Short Course

Renewable Energy Integration

Introduction to Power Systems

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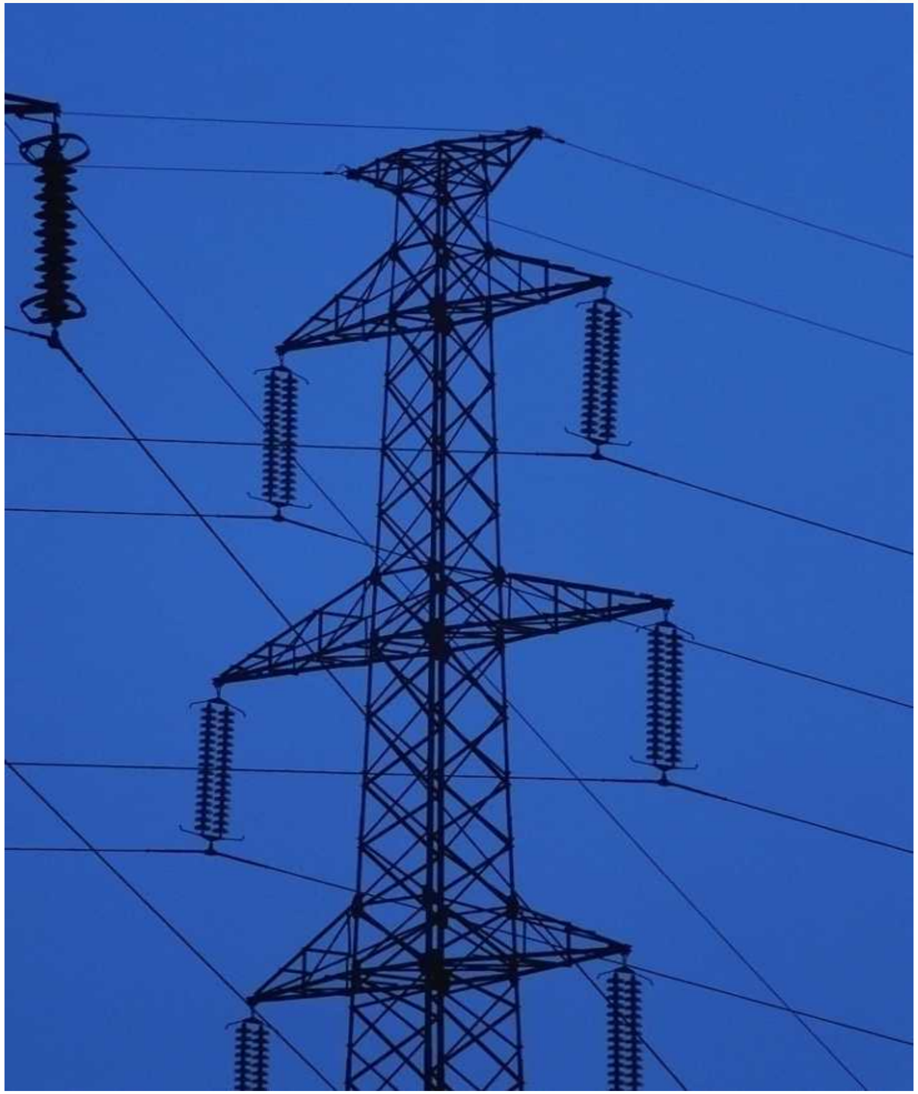
Topics



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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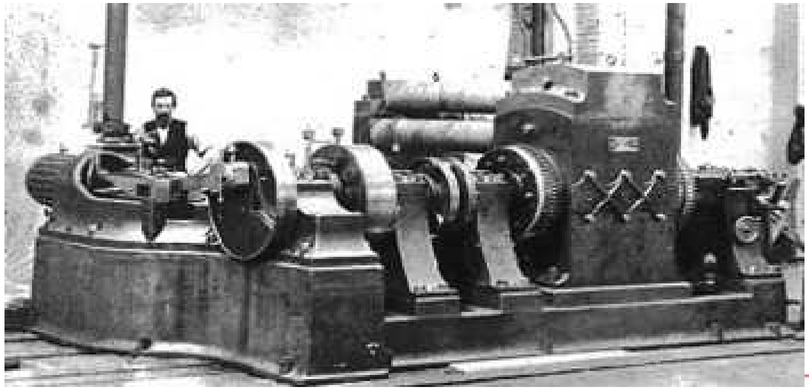
The Early Days

- 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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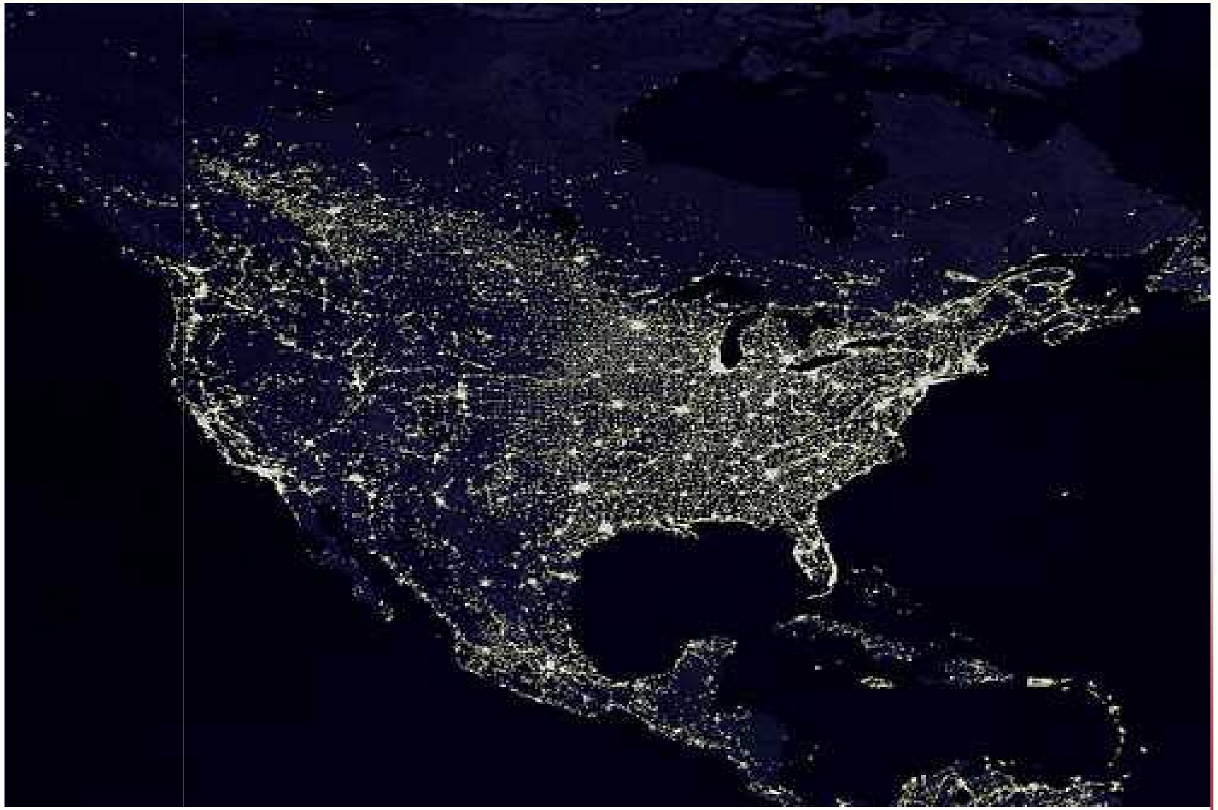
The Power System

- 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!

Basic Concepts

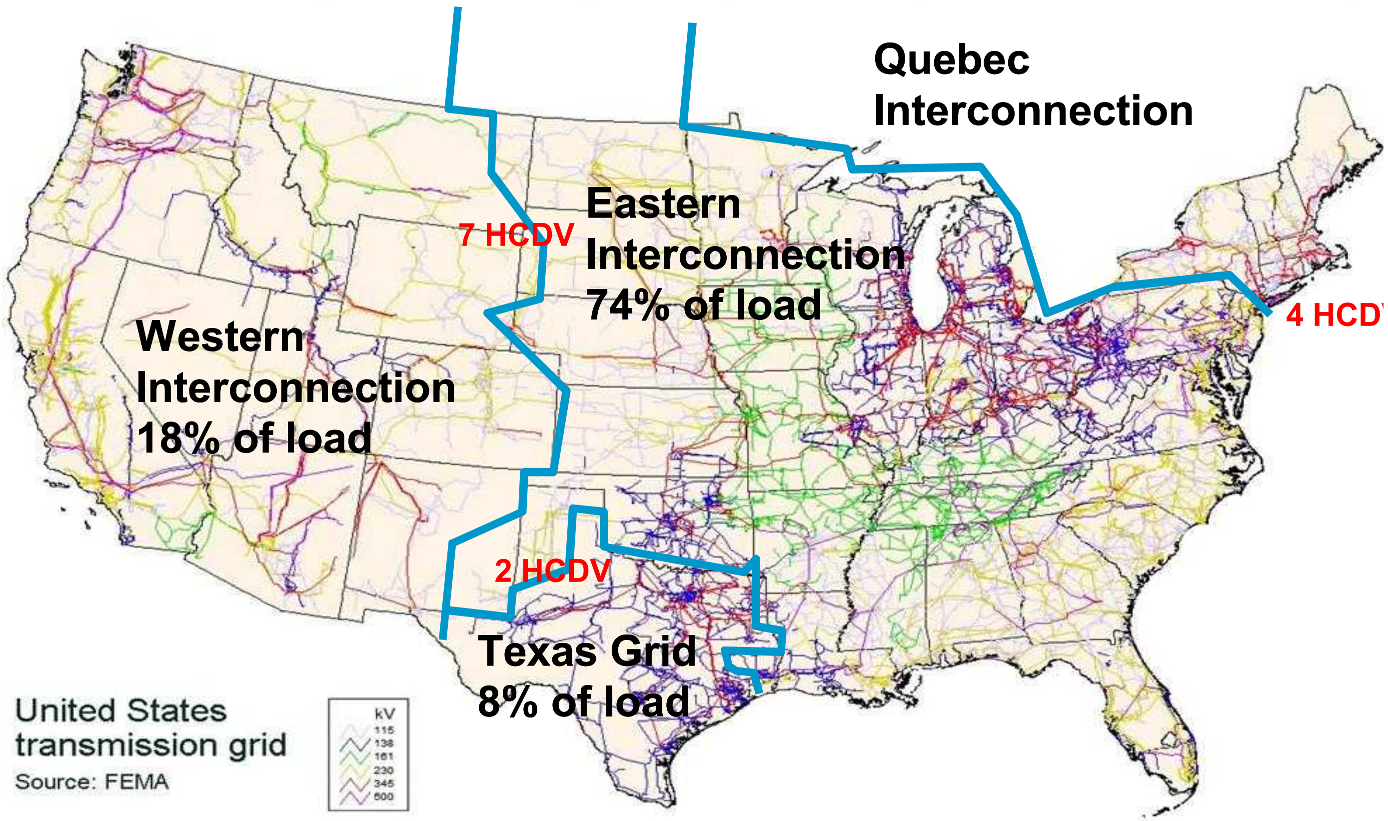
- Voltage and Current
  - Voltage [V] is equivalent to pressure
    - Excessive pressure, house could fail (“leak”)
    - Excessive voltage, insulators could fail (“fault”)
  - Current [A] is equivalent to flow
    - High flow heats the hose (friction)
    - High current heats the wires (resistance)

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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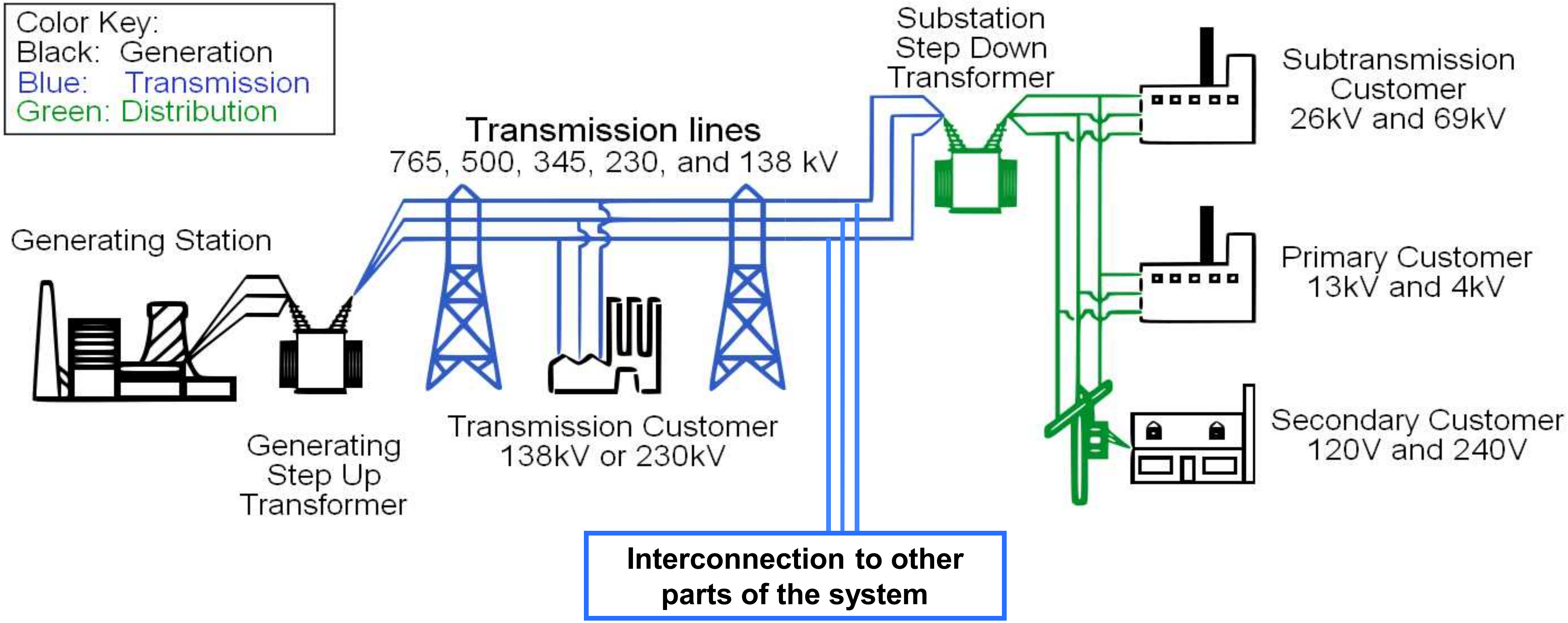
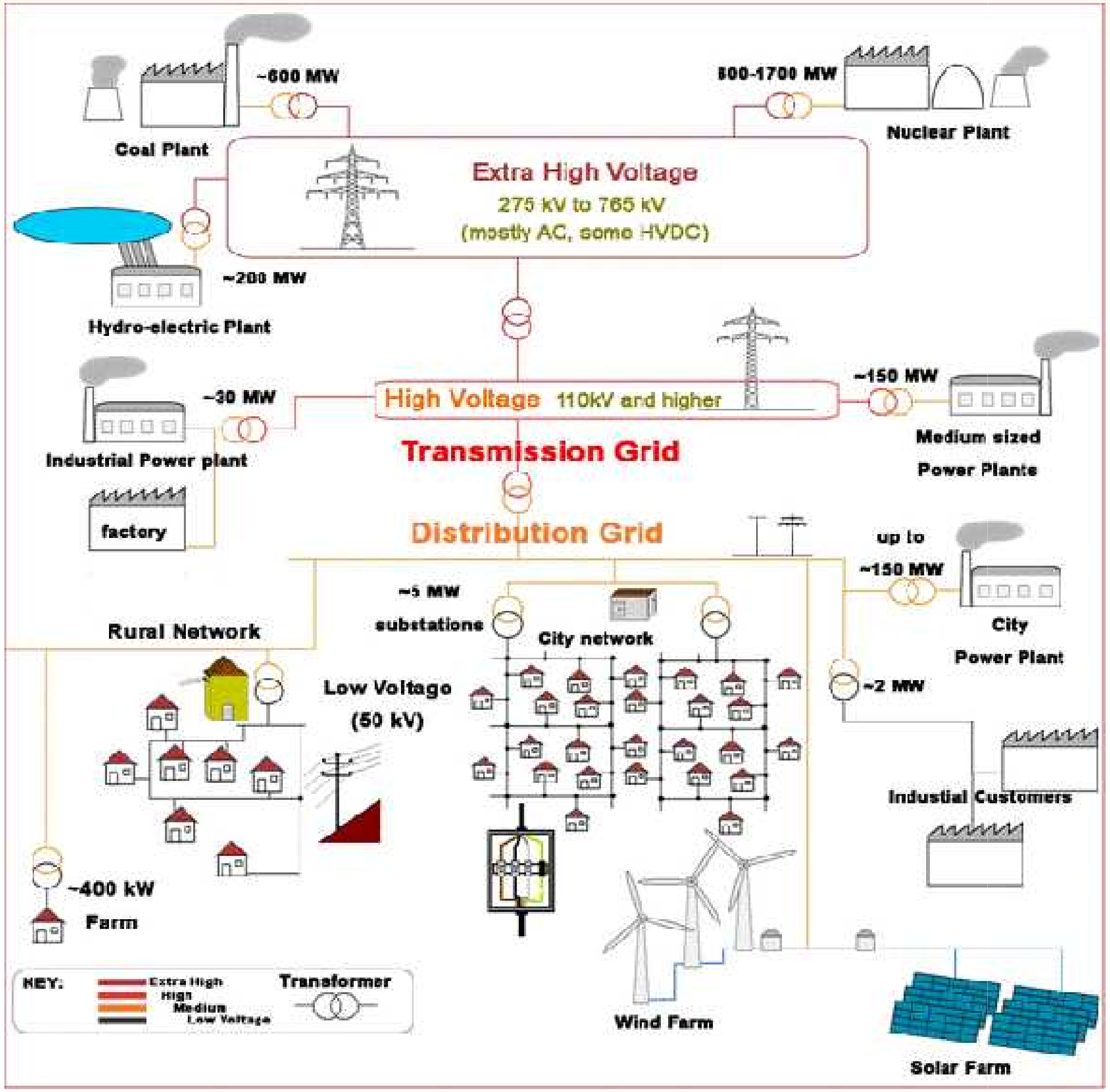
Power System Structure



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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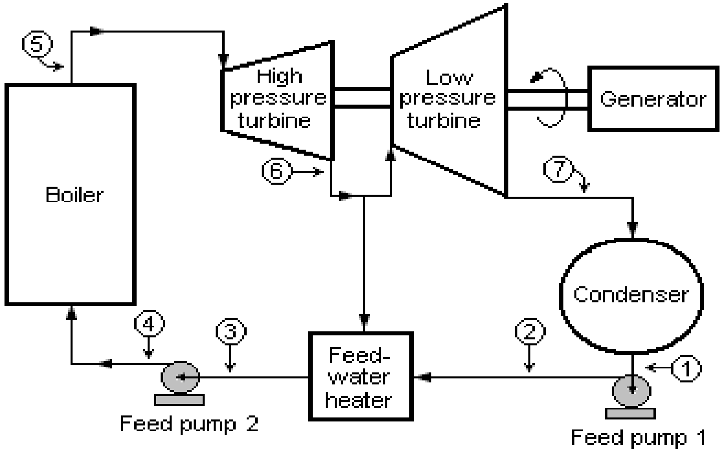
Power System Components

- 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)



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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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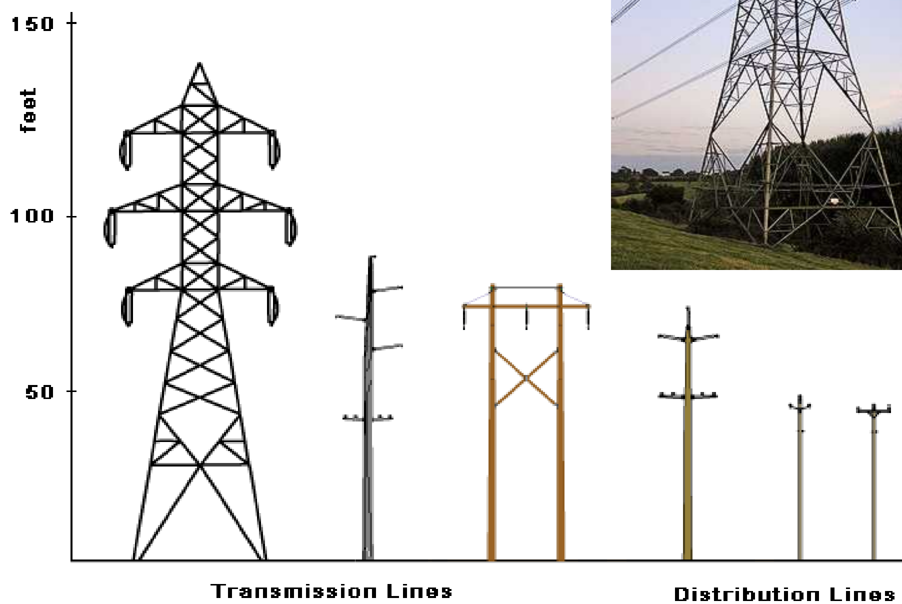
Power System Components

- 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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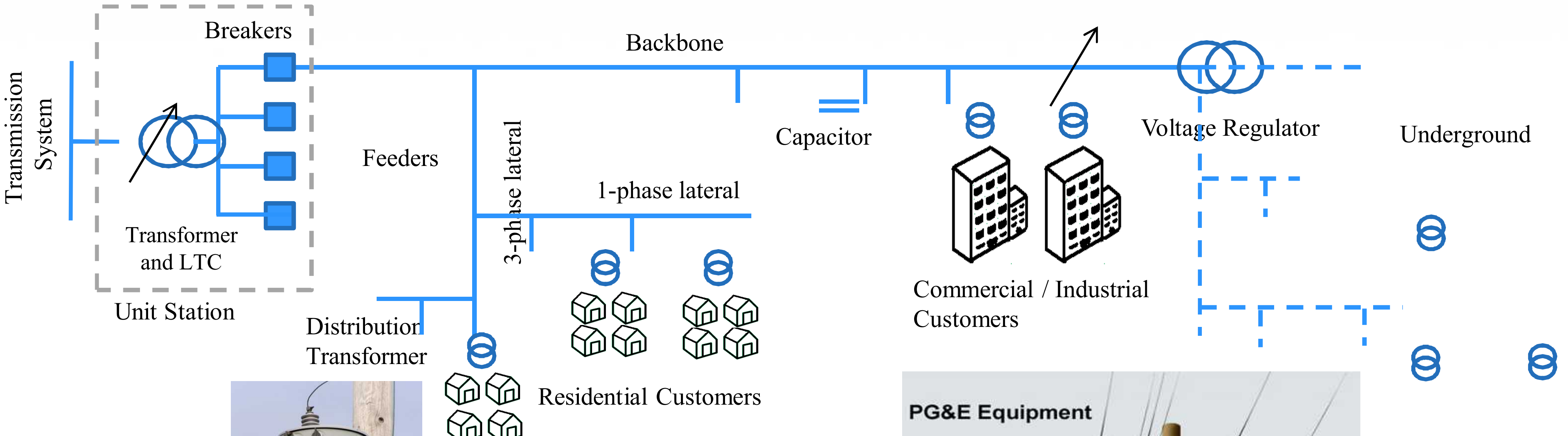
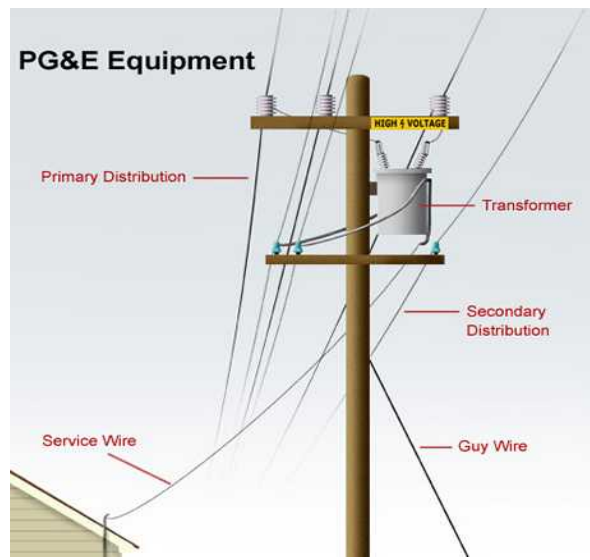
Power System Components

- 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)

Power System Components

- **Distribution System Structure and Components**





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

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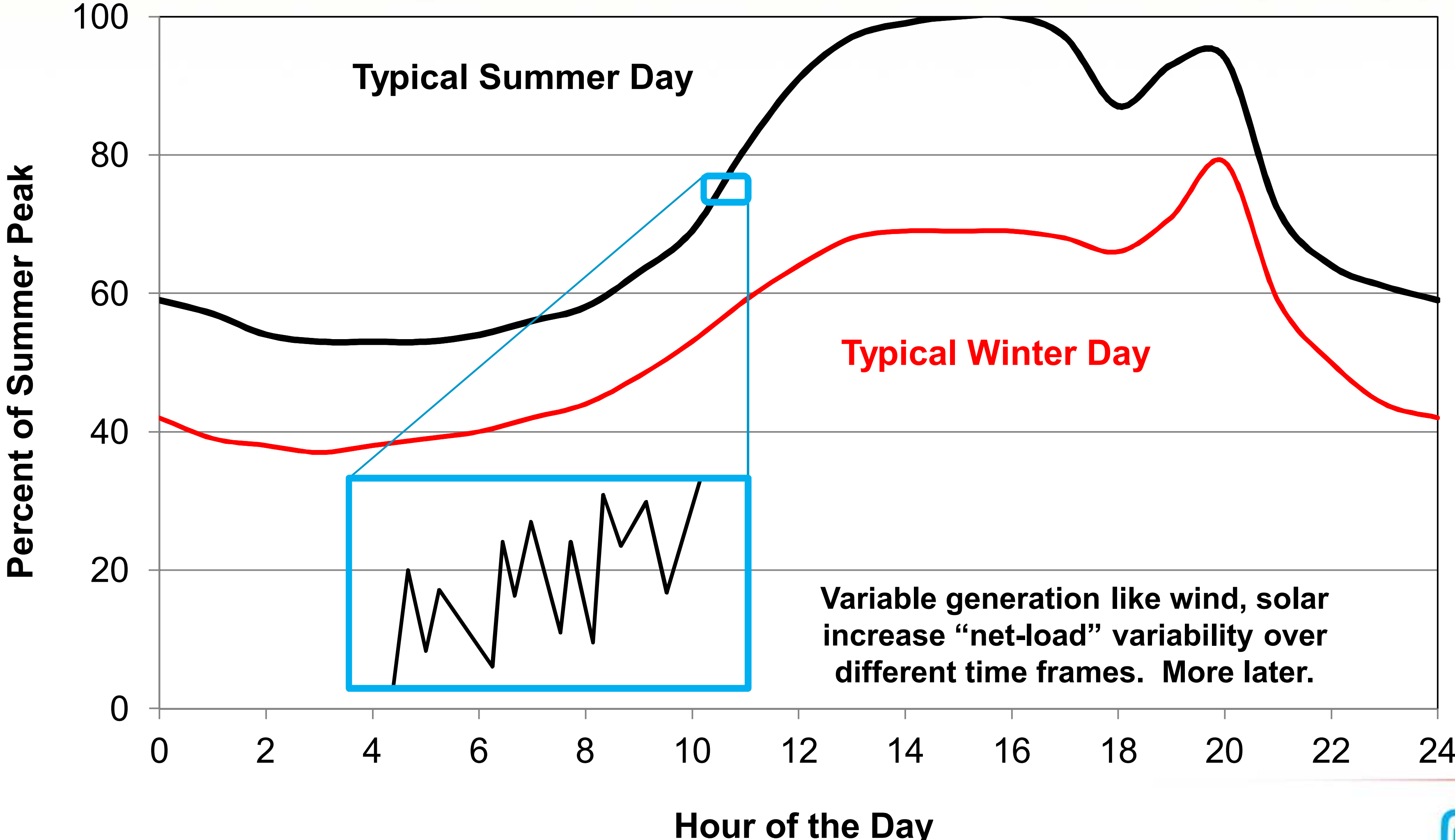
Maintaining Generation – Load Balance



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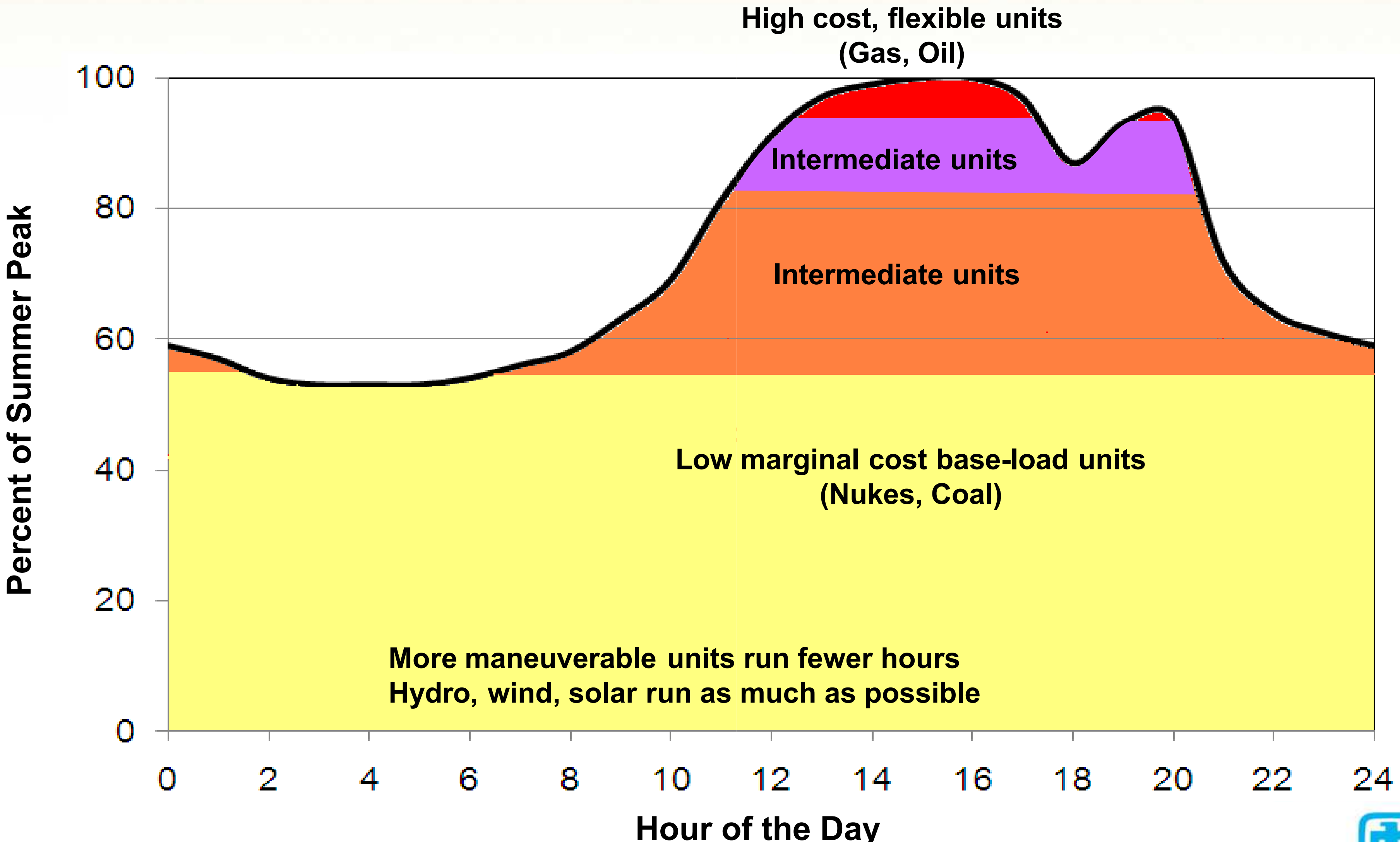
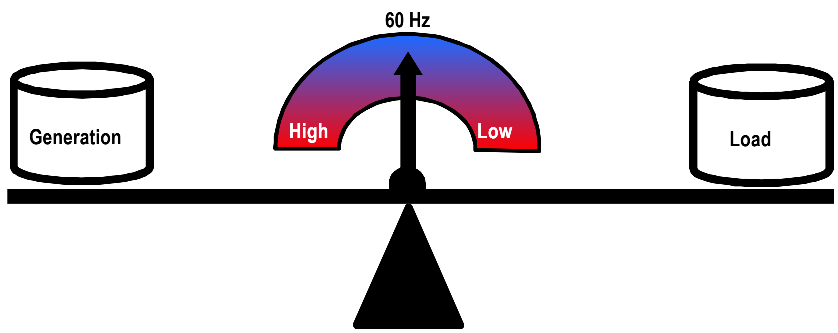
Maintaining Generation – Load Balance



Power System Operations

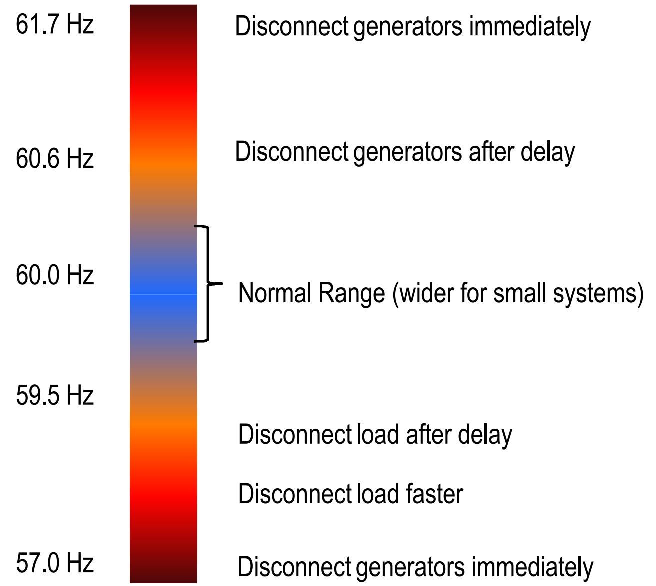
- Work with available/accessible system assets
- Operate within physical limits
  - Maintain voltage and current within equipment specifications
  - Balance overall load and generation to maintain system frequency



- 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)**



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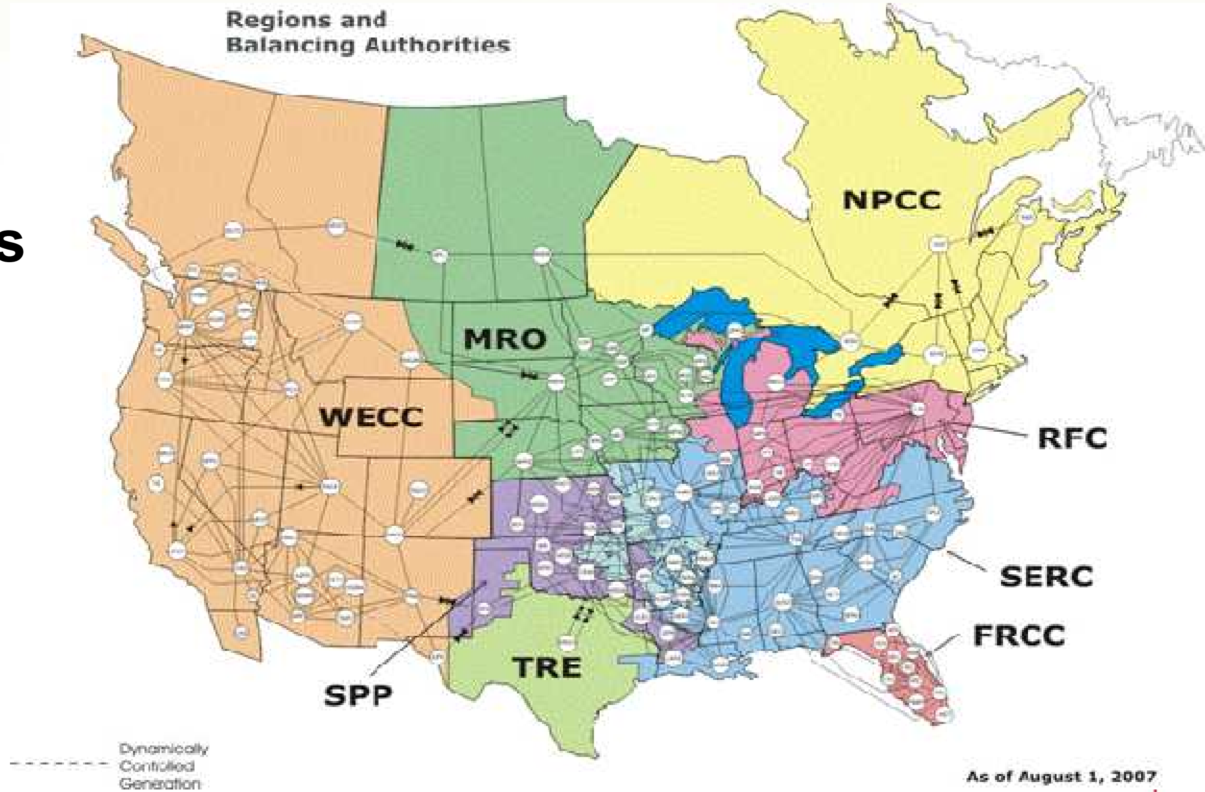
Maintaining Generation – Load Balance

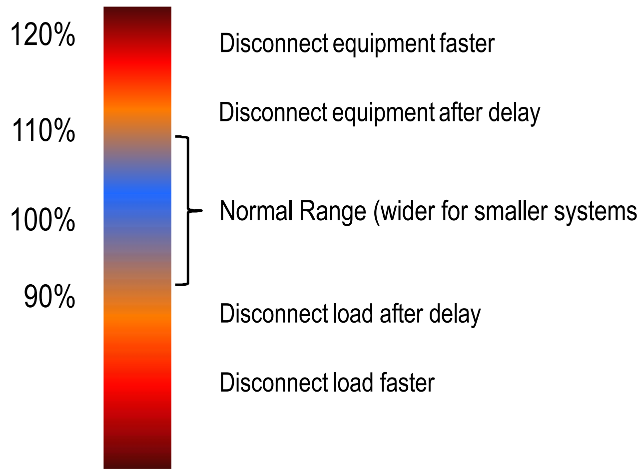
- **BA functions**
  - Maintain desired level of interchange with other BAs
  - Balance demand (load) & supply (generation)
  - Support interconnection frequency
- **Larger BAs are generally more efficient**
  - More generation flexibility
  - BA consolidation being explored in some areas



Source: NERC

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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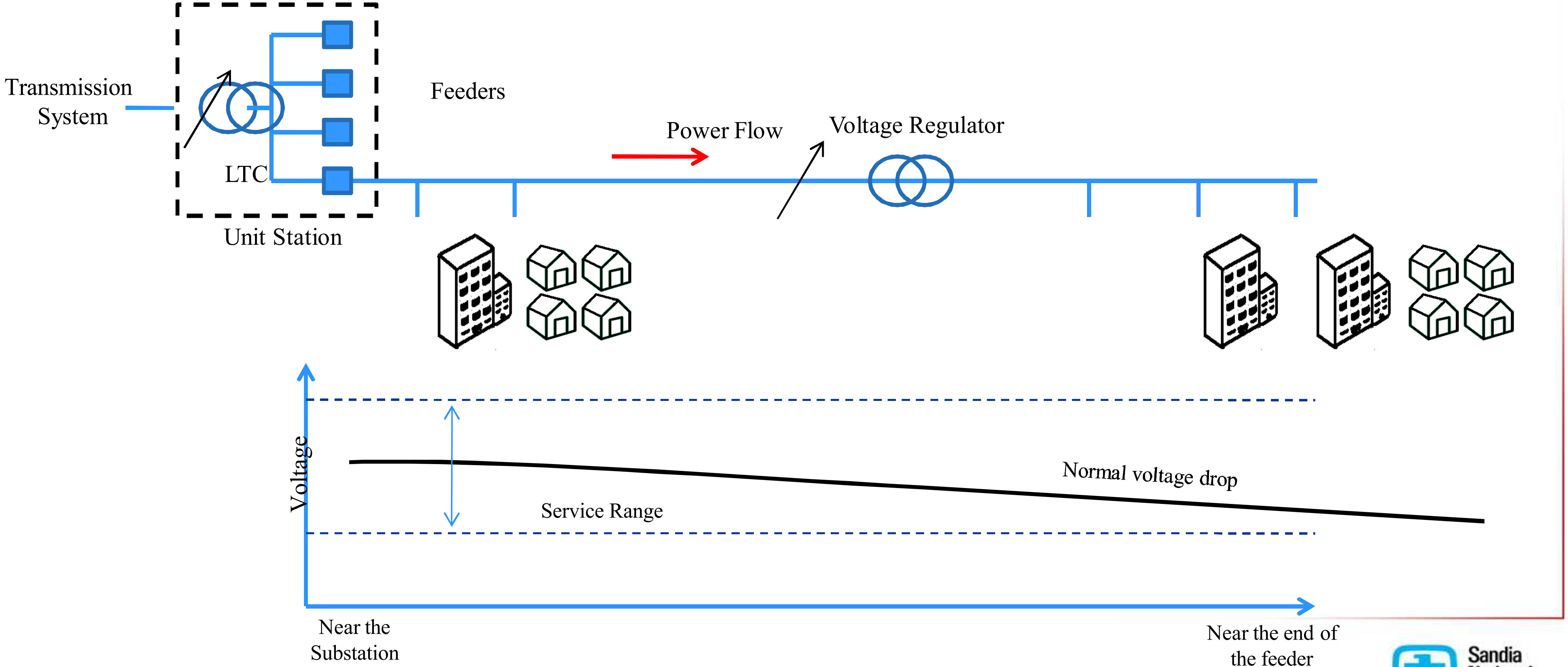
Maintaining System Voltage

- **Distribution System – Feeder**



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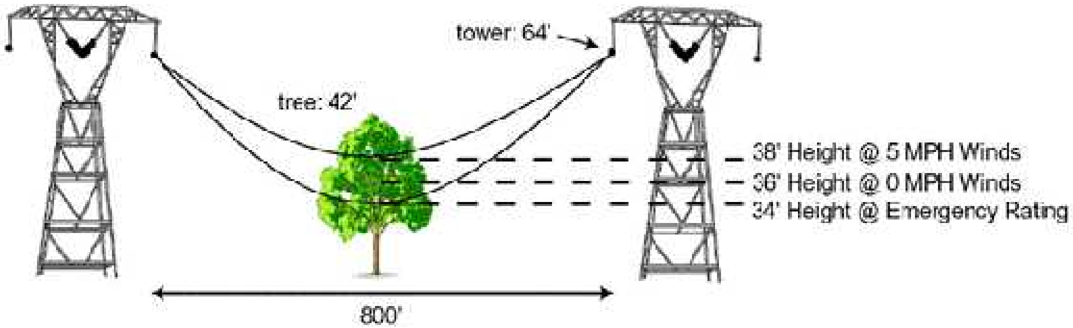
System Contingencies

- 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

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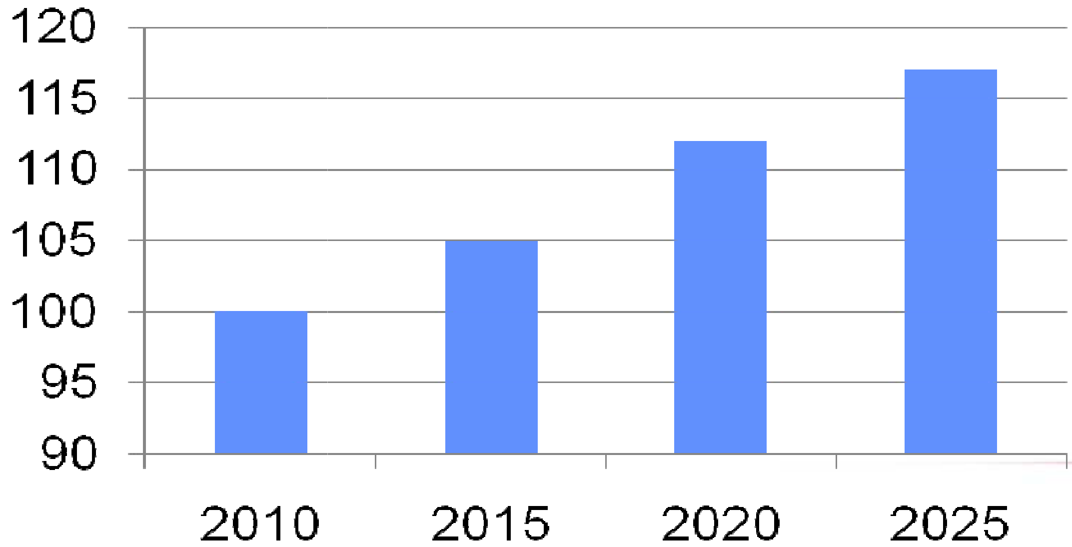
Generation Planning

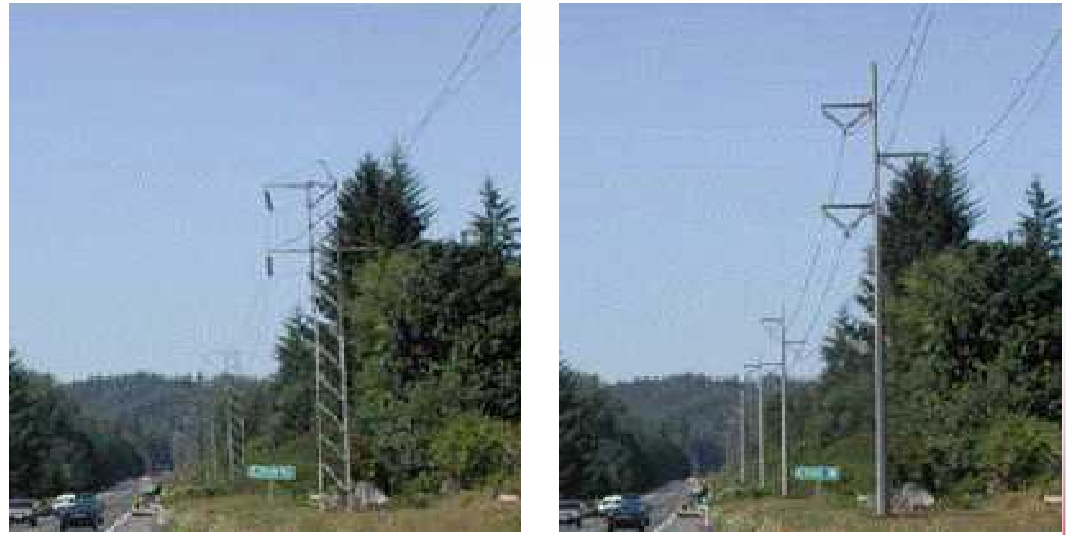
- Key considerations
  - Forecasted load growth
  - Generation reserve requirements
  - Unit retirements
  - Policy guidelines (e.g., energy efficiency, RPS)
  - Availability/feasibility of transmission
  - Many others



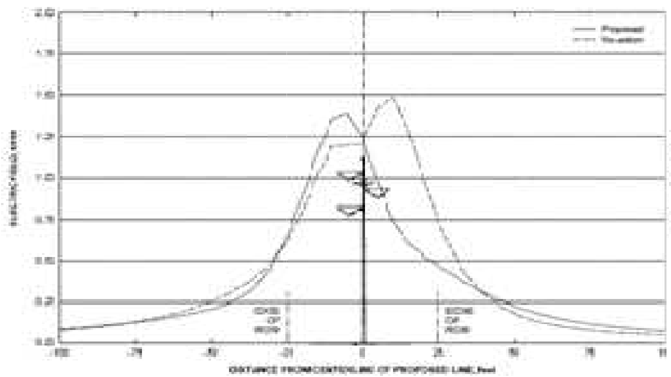
Transmission Development

- **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

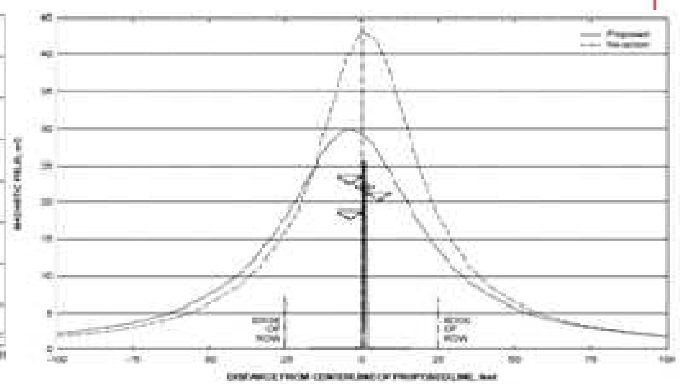
Sample 115 kV line rebuild project



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

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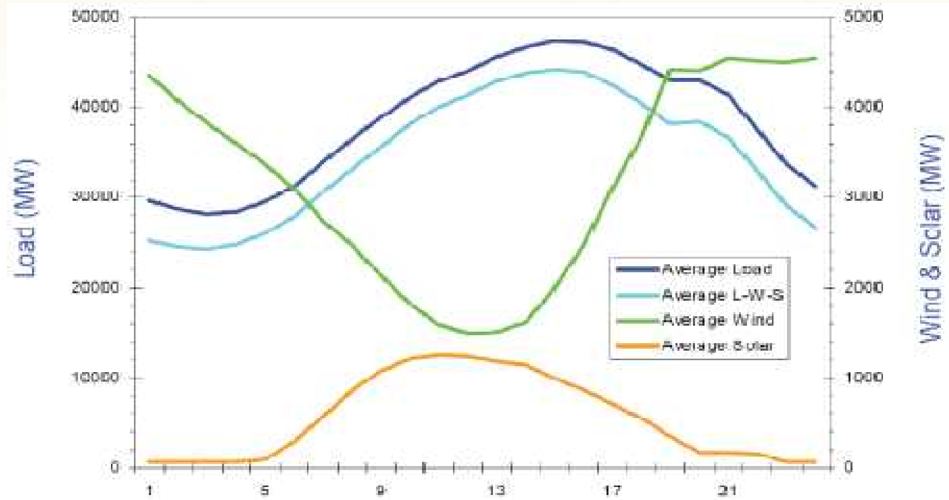
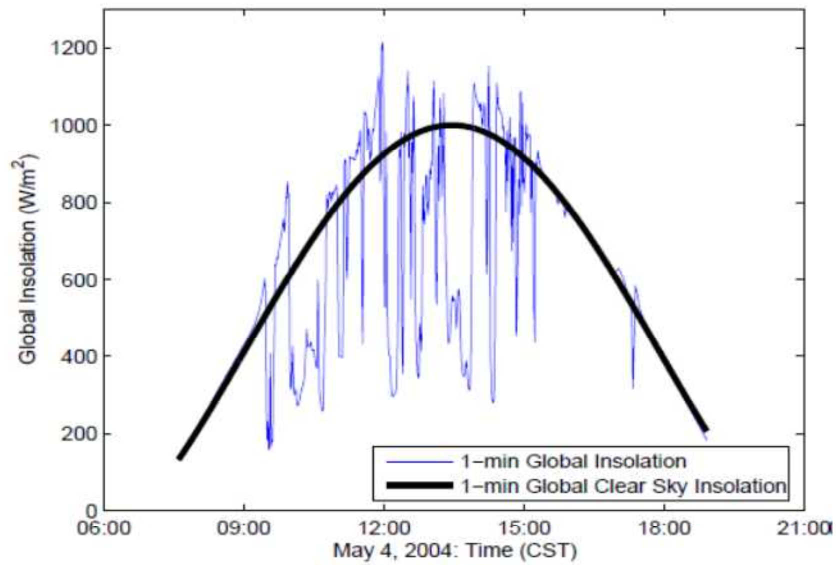
What is Variable Generation?

