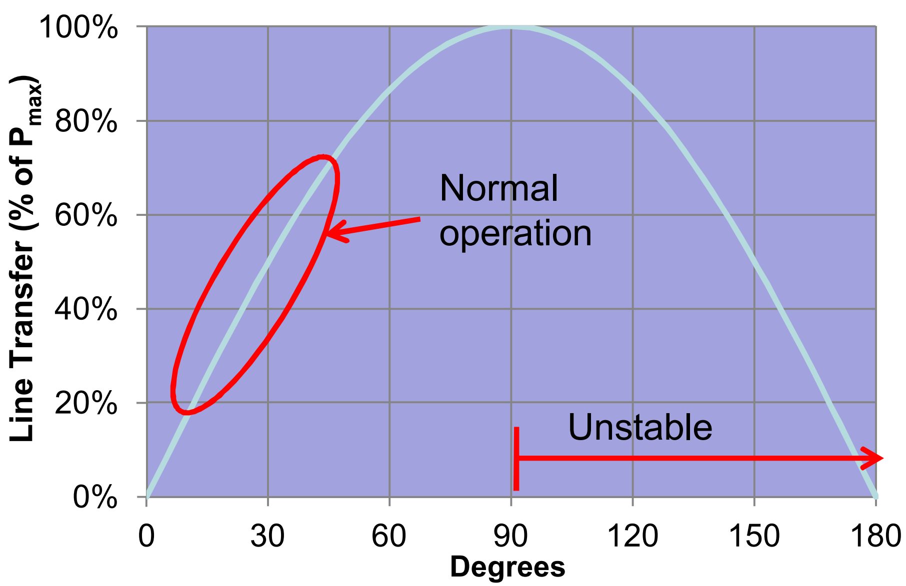
Transmission System Limits

- Angle (small signal) stability
  - Generators connected at the end of the line may “fall out of step” (loose synchronism) when an electrical disturbance occurs
  - Can be an issue when line reactance *(X)* and power transfer are high
  - Limits can be improved capacitive series compensation or FACTS devices

$$P = \frac{V^2}{X}\sin(\delta)$$ $P_{max} = V^2 / X$

$$X = 2\pi f L$$ Line reactance

f is frequency in Hz
δ Is difference in voltage angle across line

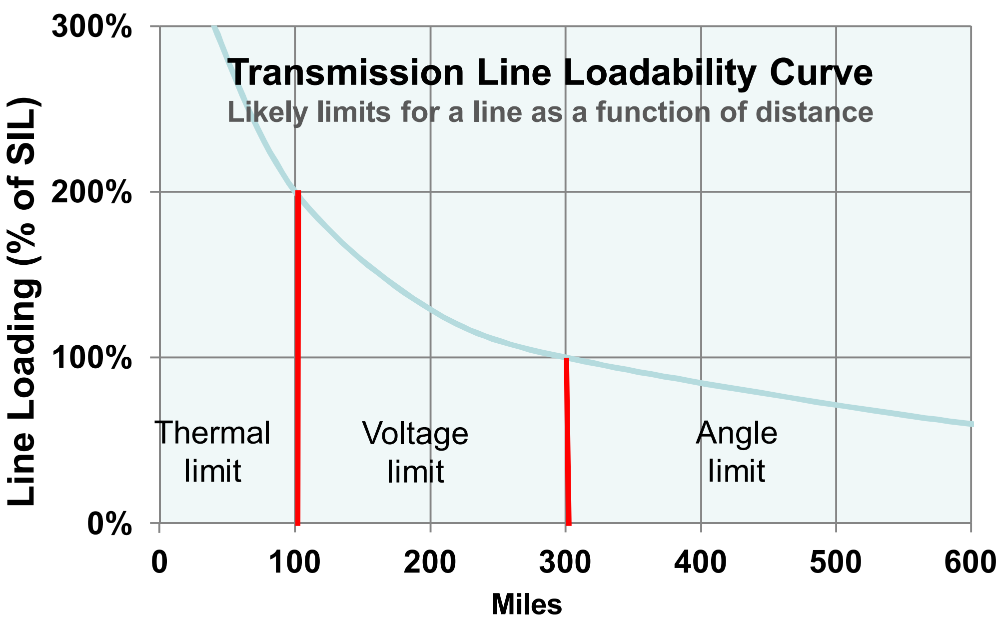


Transmission System Limits

- Line loadability
  - Short lines are often thermally (conductor/sag) limited
  - Longer lines often have voltage/reactive limits – more constraining)
  - Very long lines often have even are angle stability limits – even more constraining!