- 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



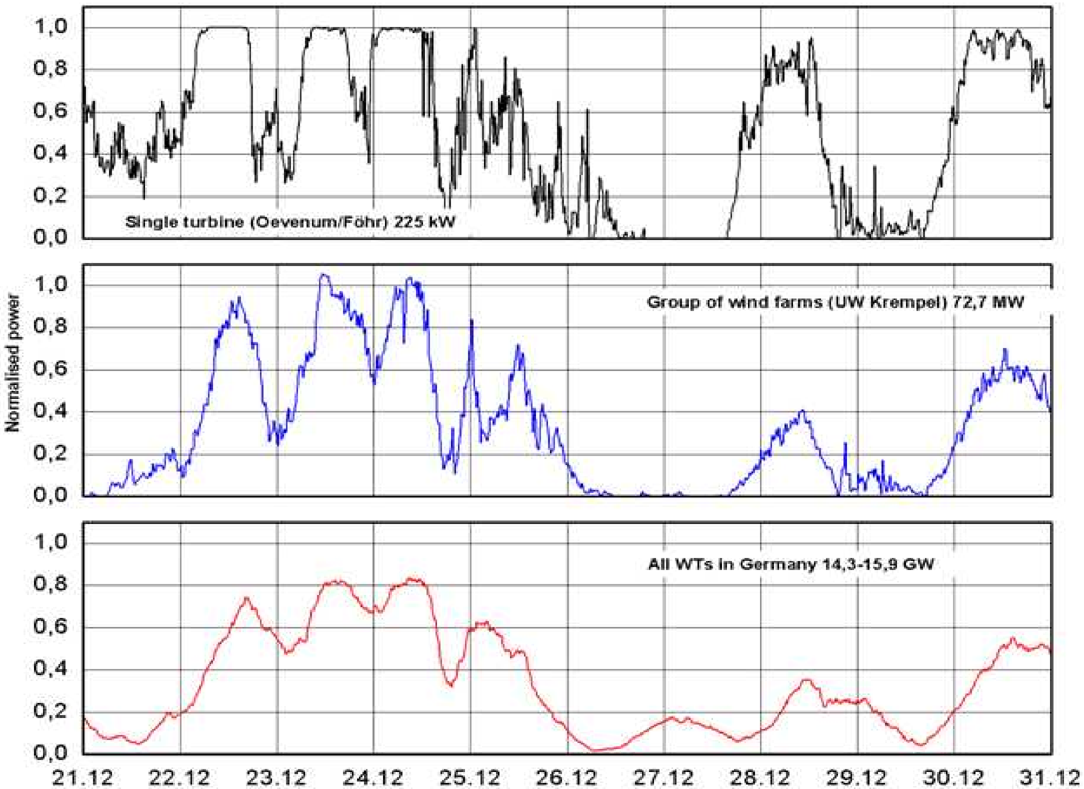
Average PV and wind output patterns in CA



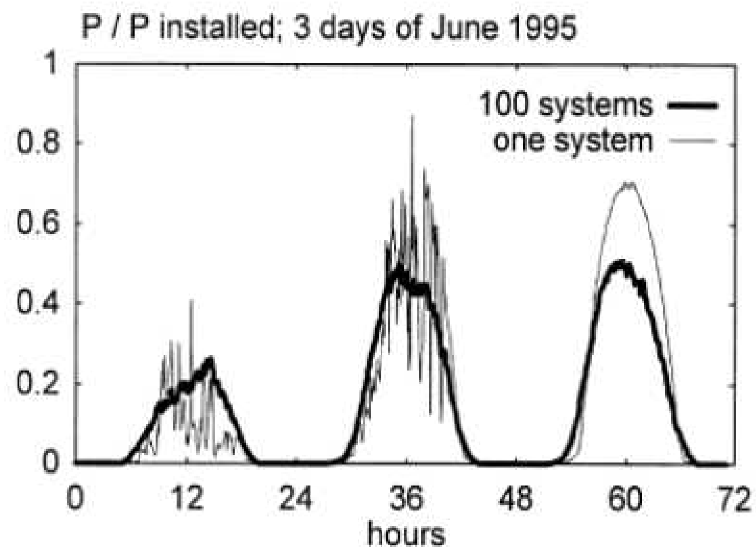
Variable Generation

- **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

* Most commonly used definition

- From the bulk system point of view
  - Annual VG Energy / Annual Load Energy*
  - VG Capacity / Peak Load or Minimum Load

- 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

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

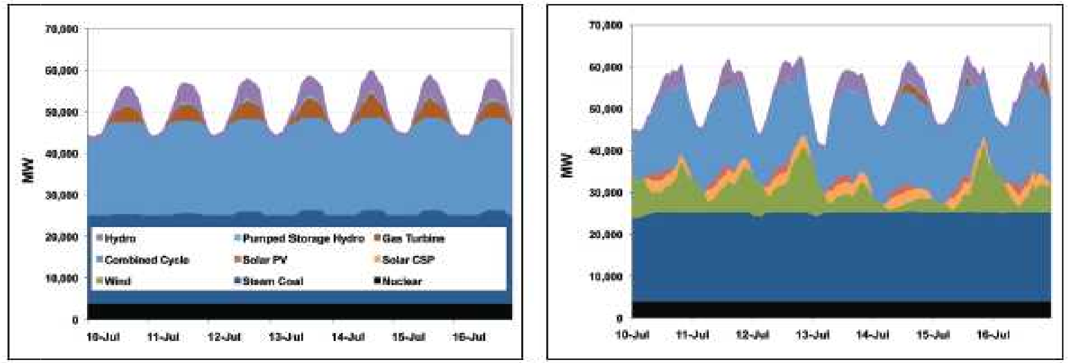


Figure 3 – 35% renewables have a minor impact on other generators during an easy week in July, 2006. WestConnect dispatch - no renewables (left) and 30% case (right)

“Hard” Week

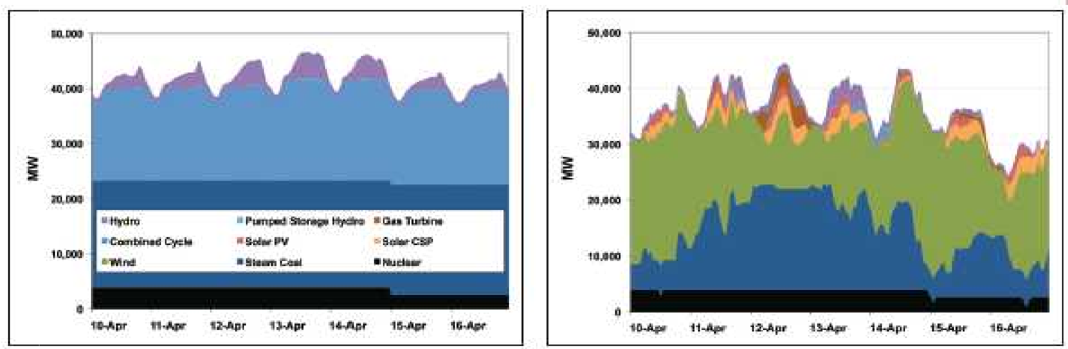
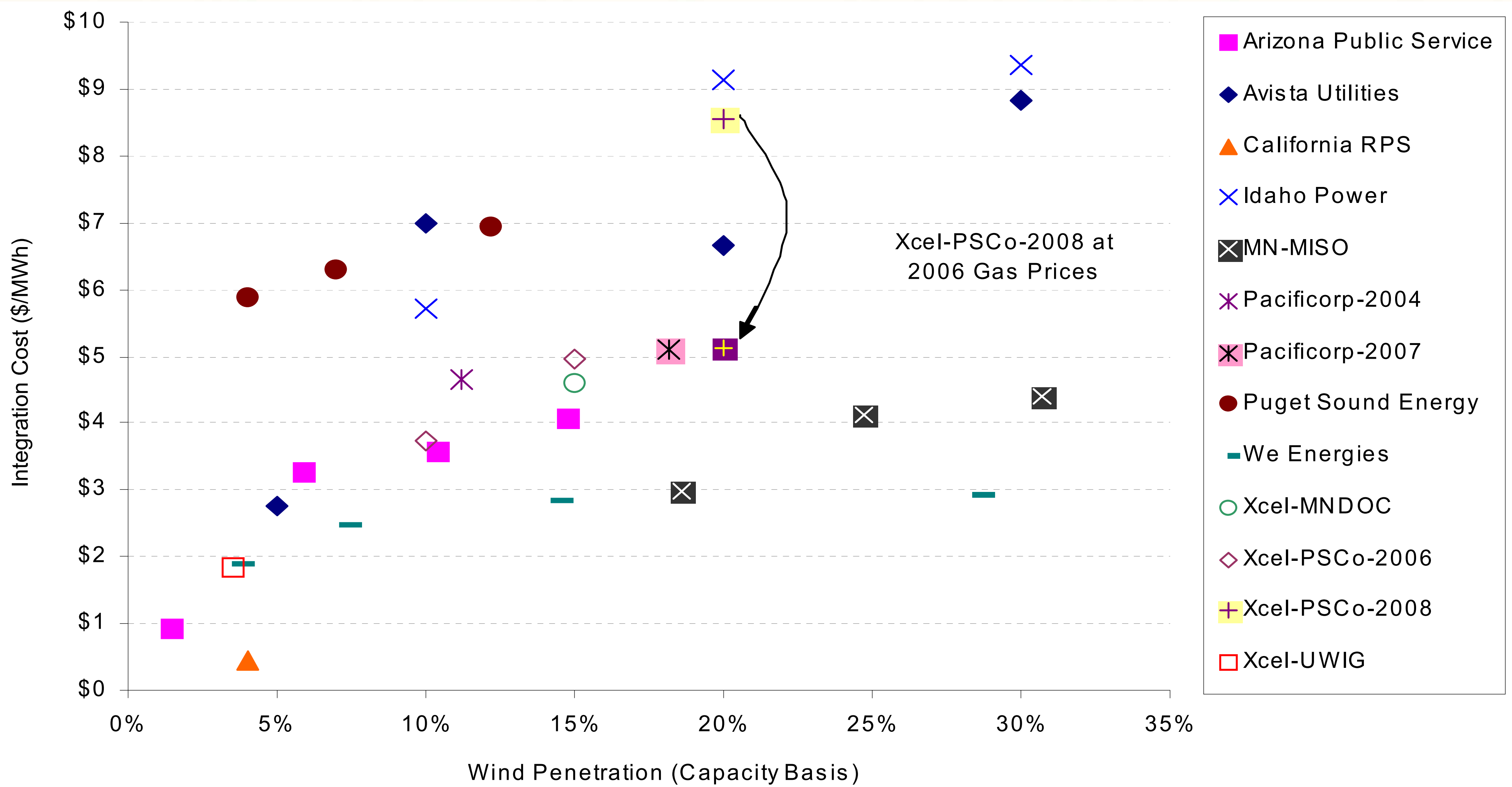


Figure 4 – 35% renewables have a significant impact on other generation during the hardest week of the three years (mid-April 2006). WestConnect dispatch - no renewables (left) and 30% case (right)

Figures from Western Wind and Solar Integration Study, 2010

Increase in Operating Cost



Source: LBL

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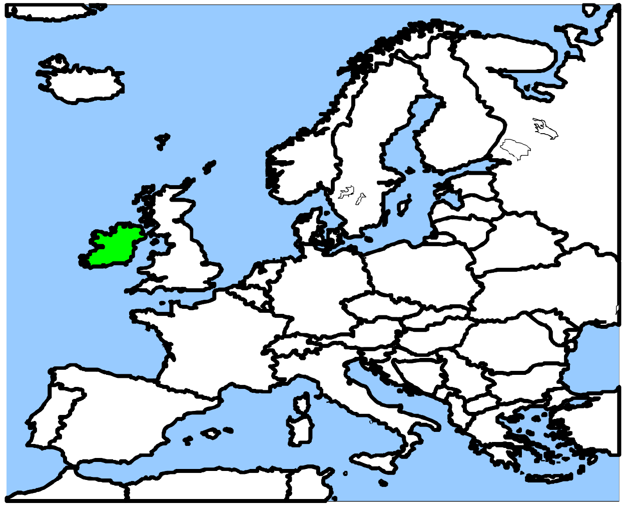
Other Bulk System Operation Issues

- 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

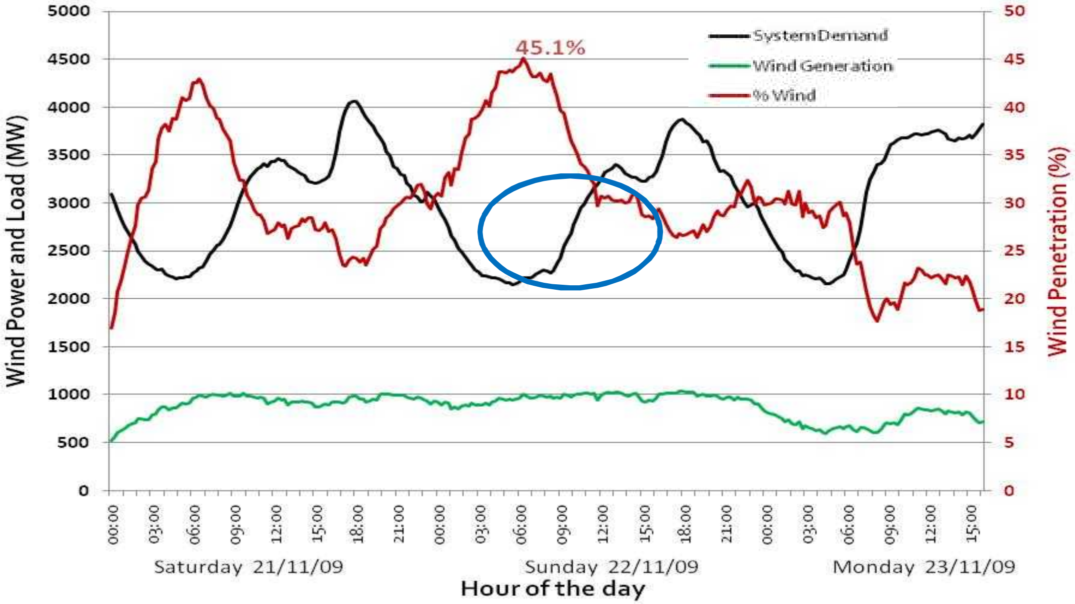
Examples of Very High Penetration

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

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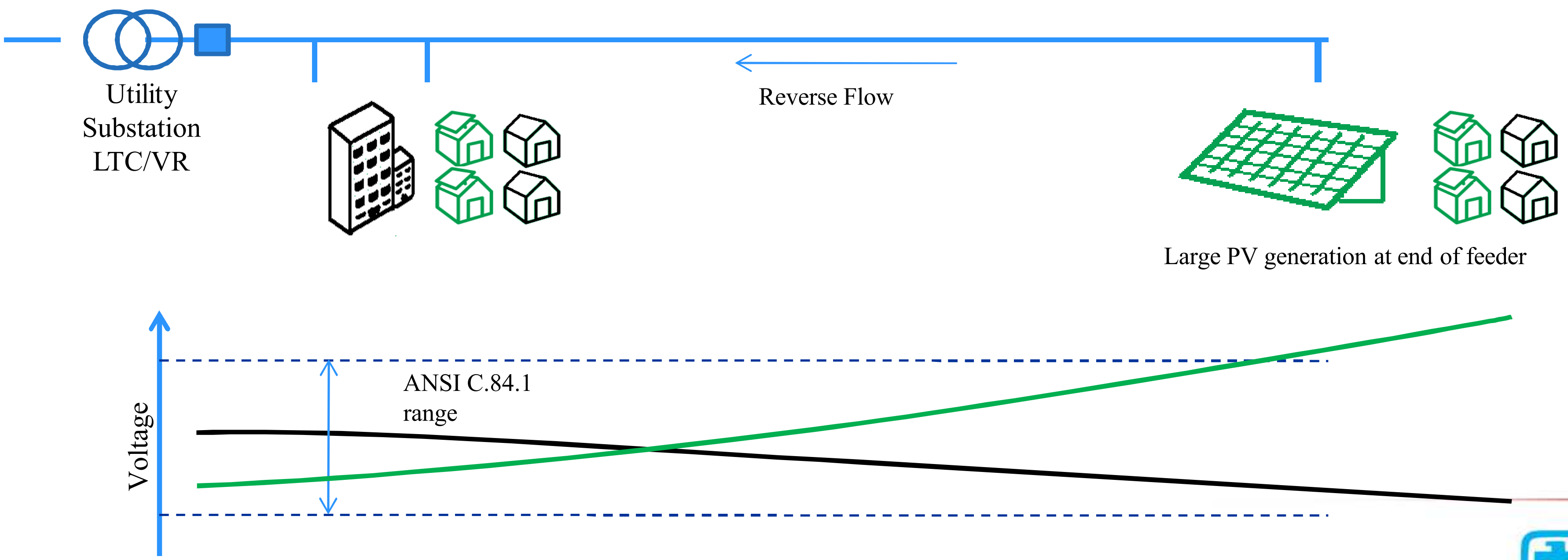
Distribution Operations Issues

- 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

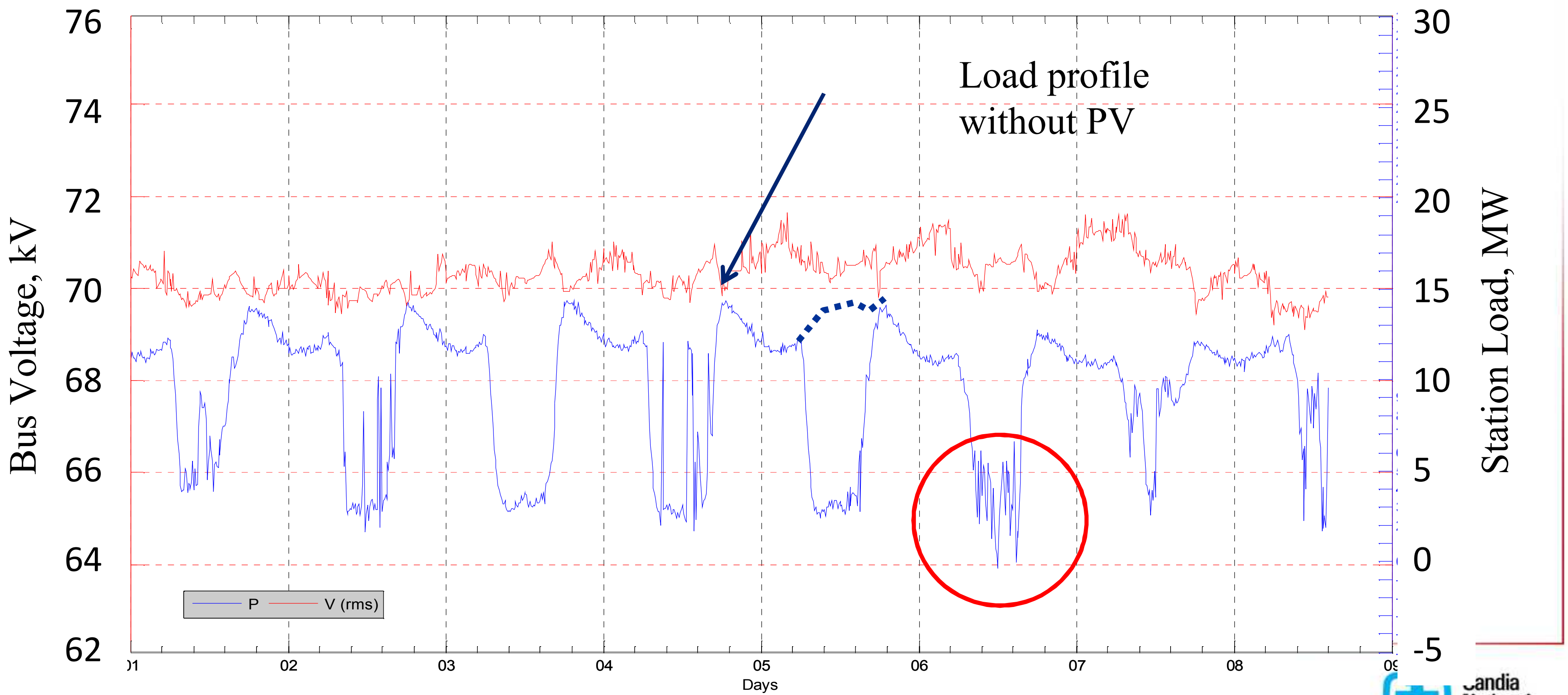
Voltage Control

- 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

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



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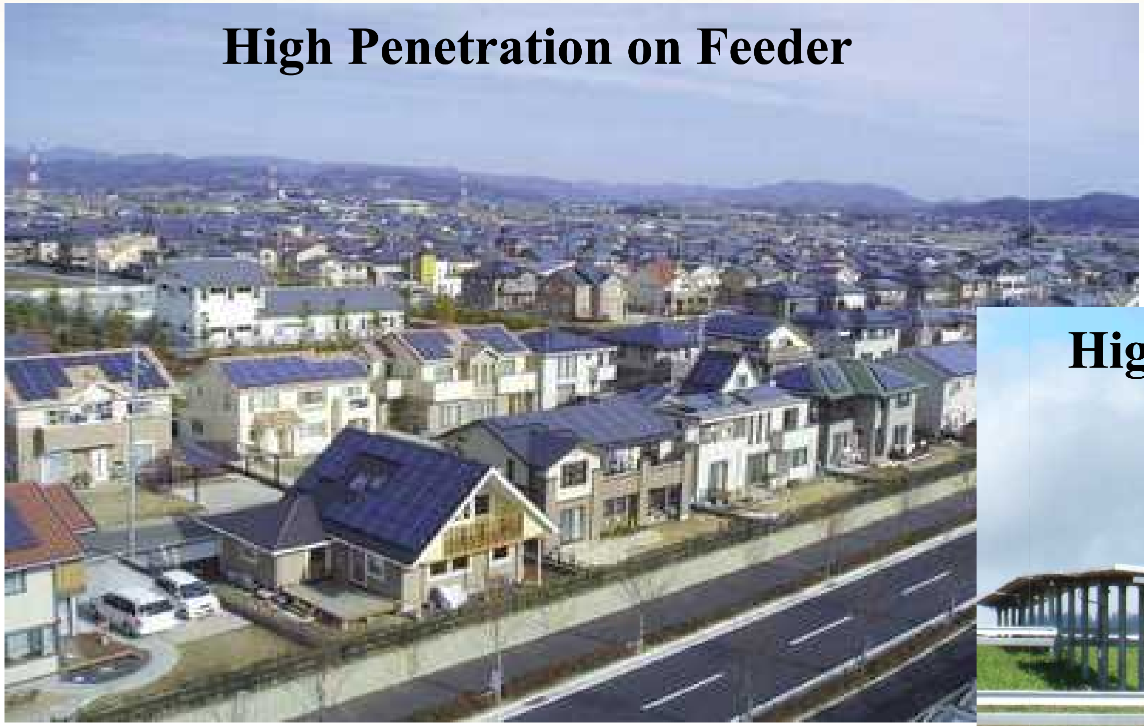
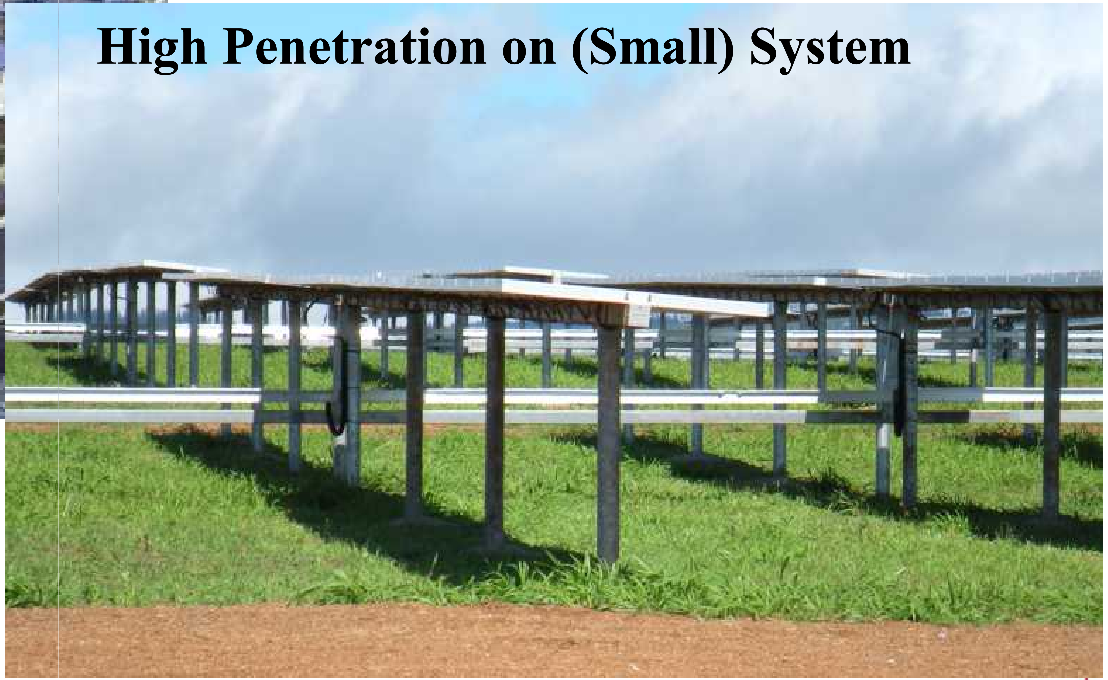
Other Distribution Operations Issues

- 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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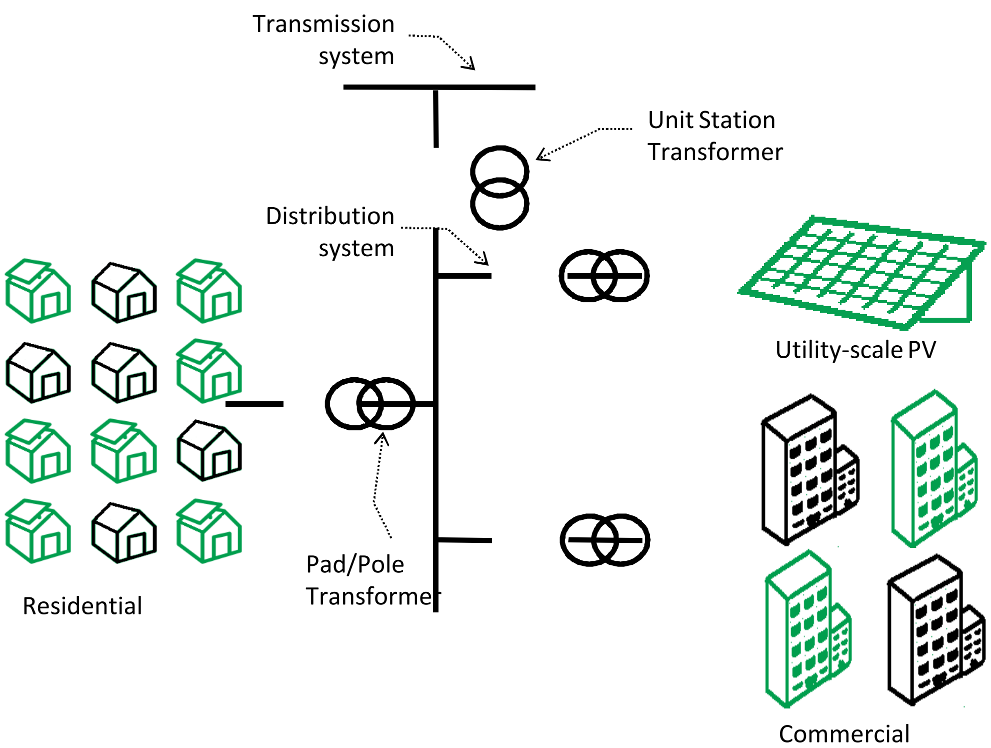
Current Research on Grid Integration

- 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**



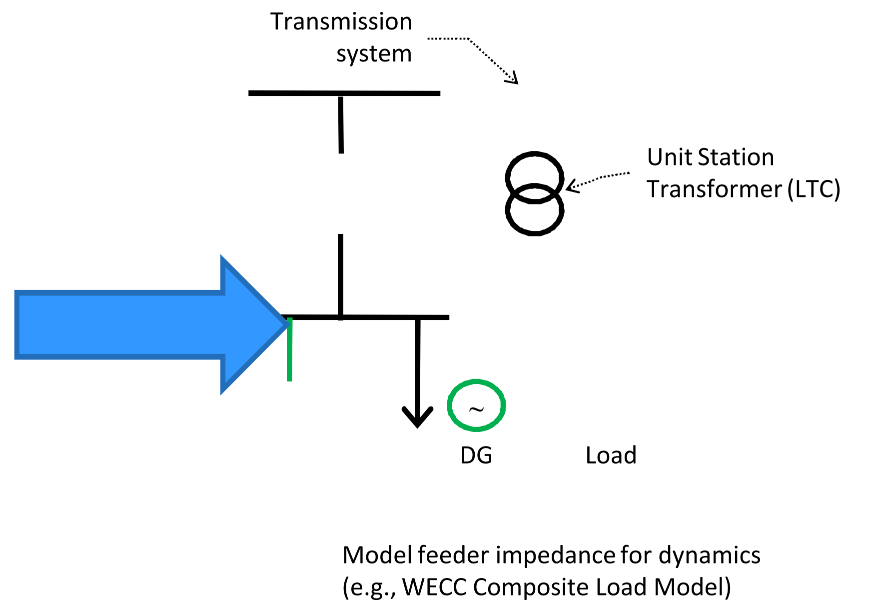
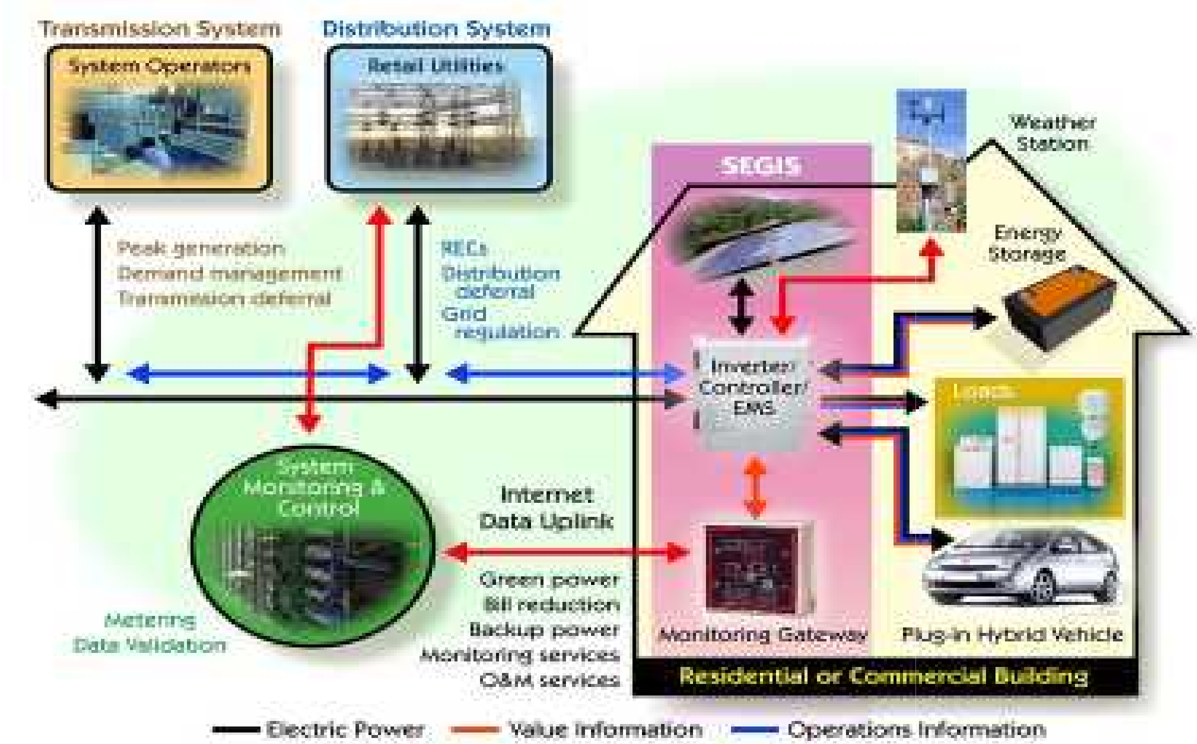


Illustration by WECC Renewable Modeling Task Force (REMTF), coordinated by Sandia

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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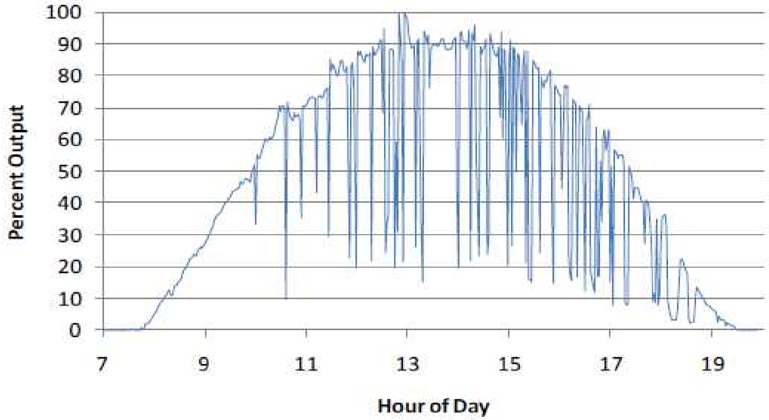
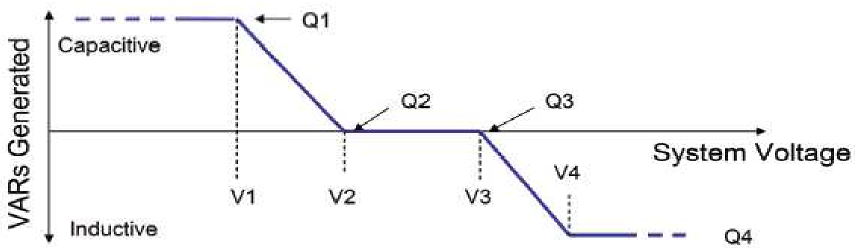
Codes and Standards Development

- **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

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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

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Short Course

Renewable Energy Integration

Overview: Wind Energy

Roger Hill
Wind Energy Technology Department
Sandia National Laboratories
Albuquerque, NM

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for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

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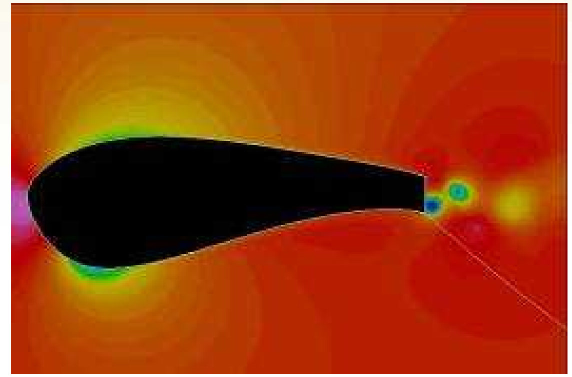
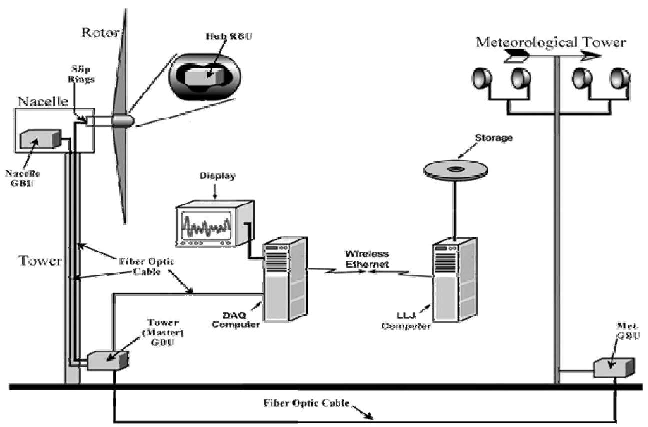
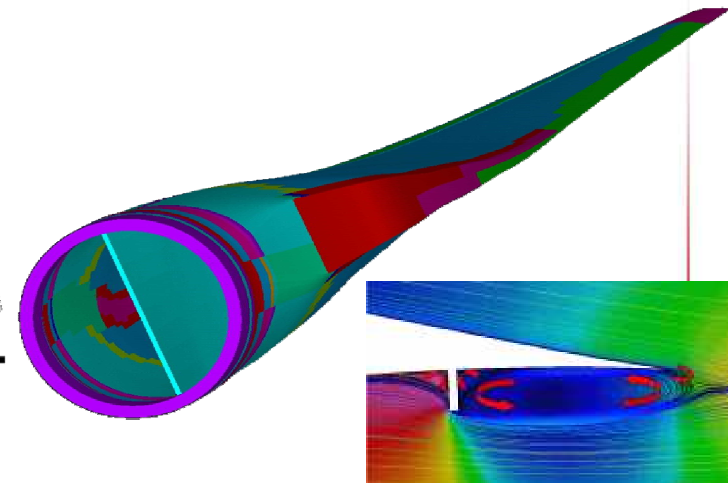
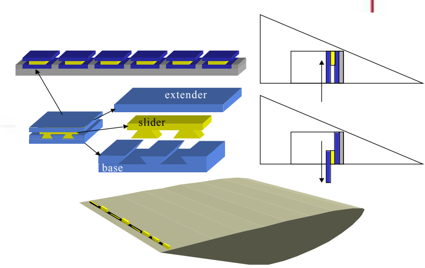
SNL's Wind Energy Program

- **Blade Technology**
  - Materials and Manufacturing
  - Structural, Aerodynamic, and Full System Modeling
  - Sensors and Structural Health Monitoring
  - Advanced Blade Concepts
  - Lab - Field Testing and Data Acquisition
- **System Reliability**
  - Industry Data Collection
  - Improve reliability of the existing technology and future designs
- **System Integration & Outreach**
  - Wind/RADAR Interaction
  - DOE/Wind M&O









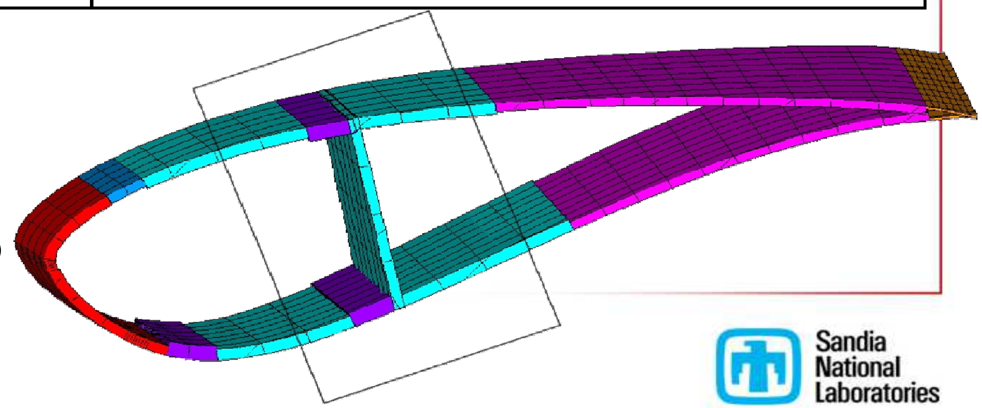
Department Background & Accomplishments

- **Established in Mid 1970's**
  - Primary focus VAWT's
  - Industry partnerships
- **Transitioned to Blades in early 1990's**
- **15 Full-Time Employees**
- **Several Contractors and Students**

1975	SNL Wind Program Established
1977	17m VAWT Fabricated
1981	1st Wind-Turbine Specific Airfoils
1982	FloWind Technology Transfer
1984	34m VAWT Test Bed
1988	SNL/MSU Material Dbase Established
1994	SNL Blade Program Started
1998	Blade Manufacturing Initiative
2003	Incorporation of Carbon on Blades
2005	K&C Swept Blade Contract
2006	Reliability Program Started
2007	RSI Program Started

Mission:

To provide a knowledge base expertise in the design and advancements of composite wind turbine blades and turbine reliability, in order to accelerate the penetration of Wind Energy.