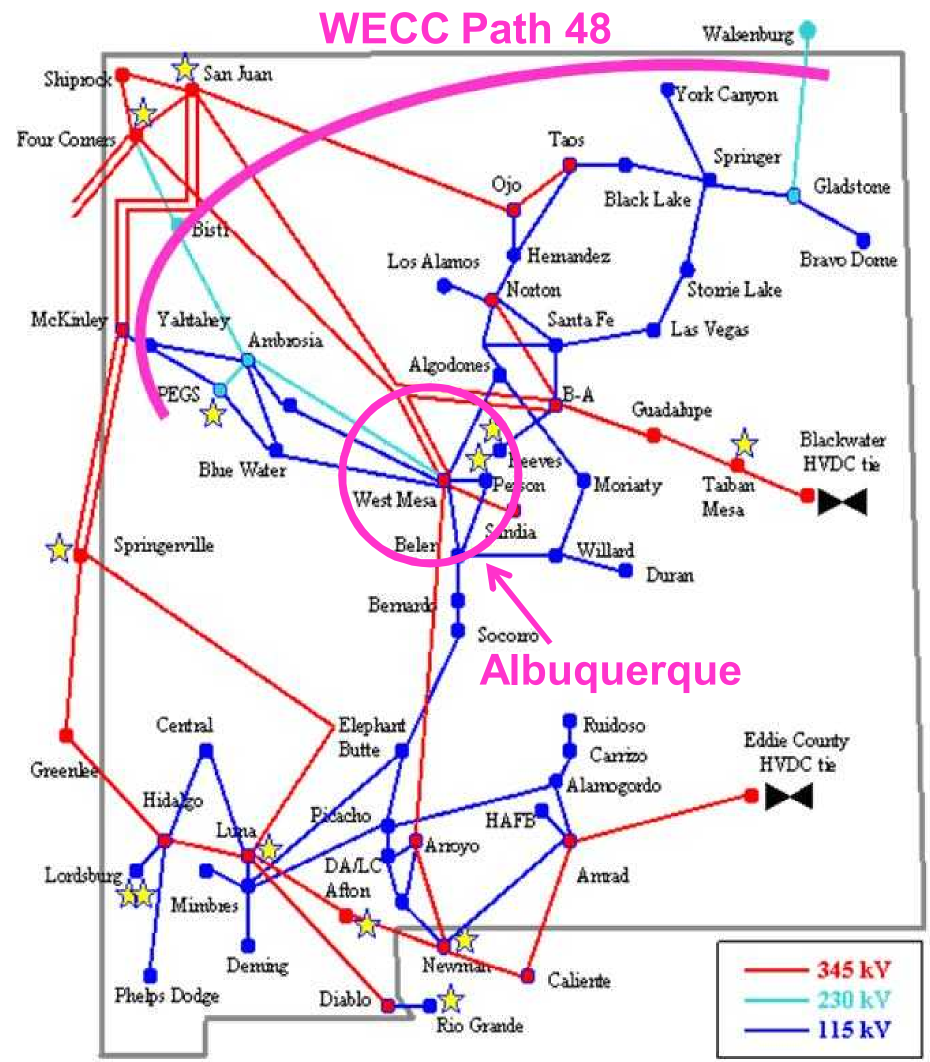
Typical OH Transmission Line Rating and SIL

Voltage (kV)	Thermal Capacity (MW)	Surge Impedance Loading (MW)
230	500	140
345	967	420
500	2,040	1,000
765	5,000	2,280



Transmission System Limits

- Other operating constraints could come into play
  - Contingency security
  - Voltage (load) stability
  - Loop flows and line capacity/ownership rights