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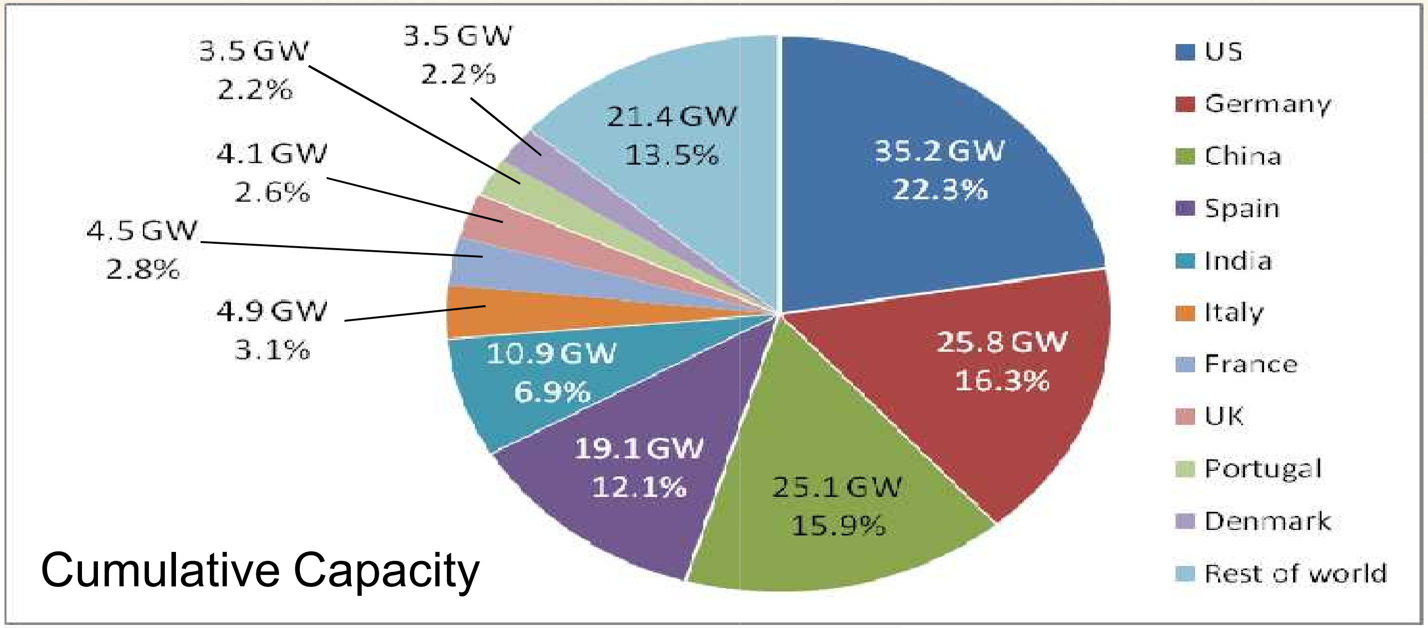
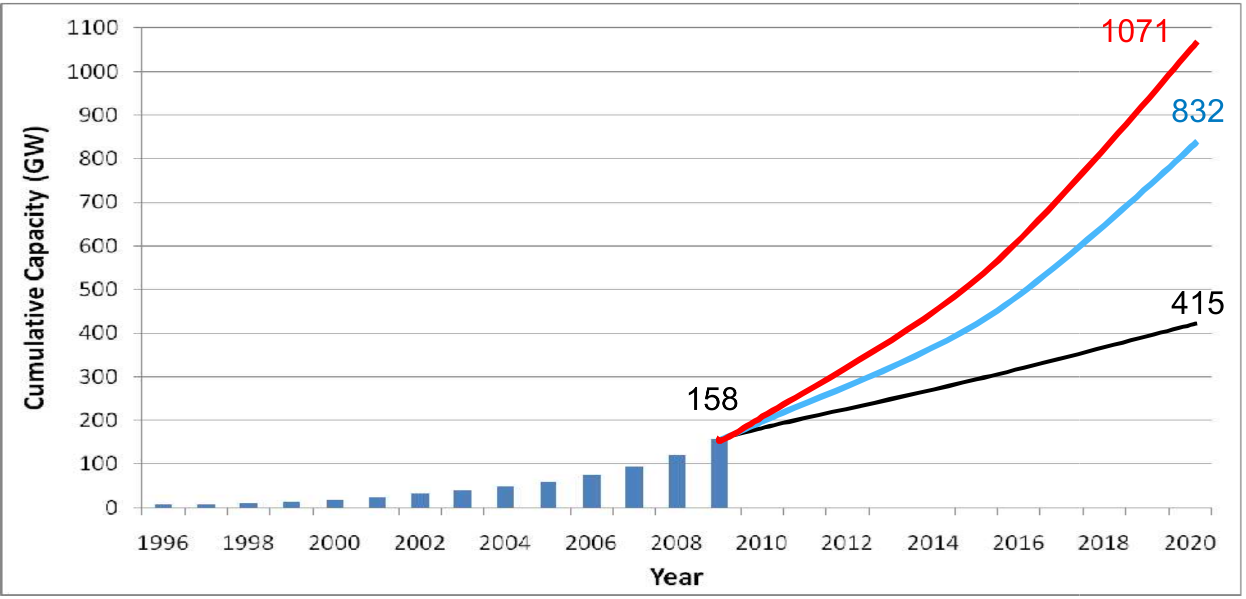
Global Installed Capacity





Advanced: Best wind case scenario for policy and market

Moderate: Supportive policy measures enacted & emissions reductions implemented

Reference: Based on IEA 2009 World Energy Outlook w/existing policies

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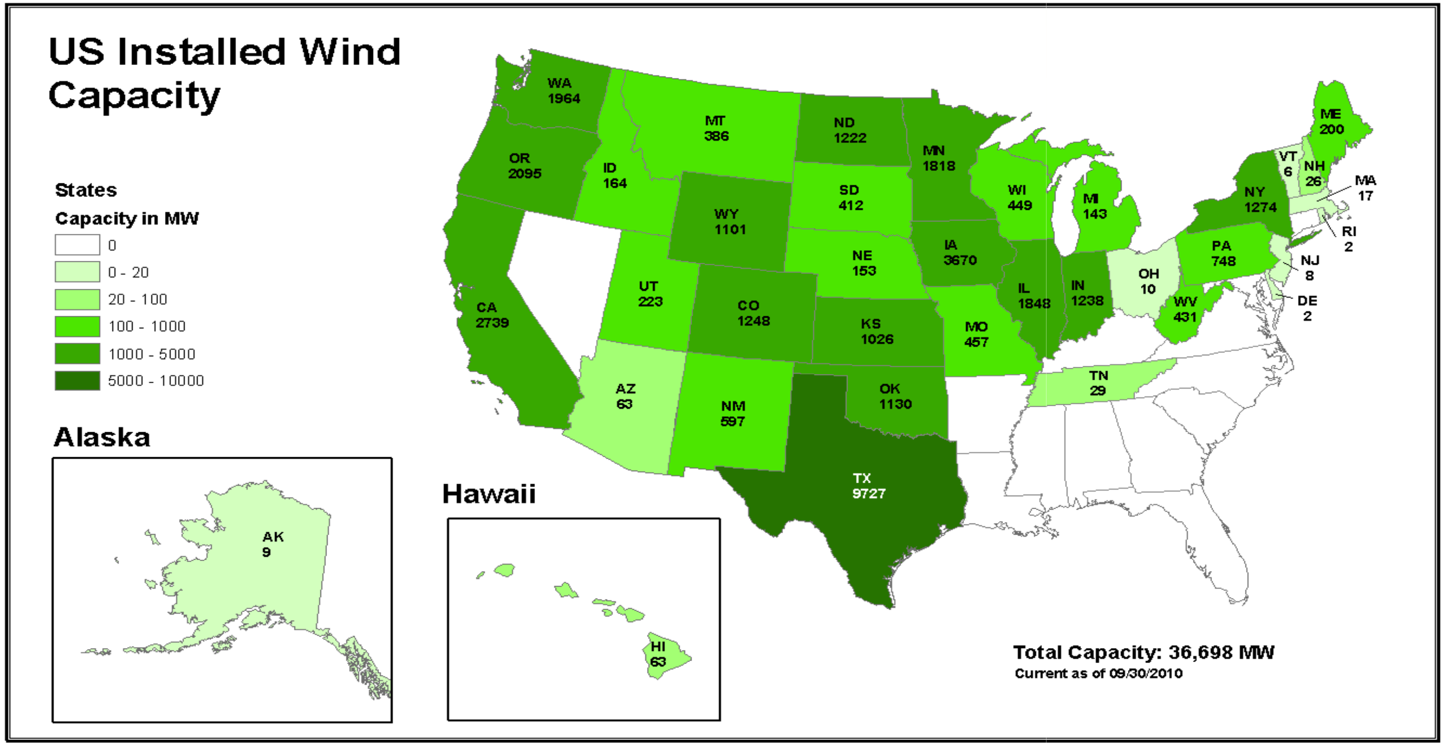
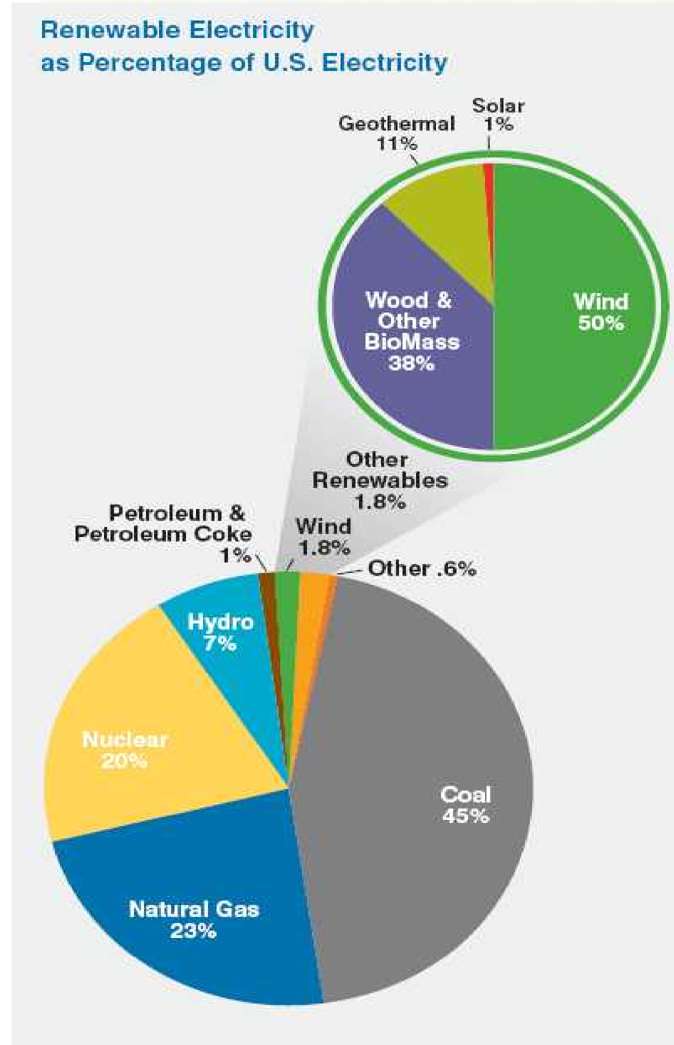
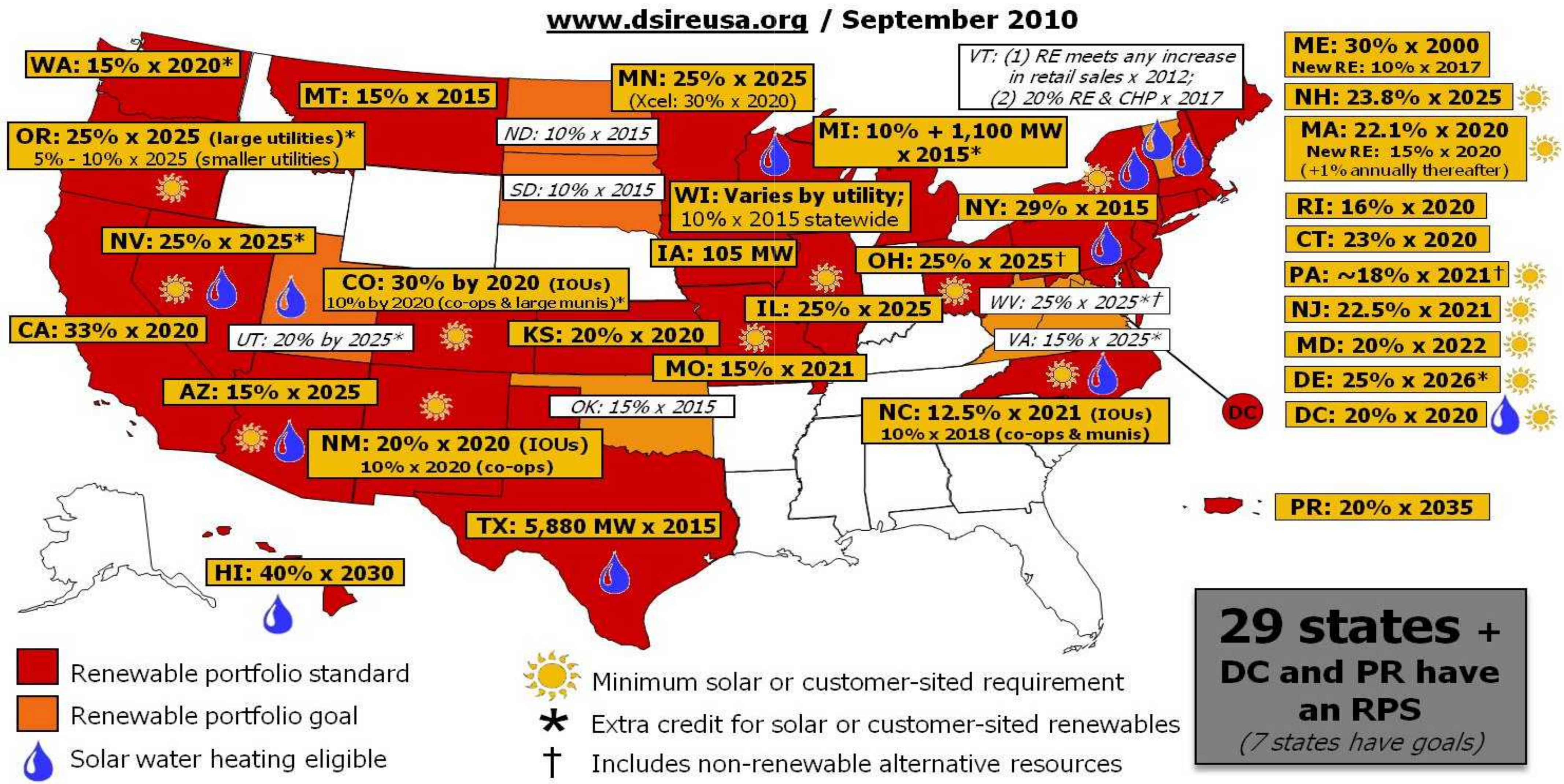
Installed Capacity in the United States





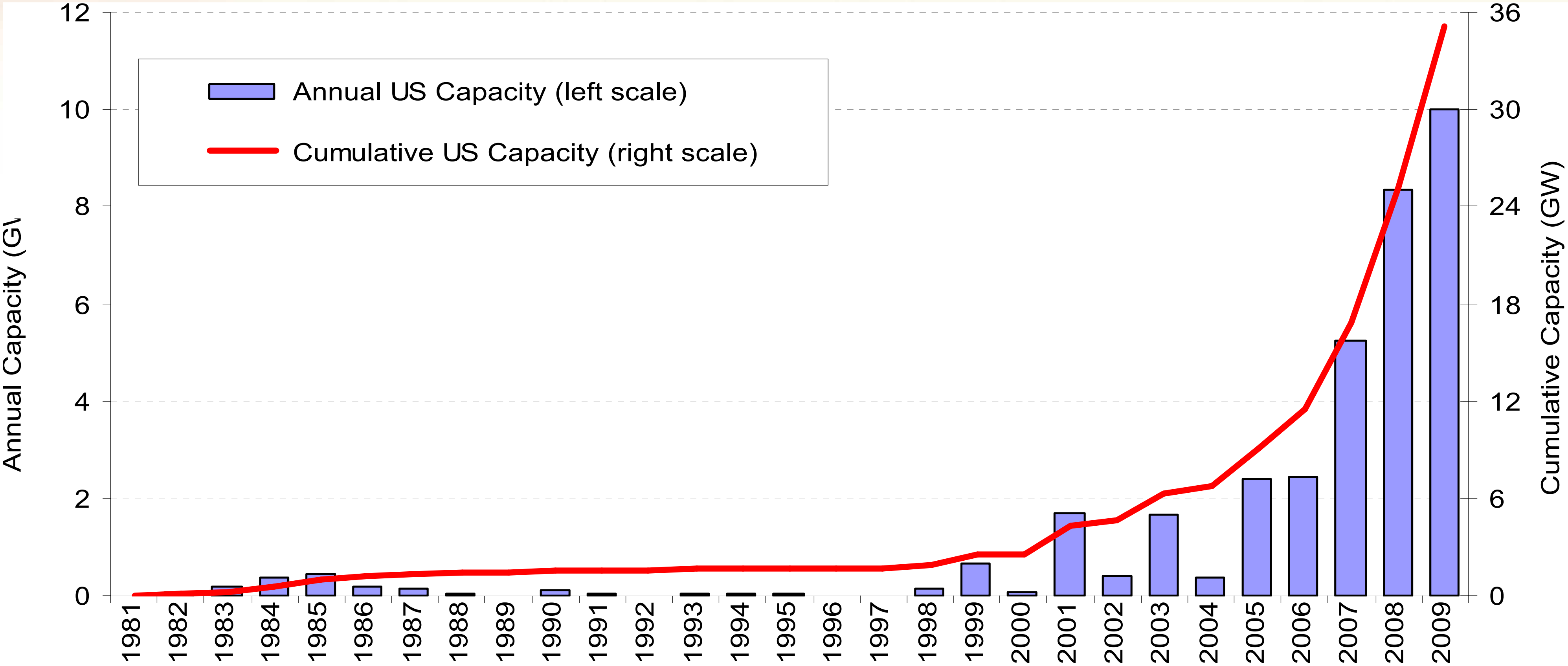
- All renewable energy sources provided 10.5% of the U.S. power mix in 2009;
- Wind generation is approaching the two percent mark of the U.S. power mix, reaching 1.8% of U.S. generation in 2009;
- Hydro generation is approximately 7%. DOE focus and investment in efficiency upgrades and water use optimization.

Renewable Portfolio Standards



Laboratories

U.S. Wind Power Capacity Up >40% in 2009



Record year for new U.S. wind power capacity:

- 10 GW of wind power added in 2009, bringing total to ~35 GW
- Nearly $21 billion in 2009 project investment

Source: DOE 2009 Wind Technologies Report

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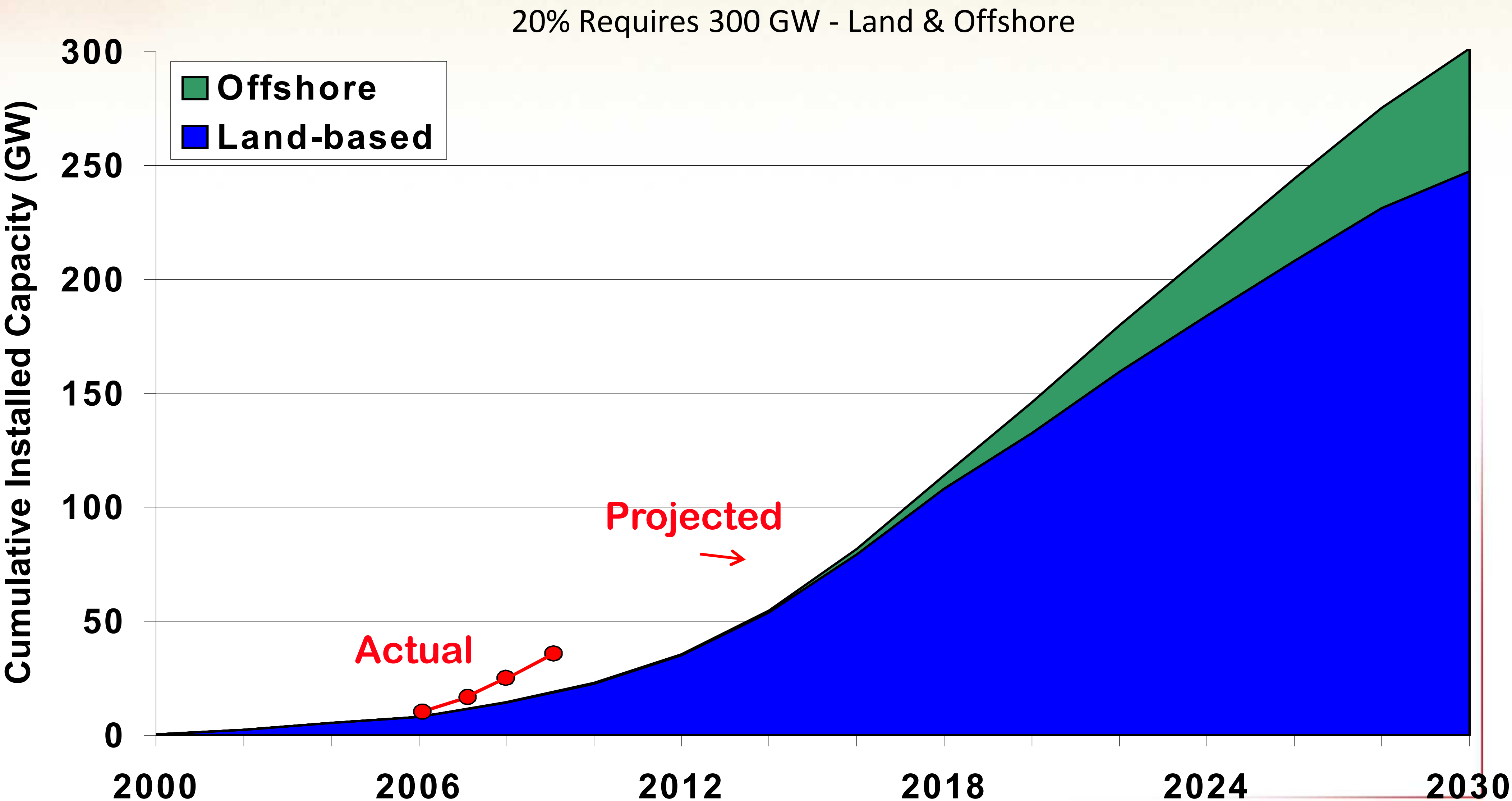
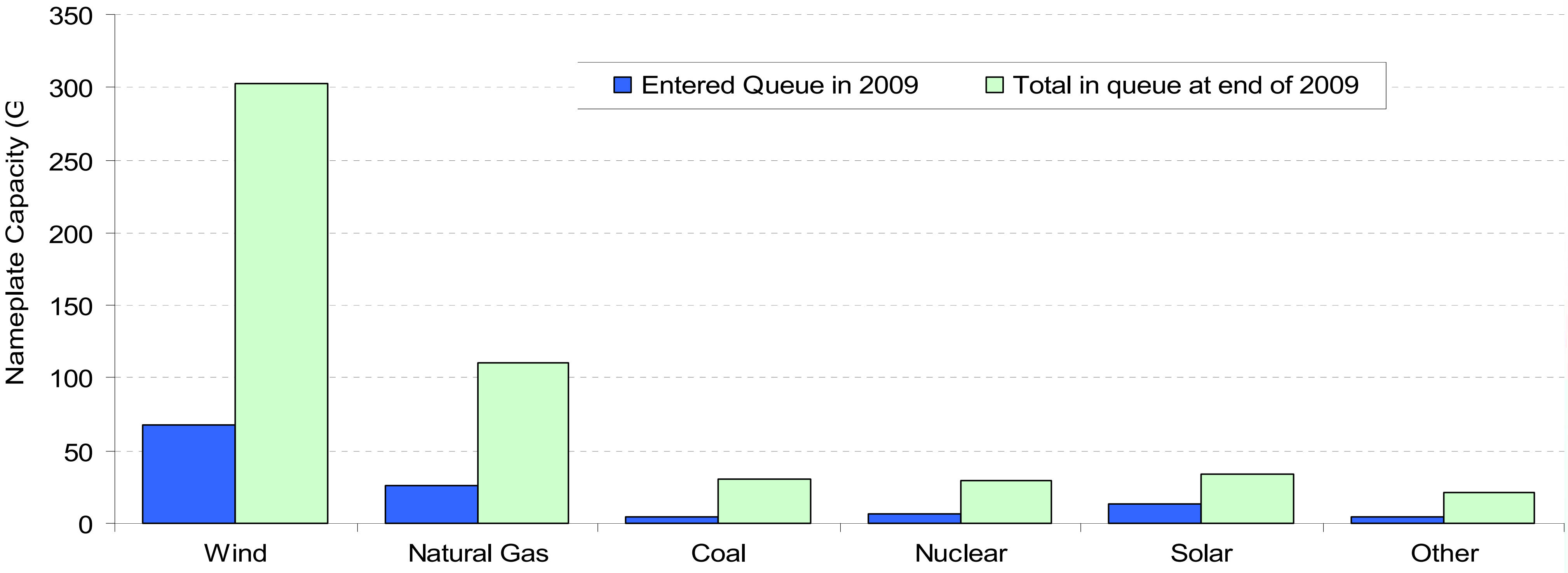
Projected Growth



Source: DOE 20% Wind Energy by 2020 Report

Wind Power Capacity In Queue

- **Roughly 300 GW in Transmission Interconnection Queues.**



Not all of this capacity will be built….

Source: DOE 2009 Wind Technologies Report

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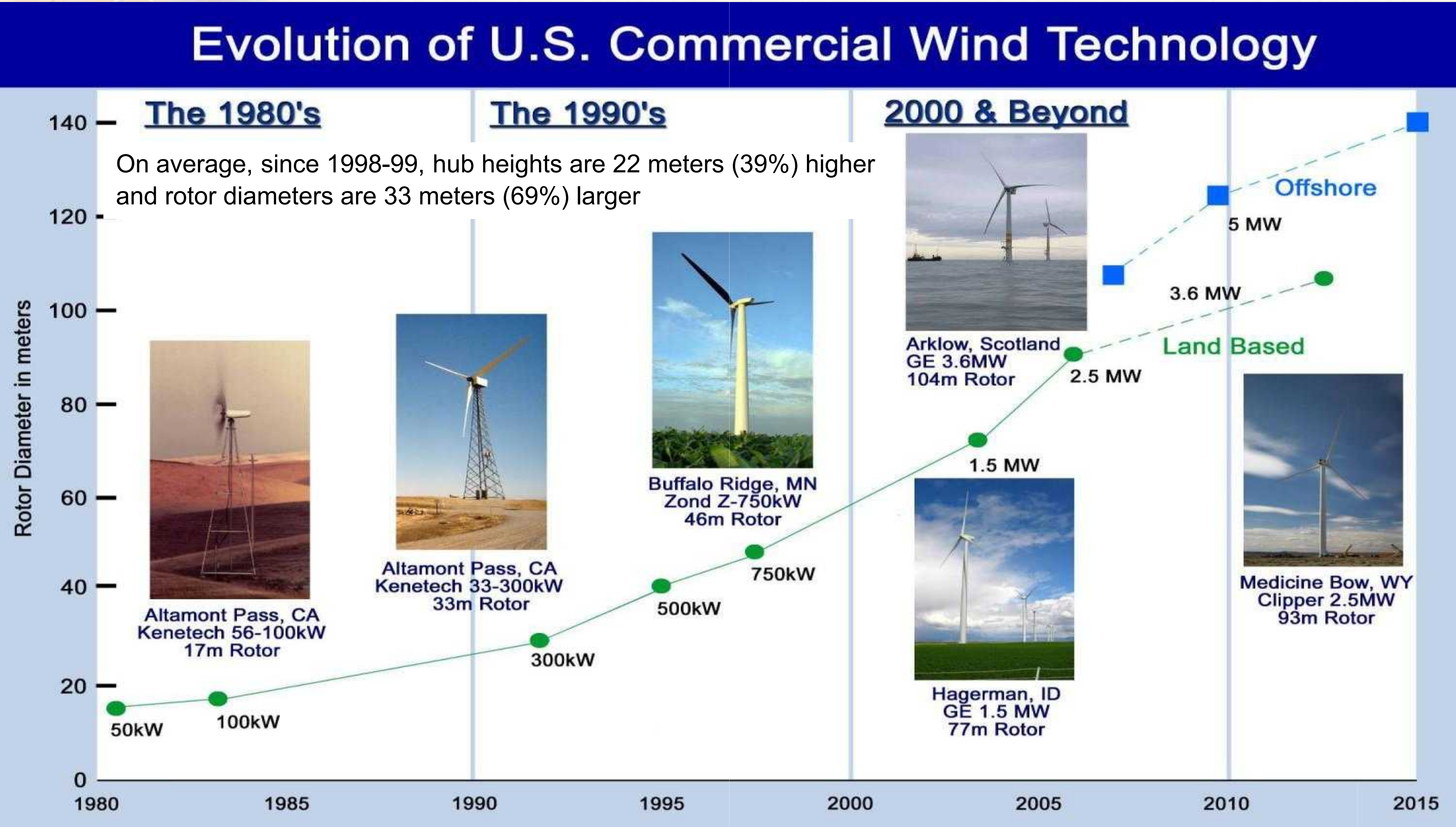
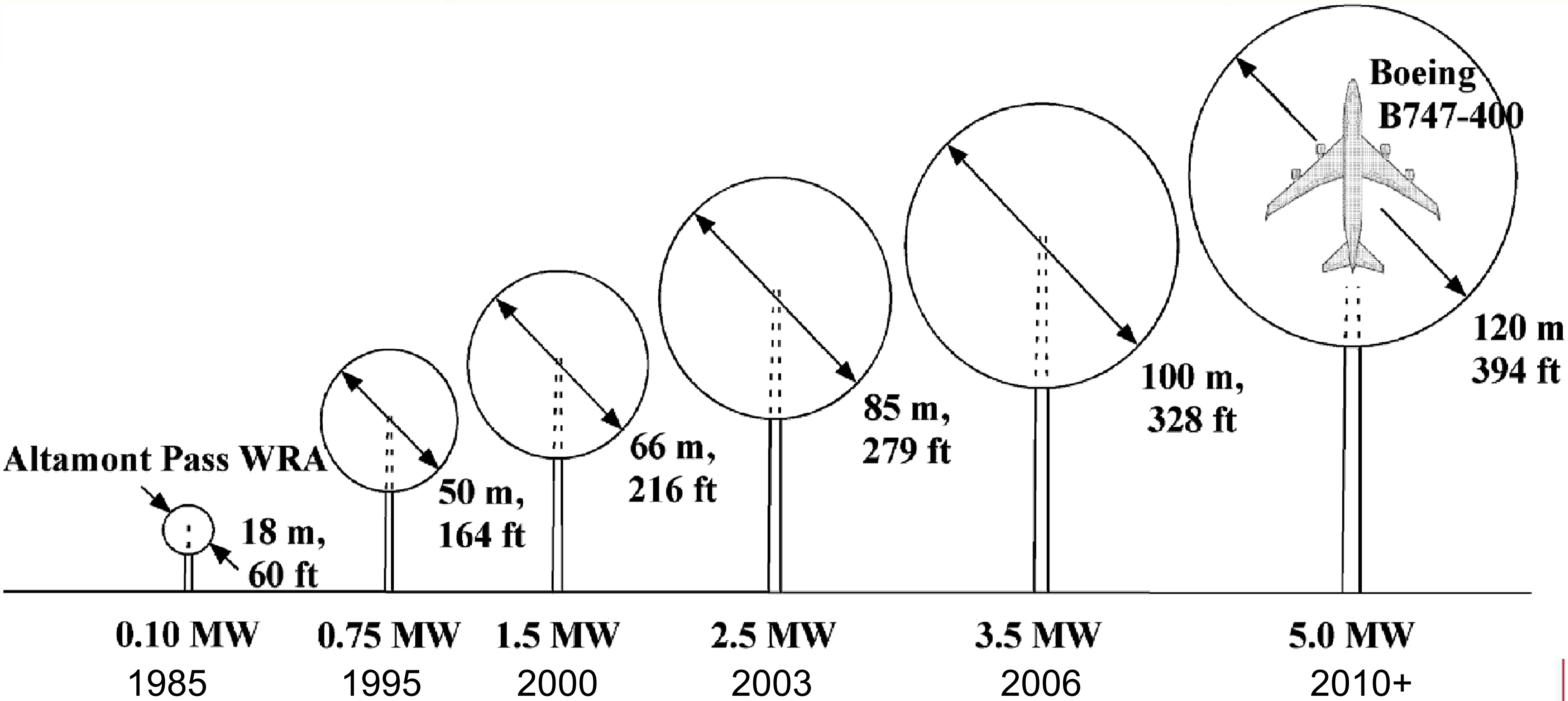
Average Hub Heights and Rotor Diameters Have Increased

On average, since 1998-99, hub heights are 22 meters (39%) higher and rotor diameters are 33 meters (69%) larger



Turbines Getting Larger



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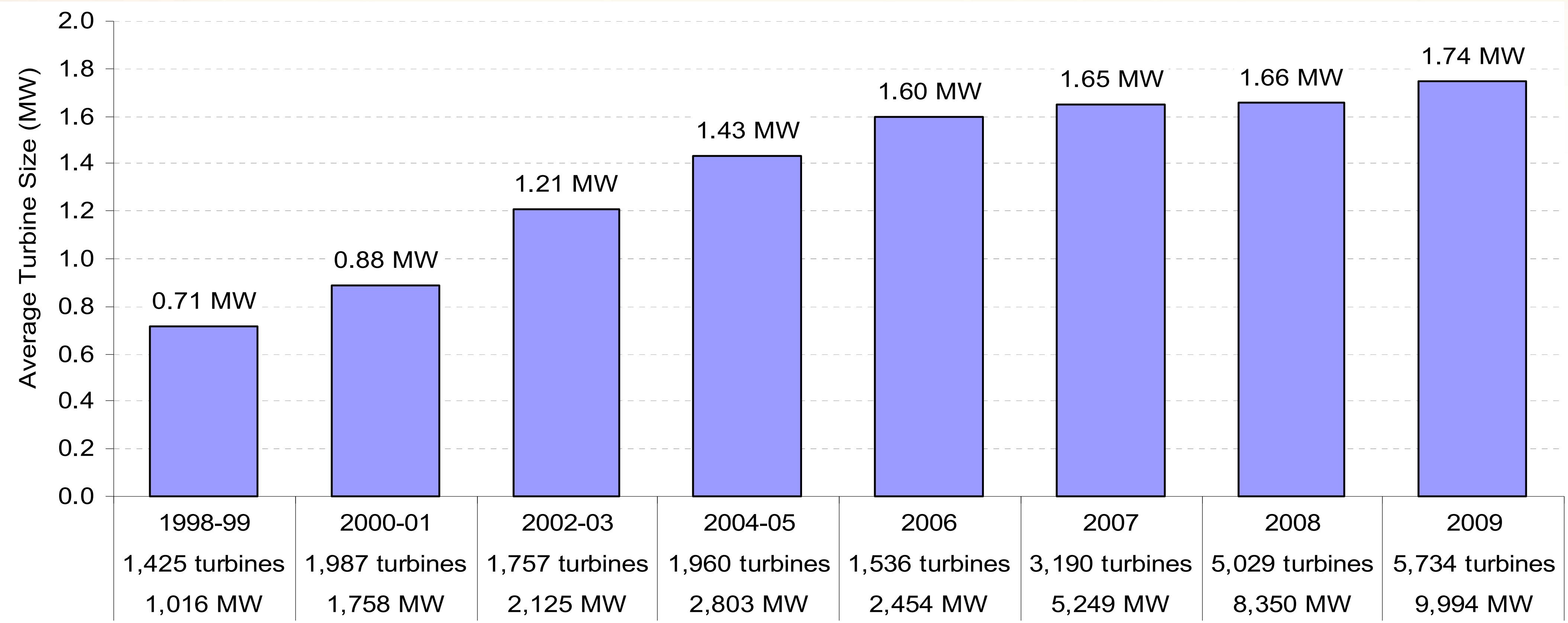
Average Turbine Size Higher in 2009



25% of turbines installed in 2009 were larger than 2.0 MW, up from 19% in 2008, 16% in 2006 & 2007, and just 0.1% in 2004-05.

Source: DOE 2009 Wind Technologies Report

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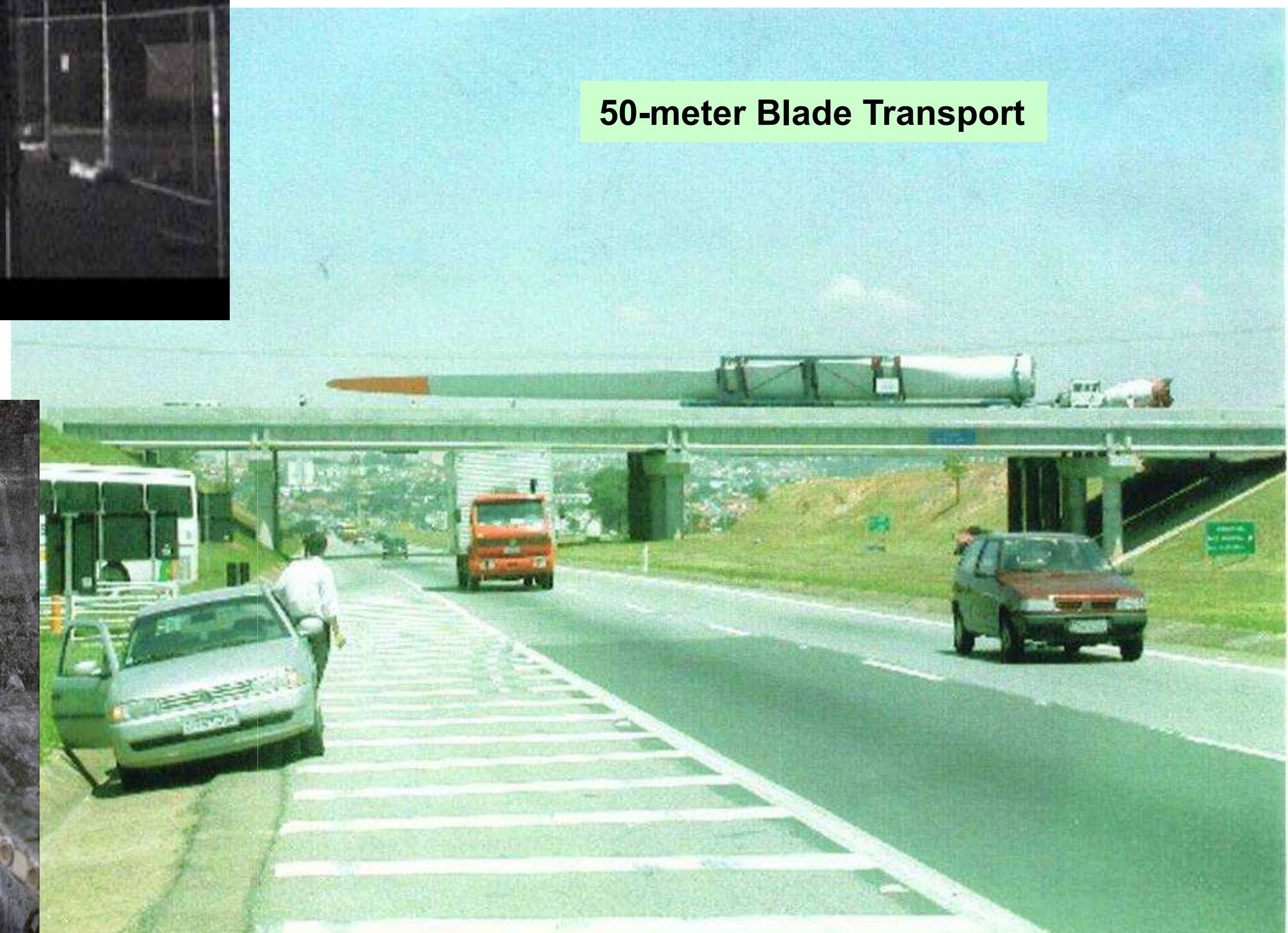
Logistics become difficult as size increases

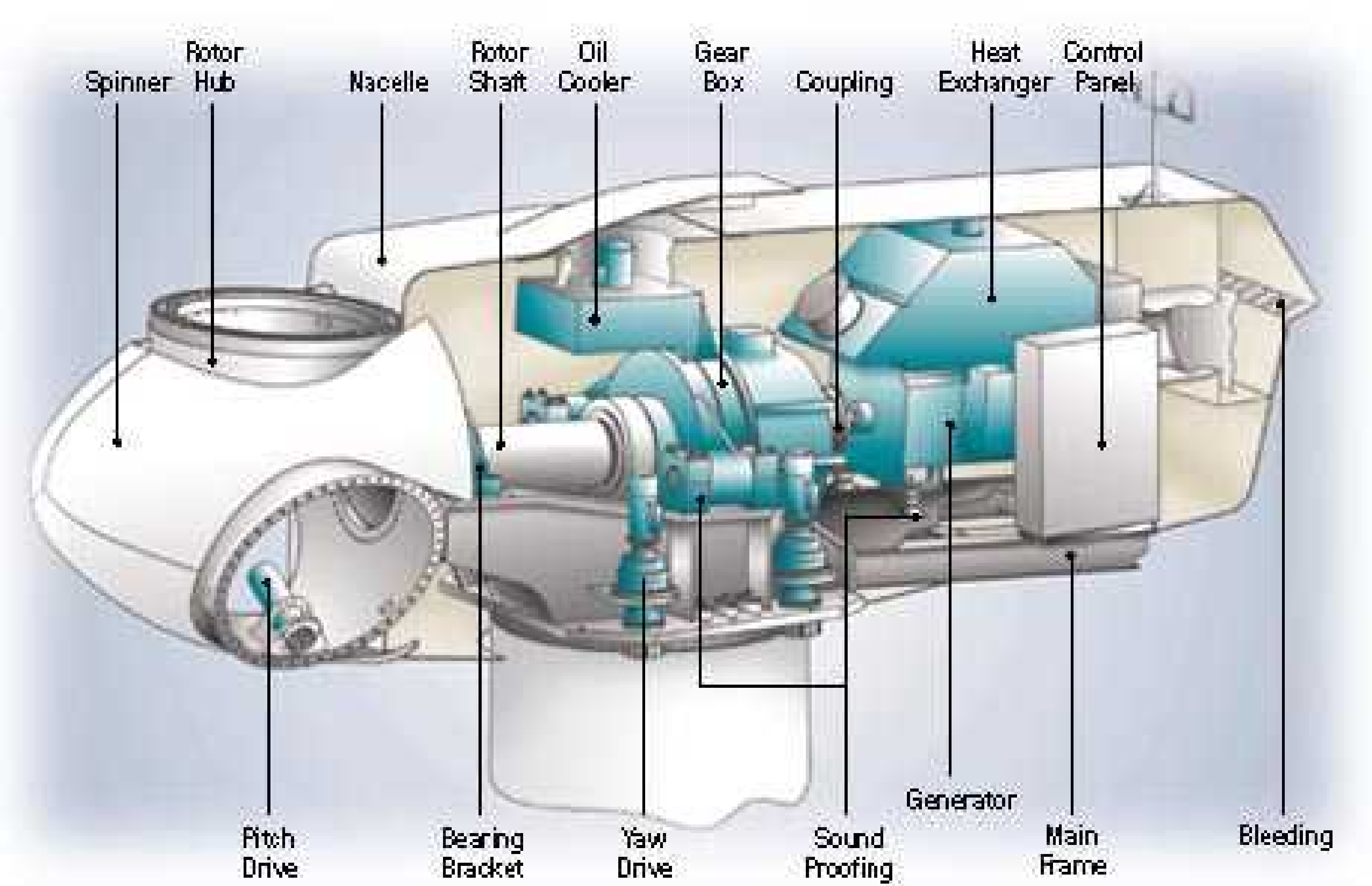
45-meter Blade Fatigue Test at NREL/NWTC

Courtesy of LM Glassfiber



50-meter Blade Transport

Typical Modern Turbine



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Taxonomy of a Wind Plant

Over 8,000 individual components in a single wind turbine

Wind Turbine

- **Blade**
  - Aero-dynamic brake
  - Internal structure - laminates
  - Lightning protection
  - Paint and coatings
  - Skins – laminates
  - T-bolt/root insert
  - De-icing system
- **Rotor**
  - Nose cone
  - Pitch system
  - Hub
  - Slip ring
  - Root attachment
- **Drivetrain**
  - Low speed shaft
  - High speed shaft
  - Braking system
- **Gearbox**
  - Bearings
  - Gears
  - Lube system
  - Housing
  - Torque arm system
- **Generator**
  - Cooling system
  - Stator
  - Rotor
  - Housing
  - Commutator and brushes
  - Bearings
- **Electrical**
  - Power converter
  - PFC system
  - Soft starter
  - Wiring and connections
  - Grounding system
  - Main transformer
  - Components
- **Nacelle**
  - Enclosure
  - Meteorological equipment
  - FAA lights
  - Internal environment
  - Crane
- **Yaw**
  - Cable twist/untwirst
  - Brake
  - Drives
  - Bearings (slew ring)
  - Gear
  - Damper
  - Hydraulics
- **Control system**
  - Sensors
  - Communications
  - SCADA interface
  - Controller
  - Cabinet
  - UPS
- **Foundation & tower**
  - Foundation
  - Tower structure
  - Tower equipment
- **Balance of plant**
  - Substation
  - Meteorological tower
  - SCADA
  - Converter
  - Grid connection
  - Collection and distribution
  - Metering and relays
- **Maintenance**
  - Troubleshooting
  - Fault Reset
  - Scheduled Maintenance
  - Miscellaneous

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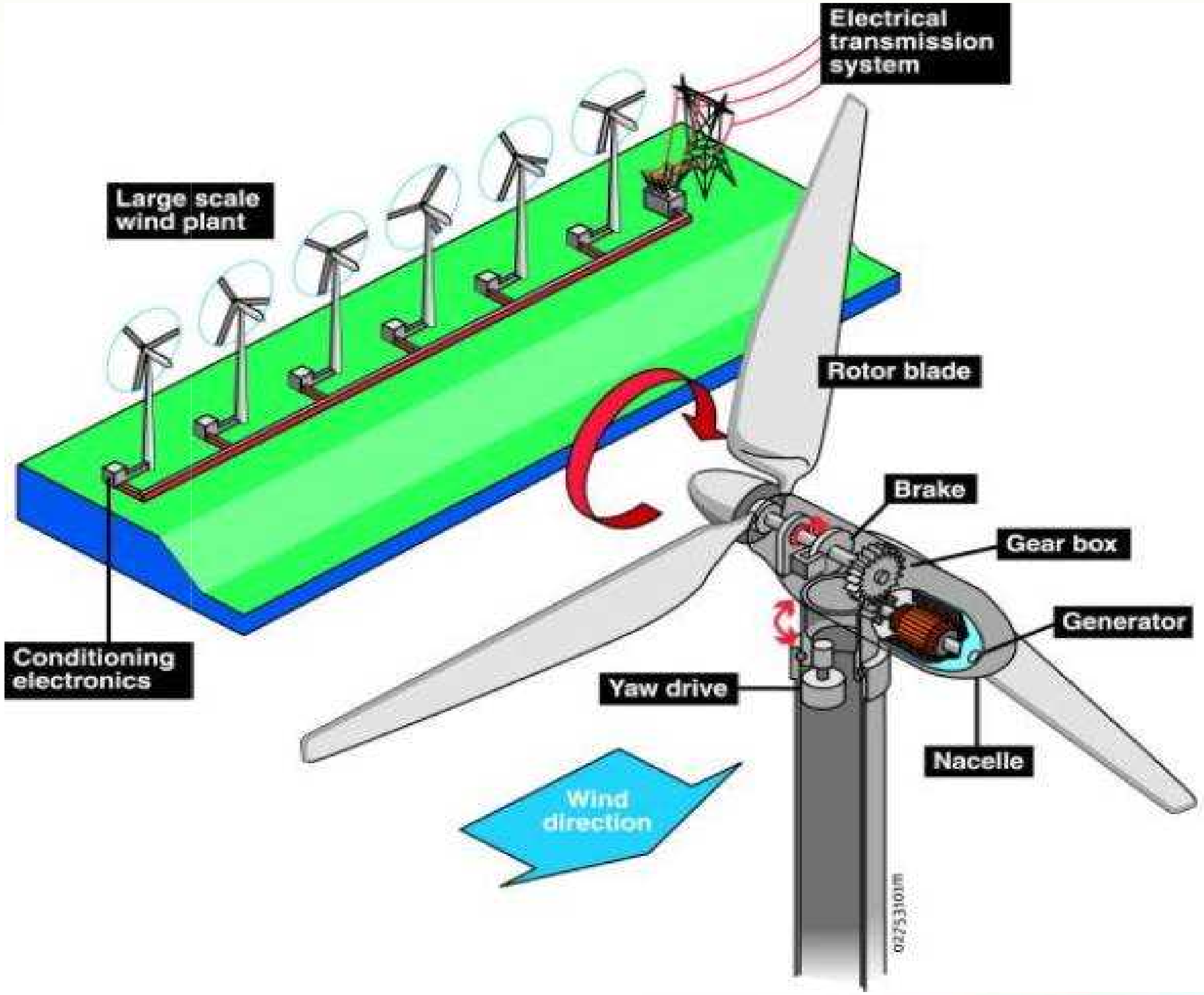
Typical Wind Farm Components

- Turbine
- Foundations
- Electrical Collection System
- Power quality conditioning
- Substation
- SCADA
- Roads
- Maintenance facilities



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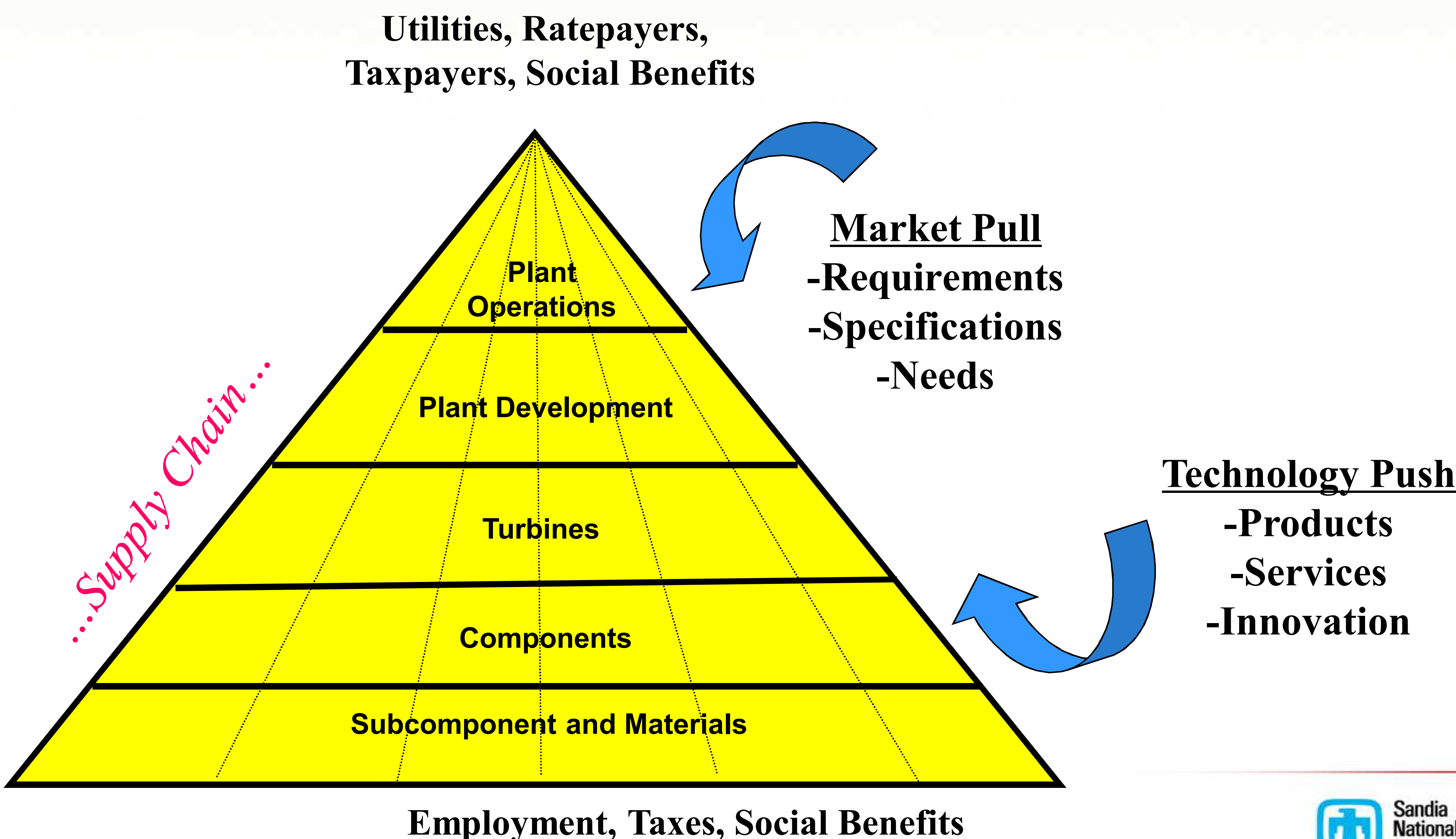
Wind Turbine Supply Chain Model



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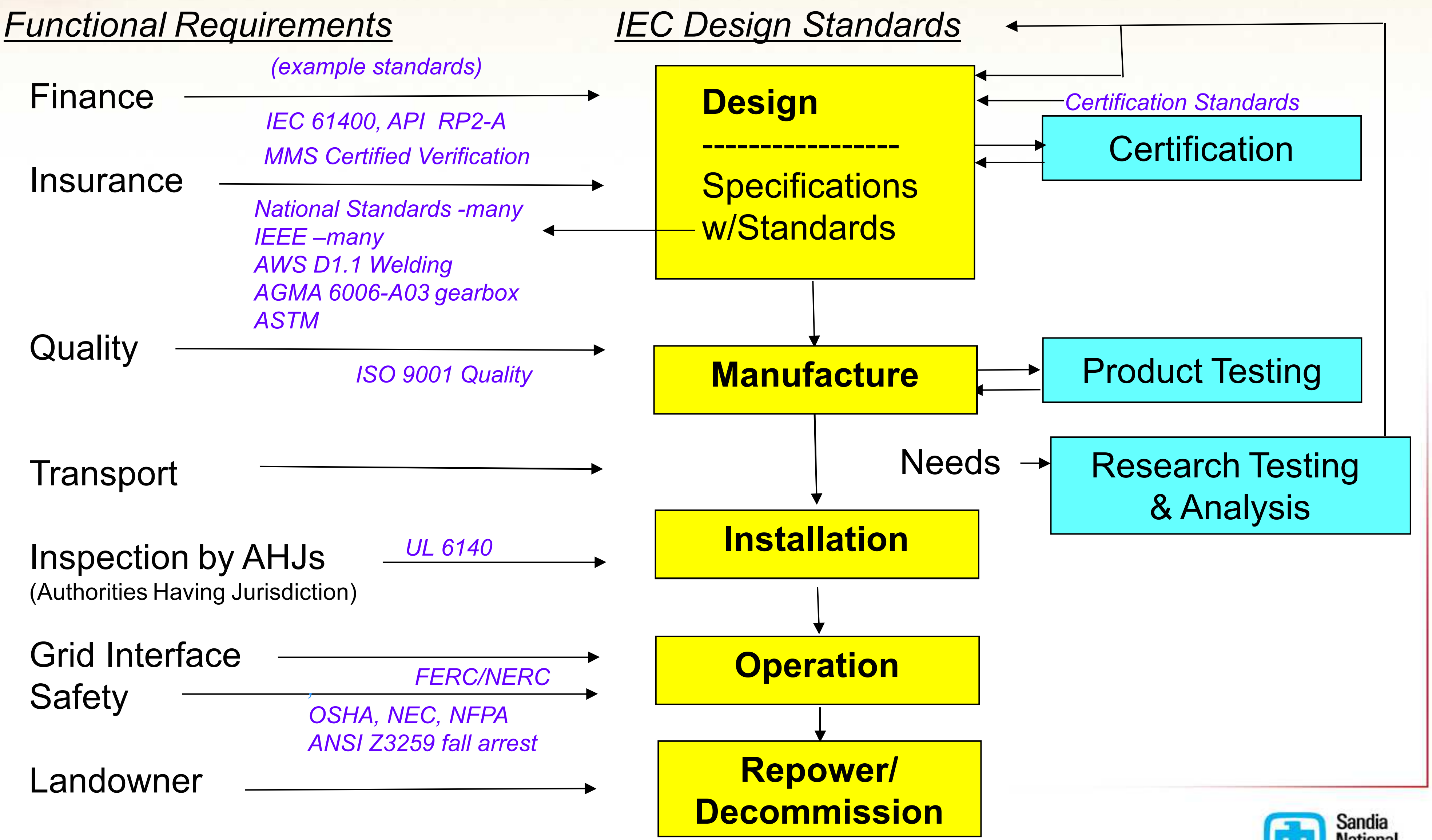
Another Perspective with Adjacent R&D Space



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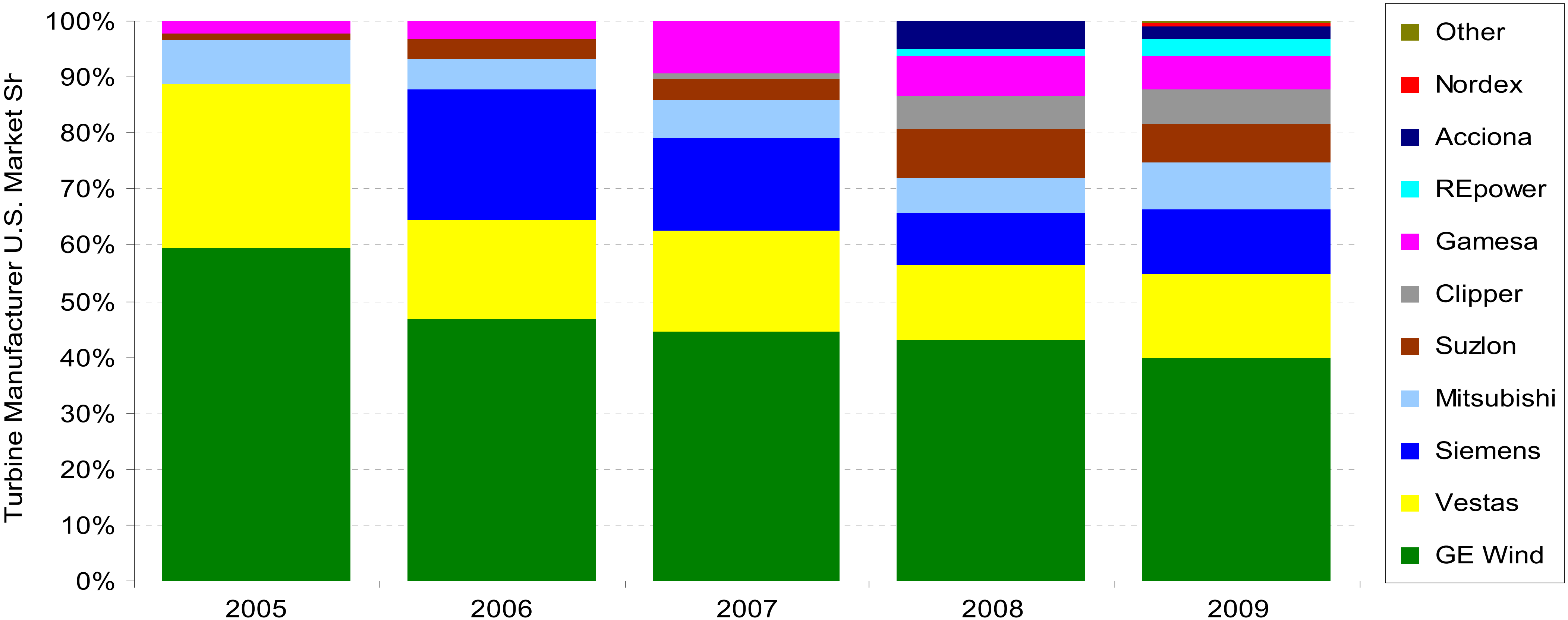
US Turbine Vendors

- **GE Remained the Top Turbine Vendor in the U.S. Market, But a Growing Number of Other Manufacturers Are Capturing Market Share.**



- Chinese and South Korean manufacturers seeking entry into U.S. market;
- For first time in 2009, a turbine vendor from China (Goldwind) saw sales in the U.S.

Source: DOE 2009 Wind Technologies Report

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Wind Power Basics

Air Density — **Rotor Area** — **Wind Speed**

$$WindPower = \frac{1}{2}\rho A C_P V_\infty^3$$

Wind Power output is proportional to wind speed cubed.

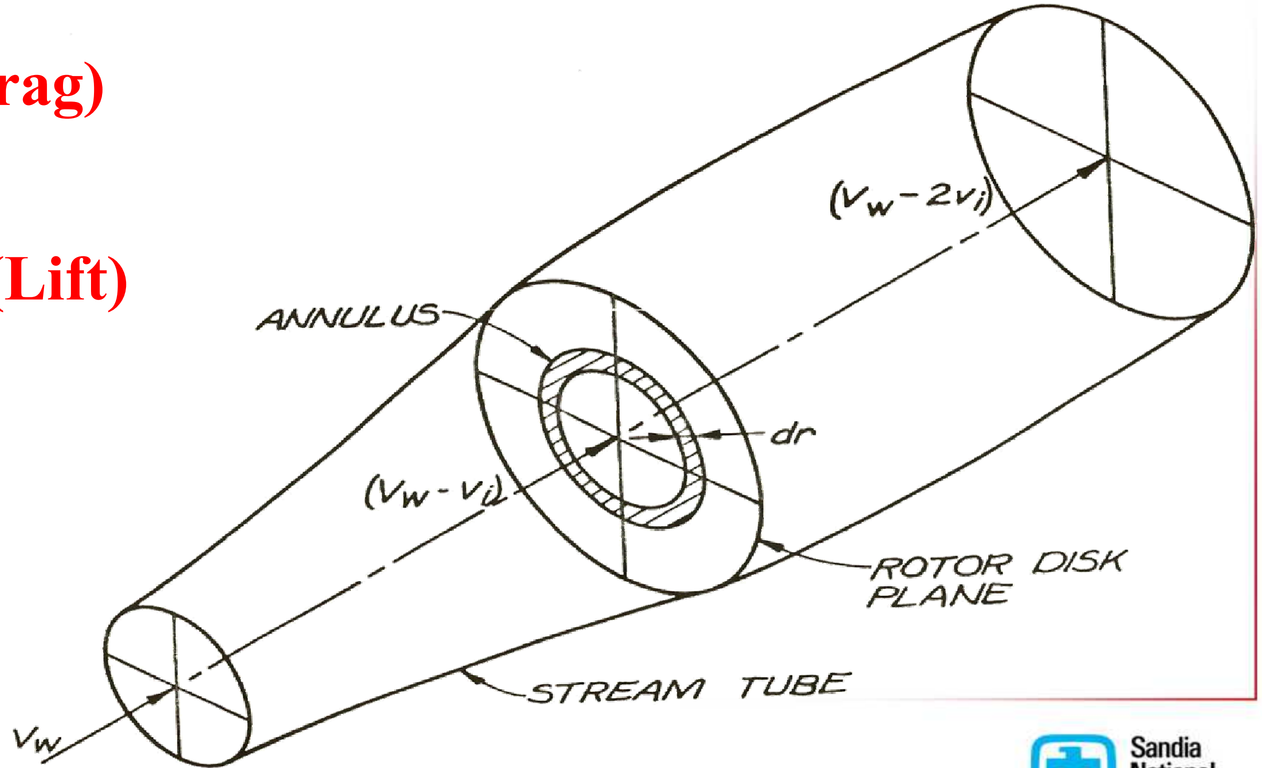
$$C_{P\max} \cong 0.3$$ **(Drag)**

$$C_{P\max} \cong 0.59$$ **(Lift)**

The Betz Limit

$$V_i = \frac{1}{3} V_w$$

$$P = \frac{16}{27}\left(\frac{1}{2}\rho A V_w^3\right)$$



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Generation Potential

Depends on:

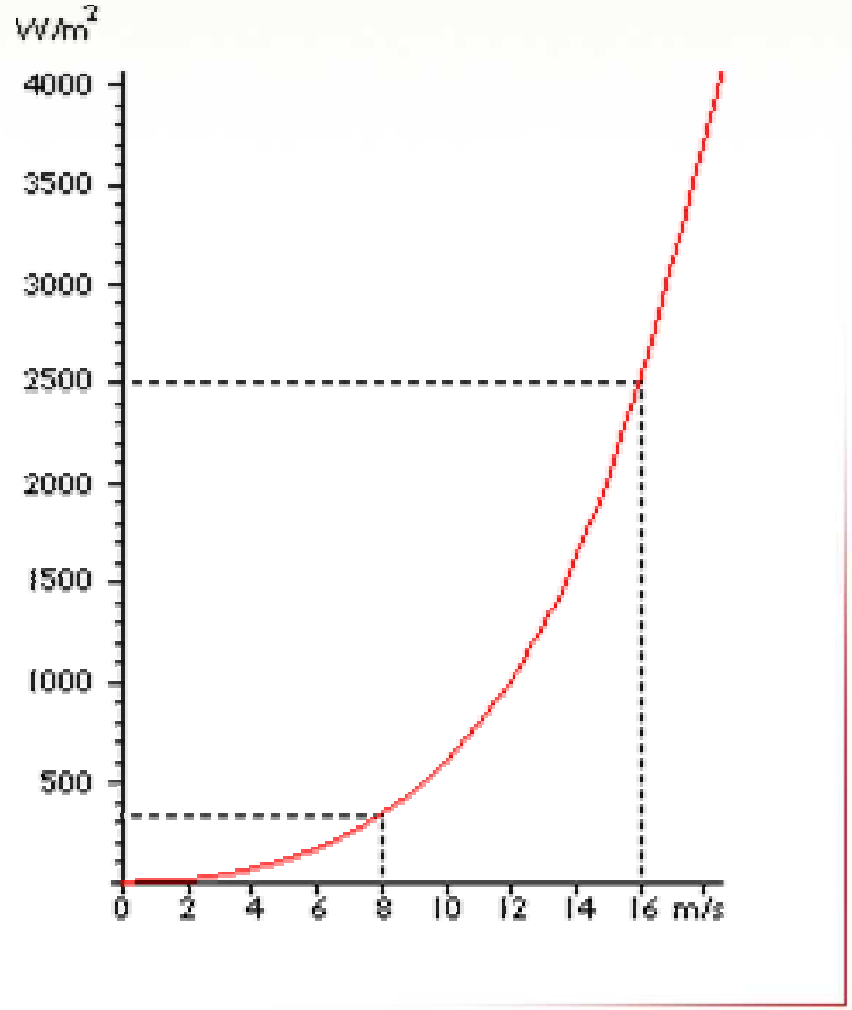
- Available resource;
- Turbulence characteristics;
- Terrain and roughness influences;
- Turbine characteristics.

Remember…

Power in the wind = $K \, {}^{1}/_{2} \, \rho \, A \, V^3$

- wind speed, V
- swept area, A
- air density, ρ
- conversion efficiency constant, K
- 45% efficiency for modern machines

→ Power ~ $(\text{wind speed})^3$



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Turbine Power Basics

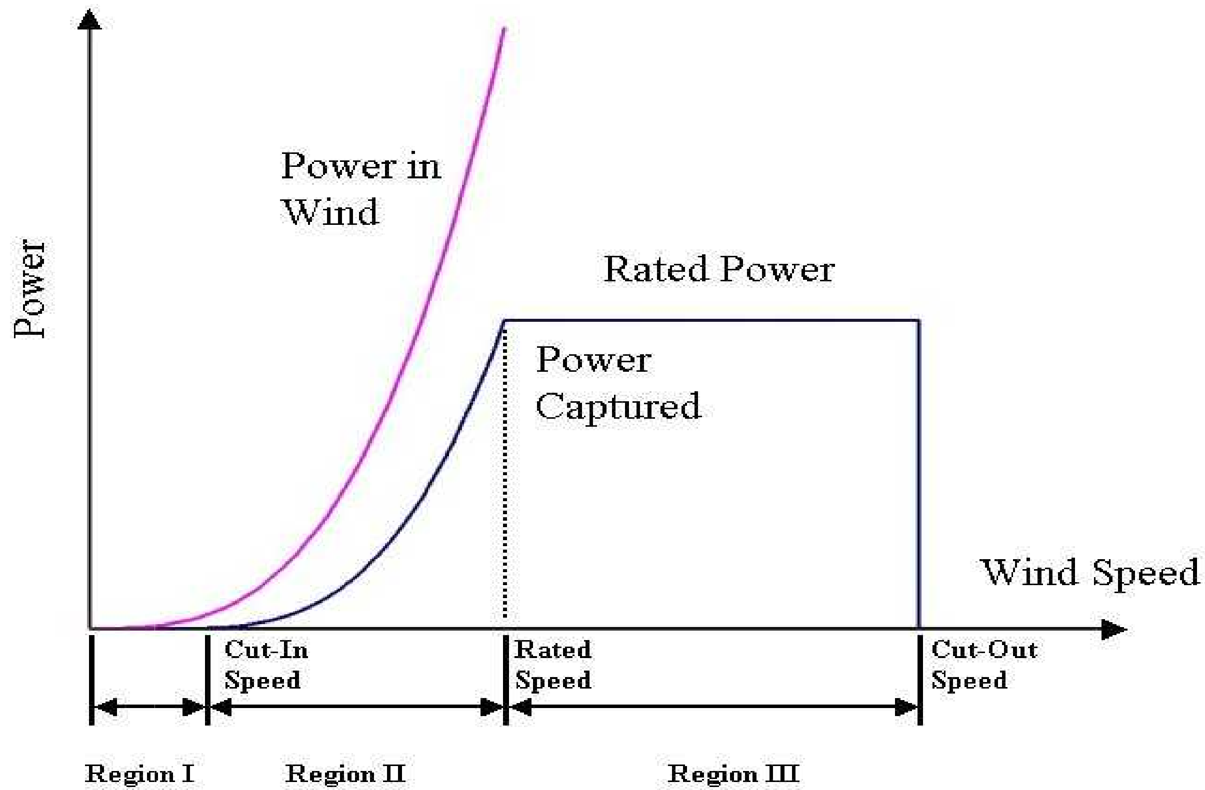
Regions of the Power Curve

Region I – not enough power to overcome friction

Region II – Operate at maximum efficiency at all times

Region III – Fixed power operation

Wind Turbine Power Curve



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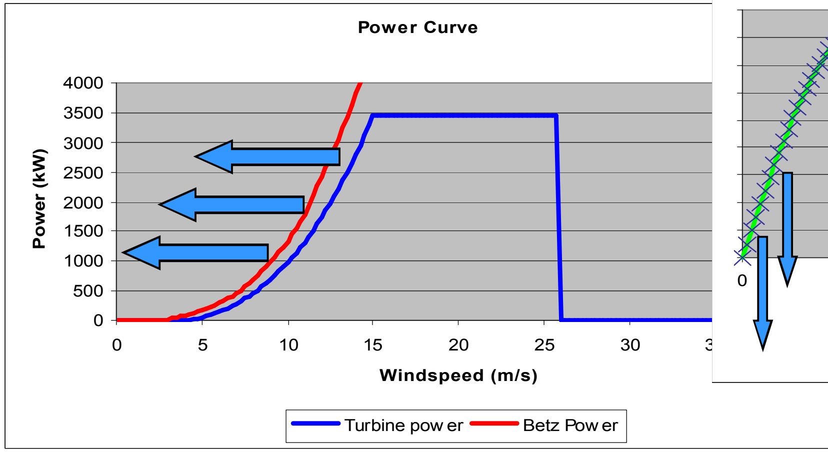
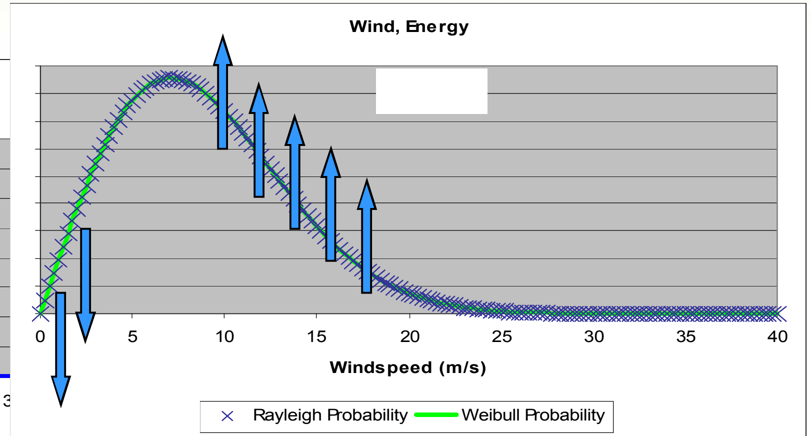
Performance Enhancement Options

Power



Resource



The cost benefits are constrained by the *squared-cubed* law

Larger Rotor

Rotor *costs* increase with diameter *cubed,* Rotor *power* grows with the diameter *squared*

Taller Tower

Tower costs increase with height to the *fourth* power

We can only win this battle if we build rotors that are smarter and components that are lighter to beat the squared-cubed law.

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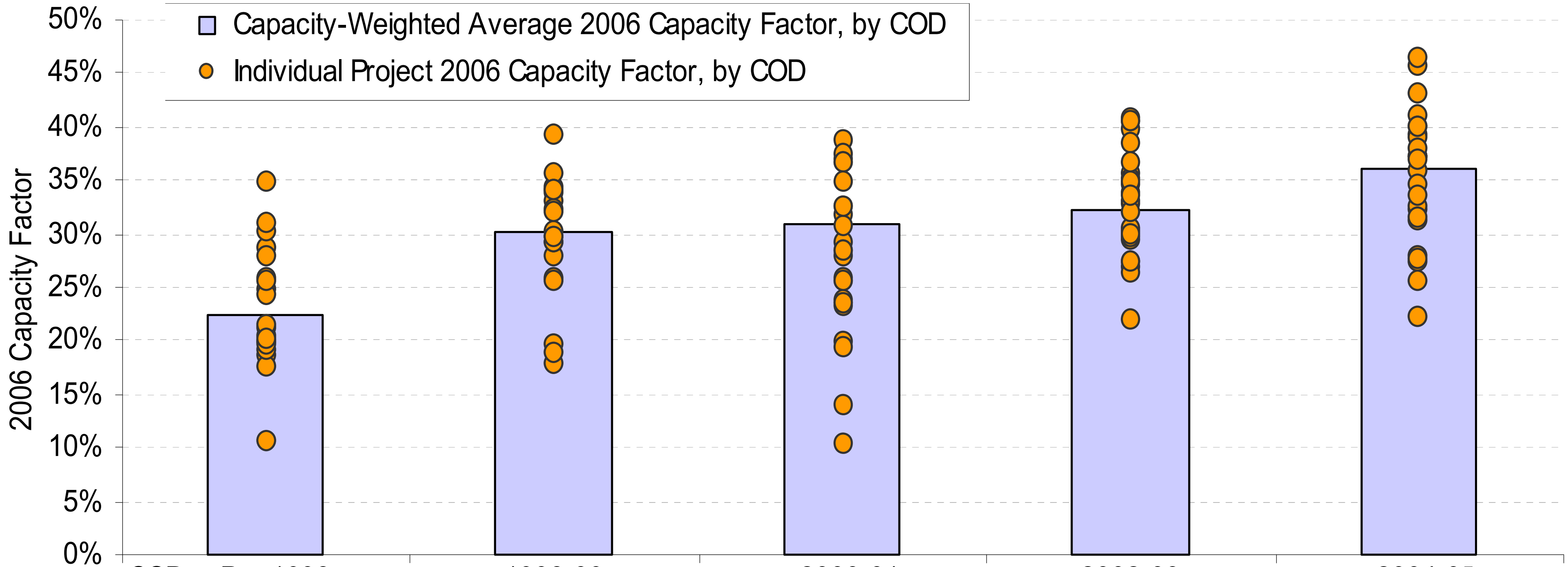
Reported Capacity Factors



COD:	Pre-1998	1998-99	2000-01	2002-03	2004-05
# Projects:	20	20	25	25	25
# MW:	936	875	1,741	1,911	2,455

CF = Generated Energy in a period of time / (Rated Power x Time period)

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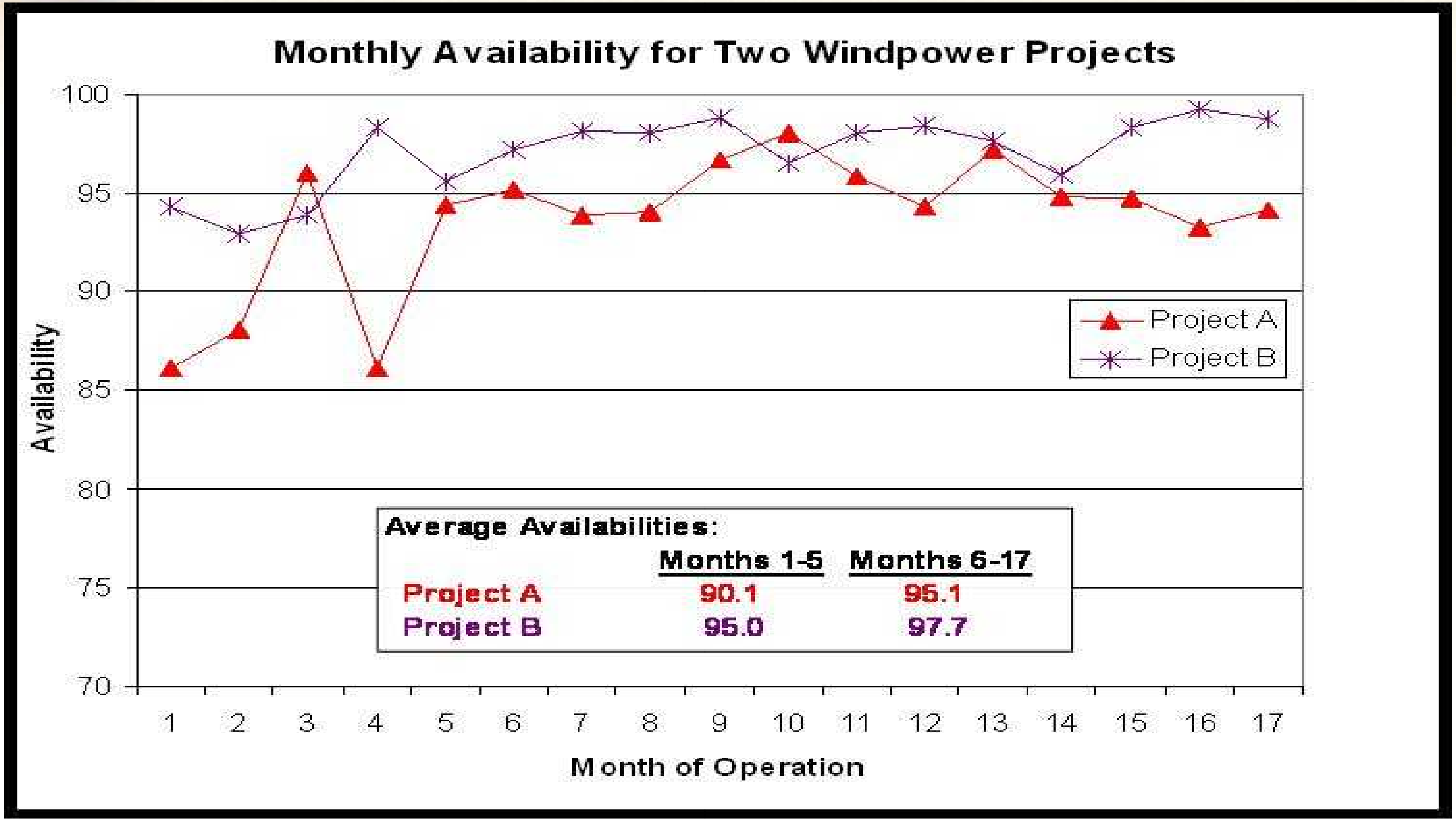
Availability

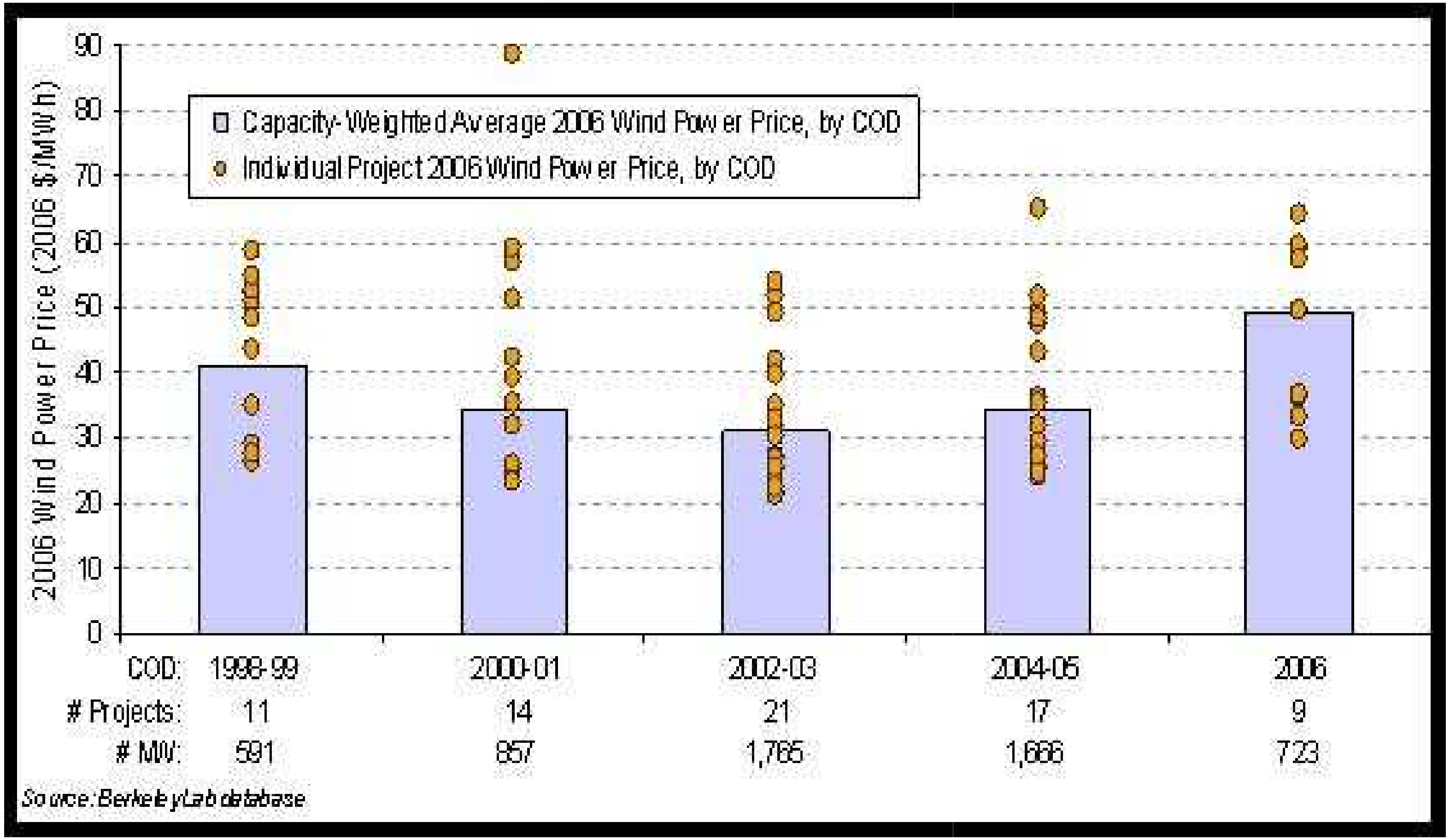


Simple Definition:

- **Availability = turbine available time/total time**

More detailed definitions are commonly used in contracts

Cost of Energy: Sales Prices



Rising prices were caused by:

- Weak Dollar
- Growing commodity prices
  - steel
  - copper
  - concrete
- Limited availability of machines

Reliability Program Goals and Objectives

Working through industry partnerships to:

- **Develop National reliability baseline statistics for the US wind energy industry**
  - **Turbine component failure rates are higher than expected by some**
  - **This is the first long-term, data based, national effort to quantify and track these failures**
- **Guide efforts to address important component reliability problems**
- **Provide feedback for improving design and manufacturing practices**
- **Help wind plants:**
  - **Optimize O&M practices**
    - Preventive maintenance
    - Parts inventory optimization
    - Condition-Based Maintenance (CBM)
    - Prognostic & Health Management (PHM)

Technology Improvement Summary
20% by 2030 Report

Subsystem	Description	Increased Energy	Capital Cost
Towers	Taller with new materials/self erecting	+11/+11/+11	+8/+12/+20
Rotors	Lighter & larger with smart structures	+35/+25/+10	-6/-3/+3
Site Energy	Improved reliability – less losses	+7/+5/0	0/0/0
Drive Train	Innovative designs – high reliability	+8/+4/0	-11/-6/+1
Manufacturing	Process evolution and automation	0/0/0	-27/-13/-3
Totals		+61/+45/+21	-36/-10/+21

20% Report, Table 2-1, page 41 (working from 2002 baseline)

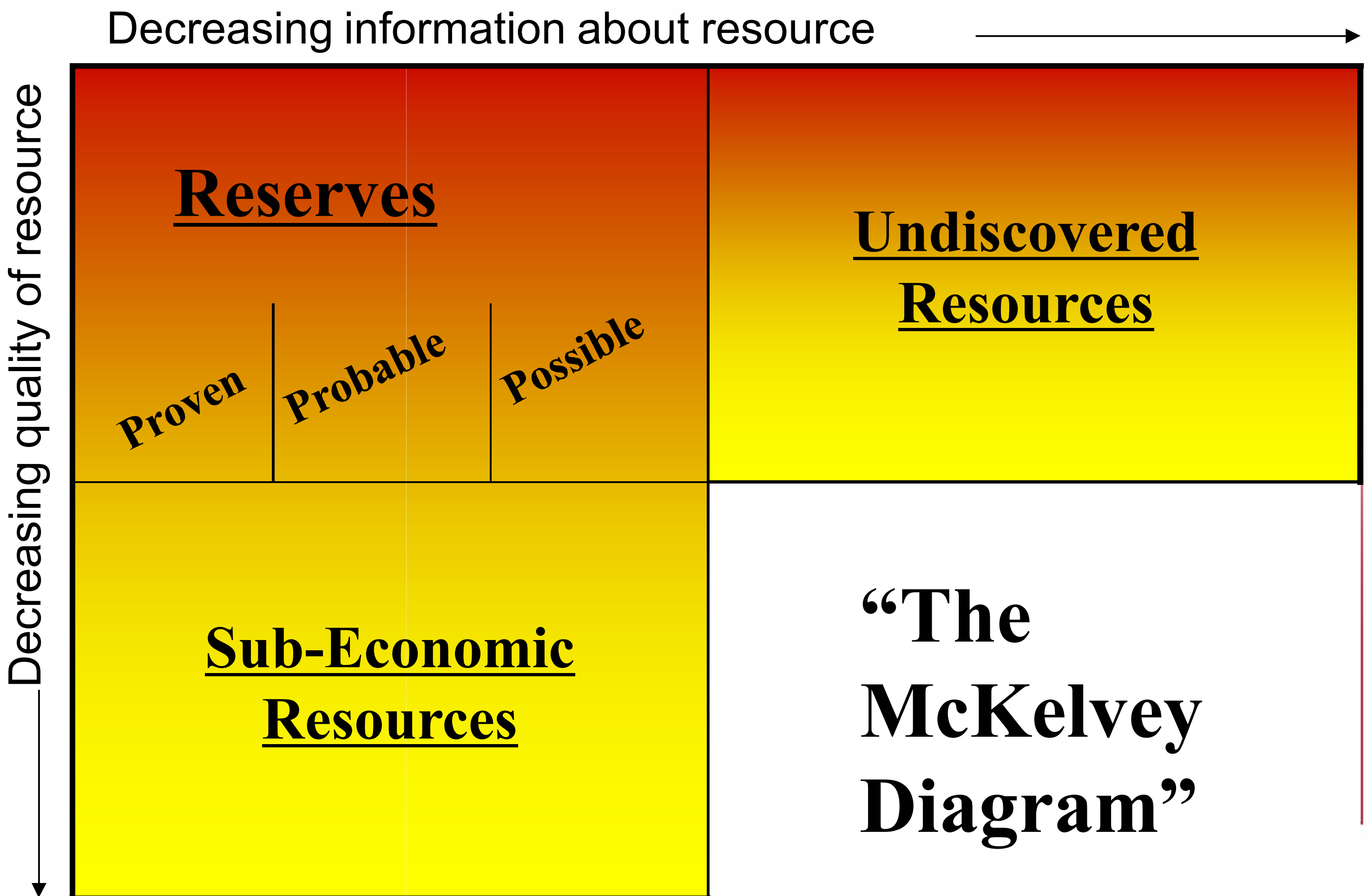
Wind Development Overview

WHTP Mission: Focus the passion, ingenuity, and diversity of the Nation, to enable rapid expansion of wind and water power production of clean, affordable, reliable, domestic energy for national security, economic stimulation, and global sustainable health.

- Wind Resource
- Infrastructure Requirements
- Land issues, permitting, environmental
- Value and financing

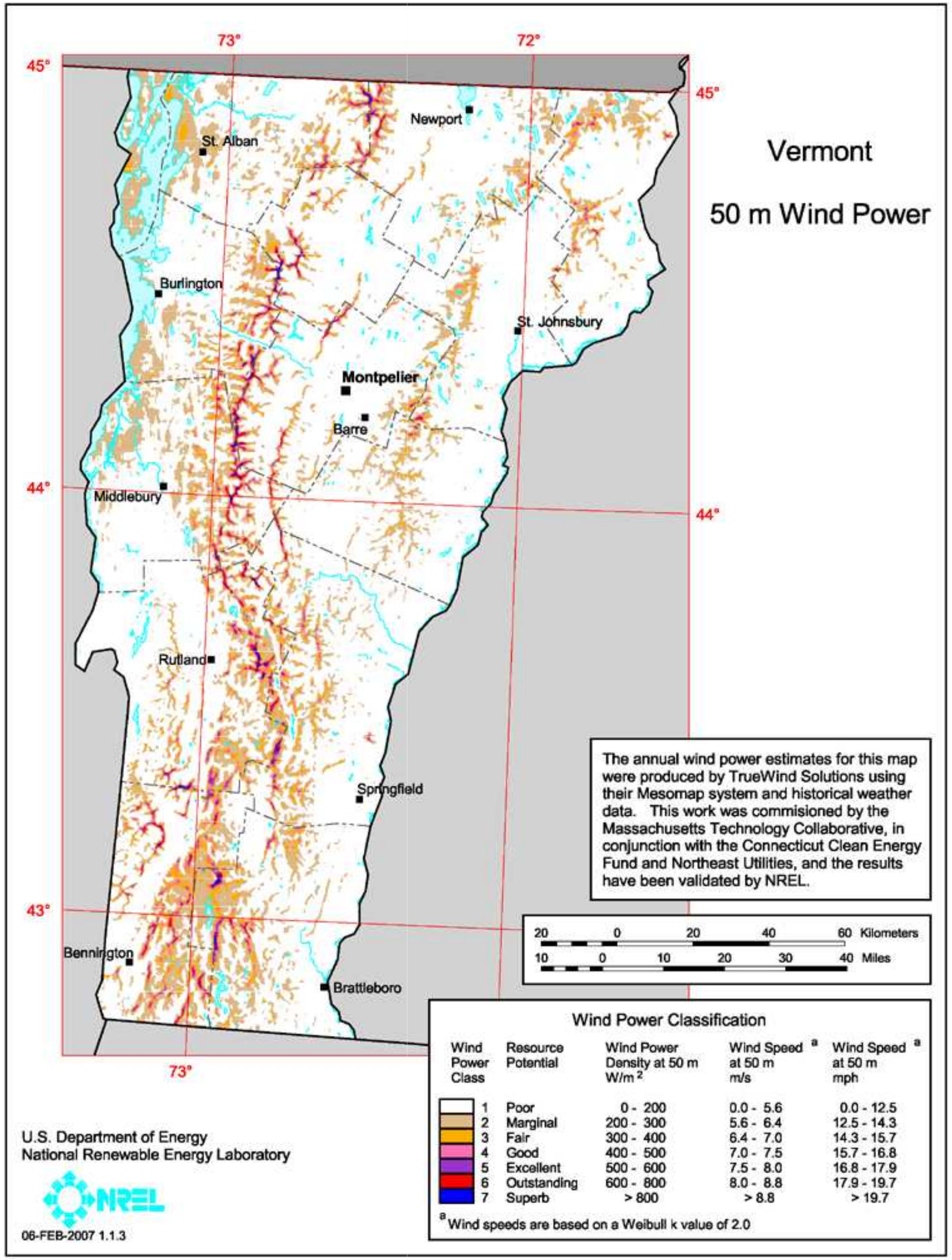
Wind Resource

What is known about the wind resource in a prospective location?
What is needed to be known?