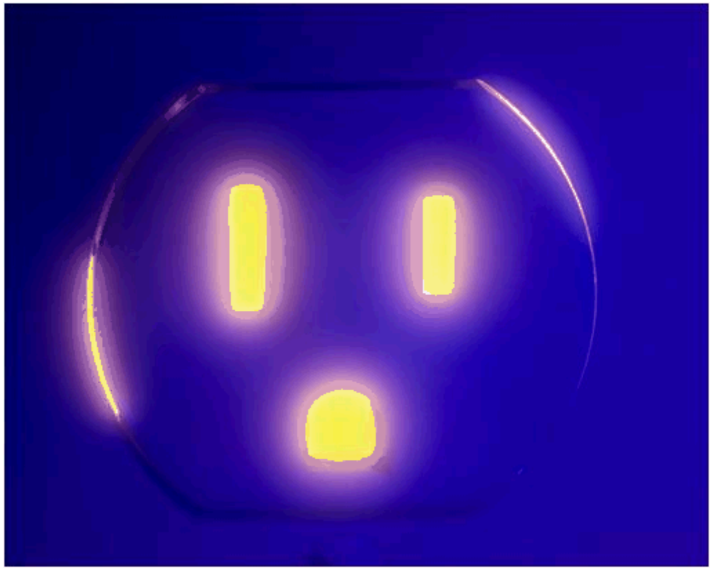


Examples of Operating Limits in NM

- WECC Path 48 is constrained in the import (southbound) direction due to voltage stability
- Flow on the two 345 kV lines feeding Albuquerque is constrained because loss of one line would overload the other
- West Mesa-Arroyo line is limited by contract

Alternative to More Wires

- A "Smart-*er* Grid"
  - Energy efficiency (consumption and production)
  - Demand response (TOU, RTP, Interruptible service, …)
  - Distributed generation (renewable, other)
  - Storage, including thermal
  - Control, communications
  - Equipment performance (generators and other grid gadgets)
  - Regulatory, policy, market mechanisms