Wind Resource

Wind Powering American Maps



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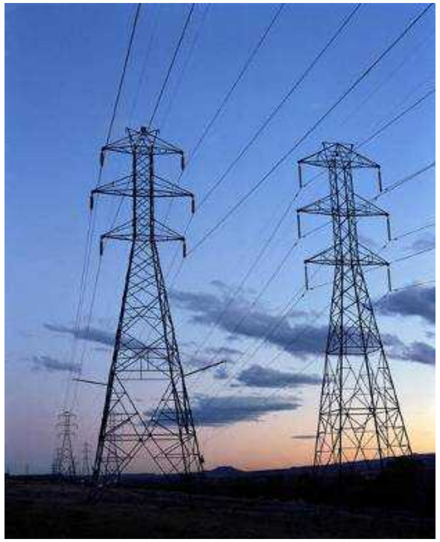
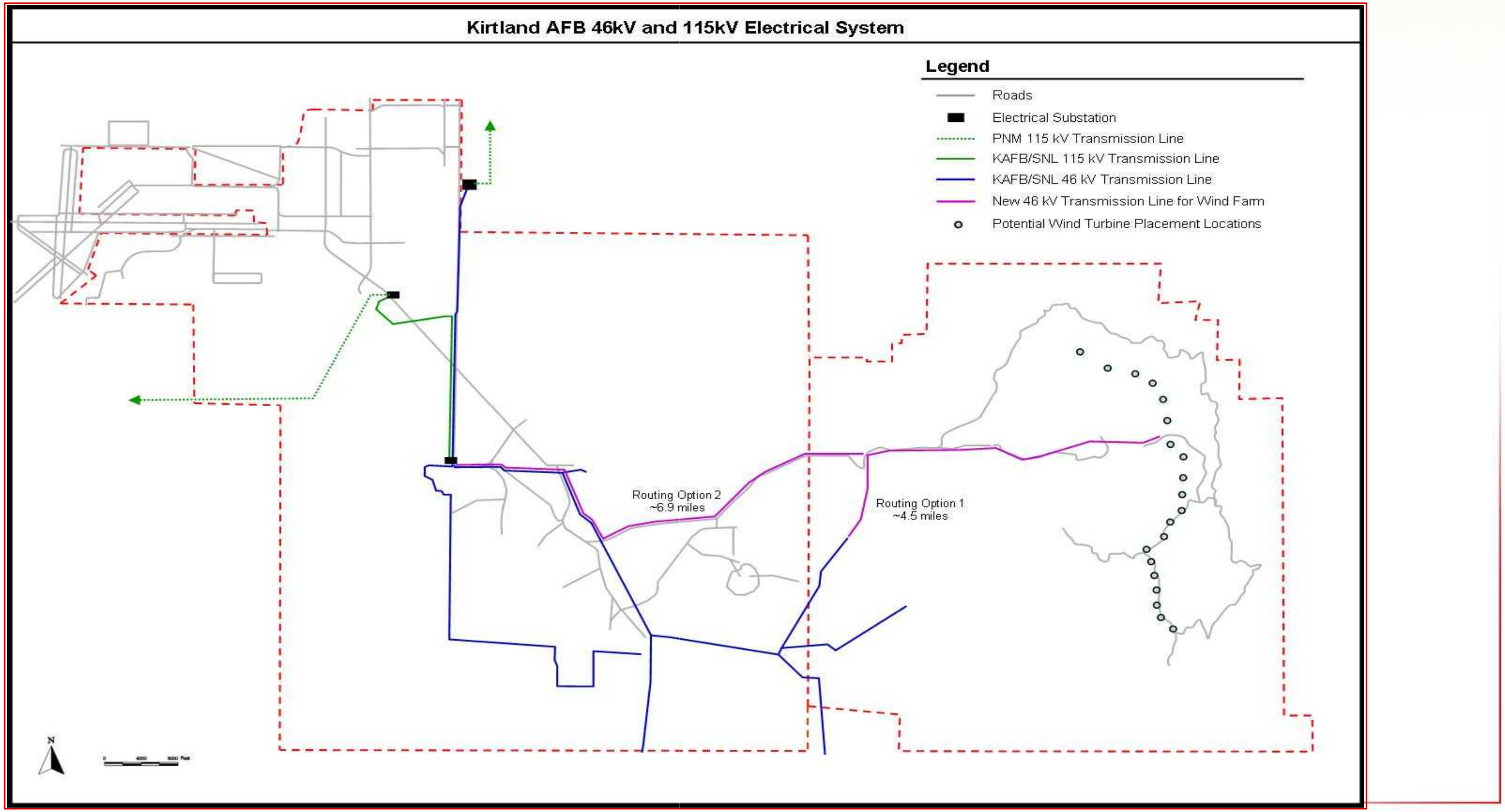
Infrastructure

- Need depends on size of plant
  - **Physical Size**
  - **Electrical Size**
- Roads/access
- Transmission interconnection/grid capacity
- Regulatory issues



Renewable System Interconnection role of WHTP!

Interconnection Study



Land, Siting, Permitting, Environmental

- Who owns the land?
- Where is it?
- How is the constructability?
- Preliminary site screening for avian, bat, wetlands, or other issues
- County ordinances
- Taxes
- Traffic, security, safety
- County ordinances
- Permits
- Environment assessments, EIS, NEPA

Value = Benefits-Costs

What makes a market?
- Power purchase agreements
- Renewable portfolio standards
- Production tax Credits

Energy needs, demand growth
Present value analysis
Economies of scale, cost engineering
Rural electrification
Pro forma
- -energy losses, waking, performance curves

How financed?
Don’t forget operations and maintenance

The Development Business

The development process needs clear definition of requirements teamwork, communication, clear-headed approaches creative solutions, dealing with external decision-makers, empowerment, ownership responsibility and continuous improvement.

Reality:
- Competition
- Cherry picking
- Reliability
- $$$

Phases of a project:
- Wild enthusiasm
- Disillusionment
- Panic
- Search for the guilty
- Punishment of the innocent
- Praise & honor for those not involved

Wind Turbine Capabilities

Induction Generators:

- Absorbed VARS – no voltage support or control;
- Tripped due to voltage or frequency excursion;
- Provided no voltage control or droop control.

New Machines:

- Dynamic reactive power;
- Low (or zero) voltage ride-through;
- Dynamic real power control – droop control, ramp mitigation.

Source: Brendan Kirby, NREL Consultant

Wind Integration Challenges

Inability to Dispatch

- Weather determines output

Variability

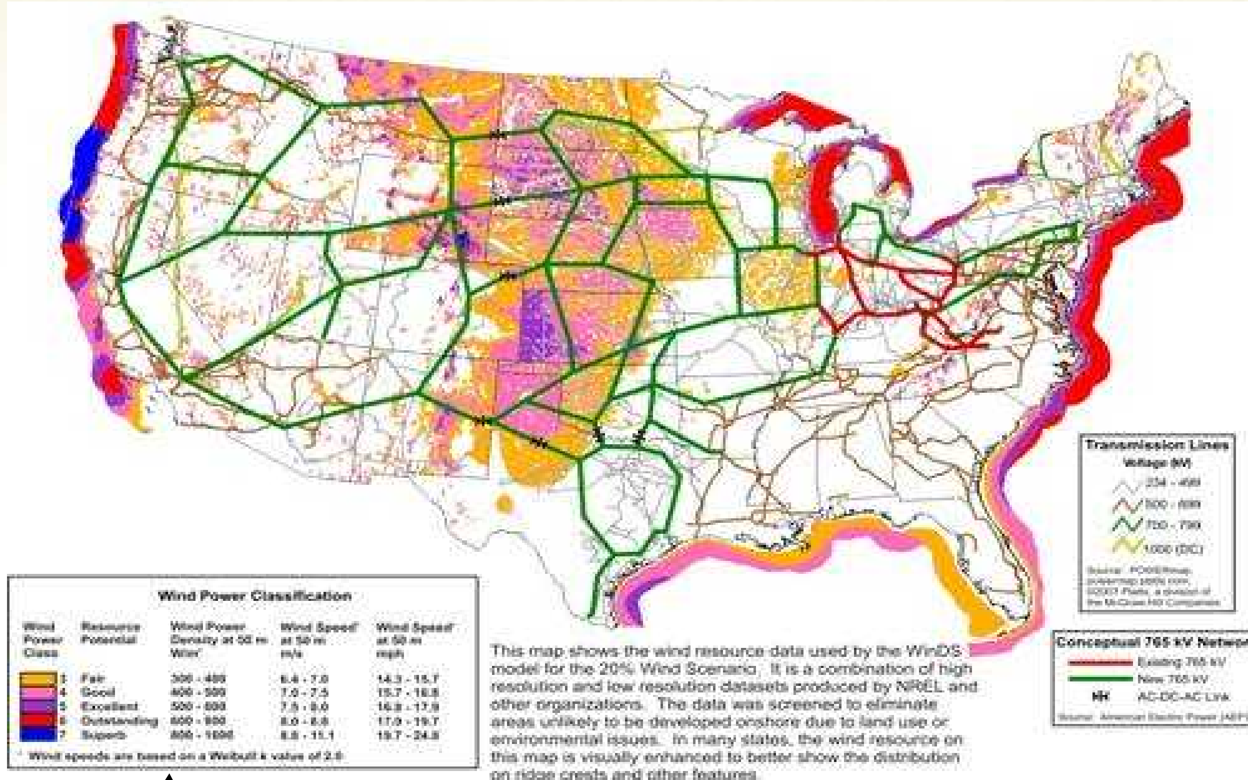
- Increases difficulty to balance load

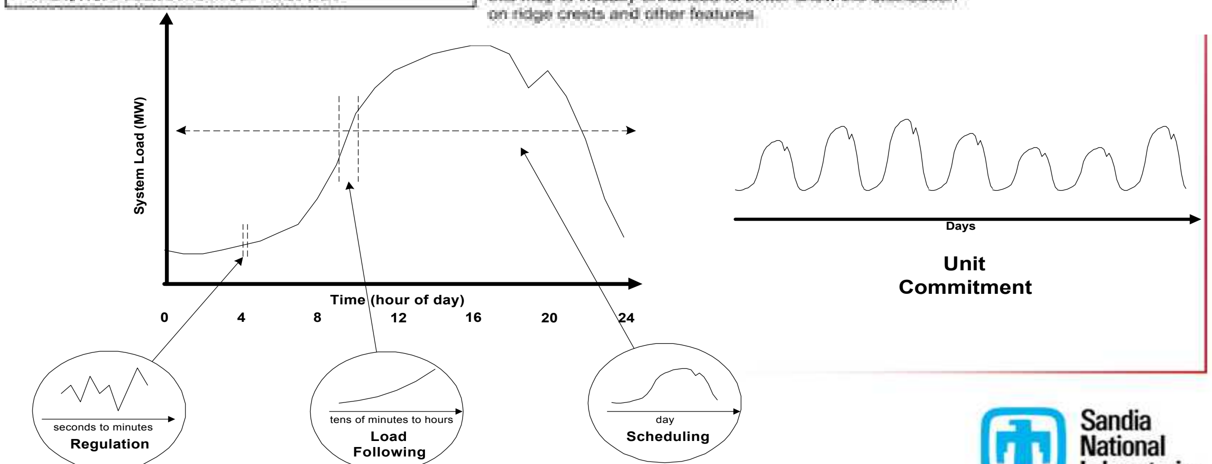
Uncertainty

- Can be forecasted to a large extent

Different Electrical Characteristics

- Lower inertia, voltage tolerance, reactive controls
- Still compatible with the grid





Areas of Consideration:

System Planning and Operation

Transmission Planning

Market Operation & Transmission Policy

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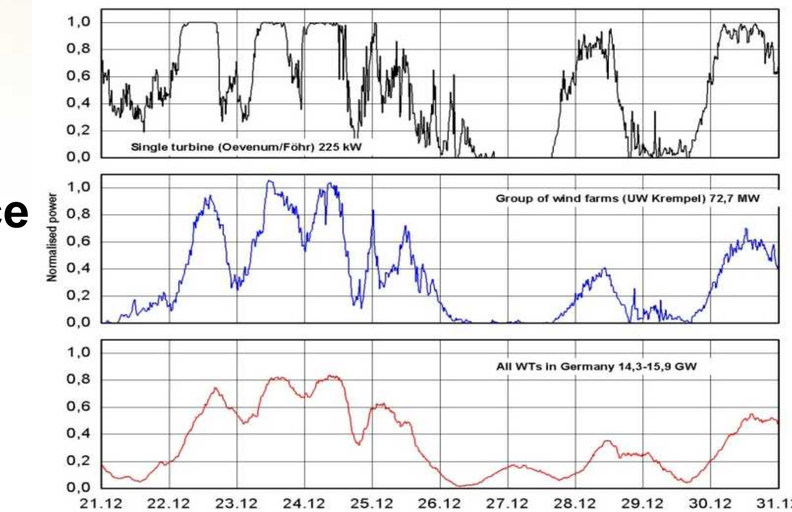
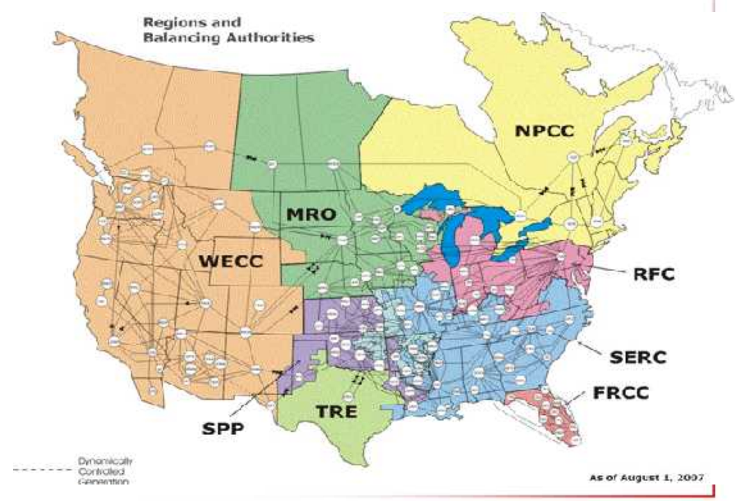
Questions of Interest for Integration Studies

- **How do local wind resources compare with higher capacity factor wind that requires more transmission?**
- **How does geographic diversity of wind power reduce wind integration costs?**
- **How does offshore wind compare with onshore wind?**
- **How does balancing area cooperation affect wind power integration costs?**
- **How much transmission is needed to facilitate higher penetrations of wind power?**
- **What is the role of wind forecasting?**
- **How are wind integration costs spread over large market footprints and regions?**
- **What additional operating reserves are needed?**





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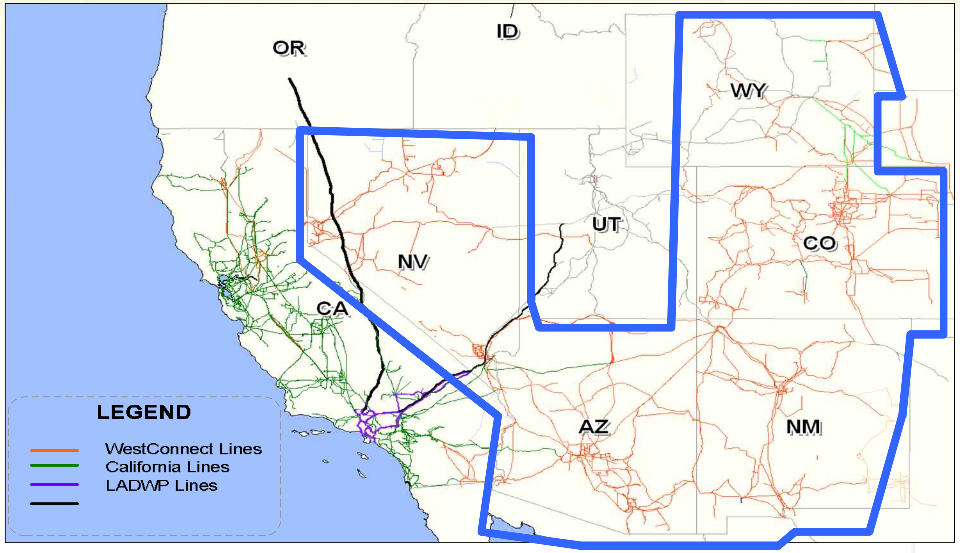
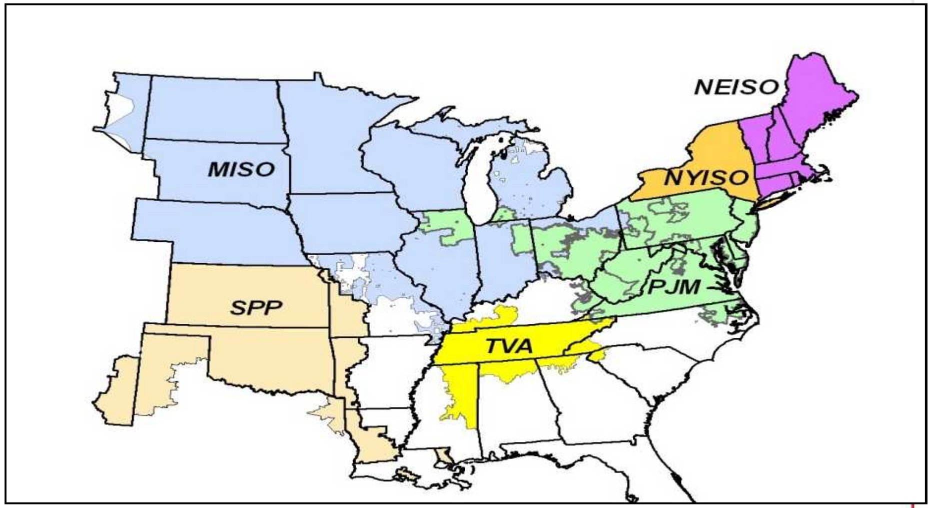
Broad Regional Studies

- Goal is to understand the costs and operating impacts due to the variability and uncertainty of 20-30% wind energy on the grid
- Heavily stakeholder driven scenario development and technical review
- Participation in other studies: Nebraska Power Authority, Portland General Electric, New England ISO, Southwest Power Pool, Hawaii, Arizona Power Authority





DOE work provides objective technical information on grid options

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Organizational and Study Web Links

Utility Wind Integration Group (UWIG) (www.uwig.org) and Wind Integration Library http://www.uwig.org/opimpactsdocs.html

NREL Renewable System Integration publication web site http://nreldev.nrel.gov/wind/systemsintegration/publications.html

Sandia National Labs Wind & Water Power Technology web site http://windpower.sandia.gov

Eastern Wind Integration and Transmission Study (EWITS) http://wind.nrel.gov/public/EWITS/

Western Wind and Solar Integration Study (WWSIS) http://westconnect.com/planning_nrel.php

International Energy Agency, Task 25. Hannele Holttinen, et.al. ***Design and operation of power systems with large amounts of wind power State of the art report***. http://www.vtt.fi/inf/pdf/workingpapers/2007/W82.pdf

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Sandia Publications are at sandia.gov/wind

- Active Aero Control Design
- Blades:
  - Adaptive
  - Aeroacoustics
  - Blade System Design Study
  - Carbon Hybrid
  - Flutter
  - General
  - Testing
- Computational Fluid Dynamics
- Control System Design:
  - Nonlinear Control Theory
  - Wind Turbine Blade Controls
- Data Acquisition and Field Measurements
- Fatigue and Reliability:
  - General
  - LIFE2
  - Loads
- Probability of Failure
- Health Monitoring
- Manufacturing
- Materials:
  - Aluminum
  - Bonded Joints
  - Composites
  - Material Testing and Fatigue
  - Property Determination
- Modal Testing and Analysis
- Non-destructive Testing
- NuMAD
- Partnerships:
  - Low Wind Speed Technology:
    - Knight & Carver
    - WindPACT
- Supervisory Control And Data Acquisition
- Structural Dynamics
- Turbine Systems
- Turbulence Simulation
- VAWT Archive
- Wind Plant Reliability
- Wind Powering America

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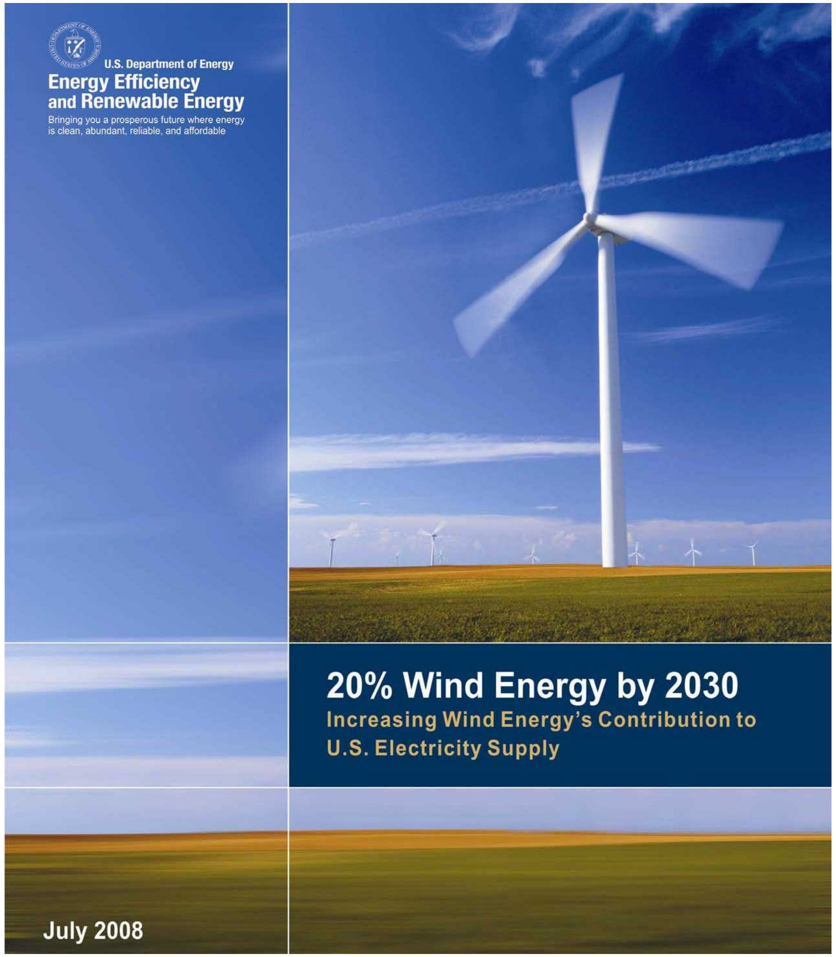
And the Conclusion is….

There are **no fundamental technical barriers** to the integration of 20% wind energy into the nation's electrical system, but …. there needs to be a **continuing evolution of transmission planning and system operation policy and market development** for this to be most **economically achieved.**



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RENEWABLE ENERGY INTEGRATION CASE STUDIES

Joshua S. Stein Ph.D.
Photovoltaics and Grid Integration Department
Sandia National Laboratories

Renewable Energy Short Course, Burlington, VT
26 July, 2011

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

Ota City, Japan

- **Basic Concepts**
  - Why is integration of variable generation (VG) a challenge?
  - Bulk System vs. Distribution Issues
- **Review of Recent and Current Studies**
- **Define next steps**

Harwich, MA

Freiburg, Germany

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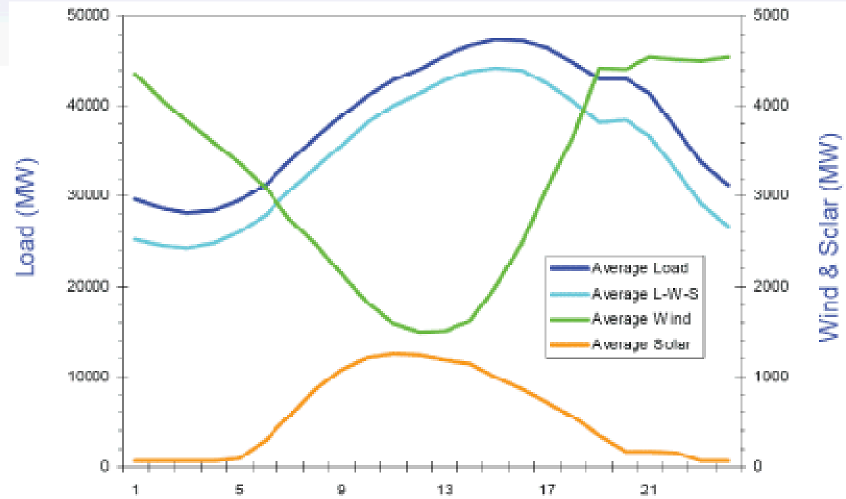
What is the Utility's Role

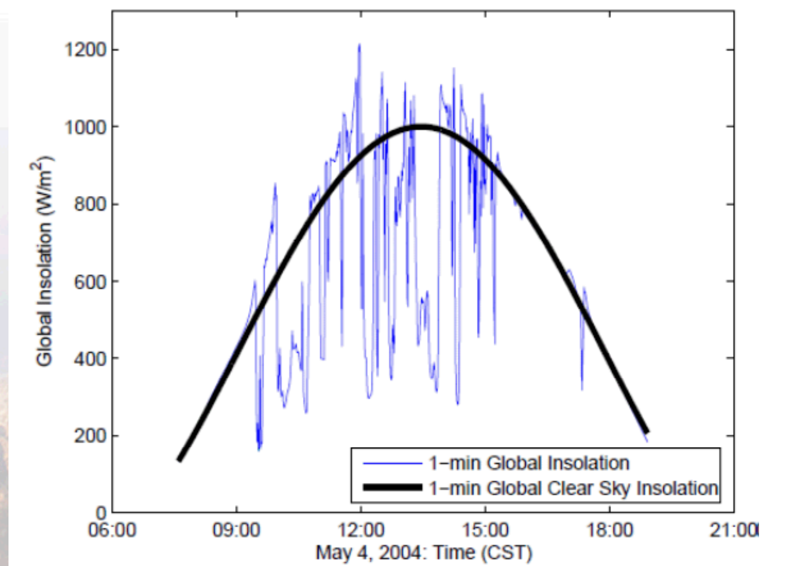
- **Provide high quality, reliable electricity to customers when they demand it.**
  - Generate or procure power to meet system load
    - Integrated resource planning (long term planning)
    - Balance system load and generation (near term planning)
  - Transmit this power to the loads using transmission and distribution resources
    - Transmission and distribution planning
    - Transmission and distribution component upgrades
    - Maintenance of transmission and distribution
- **Protect staff and public from harm**
    - Switching, protection equipment , response to emergency events
- **Private utilities must make a return on investment**
  - Bill customers for services

What is Variable Generation?

- **Typically refers to Solar (PV) and Wind**
- **Variable**
  - Long-term and short-term patterns
  - Limited ability to control
- **Uncertain**
  - Ability to forecast
  - Accuracy depends on how far ahead the forecast covers
- **Sound familiar? Many of the same characteristics associated with load**



Average PV and wind output patterns in CA

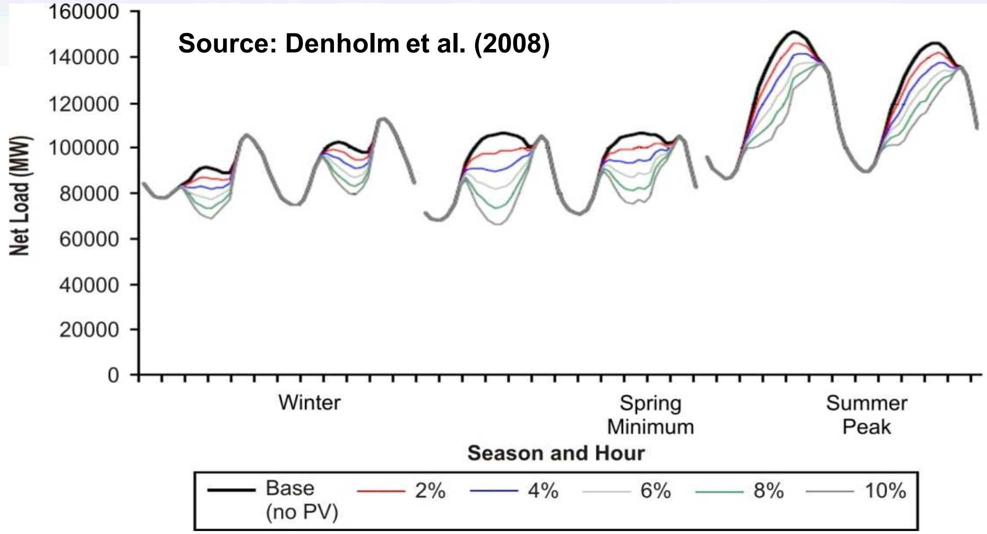


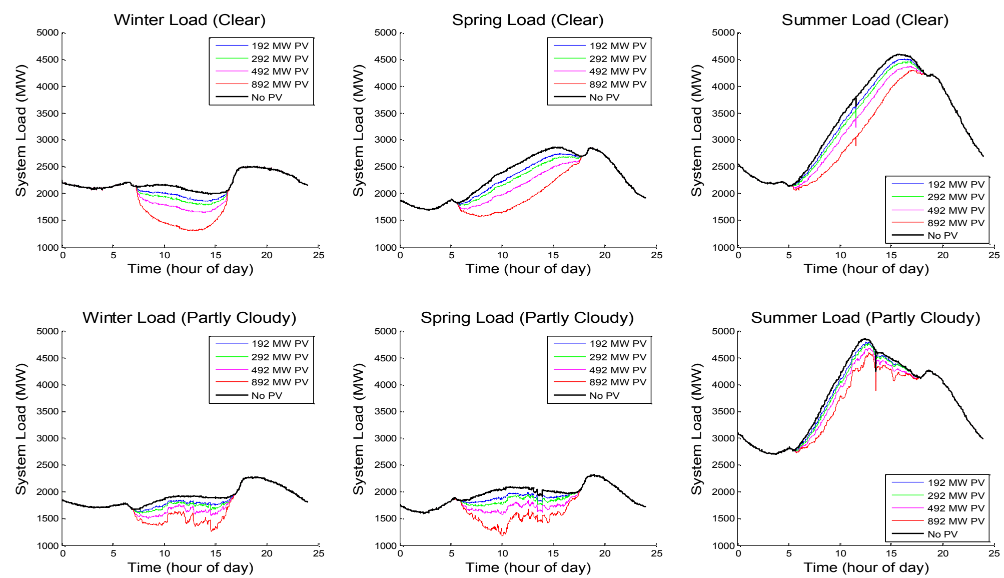
How Does VG Affect Utilities?

- **Variable generation (VG) has traditionally been a must-take resource that affects the load utilities must manage (net load)**
- **At the distribution level**
  - The interaction of variable generation and variable load can alter the normal behavior and performance of components on a distribution feeder (voltage regulators, voltage tap changers, capacitors, etc)
  - Examples: (1) frequency of tap changes may increase leading to reliability and service life concerns, (2) flicker, (3) interoperability between VG components (inverters), harmonics.
  - VG may help defer distribution upgrades due to reducing peak loads on a feeder
- **At the bulk system level**
  - Added variability may increase total variability in load, making it more costly to balance
  - Forecasting VG becomes very important in order to adequately schedule generation and manage resources
  - VG may help defer generation upgrades or addions

PV Generation and Net Load

- **Net Load = Load – VG**
  - VG is assumed to be a "must take" generation
- **During summer peak, PV helps to reduce the peak load**
  - Less fossil generation needed
  - Fewer "peakers" (dirty)
- **During low load seasons (spring and winter in SW) PV can affect operations and planning**
  - Lower temperature, sun position at equinox
  - Affects minimum load
  - Increases the morning ramp
  - Variability increases



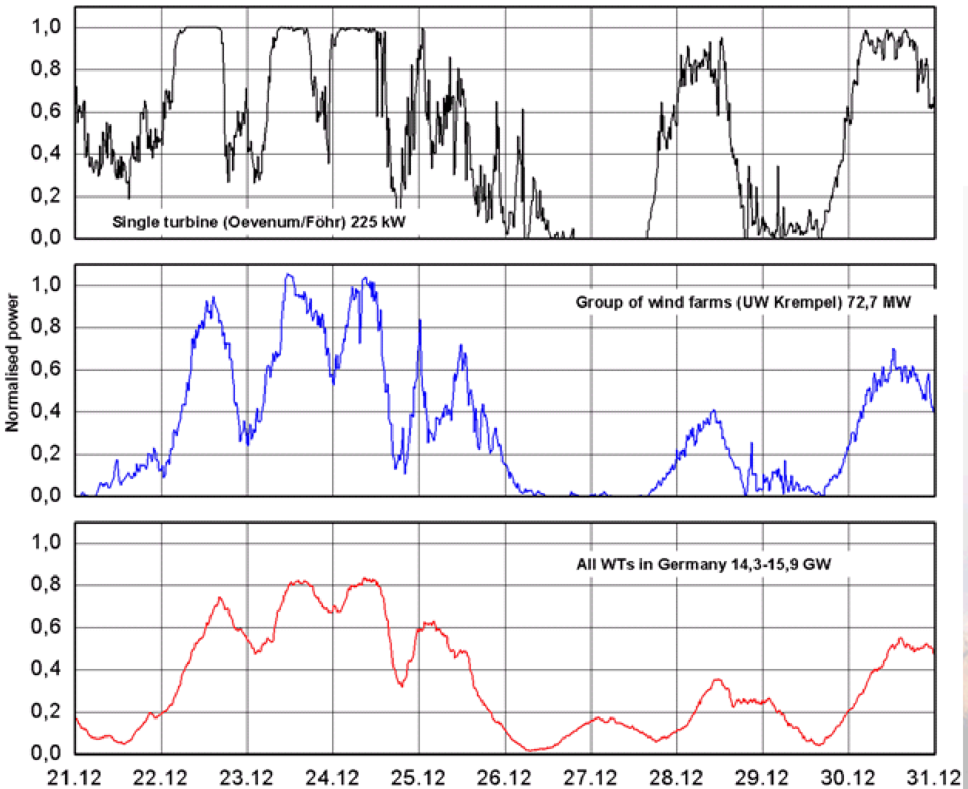


Stein et al. (2011)

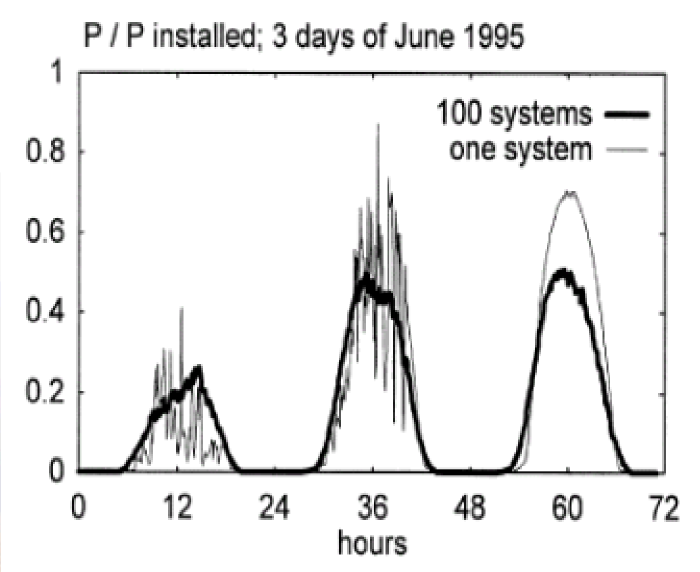
Geographic Smoothing

- **Geographic separation helps reduce variability**
  - Variability does not 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



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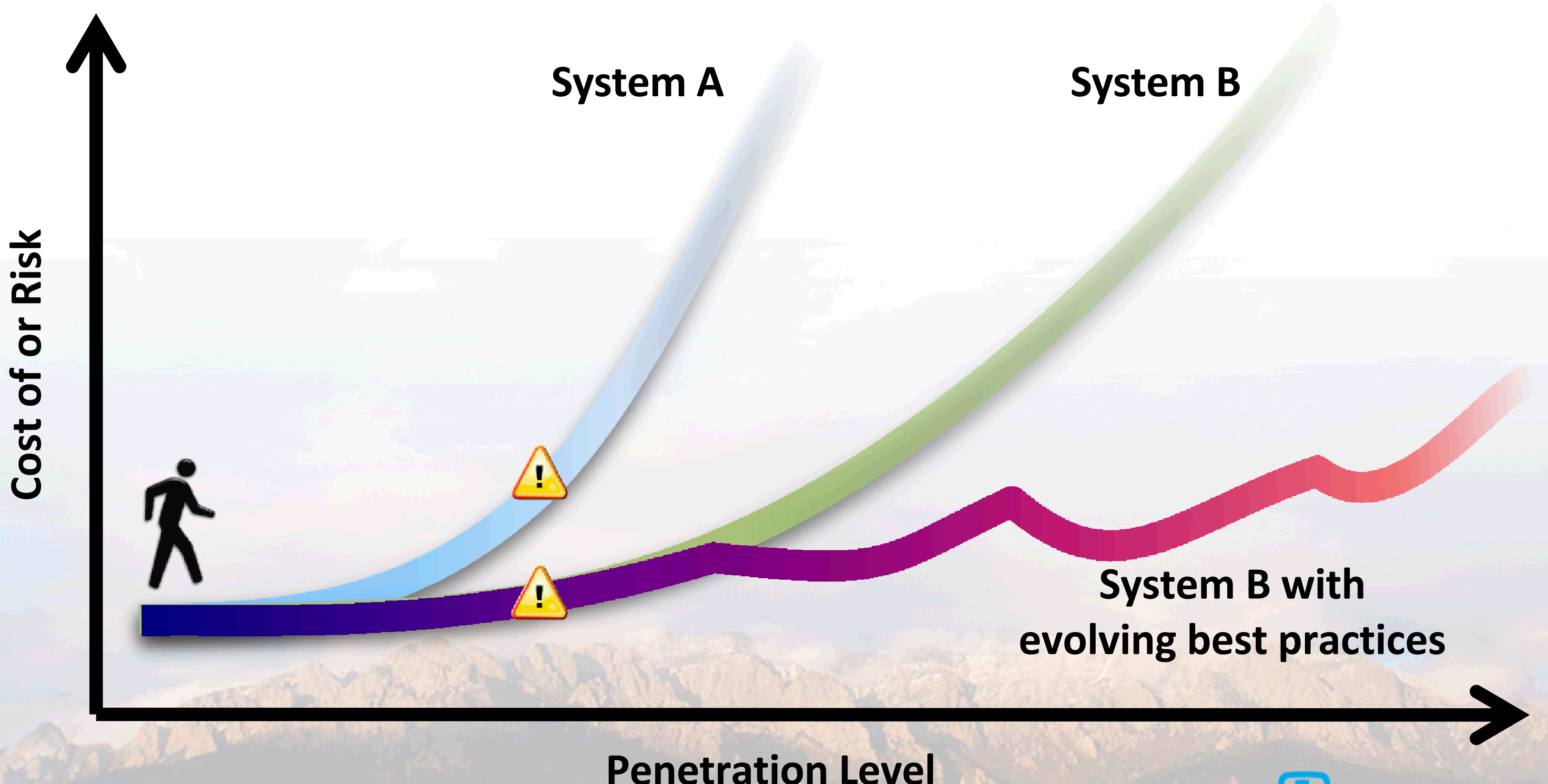
Are There Penetration Limits?

- **There are no <u>absolute</u> technical limits**
  - Impact on cost is very system-specific
  - Depends on resources, load patterns, weather, markets, regulations

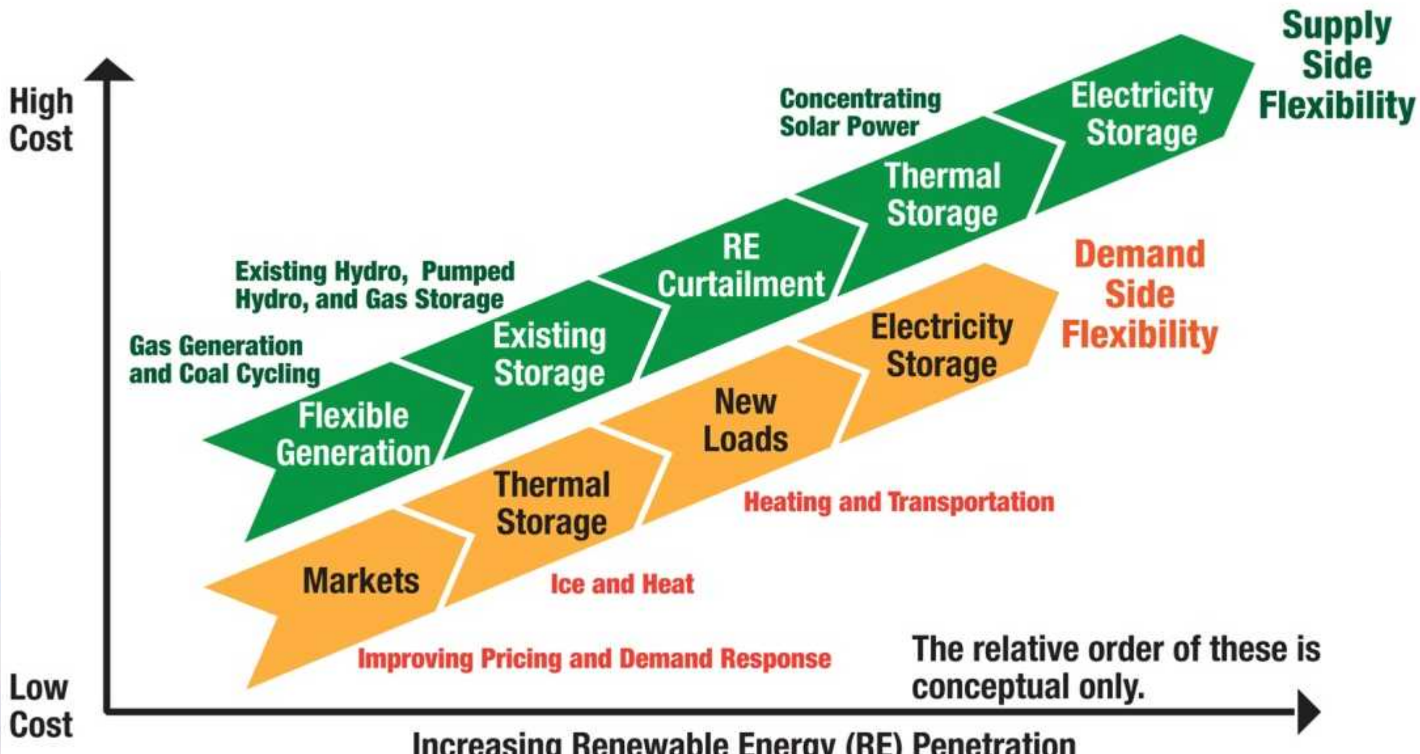


What are the Technical Challenges?

- **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, frequency, contingency
    - Planning and operations best practices
- **Distribution System Issues**
  - Voltage, protection

Integration Solutions and Costs

- Most utilities have only explored the first few solution options (flexible generation, markets)
- High cost, uncertainty, and increased complexity are the main hurdles to overcome



Source: Denholm (2008)

How are impacts assessed?

- **Integration studies help utilities better understand the impacts of and plan for increasing levels of VG on their systems.**
- **There have been several major integration studies but the study methodology is still evolving**
  - Each utility has a unique system and situation
- **Impacts to the distribution system are usually studies separately from impacts to the bulk system (balancing area)**

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

Examples of Very High PV Penetration on Distribution System

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

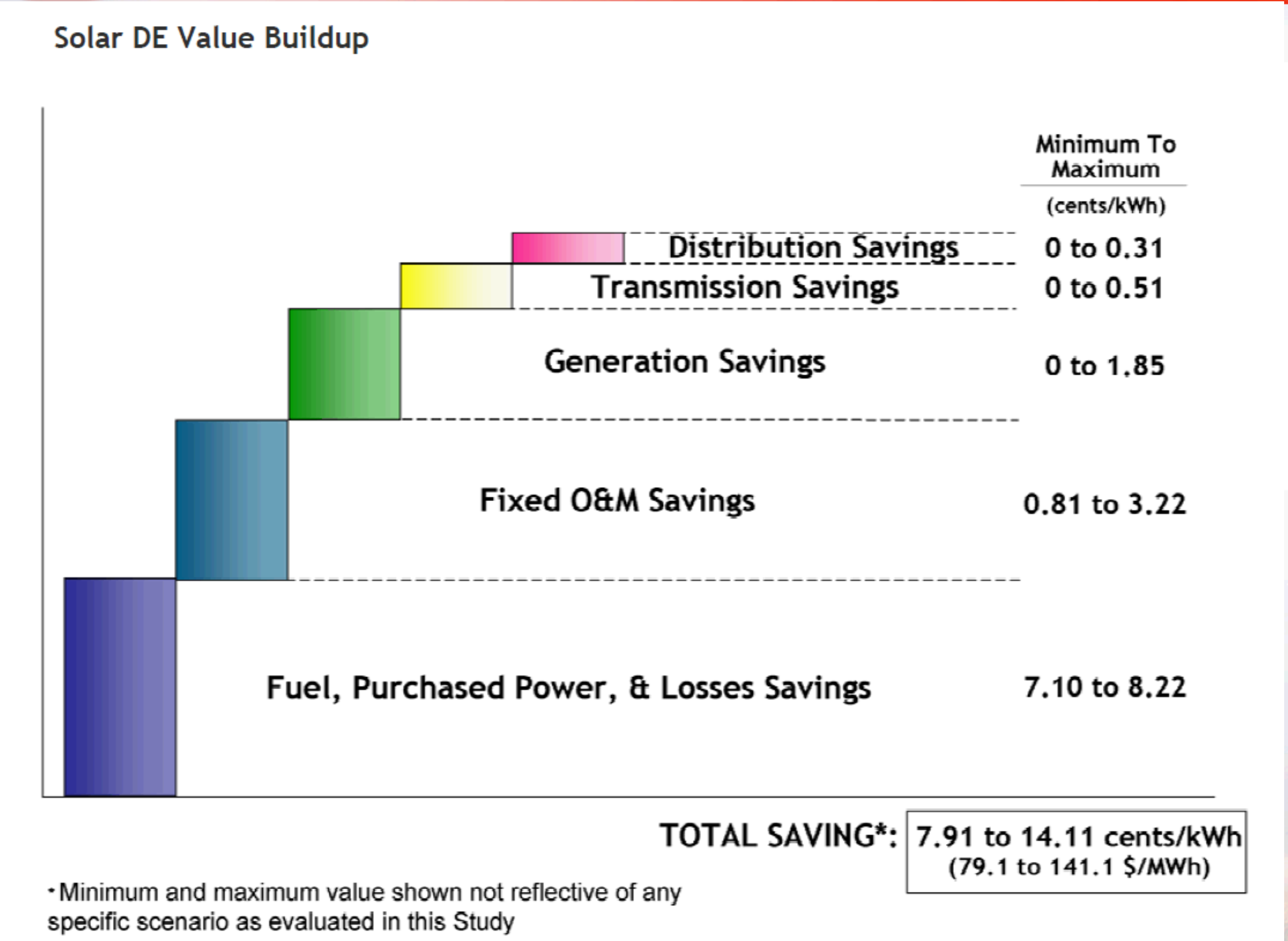
Some Examples of Integration Studies

- **Several of these studies are not publically available**
- **Distribution Studies**
  - Distributed Renewable Energy Operating Impacts and Valuation Study (Arizona Public Service, 2009)
  - Distributed Generation Study (NV Energy, 2010)
- **Bulk System Studies**
  - Eastern Wind Integration Study (NREL, EnerEx, 2010)
  - Western Wind and Solar Integration Study (NREL, GE, 2010
  - Operational Requirements and Generation Fleet Capability at 20% RPS (CAISO, GE, 2010)
  - NV Energy Solar Grid Integration Study (in process)
- **General Overview Studies**
  - 20% Wind by 2020 (2009)
  - SunShot Vision Study (in review)

Distributed Renewable Energy Operating Impacts and Valuation Study Results

- **Study focus on Value Determination of distributed renewable generation**
  - Avoided energy costs (based mainly on reduced fuel and purchased costs as well as reduced losses)
  - Reduced capital investment (Deferral of costs for future distribution, transmission, and generation)
  - Consideration of additional externalities (air quality, reputation, experience)
- **Results**
  - For entire distribution system: DG created little value because need to meet peak load when DG is unavailable.
  - For specific feeders: DG created value by deferring upgrades but were very location specific.
  - Transmission deferrals: Large amount of DG is needed to eliminate need for new transmission. Long lead times for transmission planning make value of DG hard to realize (10 year+ timeframe)
  - Generation deferrals: similar to transmission (lots of DG needed to realize value)

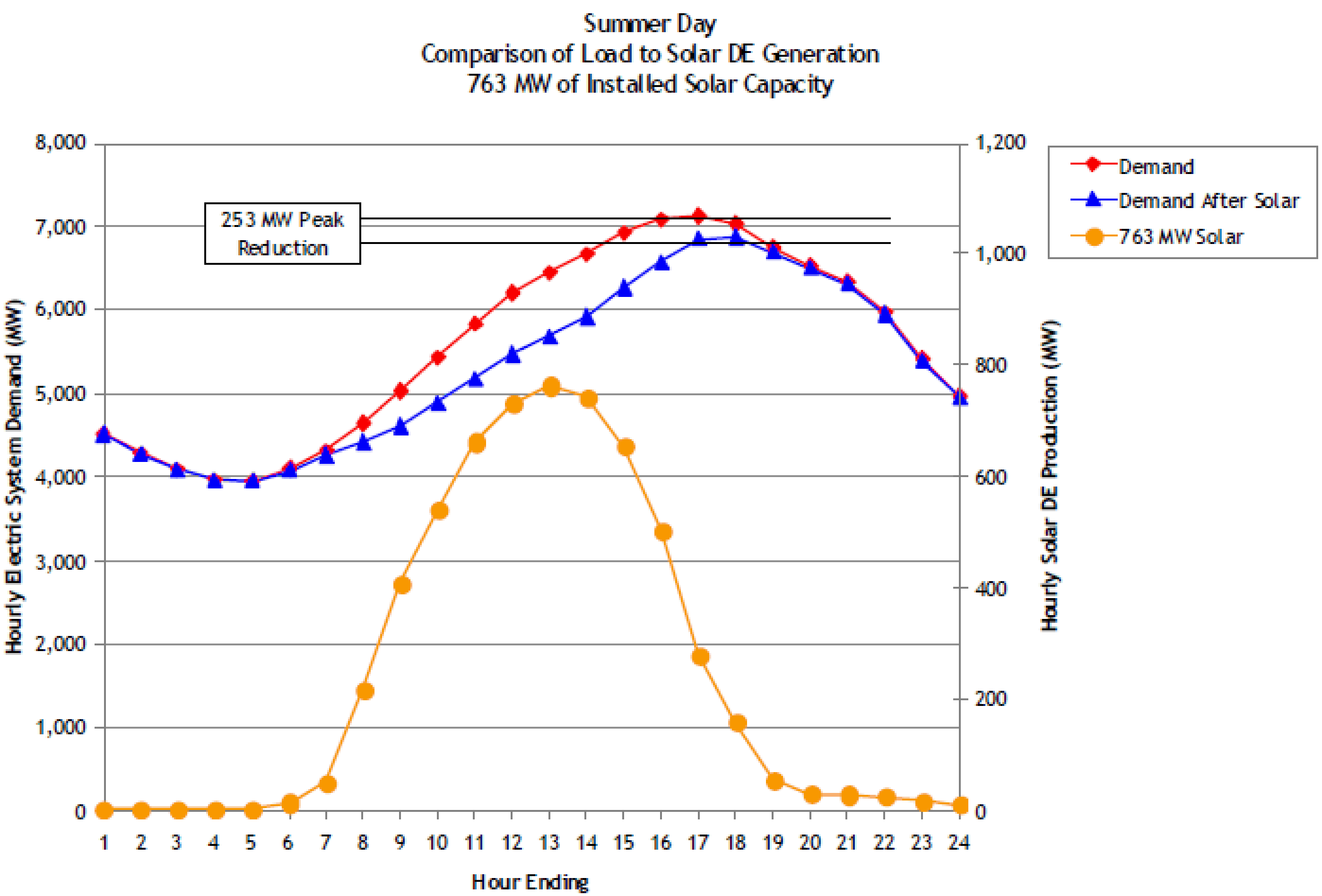
Distributed Renewable Energy Operating Impacts and Valuation Study Results



Distributed Renewable Energy Operating Impacts and Valuation Study Results

- **Solar PV peak occurs before the load peak in the early evening**
- **Solar hot water might help to alleviate**

Solar Production Versus Demand Peak



NV Energy Distributed Distribution Study Results

What is the maximum amount of DG from renewable energy that can be integrated on the distribution system within existing operating limits?

Given distribution thermal and voltage limits, what is the maximum amount of DG?

0% ← → 30%

- Most feeders can accept up to 20% or more of DG without violating voltage or thermal limits if DG is uniformly distributed
- When DG systems are strongly clustered, some feeders will potentially experience voltage regulation issues and DG penetration levels for individual feeders will be lower
- Longer feeders also limit the amount of DG that can be installed

Does transmission steady state and dynamic performance impact the amount of allowable DG?

0% To be determined 30%

- Preliminary steady state and dynamic load flow modeling of NVE's Southern transmission system indicates that DG can negatively impact transmission system performance, particularly when large renewable DG is included
- Ongoing studies evaluating integration of large PV will fully address transmission system impacts

Are there other distribution-level technical factors that limit the maximum amount of DG?

0% ← → 30%

- Based on findings for other systems with high DG penetration, NVE should evaluate the impact of clustered DG on power quality before large quantities of inverter-based devices are installed
- NVE also will need to monitor feeder performance and power quality prior to when new large PV is installed with large amounts of small DG at the distribution level

Given generation minimum run and commitment schedules, what is the maximum amount of DG?

0% To be determined 30%

- Under low load conditions, the combination of small DG and large intermittent generation can cause generation to operate at non-optimal levels
- At higher DG penetration, generating operating reserve margins likely will increase, causing added costs.
- Other transmission connected utility-scale wind or solar added to the system will decrease the amount of allowable DG

NV Energy Distributed Distribution Study

Does DG provide benefits to NV Energy?

Does DG provide avoided emissions benefits?

Yes No

- Preliminary results presented in this study do not fully reflect the impact DG will have on generation emission output caused by intermittent DG
- Higher emissions may be created by generation operating at lower efficiency level operates at the margin during periods of light loads
- The value of emissions offsets may vary as new legislation is enacted

Does DG reduce distribution losses?

Yes No

- PV daytime output corresponds to periods of highest losses at the system level, with attendant savings; however, distribution losses on many NVE feeders is low
- On lightly loaded feeders, modest DG penetration can cause losses to increase, particularly on long, rural feeders

Does DG provide fuel costs benefits?

Yes No

- Most fuel savings occur due to the displacement of natural gas generation operating during daytime hours
- At higher DG penetration levels, generation may operate at less than optimum dispatch levels – this will be analyzed in the Utility-Scale PV Integration Study
- Any DG that is net metered will transfer non-fuel costs to other ratepayers

Does DG provide avoided capacity benefits?

Yes No

- There are virtually no generation capacity benefits as PV output at the 8:00pm system peak is zero
- Similarly, most distribution feeder peaks occur during evening or shoulder hours when PV output is low
- The automatic tripping of DG under IEEE 1547 further limits DG capacity benefits at the distribution level

NV Energy Distributed Distribution Study

What are the costs to NV Energy to integrate increasing amounts of DG to the distribution system?

Does DG cause significant <u>system protection upgrade</u> costs to NV Energy?

Yes ← No

- At low DG penetration levels and where DG is uniformly distributed, protection impacts are minimal for most feeders
- At higher penetration levels reverse power flows and high flows will limit the amount of DG that can be installed
- DG may cause fault duty to approach or exceed equipment limits in the North; additional study is needed to confirm which equipment is impacted

Does DG cause significant <u>line size and voltage upgrade</u> costs to NV Energy?

Yes ← No

- Line thermal capacity generally is sufficient
- Local capacity limits should be evaluated for heavy clustering
- For heavy clustering or DG located on long circuits, voltage limits may be exceeded
- Transmission level upgrades may be needed when new large renewable projects are installed along with distribution-level DG. This issue will be analyzed in the Utility-Scale PV Integration Study.

Does DG cause significant <u>costs</u> to NV Energy?

Yes | To be determined | No

- At low DG output or penetration, generation dispatch is minimally impacted
- Under higher DG penetration levels, economic dispatch can be impacted as DG may displace low-cost generation or cause hourly imbalances
- Further, unit commitment schedules may shift due to DG, causing non-optimal generation economic dispatch

Does DG provide net <u>economic benefits</u> to NVE?

Yes | To be determined | No

- Fuel , emissions, and other benefits do not fully offset costs to ratepayers under current rates
- However, these preliminary results do not fully assess the impact of large-scale renewable projects on transmission and power system costs.
- Transmission and power system impacts will be studied as part of the Utility-Scale-Scale PV Integration Study

Bulk System Integration Study Steps

- **Develop generation and transmission scenarios based on future expectations**
  - Economic assumptions (carbon price, RPS, etc.)
- **Develop load and RE resource datasets (synchronized)**
  - Example from NV Energy Solar integration Study
- **Run production cost model to simulate economic dispatch and unit commitment process for scenarios**
- **Important details include:**
  - Locations of loads and generation
  - Size of balancing areas
  - RE forecast availability, frequency, and accuracy
  - Transmission constraints and congestion
  - Additional regulation and contingency required to balance load and generation

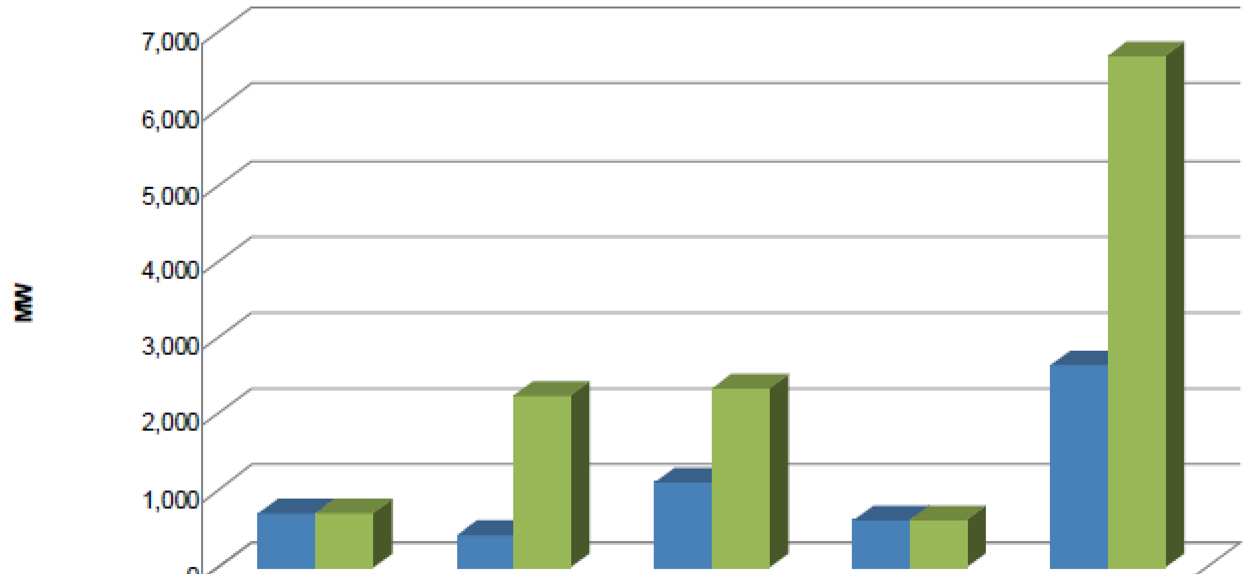
Wind Integration and Transmission Studies

- **Eastern Wind Integration and Transmission Study**
  - http://www.nrel.gov/wind/systemsintegration/ewits.html for details
- **Western Wind and Solar Integration Study**
  - http://www.nrel.gov/wind/systemsintegration/wwsis.html
- **Nebraska Wind Integration Study**
  - http://www.nrel.gov/wind/systemsintegration/nebraska_integration_study.html
- **Oahu Wind Integration Study**
  - http://www.nrel.gov/wind/systemsintegration/owits.html

California ISO Study Results

Goal: Evaluate the operational impacts of a 20% RPS in California for 2010

- **Builds off a 2007 study of impacts of 20% wind integration**



	Biomass/BioGass	Solar	Geothermal	Small Hydro	Wind
2006	701	420	1,101	614	2,648
2012 (expected)	701	2,246	2,341	614	6,688

www.caiso.com/2811/281176c54d460.pdf

CAISO Study Results

- **Key Results and Findings**
  - Operational requirements for wind and solar integration is different
  - Solar introduces problems during the morning and evening load ramps
  - Solar and wind together lessen operational requirements due to the lack of correlation between the two resources.
  - Decreases to off- and on-peak use of conventional generation (“thermal units”), which makes them less profitable and more expensive. (29-39% reduction in revenue)
  - Load-following ramp rates increase by 30-40 MW/min
  - Load-following hourly capacity increases by almost 1 GW (morning and evenings)
- **Recommendations**
  - Improve utilization of existing generation fleet’s operational flexibility (minimize self scheduling)
  - Wind and solar participation in economic dispatch markets
  - Improve/develop day-ahead and real-time operational forecasting (regulation and load following requirements)

CAISO Regulation Capacity Results

Solar ramps in morning and evening

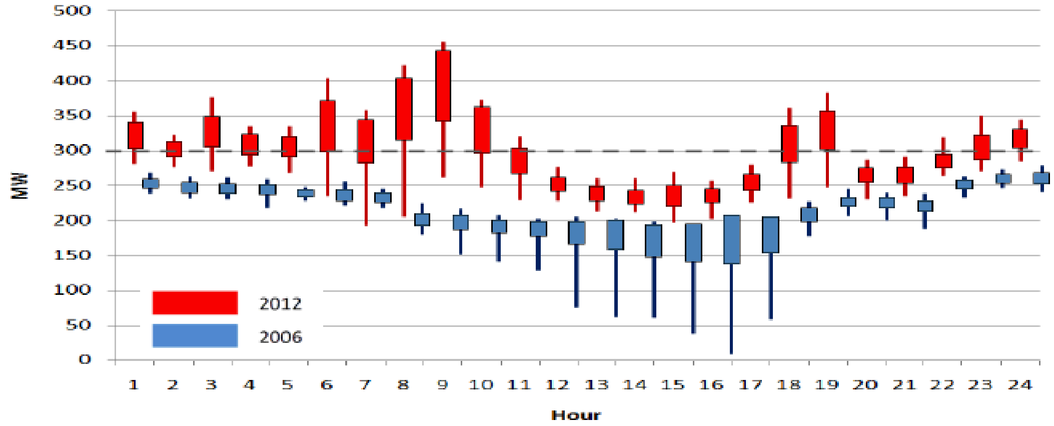
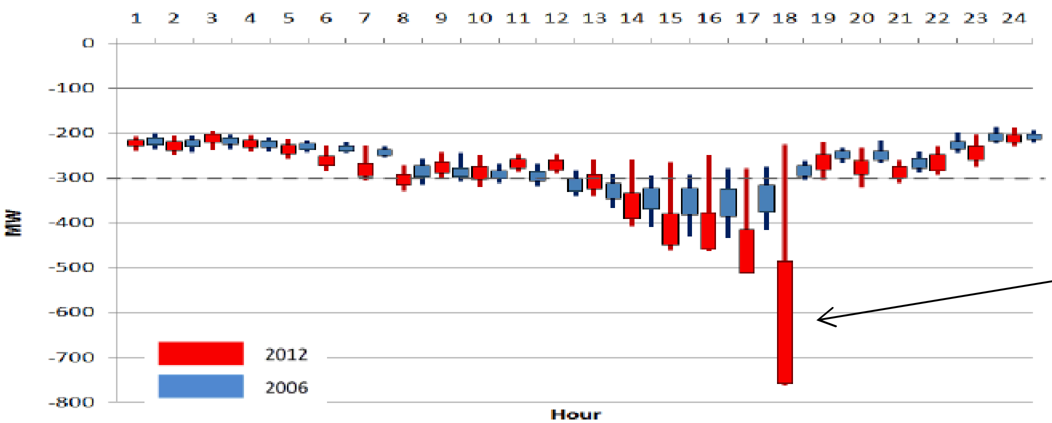


Figure ES-9: Simulated Regulation Up Capacity Requirement by Operating Hour, Summer, 2006 and 2012



Wind typically ramps up at 6PM

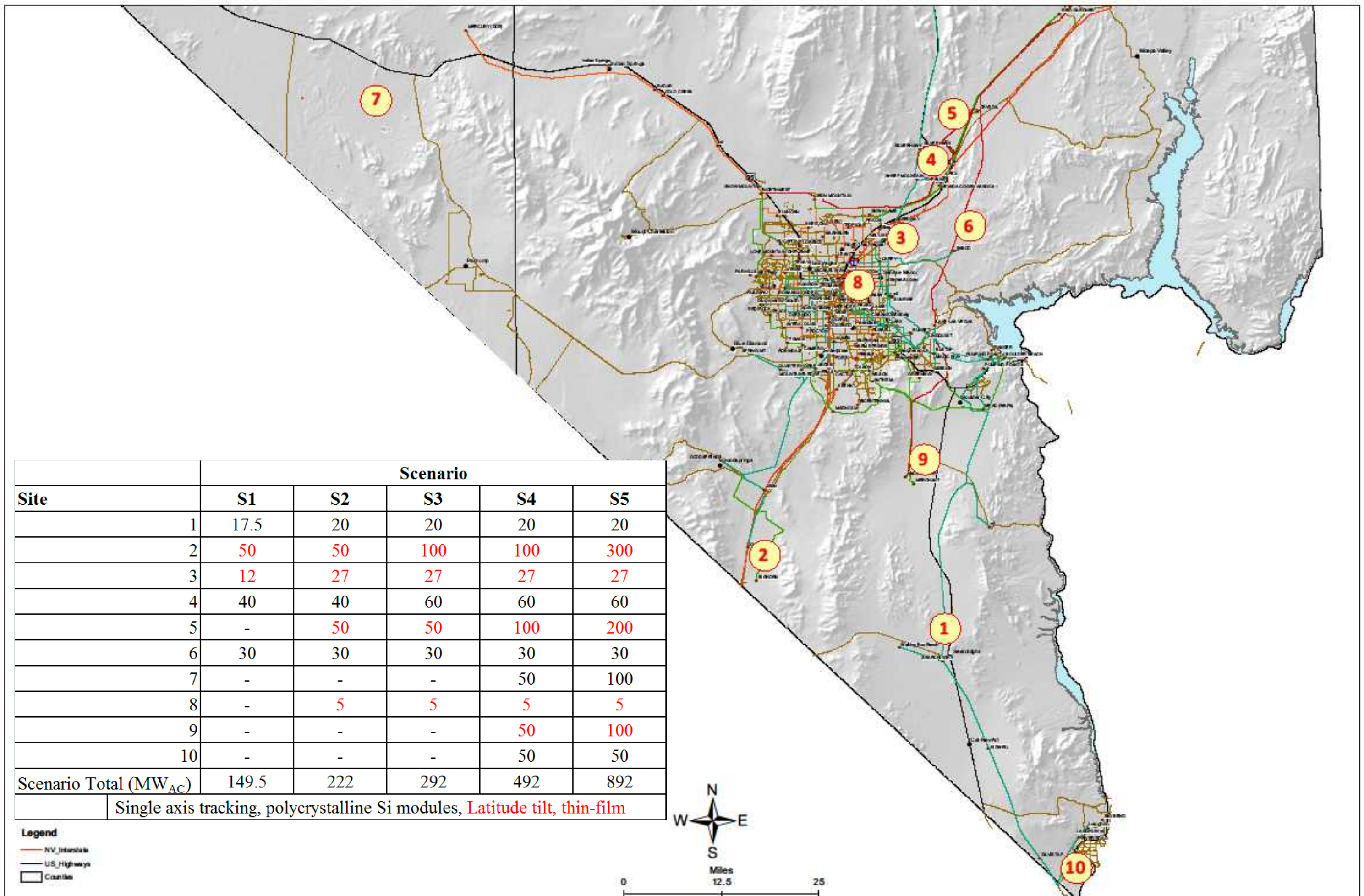
Figure ES-10: Simulated Regulation Down Capacity Requirement by Operating Hour, Summer, 2006 and 2012

www.caiso.com/2811/281176c54d460.pdf

NV Energy Solar Grid Integration Study

- **NV Energy is conducting a Solar PV Grid Integration Study**
  - Define impacts on utility operations (integration costs) of large PV plants in Southern Nevada.
- **Navigant Consulting is performing the study.**
- **Pacific Northwest National Lab (PNNL) is providing estimates of regulation and load following requirements.**
- **Sandia is contributing the estimates of the PV output profiles for the plants being considered, including power forecasts.**
- **Study will be completed by the end of the summer 2011**
- **Next few slides cover Sandia's generation of PV output profiles for study.**

PV Plant Locations for Study



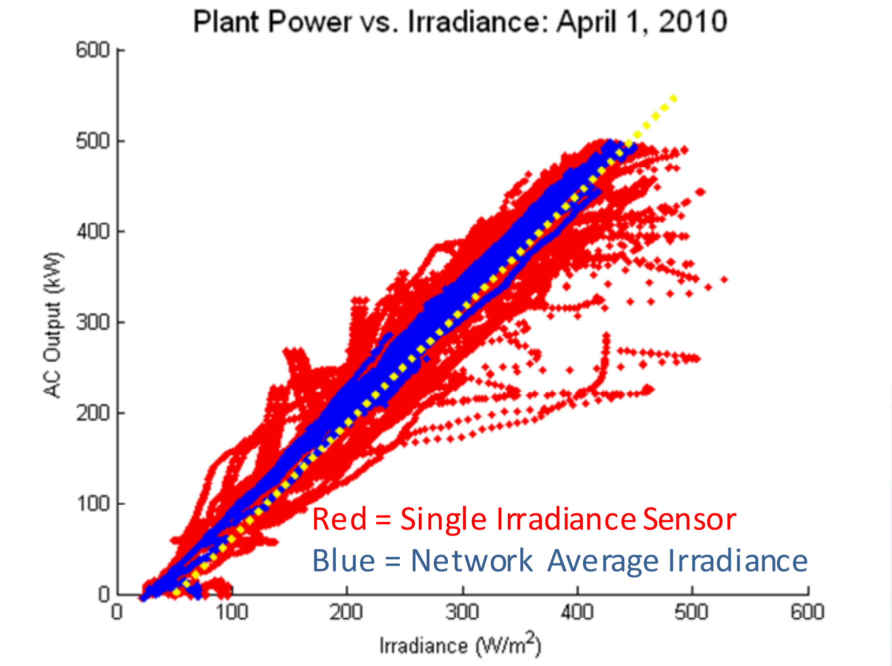
	Scenario				
Site	**S1**	**S2**	**S3**	**S4**	**S5**
1	17.5	20	20	20	20
2	50	50	100	100	300
3	12	27	27	27	27
4	40	40	60	60	60
5	-	50	50	100	200
6	30	30	30	30	30
7	-	-	-	50	100
8	-	5	5	5	5
9	-	-	-	50	100
10	-	-	-	50	50
Scenario Total (MW_{AC})	149.5	222	292	492	892
	Single axis tracking, polycrystalline Si modules, Latitude tilt, thin-film				

Data Sources

- 1- hour satellite irradiance at each of the ten sites from Clean Power Research's SolarAnywhere data
- 1-min irradiance data from six Las Vegas Valley Water District (LVVWD) sites in Las Vegas
- Upper air wind speed from NOAA weather balloon at Desert Rock, NV
- Air temperature and wind speed data from McCarran International Airport, Las Vegas

Solar Output Modeling Approach

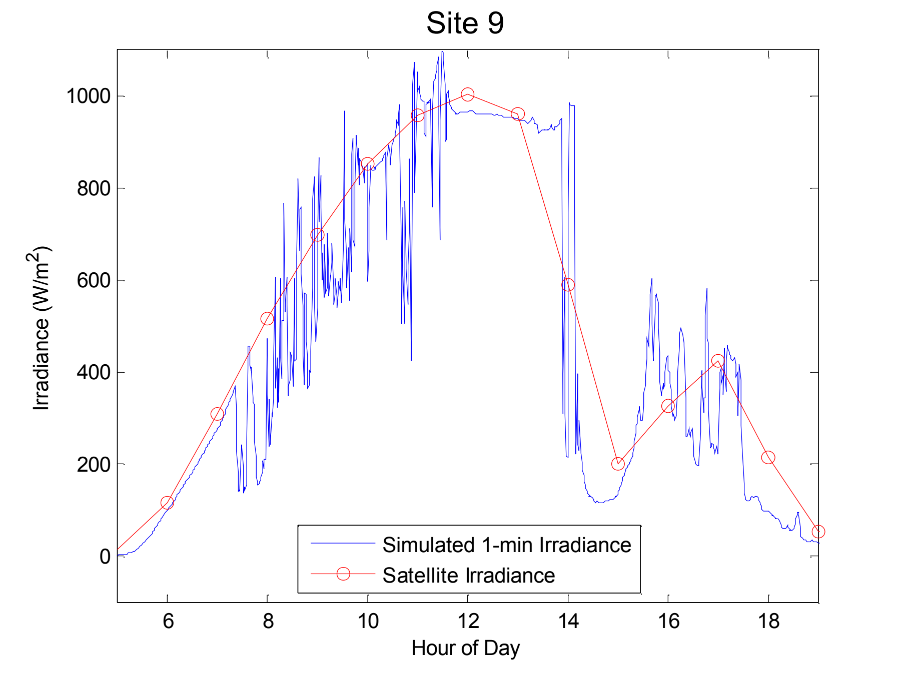
1. **Estimate 1-min irradiance at each site**
2. **Convert point irradiance to 1-min spatial average irradiance over plant**
3. **Calculate 1-min AC power output from plant**



from Kuszmaul et al., 2010

1. Estimate 1-Min Irradiance

- A library of 1-min irradiance days was created from LVVWD sites (>5,000 days)
- Hourly averages were calculated for each day
- Least-squares routine identified best fitting days in library to match day at each location
- The same library day was prevented from being assigned to more than one site for each day of the year.



Matching 1-min ground irradiance with 1-hr satellite data

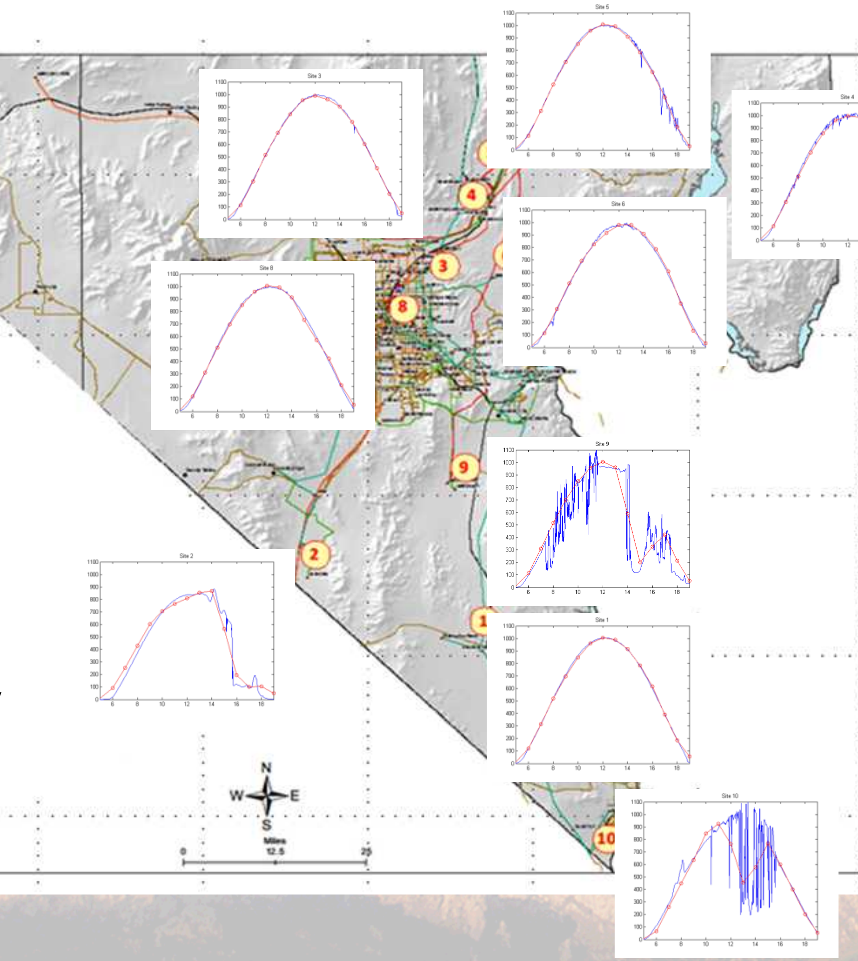
Example 1-min Irradiance Across Study Area

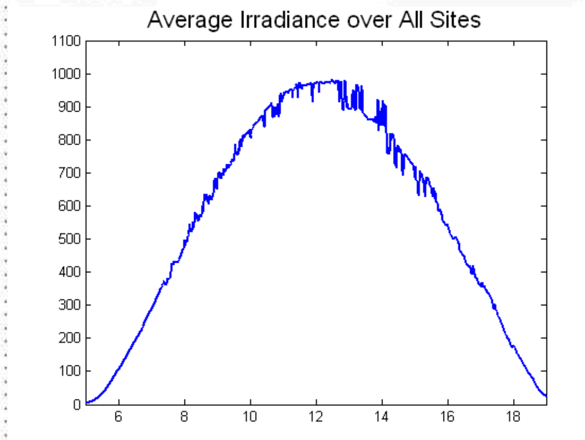
- **Simulation of PV Output**

Day of Year = 202

This example shows model represents days when only part of domain has clouds.

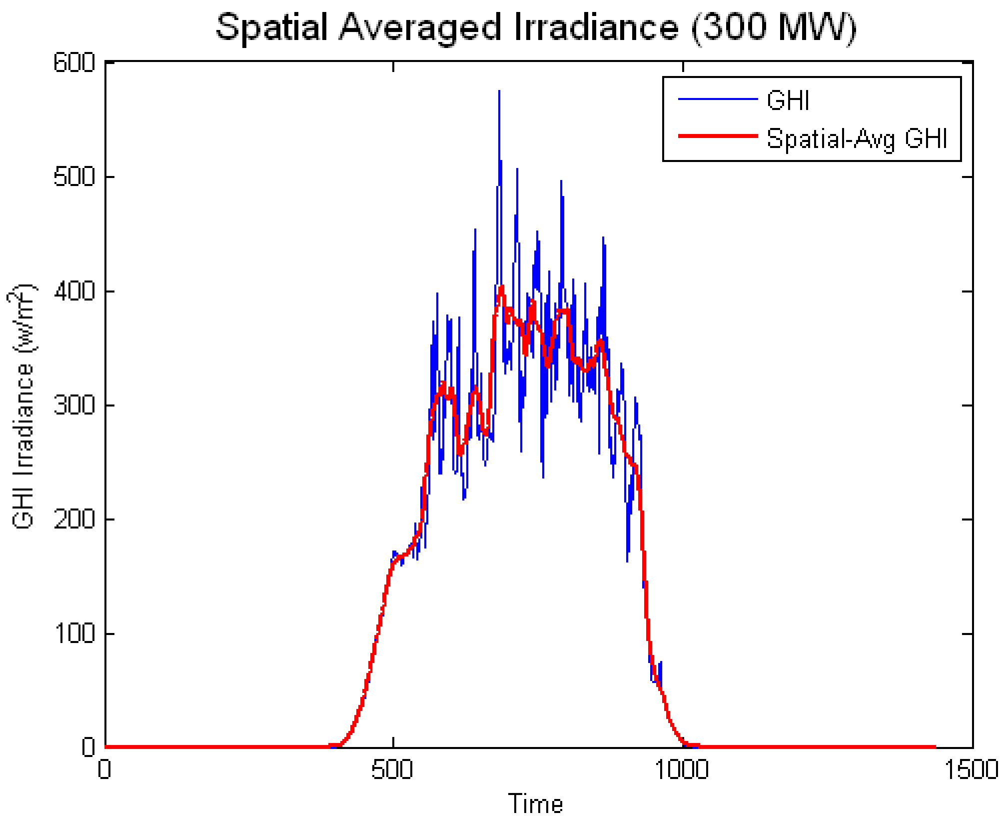
Sandia data for NV Energy Solar Integration Study





2. Spatial Average Irradiance over PV Plant

- **Spatial average of irradiance over plant is estimated as a moving average irradiance (after Longhetto et al., 1989)**
- **Averaging window = the time for clouds to pass over plant**
  - Plant size varies with module technology (efficiency)
  - Cloud speed varies with time, as measured



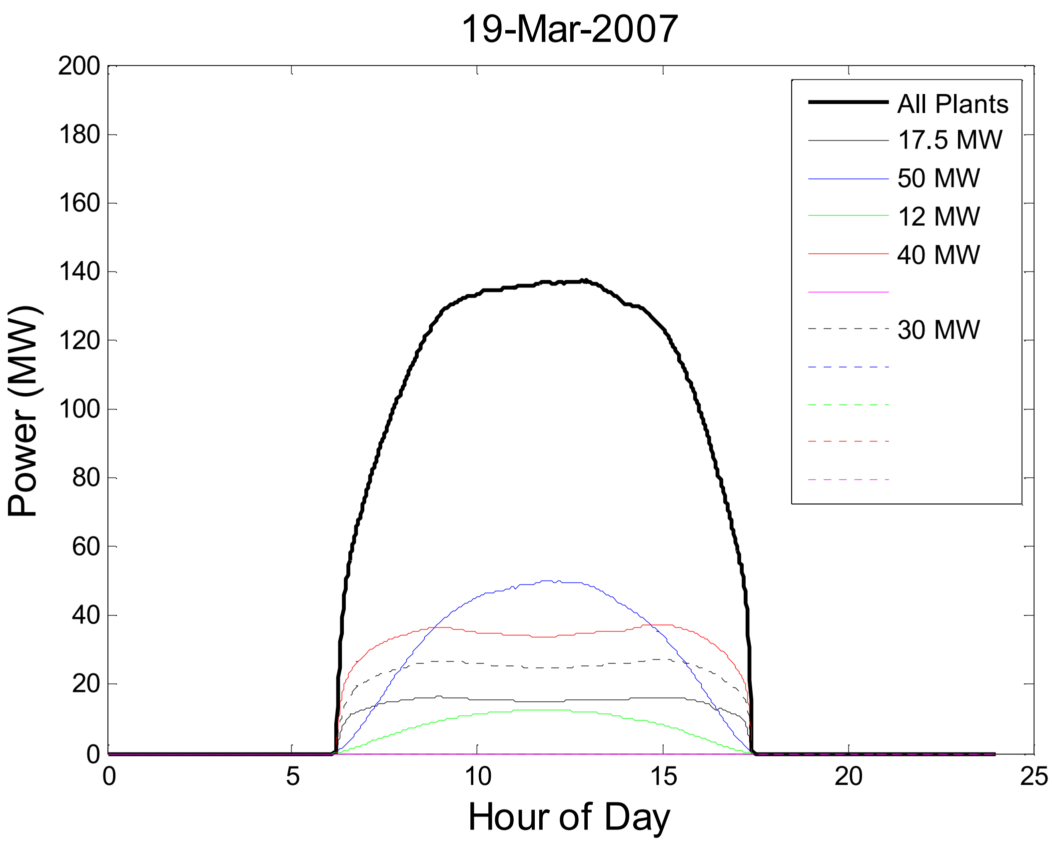
Effect of geographic smoothing within a plant

3. Calculate AC Power from Plant

- **Sandia PV Array Performance and Inverter Models were used to calculate system output**
  - These models account for:
    - Module technology characteristics (c-SI vs. thin film)
    - Temperature , angle of incidence and spectral effects
    - Inverter efficiency curves
- **Irradiance incident on array was estimated using**
  - DISC model (Maxwell, 1987) for DNI estimation
  - Perez (1990) model of diffuse irradiance on tilted plane
- **Air temperature was estimated using lapse correction for site elevation, wind speed from LAS airport**

Example Results: PV Plant Output

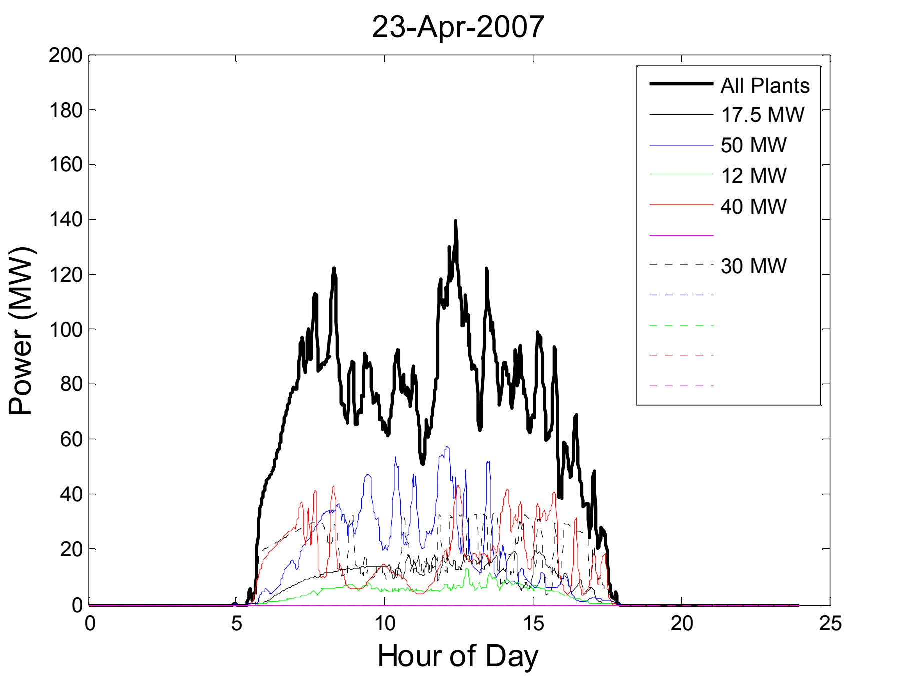
S1: 149.5 MW (5 plants)



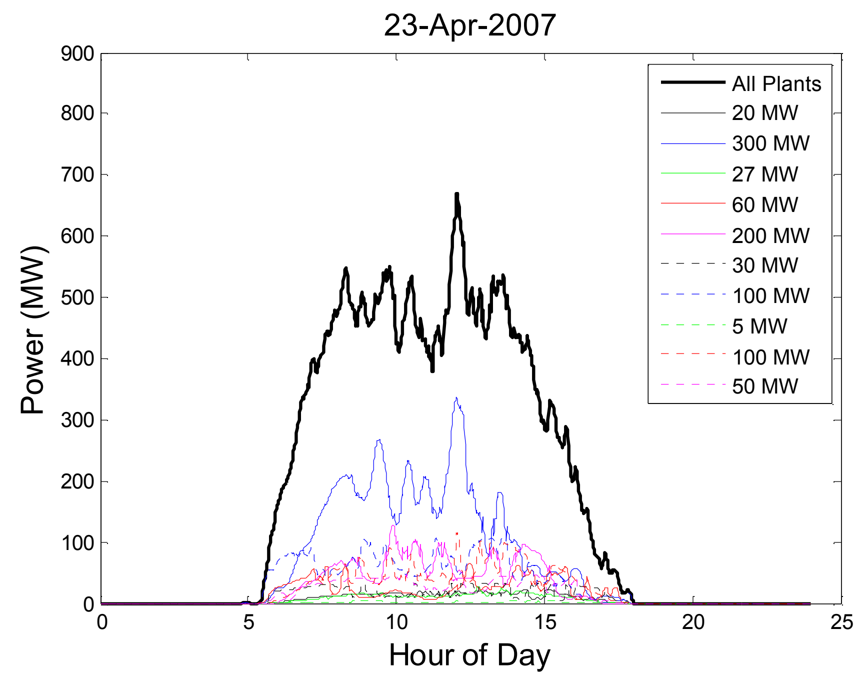
- **Output profiles reflect differences between systems**
  - Module technology
  - Plant capacity
  - Fixed tilt vs. tracking
  - Temperature differences
  - Changing cloud speeds

Example Results: PV Plant Output

S1: 149.5 MW (5 plants)



S5: 892 MW (10 plants)



Apparent reduction in
Relative variability,
But look at y-axis…

General Integration Conclusions

- **Integration studies are needed to assess the system impacts of changing the mix of generation on the grid**
  - Regional differences are very important
  - Synchronized load and RE generation is important
  - Market design is quite important (flexibility)
  - Large balancing areas are very helpful
  - Accurate forecasts are important for planning
- **There are no hard integration limits, just cost and policy constraints**
- **More technical work needs to be done to develop rigorous methods to assess penetration limits for specific feeders**
  - Current approach is ad hoc and very conservative (e.g., 15% rule)
- **Increasing flexibility in the way the grid is operated is usually the best first step.**
- **Demand response (load shifting) offers real benefits, if realized**
  - Business models need to be developed and tested
  - Becomes very important if electric vehicles take off (large load growth possible)

Questions and Discussion

Ferrisburgh Solar Farm, Vermont

SHORT COURSE: RENEWABLE ENERGY INTEGRATION

Joshua S. Stein and Roger Hill
Photovoltaics and Grid Integration Department
Sandia National Laboratories

Renewable Energy Short Course, Burlington, VT
26 July, 2011

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Class Outline

- Welcome and Introductions
- Seminar Purpose
- Schedule for the Day
- Introduction to Sandia National Laboratories

Some things not addressed in this presentation:
Organics, Dye-sensitized, nanomaterials, quantum dots, etc.

Purpose

- Increased integration of renewable energy sources into the electrical grid is a goal of many stakeholders. However due to the inherent characteristics of different renewable energy sources, such integration poses many technical challenges such as choosing the right mix of resources, managing the inherent variability of the generation sources, optimizing infrastructure upgrades, and planning for sustainability.
- The goal of this 1-day course is to provide stakeholders vital information about the specific characteristics of various renewable energy sources and the associated challenges of integrating these technologies on to the electrical grid.
- Define concrete steps to aid Vermont in its transition to renewable energy

General Rules

- **Informal environment**
  - Ask questions
  - Be respectful and listen to others
  - Offer answers or relevant experience
  - Contribute and provide feedback

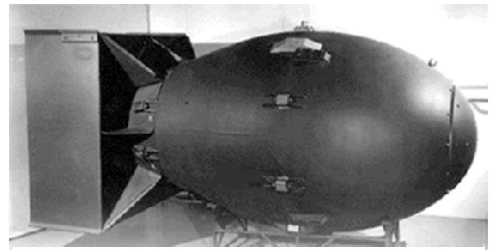
- **Introductions**
  - Name
  - Affiliation
  - Experience/interest in RE
  - What do you hope to gain/learn?