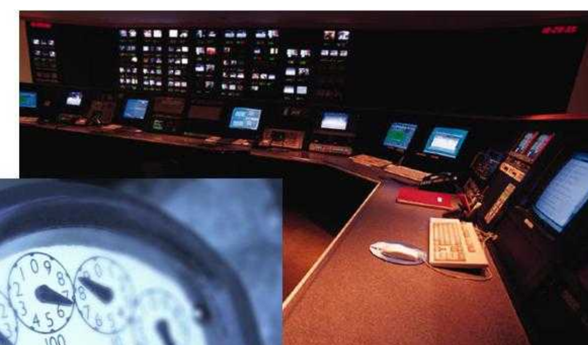


Power System Operations and Renewables Integration Challenge

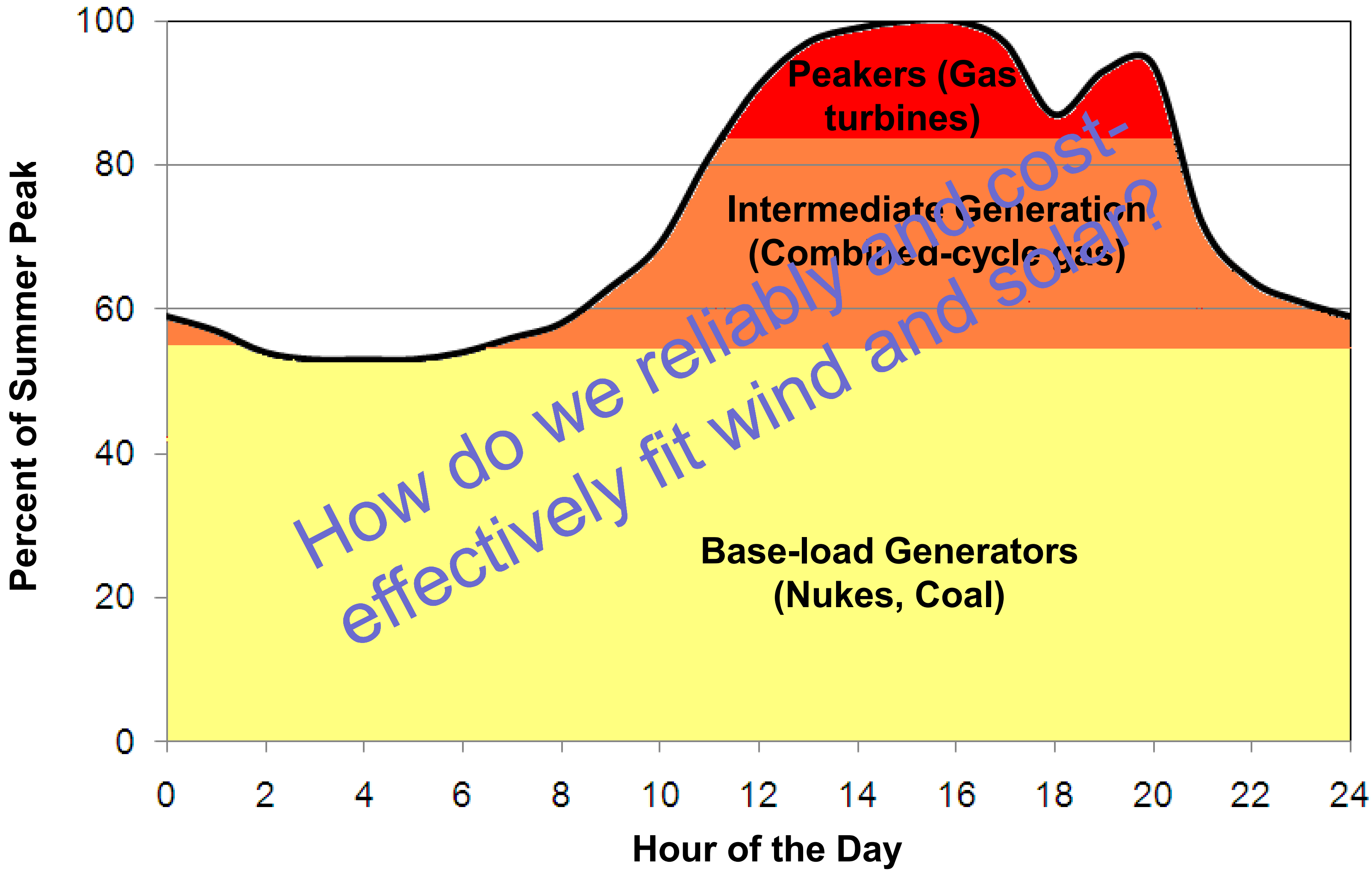
Renewables Grid Integration Challenge

- Can the grid operate reliably with high penetration wind/solar?
- What are the impacts? What is the cost?
- How should we plan and operate the grid to enable high penetration?
- What has to change?

- A closer look from the System Operations perspective follows



Remember this?