Schedule

8:30 – 9:00	Welcome, Introductions, and Seminar Purpose Introduction to Sandia (Stein and Hill)
9:00 – 9:30	Renewable energy outlook in the and World (Stein)
9:30 – 10:00	Renewable energy outlook in Vermont (TBD)
10:00– 10:15	Morning Break
10:15 – 11:30	Power Systems Fundamentals (Hill) • Generation, Transmission and Distribution
11:30-12:00	Energy Games I
12:00 – 1:00	Lunch
1:00 – 1:40	Wind Power (Hill)
1:40 – 2:20	Solar Power (Stein)
2:20 – 3:00	Energy Games II
3:00 – 3:15	Afternoon Break
3:15 – 4:00	Integration Case Studies (Stein)
4:00 – 4:30	Short Course Review, Issues, Moving Forward

Sandia's Heritage

"Exceptional service in the national interest"



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

Sandia locations

Albuquerque, New Mexico

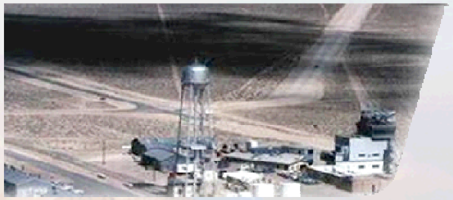
Livermore, California

Emeryville, California

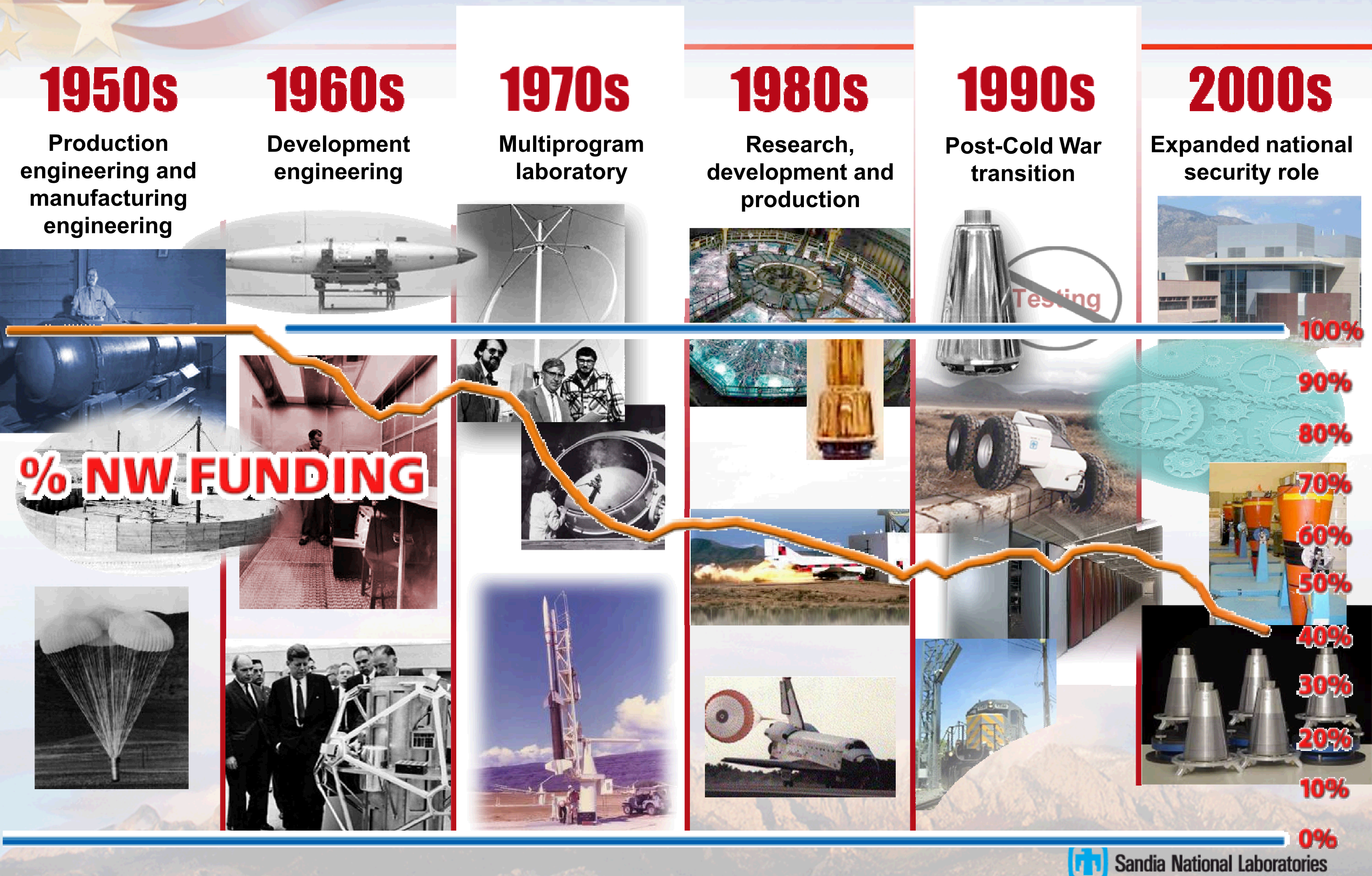
Waste Isolation Pilot Plant, Carlsbad, New Mexico

Pantex, Texas

Tonopah, Nevada

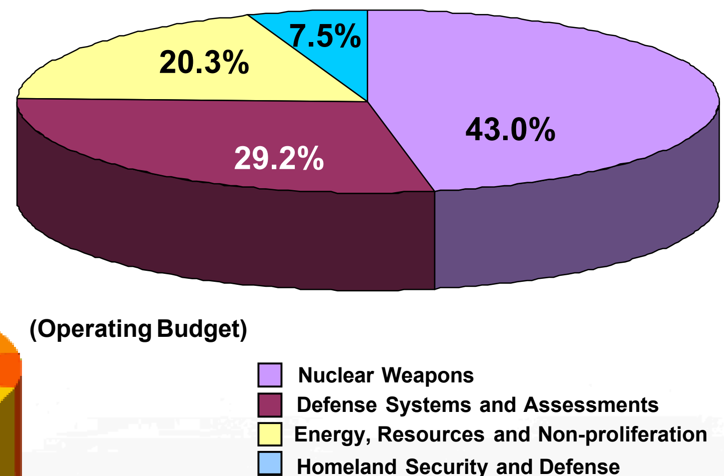


The Evolution of Our Mission

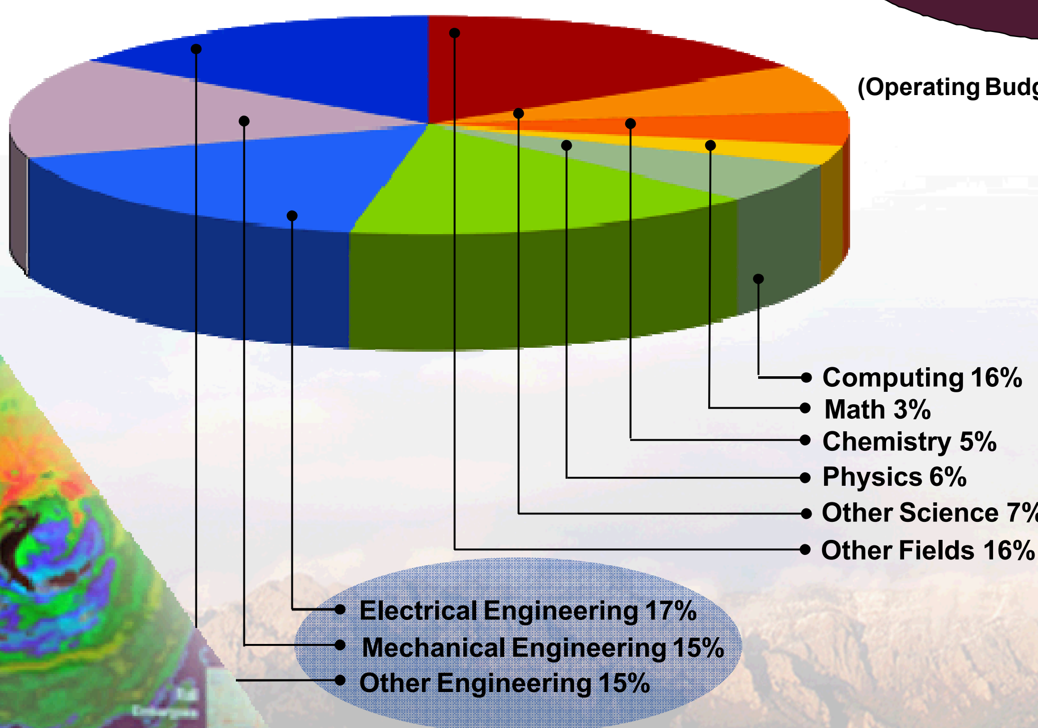


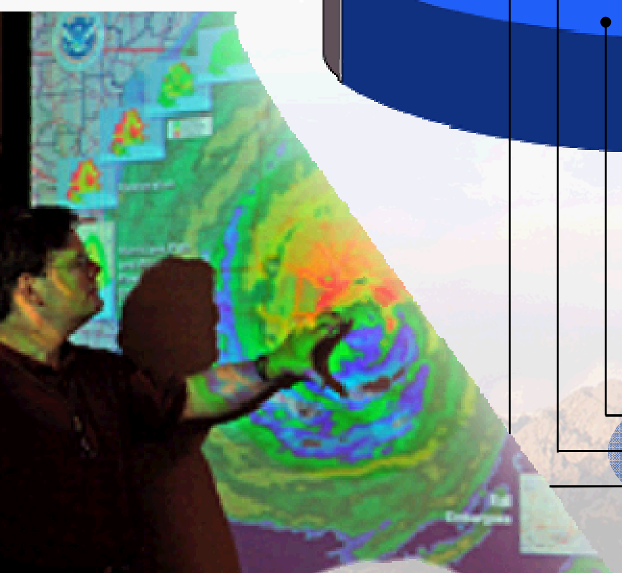
People and Budget

- FY10 permanent workforce: 8,478
- FY10 budget: $2.4B



Technical Staff (3,921) by Degree
(Start of FY09)





Sandia National Laboratories

Sandia State-of-the-Art Facilities

Microelectronic, Materials, Nanotechnology, and CSP

Sandia National Laboratories

Microelectronics and Semiconductor Materials Processing

Microelectronics Development Lab (MDL)

Microelectronics Development Lab (MDL)

Microsystems & Engineering Science Applications (MESA)

Materials Sciences, Nanotechnology Technology, and CSP

Center for Integrated Nanotechnology (CINT)

Integrated Materials Research Lab (IMRL)

National Solar Thermal Test Facility

Sandia National Laboratories

Sandia’s Photovoltaic Facilities

PV Systems Evaluation and Optimization Lab




Distributed Energy Technology Lab

Simulate small μgrid or community (25 homes and businesses), including PV-Storage-Fuel Cells-Generators

Grid Integration Studies and Technology Prototyping & Development Environment

- **Controlled Side-by-Side Component, Array and System Characterization**
- **Comprehensive Data Acquisition Systems**
- **Grid Integration, Inverters, Combiners, Disconnects- All Reconfigurable**

Thank You!

SOLAR ENERGY AND OUR ELECTRICITY FUTURE

Joshua S. Stein Ph.D.

Photovoltaics and Grid Integration Department

Sandia National Laboratories

Renewable Energy Short Course, Burlington, VT

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Sandia National Laboratories

Outline of Today's Discussion

- Background
- Solar Cells and the Photoelectric Effect
- From Cells to PV Systems
- Modeling PV Performance
- Concentrating Solar Power (CSP)

Some things not addressed in this presentation:
Organics, Dye-sensitized, nanomaterials, quantum dots, etc.

Outline of Today's Discussion

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Solar Energy Fun Facts

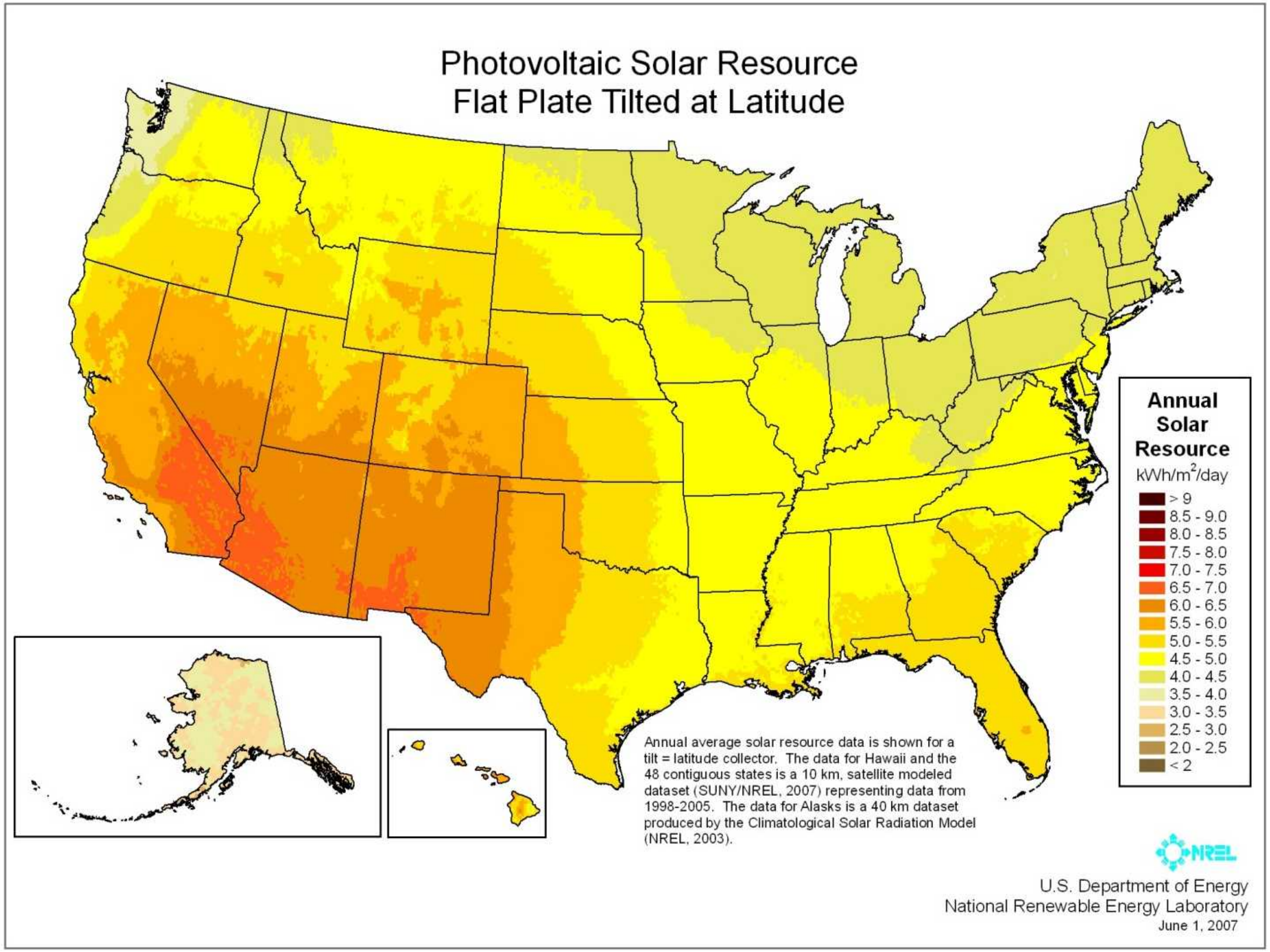
- More energy from sunlight strikes the Earth in one hour than all the energy consumed on the planet in one year (13 TerraWatts).
- Carbon “free” energy source
- Solar energy is the only long-term option capable of meeting the energy (electricity and transportation fuel) needs of our planet.

- Solar	7,500 TW
- Wind	14 TW
- Hydro	1 TW
- Ocean	0.6 TW
- Geothermal	2 TW

Estimated Extractable Resource (DOE-OS-BES)

In the U.S. solar resources significantly outweigh energy use

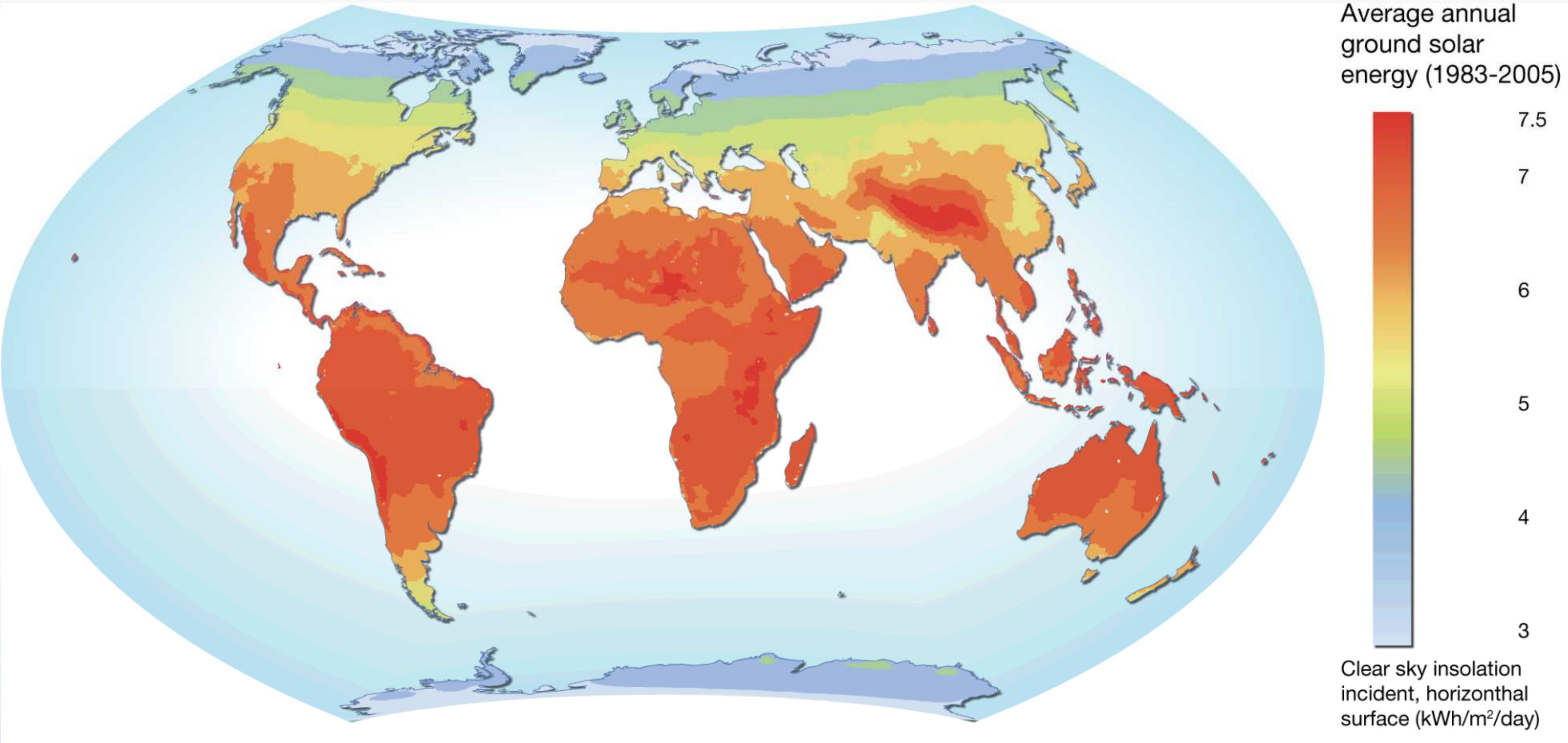
- **Currently, solar provides less than 0.1% of the electricity used in the U.S.**
- **All of the electricity in the U.S. could be provided using:**
  - Less than 2% of the land dedicated to cropland and grazing.
  - Less than the current amount of land used for corn ethanol production.



Source: Margolis, NREL 2009

Sandia National Laboratories

Also globally solar resources significantly outweigh energy use



Source: NASA 2008

- **Covering less than 0.2% of the land on the earth with 10%-efficient solar cells would provide twice the power used by the world.**

Source: Margolis, NREL 2009

Outline of Today's Discussion

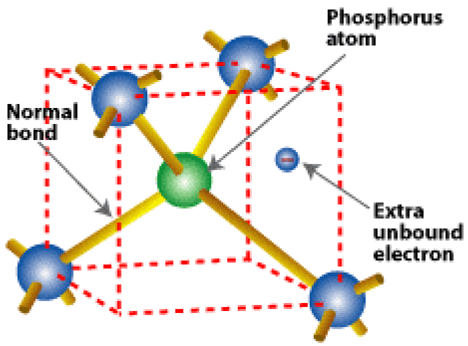
- Background
- **Solar Cells and the Photoelectric Effect**
- From Cells to PV Systems
- Modeling PV Performance
- Concentrating Solar Power (CSP)

The photoelectric effect has been known for some time

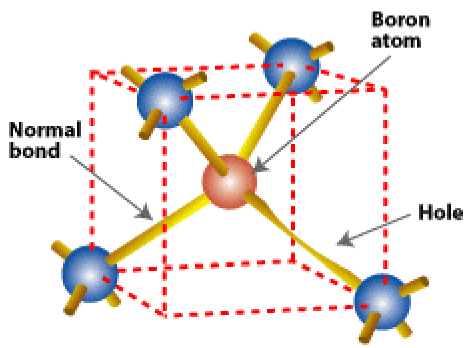
- 1839: Edmond Bequerel, French physicist discovers photoelectric effect
- 1904: Albert Einstein theoretically describes photovoltaic effect, for which he won the Nobel Prize in 1921
- 1916: Robert Millikan practically demonstrates Einstein's theory
- 1918: Jan Czochralski, Polish physicist discovers method of producing monocrystalline silicon – still in use today
- 1941: first monocrystalline silicon cell produced
- 1954: AT&T Bell Labs publishes reports on solar cells with 4.5% efficiency

http://www.pvresources.com/en/history.php

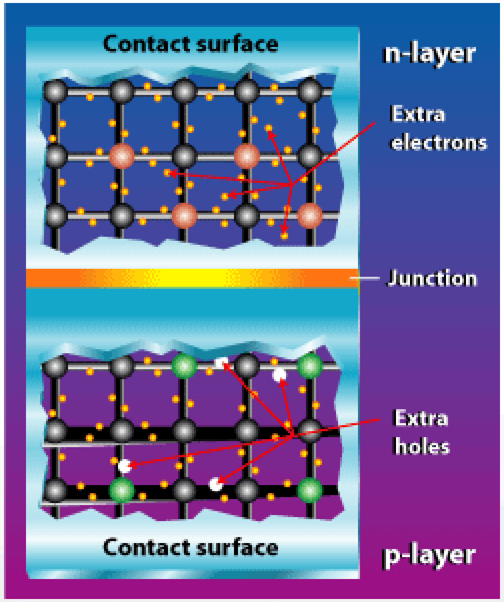
The concept of a simple crystalline solar cell



Substituting a phosphorus atom (with five valence electrons) for a silicon atom in a silicon crystal leaves an extra, unbonded electron that is relatively free to move around the crystal.



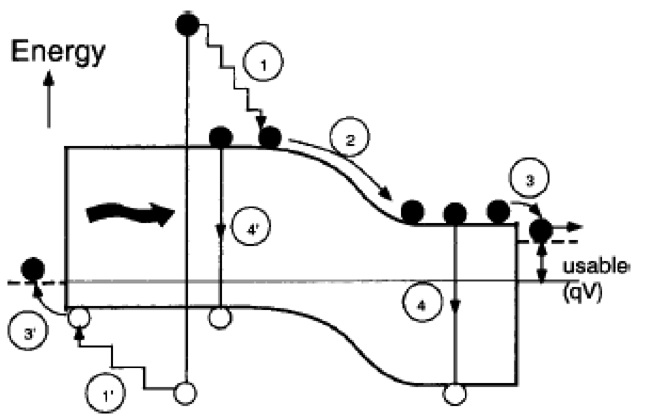
Substituting a boron atom (with three valence electrons) for a silicon atom in a silicon crystal leaves a hole (a bond missing an electron) that is relatively free to move around the crystal.



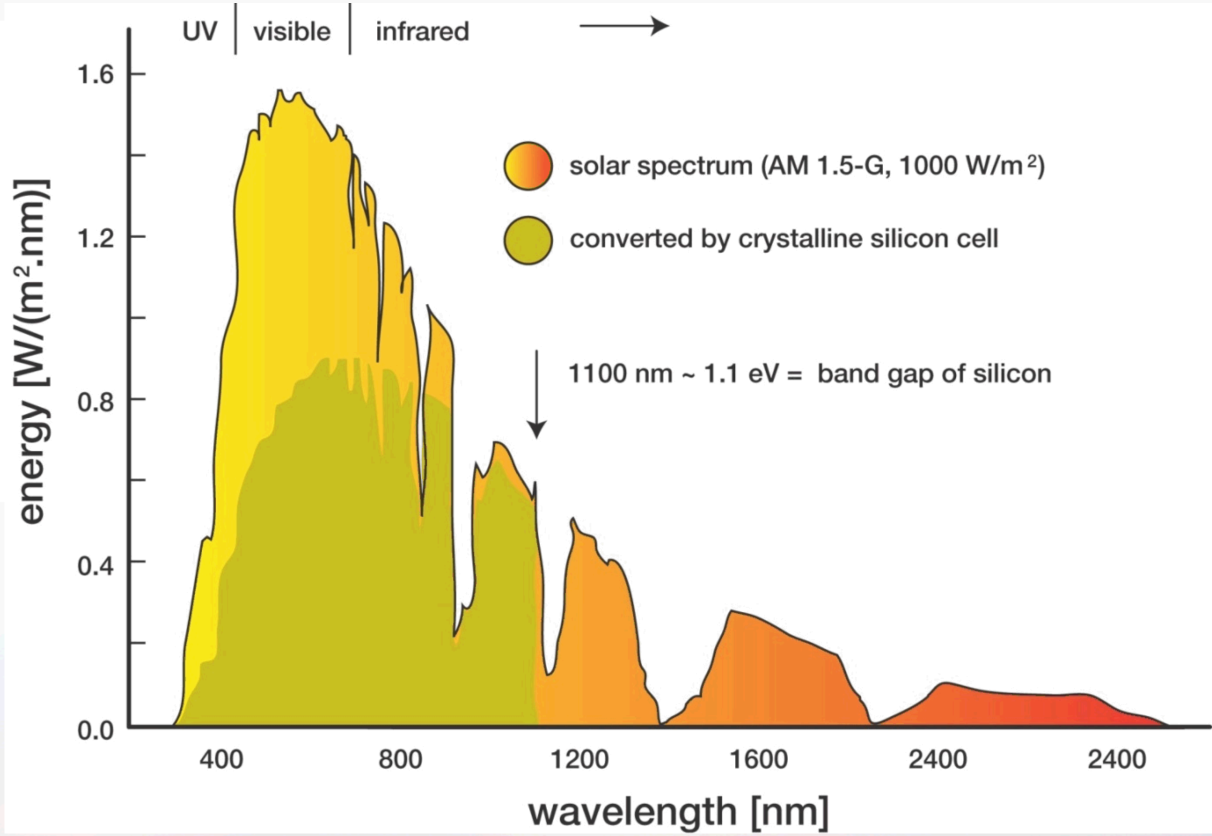
Although both materials are electrically neutral, n-type silicon has excess electrons and p-type silicon has excess holes. Sandwiching these together creates a p/n junction at their interface, thereby creating an electric field.

http://www1.eere.energy.gov/solar

The Photoelectric Effect



Excitation and loss processes in a standard solar cell: (1) thermalization loss; (2) and (3) junction and contact voltage loss; (4) recombination loss.



http://www.vicphysics.org/documents/events/stav2005/spectrum.JPG

(Courtesy of Feng Shi, Northern New Mexico College)

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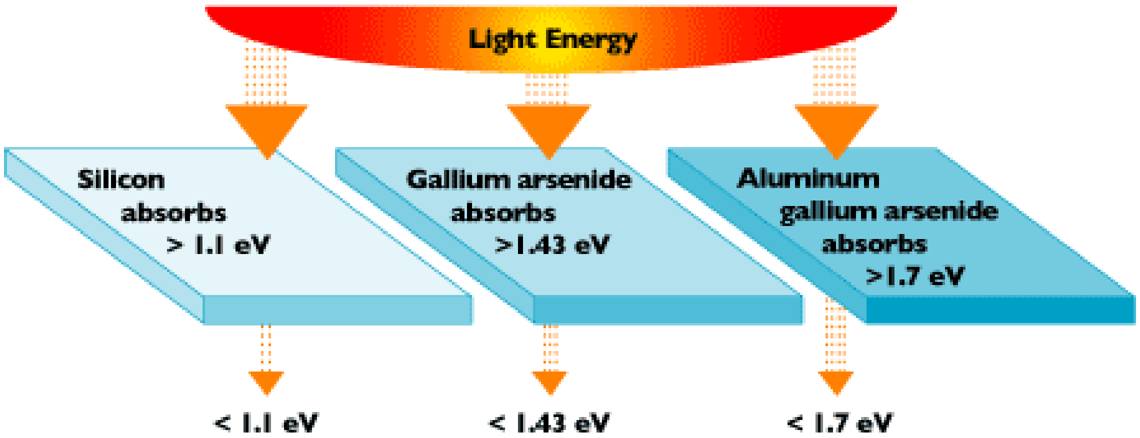
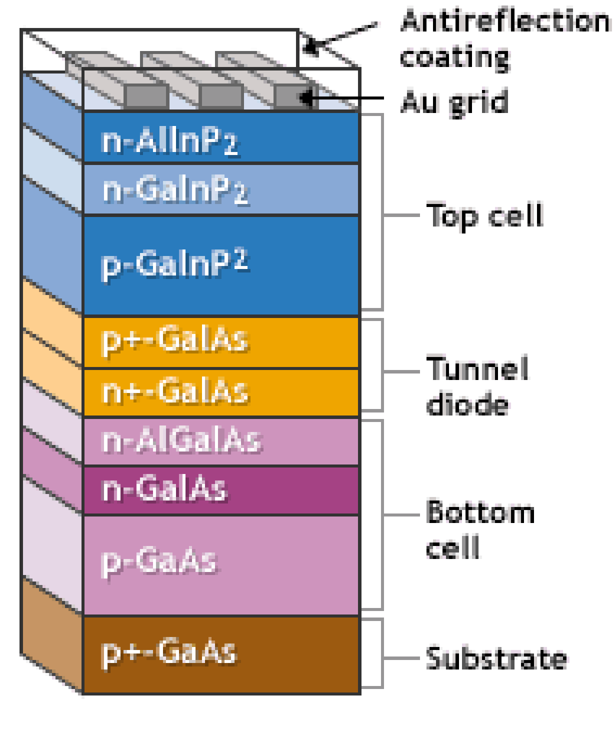
Multi-junction cells absorb more photons for higher efficiencies



Different PV materials have different energy band gaps. Photons with energy equal to the band gap energy are absorbed to create free electrons. Photons with less energy than the band gap energy pass through the material.

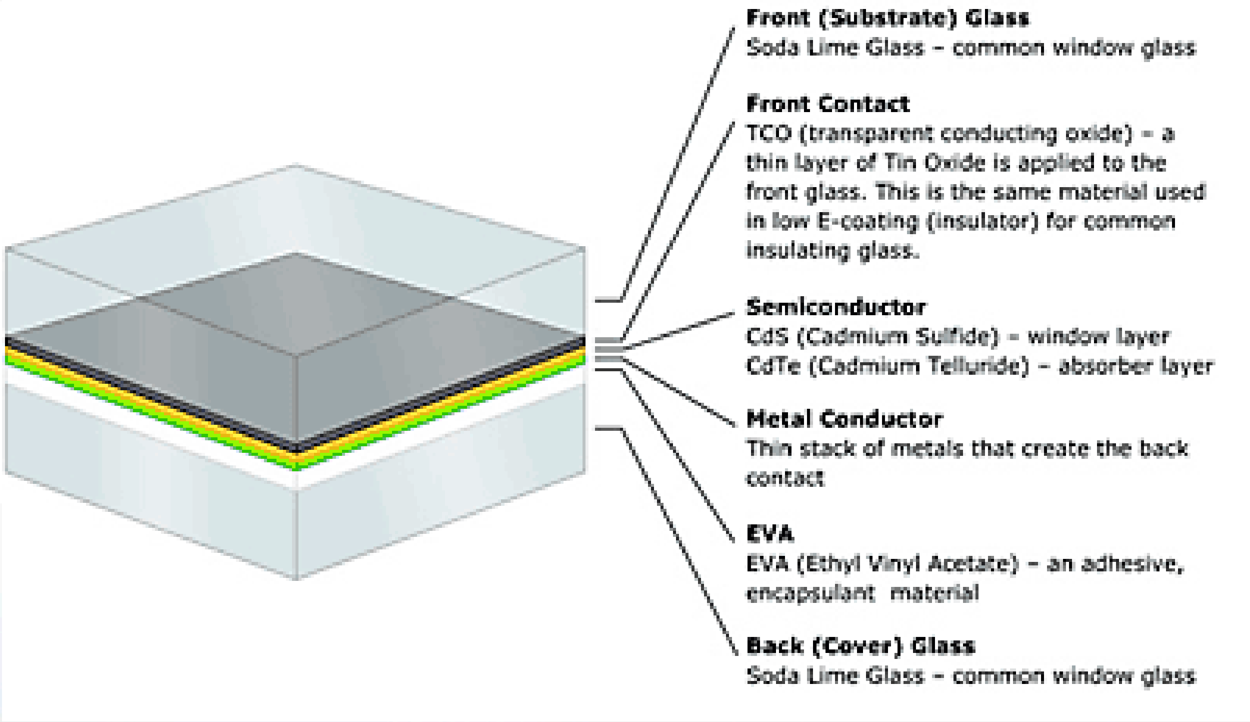


- Complex, high manufacturing cost
- Used in concentrating systems for high output

This multijunction device has a top cell of gallium indium phosphide, then a "tunnel junction" to allow the flow of electrons between the cells, and a bottom cell of gallium arsenide.

http://www1.eere.energy.gov/solar

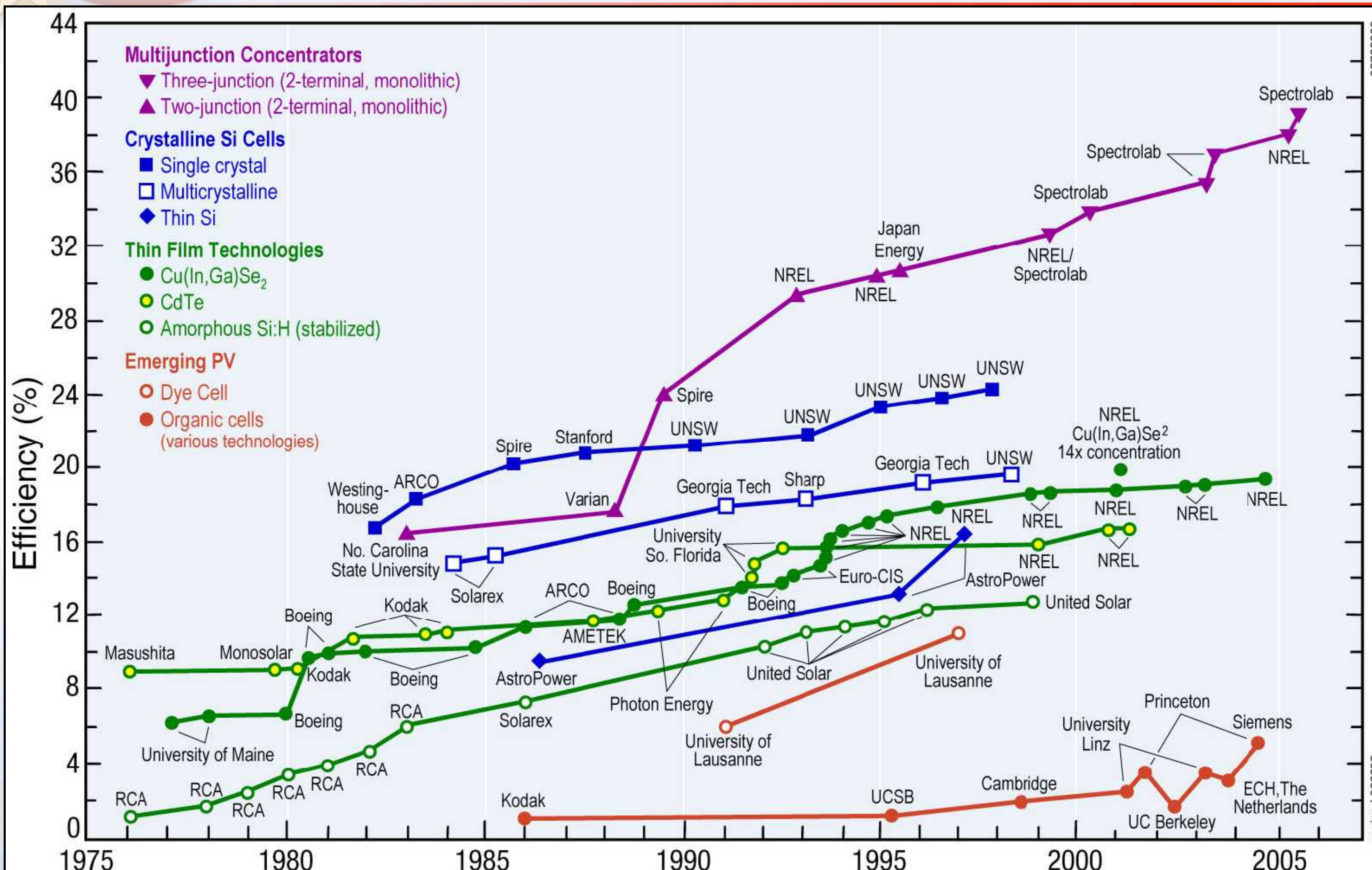
Thin Film Devices Use Much Less Semiconductor Material



- 1-2 microns thick vs. ~180 microns for c-Si
- Lower efficiencies mean more balance-of-system
- Glass substrate limits usability (weight, flexibility)

Source for figures: www.firstsolar.com

Best Research-Cell Efficiencies



Lewis et al, Basic Research Needs for Solar Energy Utilization Department of Energy Paper, 4.18.05 (courtesy F. Shi, NNMC))

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PV Conversion Technology Tradeoffs

Technology	Advantages	Disadvantages
Mono-Crystalline Silicon	Proven technology Higher Efficiency (22%)	High material usage
Poly-Crystalline Silicon	Proven technology Lower cost than mc-Si	Lower efficiency (13-16%) High material usage
Amorphous Silicon Thin Film	Proven roll-to-roll high throughput manufacturing Low materials usage	Low efficiency (~7%) High Cap-Ex Costs
CdTe Thin Film	Low manufacturing cost Low materials usage	Lower efficiency (~10%) Lifetime not demonstrated Glass required
CIGS Thin Film	High Thin Film Efficiency (~12-13%) Low materials usage	Currently expensive & difficult to manufacture Lifetime not demonstrated
Multi-junction concentrators	High efficiency (~36%) Very low material usage	Expensive to manufacture Need for high tracking accuracy Expensive balance-of-system Thermal management issues
Organics (not yet commercial)	Very low cost to produce	Low efficiency (~4-6%) Unstable

Outline of Today's Discussion

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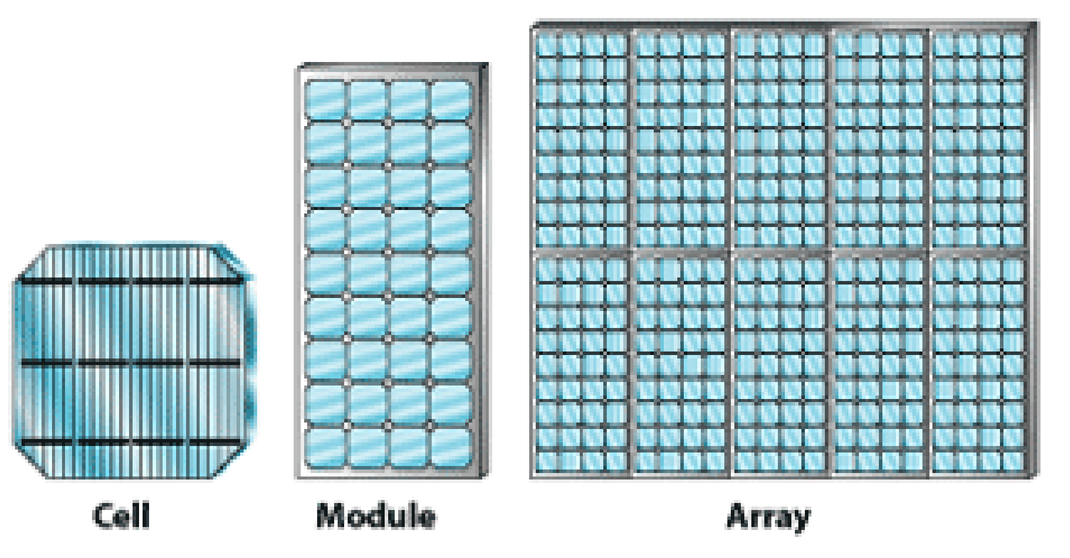
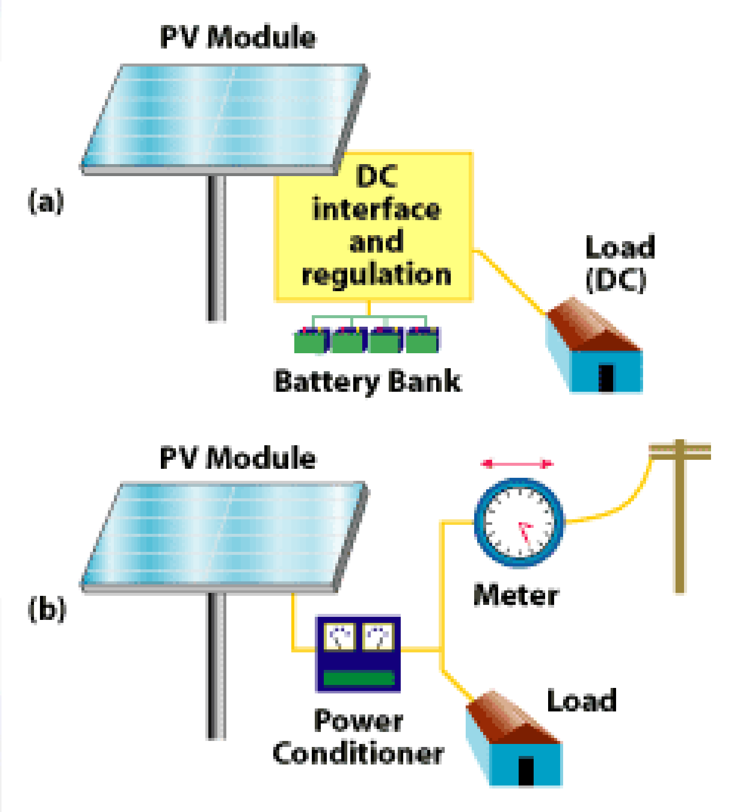
The Photovoltaic System Slide

(in lieu of “The Photovoltaic System Presentation”)



The basic photovoltaic or solar cell typically produces only a small amount of power. To produce more power, cells can be interconnected to form modules, which can in turn be connected into arrays to produce yet more power. Because of this modularity, PV systems can be designed to meet any electrical requirement, no matter how large or how small.



This simple illustration shows the elements needed to get the power created by a PV system to the load (in this example, a house). The stand-alone PV system (a) uses battery storage to provide dependable DC electricity day and night. Even for a home connected to the utility grid (b), PV can produce electricity (converted to AC by a power conditioner) during the day. The extra electricity can then be sold to the utility during the day, and the utility can in turn provide electricity at night or during poor weather.

http://www1.eere.energy.gov/solar

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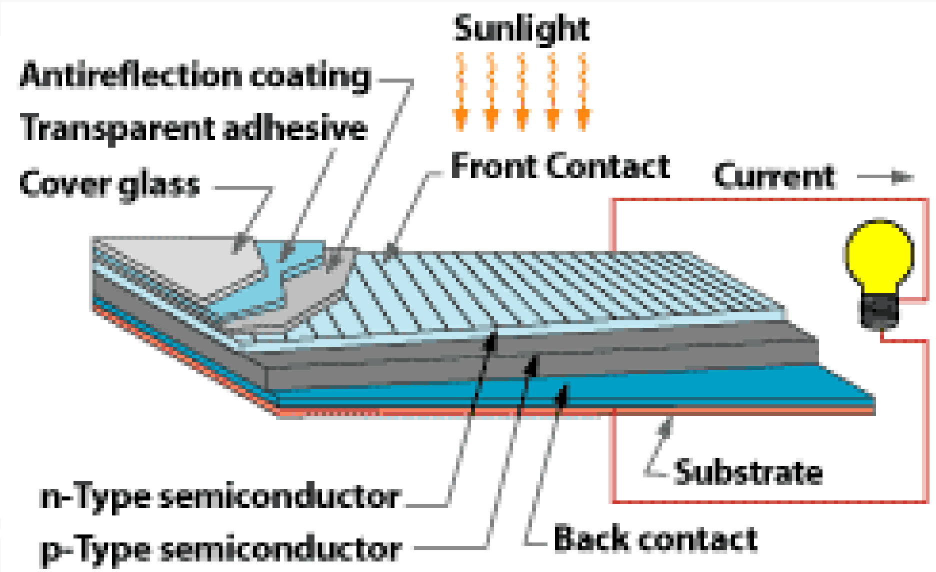
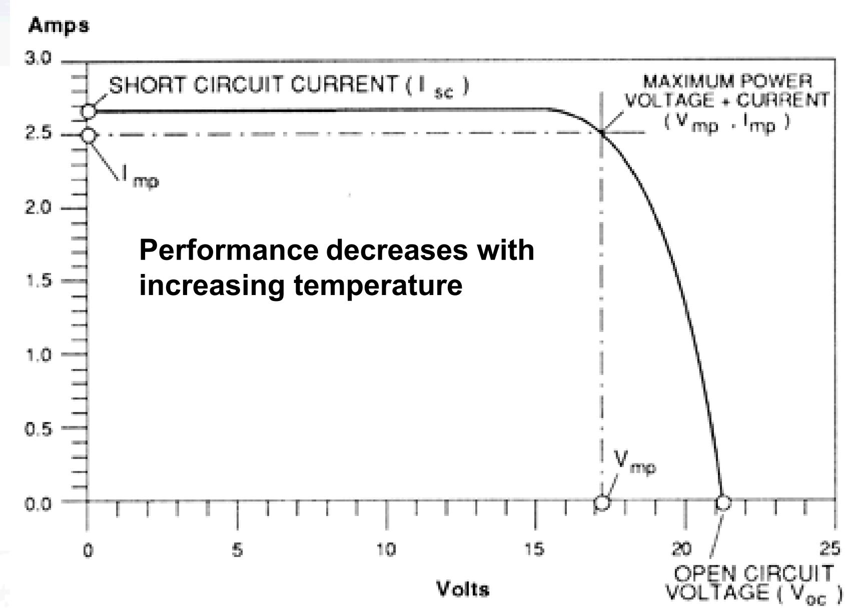
The Photovoltaic Module

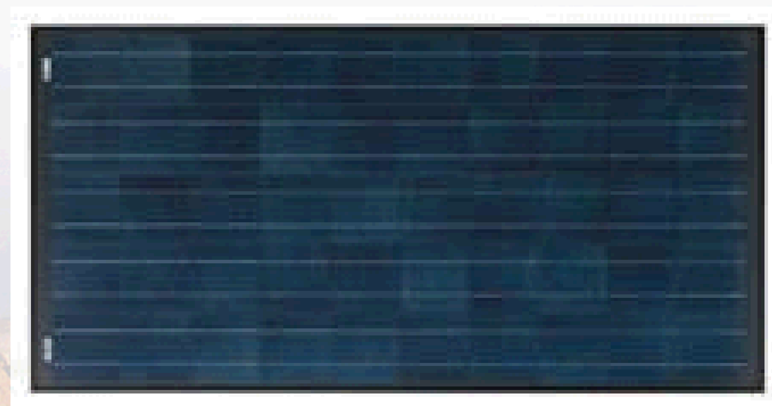


http://www1.eere.energy.gov/solar



http://www.daviddarling.info/encyclopedia

- One typical flat-plate module design uses a substrate of metal, glass, or plastic to provide structural support in the back; an encapsulant material to protect the cells; and a transparent cover of plastic or glass.