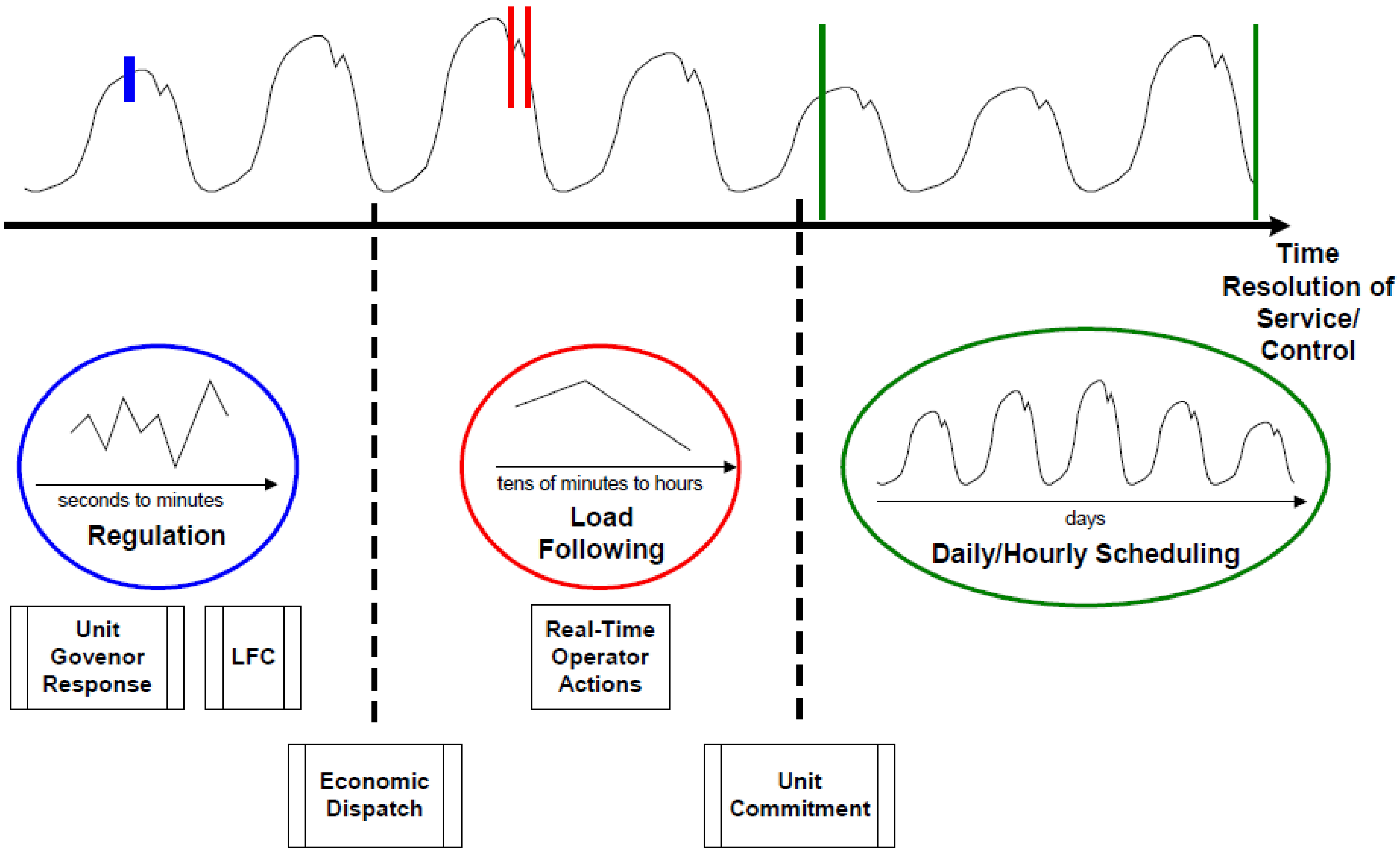


How It Actually Works…

1. Schedule generating units ahead of time to ensure that the load can be met at (very nearly almost) all times
   - Process is called *Unit Commitment*, done hours to days ahead based on
     a. Load and variable generation forecast
     b. Generating unit characteristics (cost, minimum loading, start/stop time, min up/down times, up/down ramping capability, availability)
   - Reserves are generation capacity above forecasted load that needs to be committed to cover for regulation, forecast error, forced outages
     - Can be Spinning or Non-Spinning
2. Operators dispatch units based on actual system needs
   - Process is called *Load Following*
3. Generators adjust output automatically in response to phenomena faster than operators have time to react
   - Regulation, frequency control, voltage control

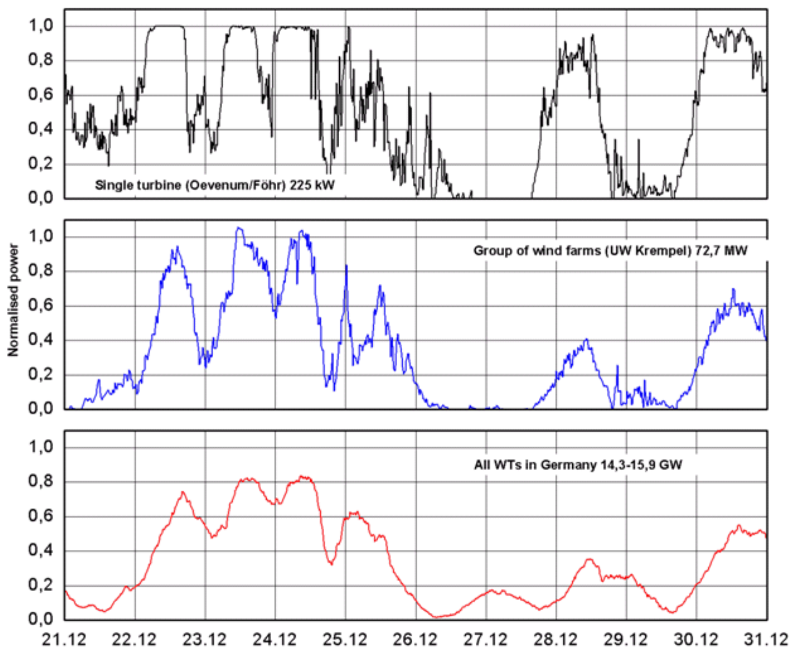
Bulk System Operations

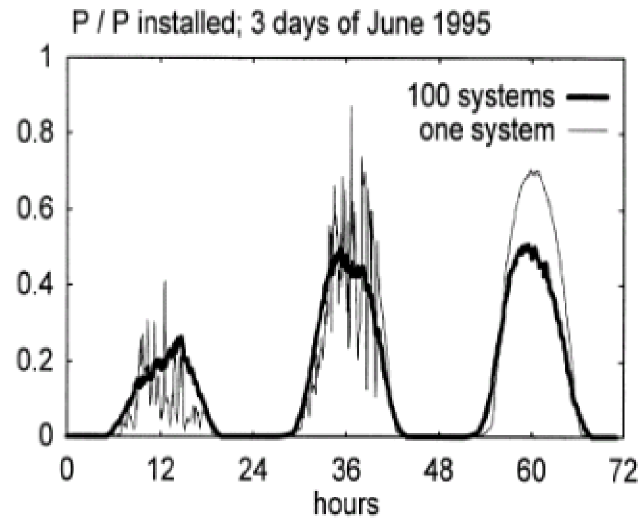
- Scheduling, Load Following and Regulation



Wind/Solar Output is Variable (so is load)

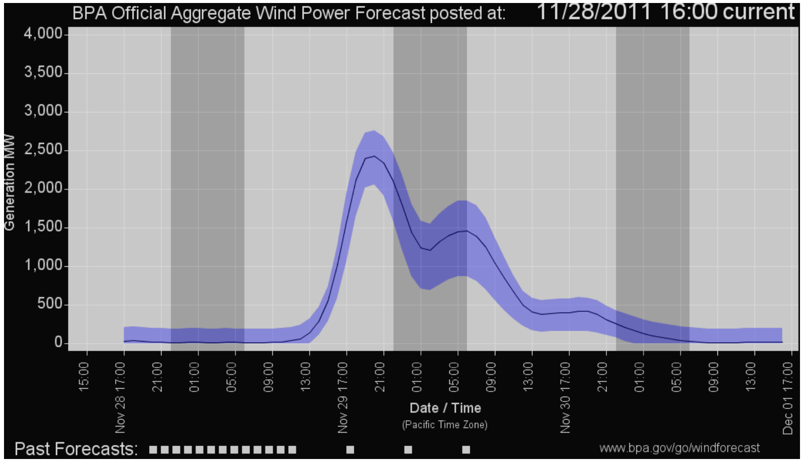
- Variability refers to changes in wind generation output (magnitude and frequency) over time
  - Geographic diversity and plant footprint reduces variability (smoothing effect)
  - Smoothing effect is greatest in the short time frames



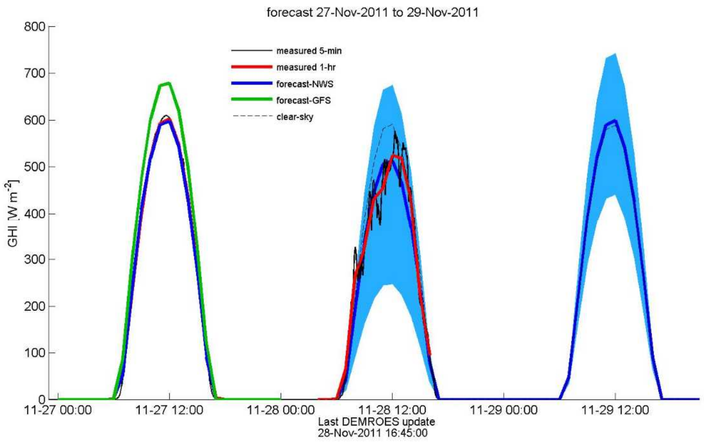


Wind/Solar Output is Uncertain (so is load)

- Uncertainty refers to inability to precisely predict wind or solar output ahead of time
  - Several methods to forecast, some commercial, for both wind and solar
  - Forecasting has significant benefit in high penetration scenarios
  - How to present the information to operators is critical
    - Need to show prediction as well as describe meaning (confidence intervals)



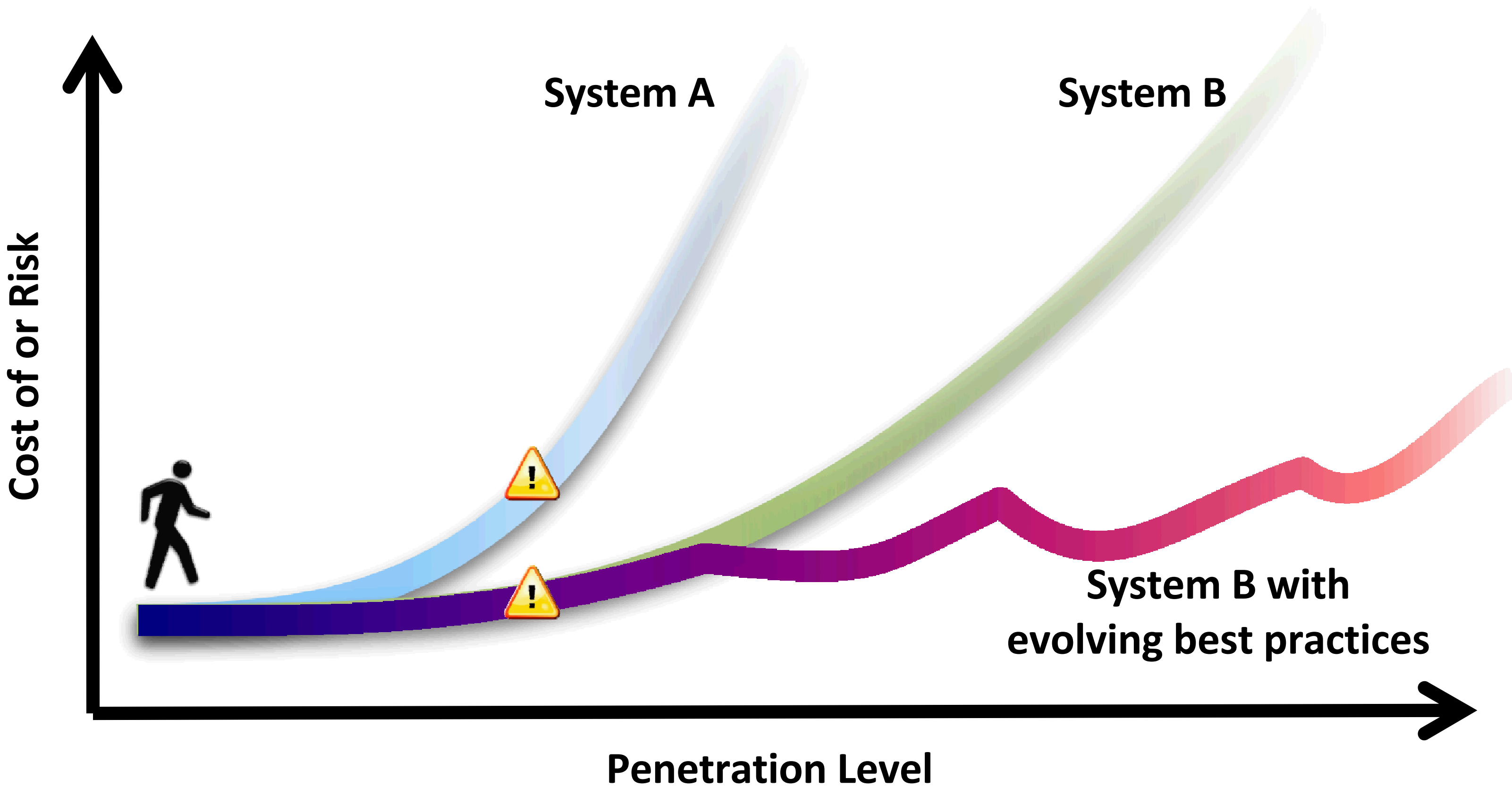
Source: http://transmission.bpa.gov/Business/Operations/Wind/forecast/forecast.aspx



Source: http://solar.ucsd.edu/lave/

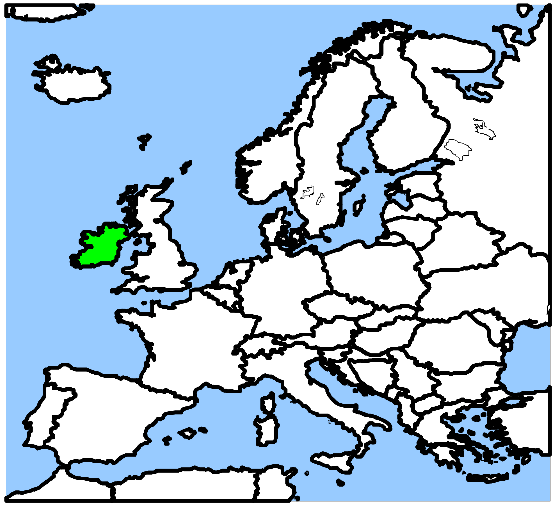
Are There Penetration Limits?

- There are no absolute technical limits to integration of variable generation on any system
  - It all boils down to cost, and the impacts are system-specific



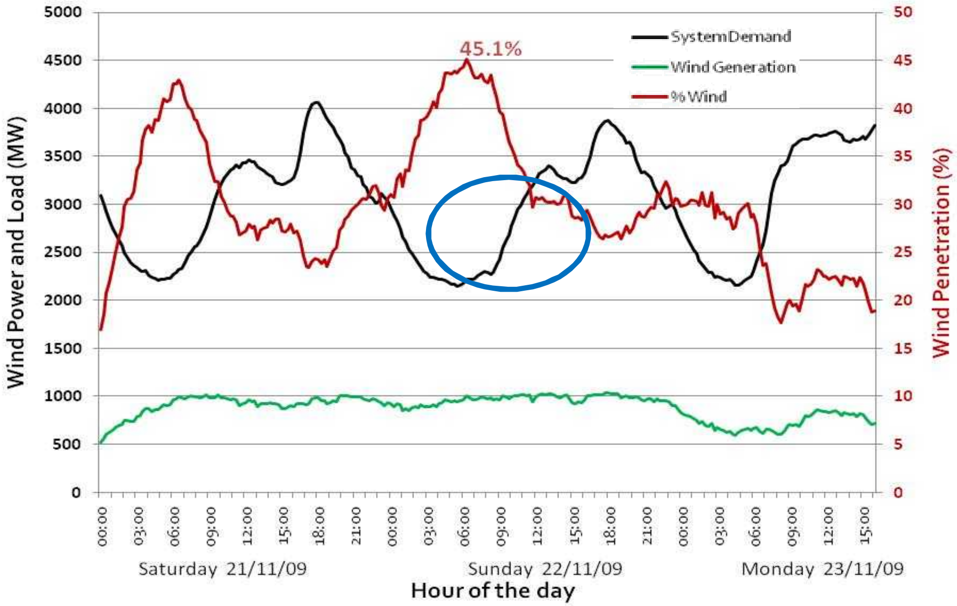
Example of High Penetration

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

What do we mean by Integration Cost?

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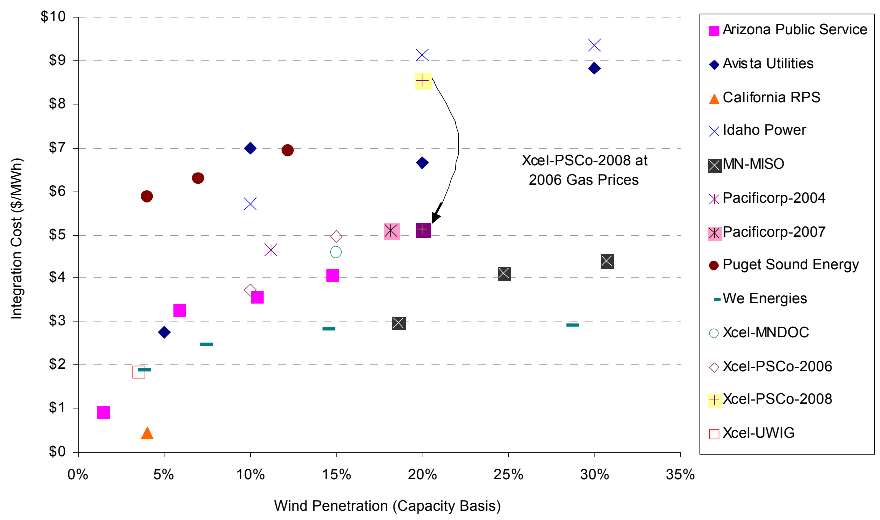
- **Depends how** "cost" is defined
  - Cost of having to deploy additional reserves to manage variability + cost of sub-optimal unit commitment due to uncertainty



Source: LBL

  - **Plus (arguably)…** cost of renewable generation, cost of additional transmission, …
  - **But consider also…** fuel savings, lower emissions, lower water usage, energy security, …

Questions and/or Answers