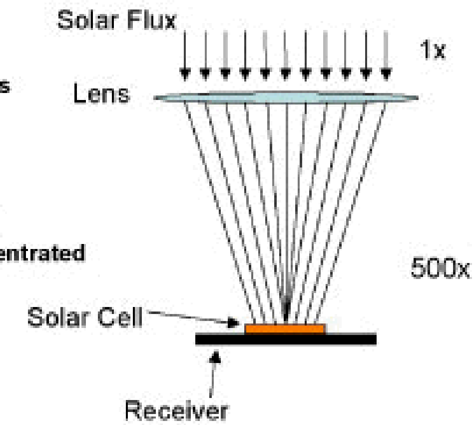


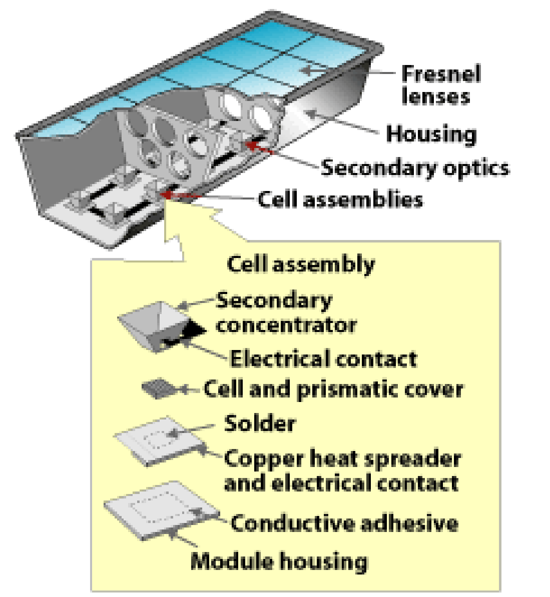
Concentrating Photovoltaic (CPV) Modules

500 Times Normal Irradiance

Lens Concentrates Solar Flux to 500 Times Normal Irradiance

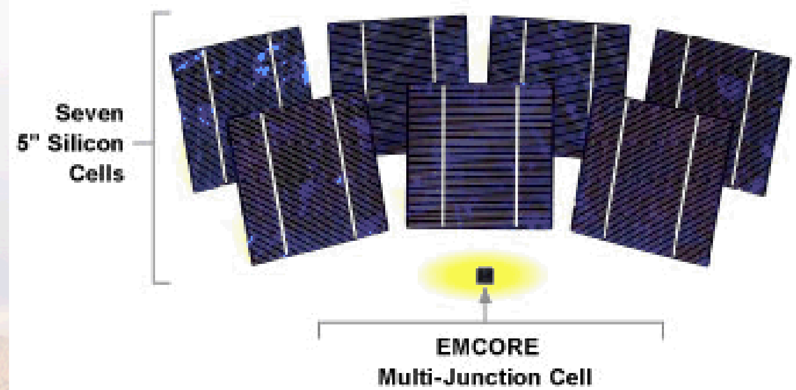
Conversion Efficiency Improves Under Concentrated Illumination





Equal Power Output

Concentration Enables the Use of Very Small Solar Cells



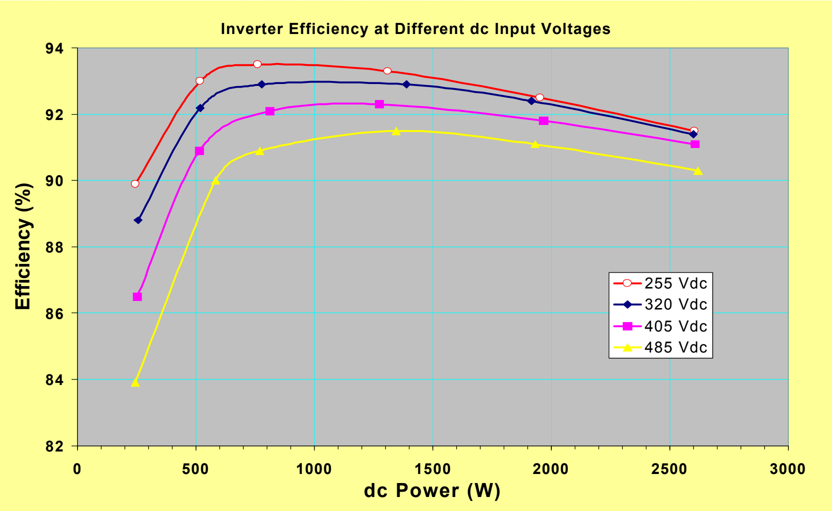
www.emcore.com

Sandia National Laboratories

PV Inverters and Balance-of-Systems

- **Convert DC to AC**
- **Available at module-scale (200W) up to 2 MW**
- **Principal hardware:**
  - High power transistor bridges for conversion
  - Transformer for isolation of AC signal
  - Capacitors for signal smoothing
- **Principal software:**
  - Maximum Power Point Tracking (for optimum module utilization)
  - Anti-islanding (to detect grid loss)
  - Signal detection (turn on/off)
- **Reliability: viewed as the weak link in the system**
- **Additional BOS: AC, DC disconnects; wiring, fuses, racks, meters, …**

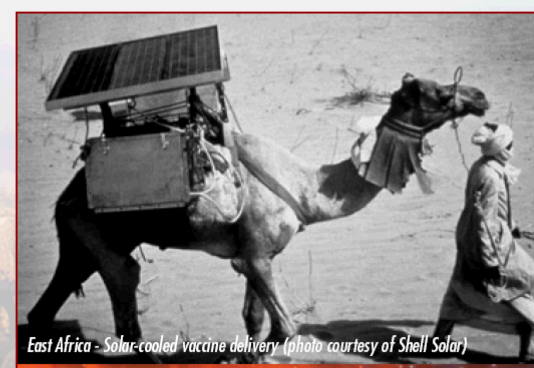
Residential inverters and related disconnects/meters at Sandia's PV Systems Optimization Laboratory



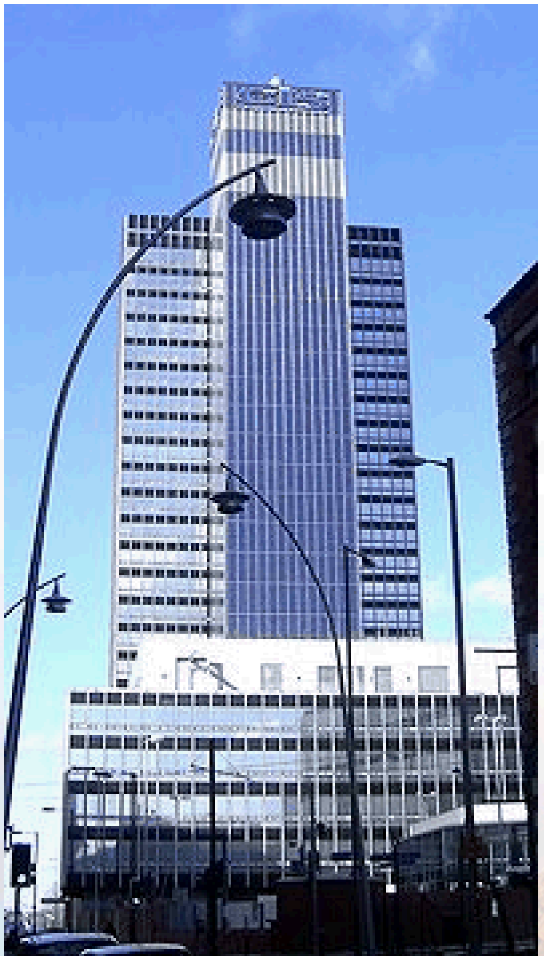
Typical inverter efficiency plot (from SNL DETL)

PV Applications

- Residential
- Commercial
- Utility
- Off-grid


East Africa - Solar-cooled vaccine delivery (photo courtesy of Shell Solar)

Building-Integrated PV (BIPV)



3kW a-Si rooftop at Sandia's Distributed Energy Technologies Laboratory (DETL)

- Take advantage of architectural characteristics of a building
- Integrally mounted as part of structure
- Can be difficult to access for maintenance
- Can have higher operating temperatures (low air flow) and lower performance

Outline of Today's Discussion

- Background
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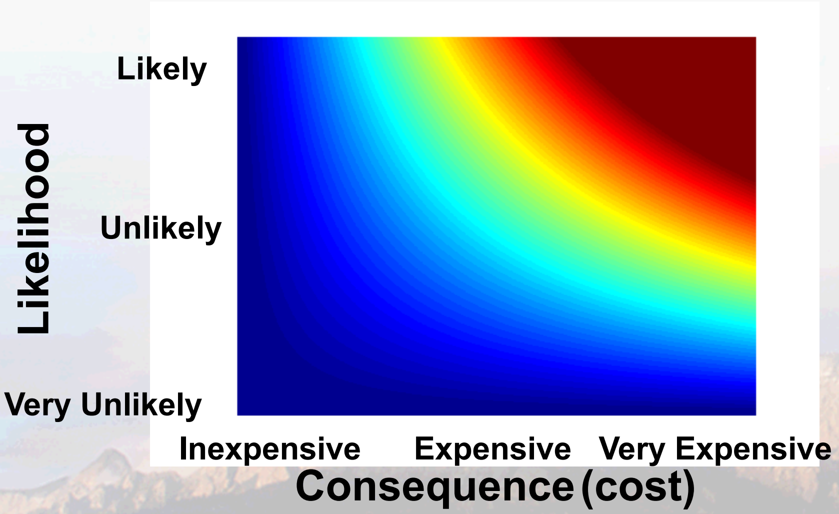
Design Issues

- **Goal is to maximize investment return while minimizing risk**
  - Multivariate, nonlinear optimization problem with considerable uncertainties
  - Risk can be defined as the probable frequency and probable magnitude of future loss
    - Product of probability and consequence



Other Examples of Risks:

- **Irradiance lower than expected**
- **Soiling worse than expected**
- **Components fail sooner than expected**
- **Degradation faster than expected**
- **Warranty not honored**
- **Design flaws**

Design Options

1. Site (weather data availability, uncertainty)
2. Technology (module, inverter, and BOS)
3. Orientation (fixed tilt, tracking, roof or ground mount, ground coverage ratio, shading)
4. System configuration (central or distributed power conversion, module and string layout)
5. Operation (monitoring, cleaning, preventative maintenance, etc.)
6. Modeling of expected system performance

1. Site Choice

- **What type of weather data is available?**
  - Typical Meteorological Year (TMY)
    - TMY (1952-1975); TMY2 (1961-1990); TMY3 (1991-2005)
    - Not available everywhere (how to interpolate between sites?)
    - Variable data quality
  - Field Data
    - Expensive, Short duration, data quality
  - Satellite Data
    - Free and for a fee depending on period and supplier
- **Uncertainties**
  - TMY annual uncertainties are typically +/- 9% (95% CI). Approximately equal to +/- 1% for 25 yr average (4.5%/sqrt(25))

2. Technology Choices

- **Efficiency vs. area-related costs (a balancing act)**
  - High efficiency modules more expensive per watt
    - Typically mounted on trackers to increase energy yield
  - Lower efficiency modules less expensive per watt
    - Require longer wire runs (greater DC losses), more racking, ground prep, O&M, etc.
- **Reliability track record**
- **Financial health of company (warranty risk)**
- **Installer experience**
- **Equipment availability**
  - Characterization and testing data

3. Orientation Choices

- **Tracking vs. fixed tilt**
- **Mounting options (thermal consequences)**
  - Roof mount
    - Ballasted vs. penetrations
    - Flat or tilted (soiling)
    - Access to fix leaks, replace roof
  - Shade Structure (parking garages)
  - Ground Mount
    - Vegetation/animal control
- **Time of Use Rates**
  - Trade total energy for energy at peak periods
  - Battery storage options?

4. Operational Decisions

- Level of Monitoring
  - Inverter level
    - Least expensive, hard to identify incremental problems
    - Usually combined with a PM cycle (how often?)
    - Accuracy concerns unless revenue grade meter is used (extra expense)
  - String Level
    - Uses smart combiner boxes or alternatives
    - Can be combined with string-level power conversion
    - Extra communications overhead (reliability)
  - Module Level
    - Microinverter or DC/DC converters
- Preventative Maintenance
  - What to do? How often? Contract or in-house?
- Utility Interactions
  - Large systems are being asked to coordinate with utilities, provide forecasts, etc.

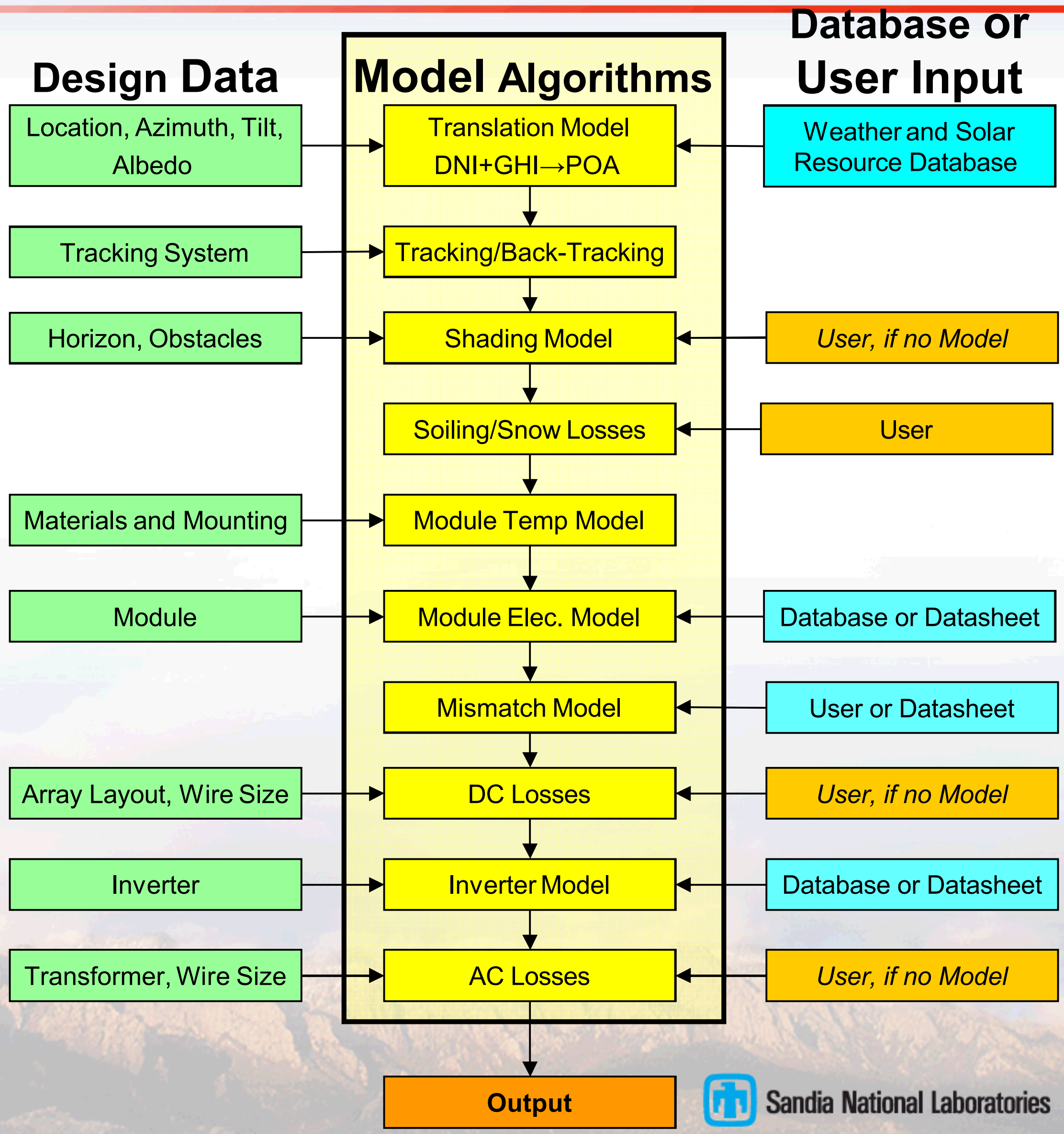
5. Modeling Issues

- **PV performance models are being used to assess design issues.**
  - Are they up to it?
- **Sandia organized a workshop to begin to address these issues:**
  - PV Performance Modeling Workshop September 23-24, 2010, Albuquerque, NM
  - Attended by 50 including Modelers, Manufacturers, Integrators, Independent Engineers, Analysts, Universities, and National Labs

PV Performance Modeling Steps

Modeling Process

- How much light enters module?
- What is the spectral content of the light?
- What is cell temperature?
- String Mismatch
- Balance of system
  - Wiring losses
- Inverter performance
  - MPPT
  - Efficiency



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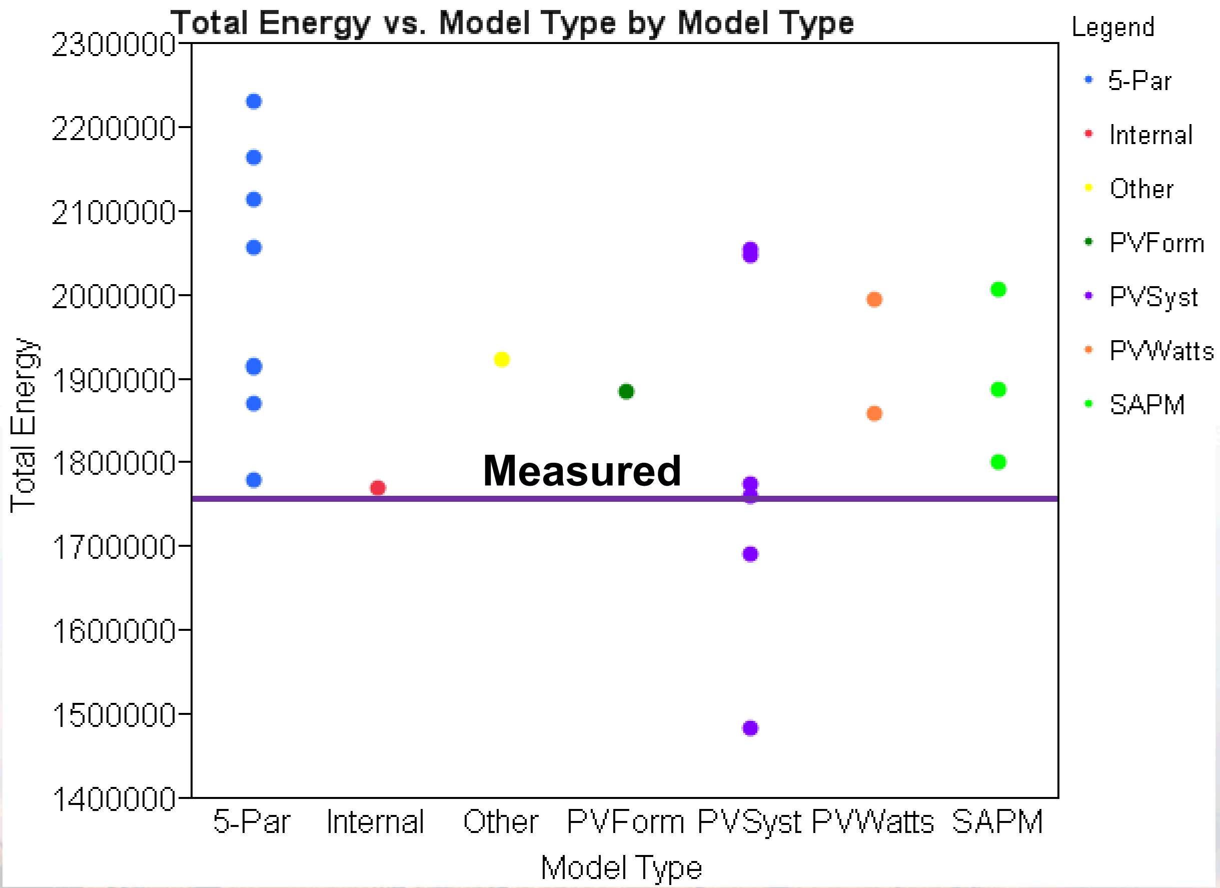
Current Status of PV Performance Modeling

- **Models Do Not Agree**
  - Even the same model, applied by different users may produce different answers
- **Model accuracy and uncertainty, in general, have not been independently verified**
  - Uncertainty (x ± y) generally not stated
  - No accepted validation process
- **Potential impacts include**
  - Choosing a technology because the model associated with an incentive treats it favorably
  - Choosing a technology based on performance that is not a better value when uncertainty is considered.
  - High market hurdles for new technologies lacking extensive field performance data to justify tweaking models
  - A decrease in investor confidence, leading to higher financing costs

Model Results Can Vary

- **Blind study**
  - 20 modelers
  - 7 models
- **Results differ within and between models**
  - Losses are hard to estimate
  - Assumptions are necessary



Preliminary Summary of Outcomes

- Model developers are improving their models to boost accuracy for all technologies
- All models, even the simplest, require user estimates for some inputs, e.g. derate factors in PVWatts
  - Modelers in same company using same model may get significantly different results
  - Experienced project developers have tuned models to match output of fielded systems and/or have developed internal models
  - Model tuning and validation requires data on fielded system performance with accompanying weather data
    - Public data is not available, especially for larger systems
- Modelers who lack system data for model tuning and/or who are modeling new technologies will likely produce varying estimates of annual output, as illustrated by analysis of the workshop pre-work.
- Needs
  - Validated data for model inputs, e.g. from 3rd parties
  - Standard sets of data from public installations of a variety of systems types and locations for use in model validation and improvement
  - Characterization of model uncertainty, including which inputs have greatest effect.

Model Development Issues

- **Existing spec sheet data are insufficient for building a sophisticated model**
  - Multiple irradiance and temperature conditions (more than two) are needed (proposed for IEC 61853-1)
  - Adequate sampling of modules (how many is enough?)
  - Third party testing (auditing?)
  - Stability of characterization data between technology (light induced changes: Are IEC 61215 and 61646 adequate for new technology?)
- **Agreement on modeling losses is needed**
- **New module and BOS components difficult to assess (e.g. BIPV, Solyndra, bifacial, DC-DC converters)**

Large Systems Issues

- **Certain factors need to be represented differently for large and small systems.**
  - Irradiance issues (point vs. array measurements)
  - Module Temperature issues (spatial fluctuations, Heat Island effect, etc.)
  - Reliability Issues (O&M strategy is important)
  - DC Loss Issues (longer wire runs, uneven soiling)
  - Tracking issues (backtracking algorithm, failures, parasitic loads)
  - Inverter issues (MPPT performance, multiple inverters)
- **Industry knows how to do this for their systems**
- **Customers/Financiers need independent tools to validate performance estimates**

Current Efforts and Next Steps

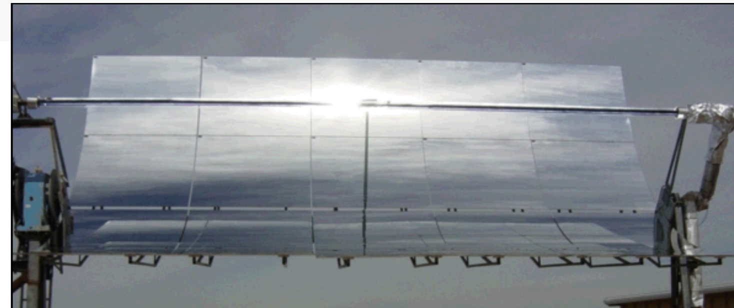
- **Guide industry to adopt standards that allow more accurate modeling of performance**
  - Better characterization at different irradiance and temperature conditions on spec sheets
- **Develop publically-available resources for PV modeling**
  - PV Performance Modeling Collaborative
    - Launch website and resources
    - Documented and validated modeling functions (Matlab)
    - Host 2nd PV Performance Modeling Workshop (Fall 2012)
- **Regional Validation Test Centers**
  - Test and validate U.S. PV technology in different climates

Outline of Today's Discussion

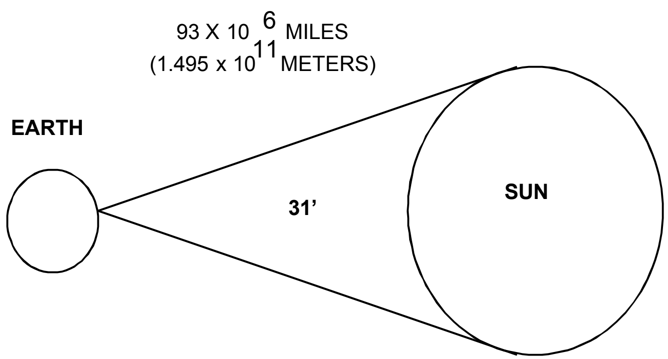
- Background
- Solar Cells and the Photoelectric Effect
- From Cells to PV Systems
- **Concentrating Solar Power (CSP)**

Heat Transfer Fundamentals

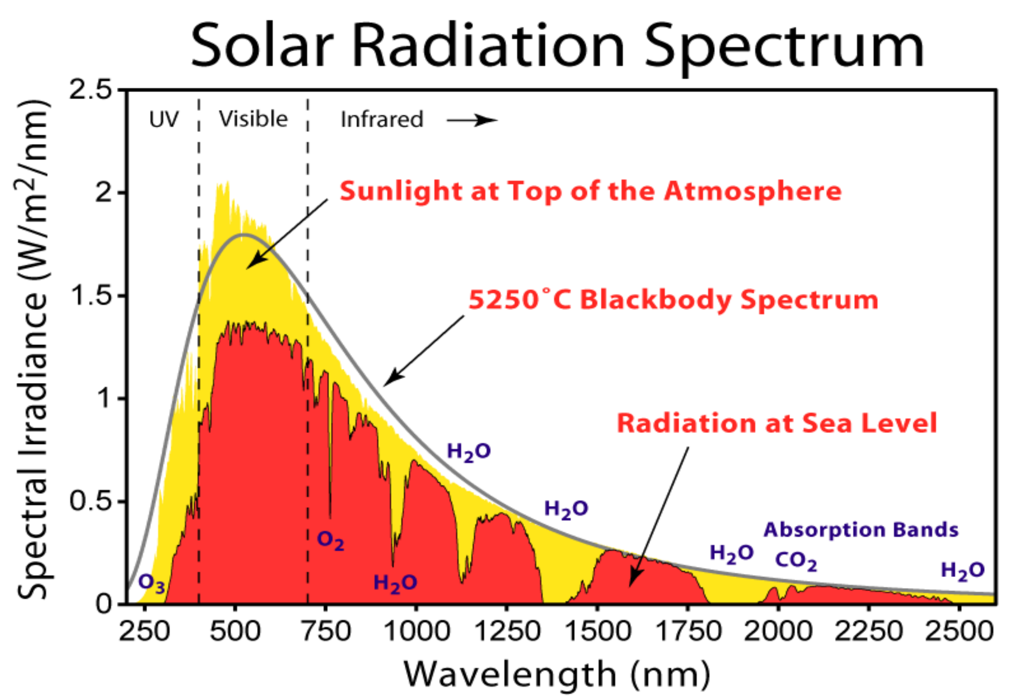
- **The solar energy resource**
  - Sunshape and solar energy spectrum
- **Heat transfer issues**
  - Conduction, convection, radiation
  - Absorption and IR emission
- **Solar concentrator optics**
  - Single-axis tracking trough collectors
  - Double-axis tracking heliostats and dishes
  - Specular reflection
- **Power cycles**



Spectrum and Sunshape



- The visible spectrum is from 400 nm to 700 nm
- Note 5250 C Blackbody spectrum



- Unlike PV, CSP responds to the full spectrum of the sunlight ("Broadband")
- CSP only uses the "direct" component of the light
  - Flat-plate PV can use the direct and diffuse components

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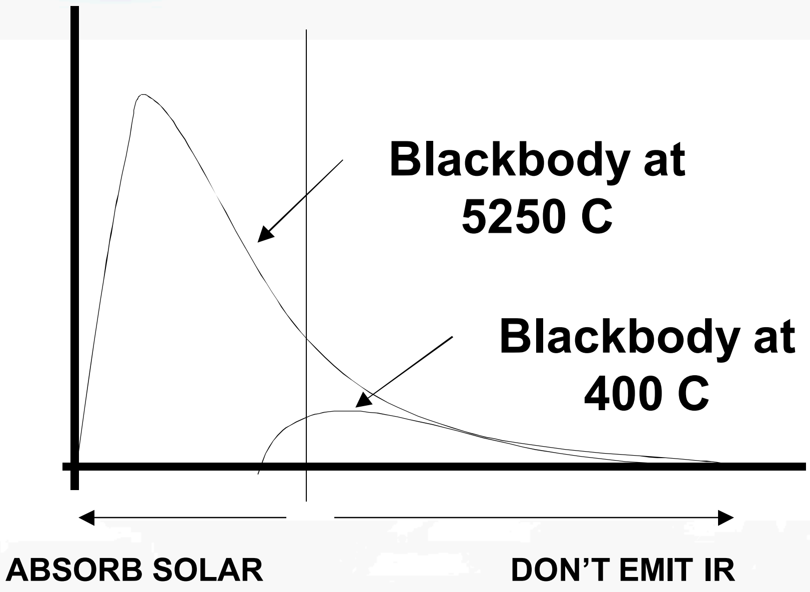
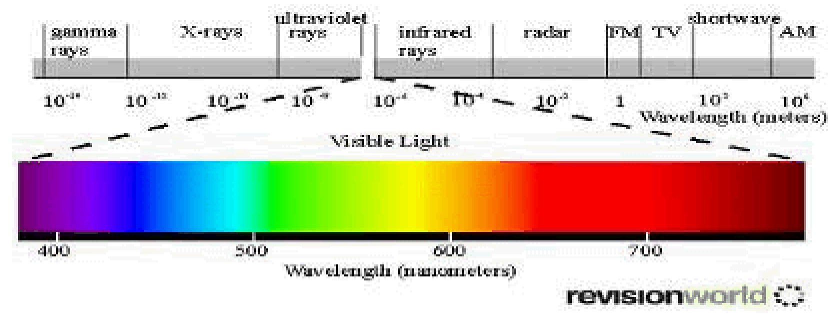
Absorption and emission

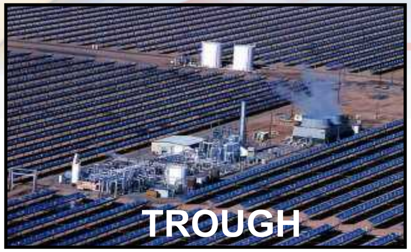


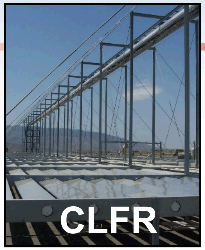
Solar energy is part of the electromagnetic wave spectrum.



- The first objective is to capture all of the solar energy
- The second objective is not to lose it
- Surface characteristics of absorptivity (α) and emissivity (ε) vary with wavelength
- It is desirable to have a high solar α and a low IR ε

What can CSP do?

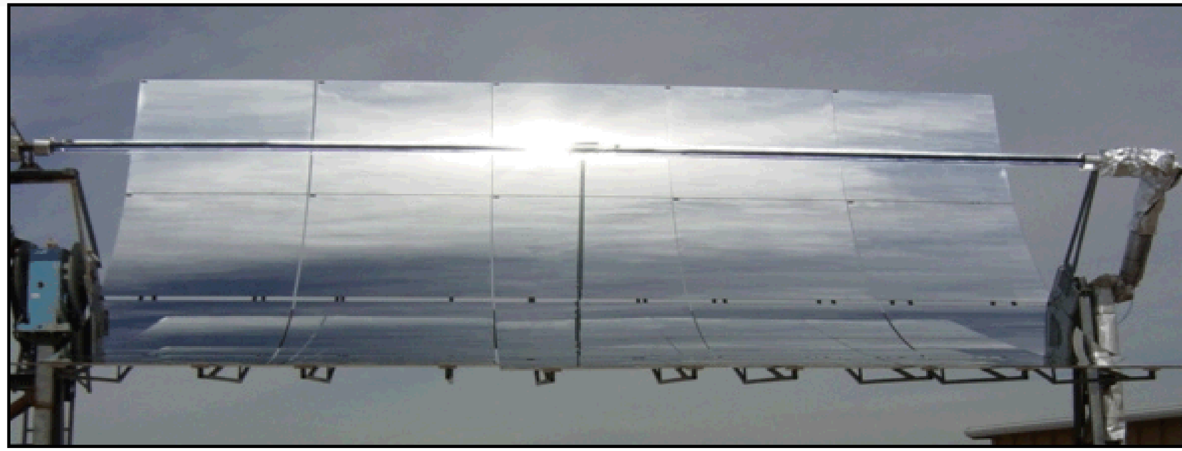




- **Convert the sun's energy to heat and use that heat to power and engine/generator.**
- **Are utility-scale solar power (> 100 MW).**
- **Comprise three generic system architectures: line focus (trough and CLFR), point focus central (power tower), and point focus distributed (dish engine).**
- **More than 140 plant-years of commercial operation (10 plants, 400MW) in the Southwest.**
- **Capable of providing dispatchable power for peaking and intermediate loads (storage or hybridization).**
- **Mostly uses commodity items (turbines, glass, steel, aluminum, piping, controls, etc)**

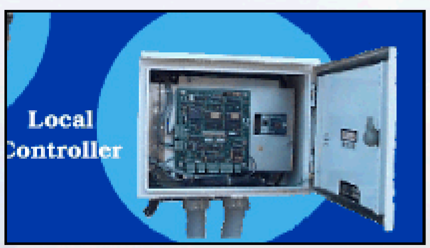
Trough Components

Trough Collector



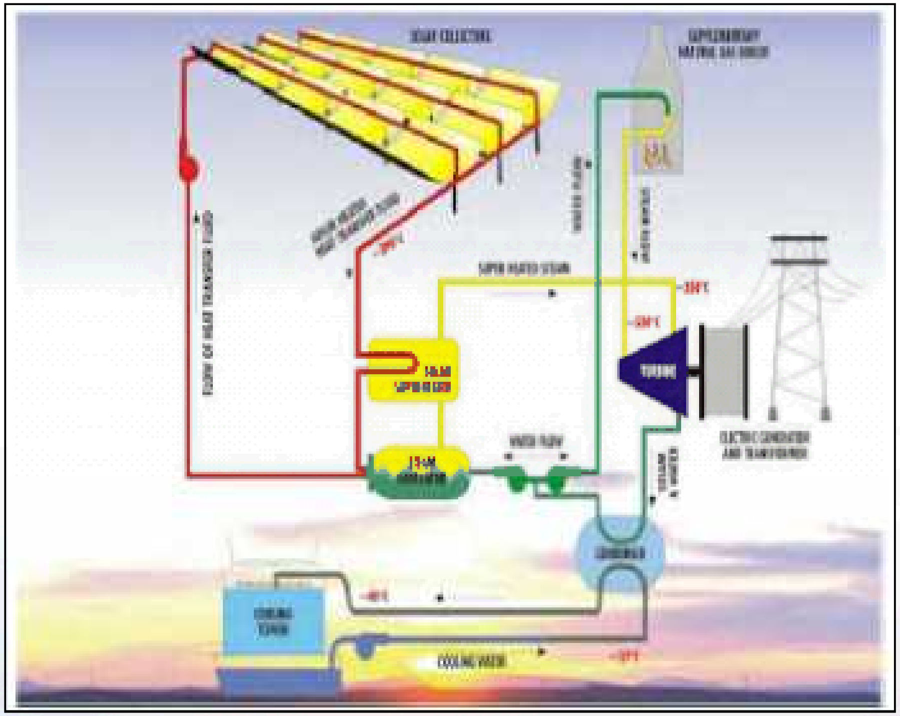
Drive

Receiver



Controller

How a Trough System Works



- Synthetic Oil circulated through the collectors and heated from 290 to 390 C.
- Hot oil circulated through the steam generator to produce superheated steam.
- Steam routed through the turbine generator producing electricity.
- Steam condensed using water cooled in cooling tower.

CLFR Designs

- **Continuous Linear Fresnel Reflector**
- **Approximates a line-focus trough collector**
- **May be lower cost because it doesn't use curved mirrors and places the reflectors near ground level -- reducing wind loads**

SEGS Plants

- Solar Electric Generating Stations
- Total annual ave. solar-to-electric efficiency at 12%.
- Plants use conventional equipment and are "hybridized" for dispatchability (25% Natural gas)

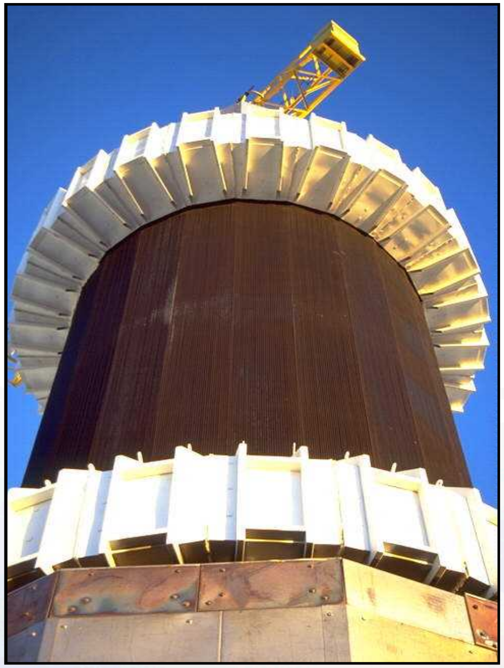
30 MW increment based on regulated power block size

Nevada Solar One

- 64 MW Capacity
- 357,200m² Solar Field
- 30 Minutes Thermal Storage
- Minimal Fossil fuel
- Long term PPA signed with Nevada Power
- EPC Notice to Proceed – January 2006
- Startup April 2007

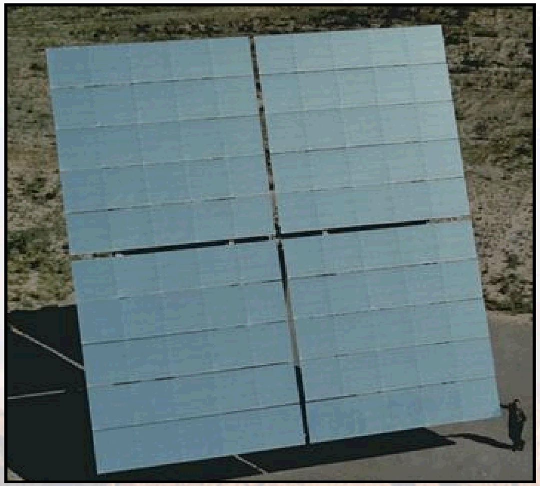
Power Tower Components

Receiver



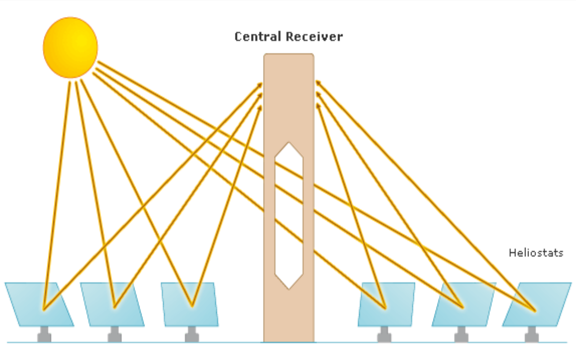
Storage Tanks

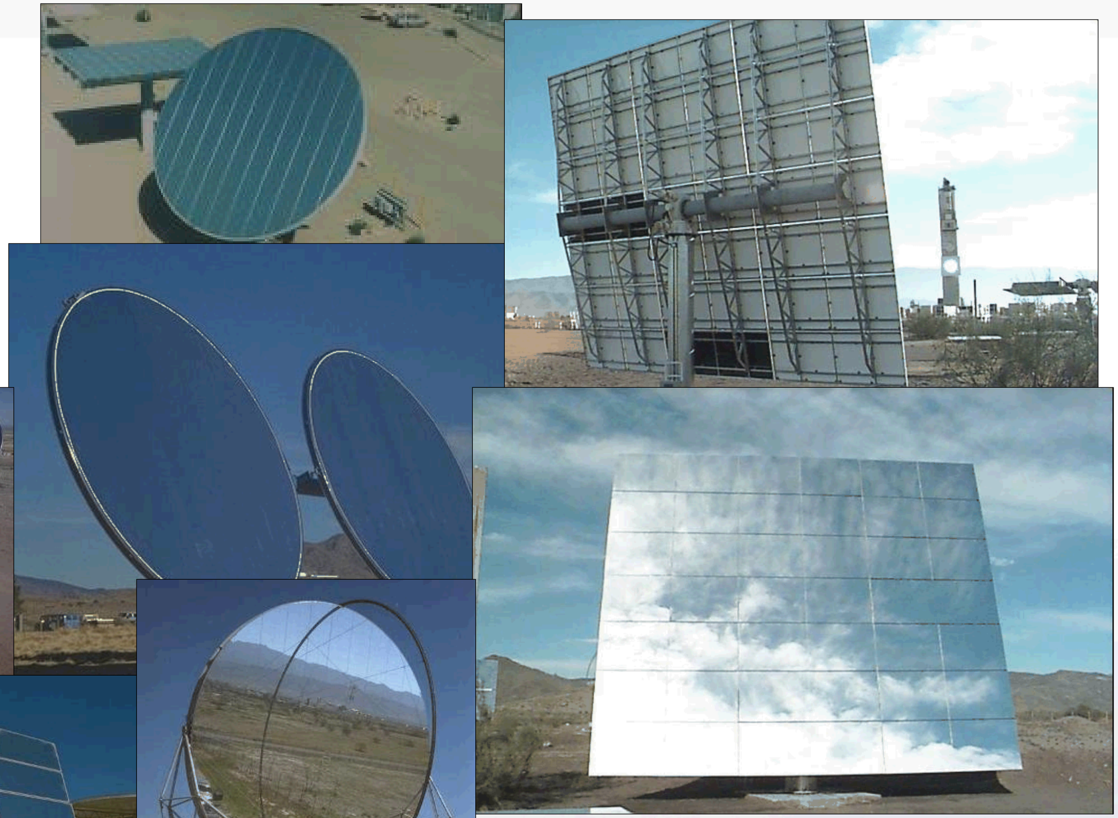
Heliostat

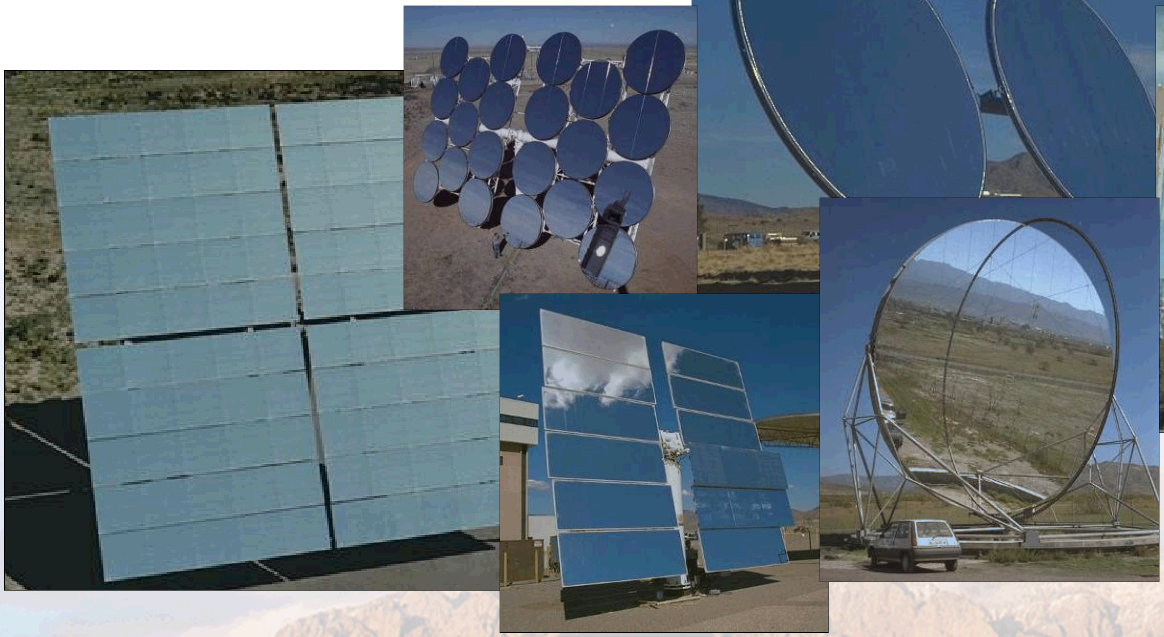


Steam Generator

Heliostat Designs



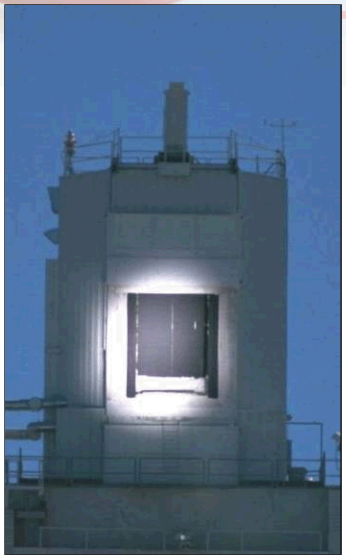




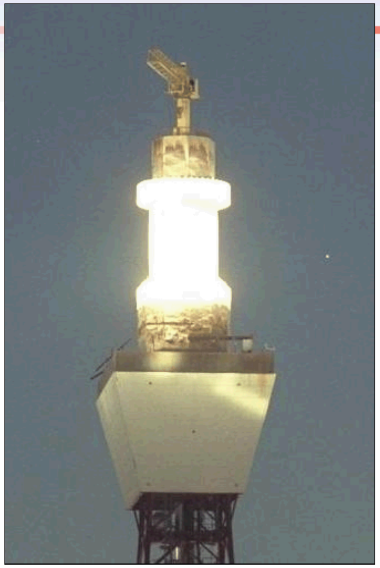
Deflection limited designs

Wind load survival at stow

Central Receiver Receivers



CAVITY MOLTEN SALT RECEIVER



SOLAR 2 MOLTEN SALT RECEIVER

WINDOWED BEAM DOWN AIR RECEIVER

- **Central Receivers are**
  - Cavity receivers
  - Windowed
  - Direct steam generators
  - Can use Molten-Salt working fluids
- **Design Considerations**
  - Inlet/Outlet Temperatures
  - Materials
  - Pressure
  - Low volatility working fluids

Power Towers

PS 10 (2006) PS 20 (2009)

11 MW & 20 mw Capacity

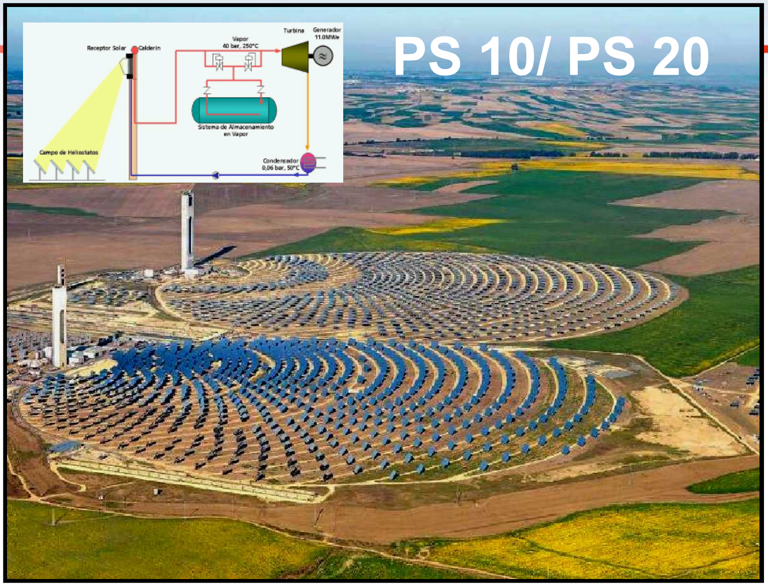
Once-through steam boiler

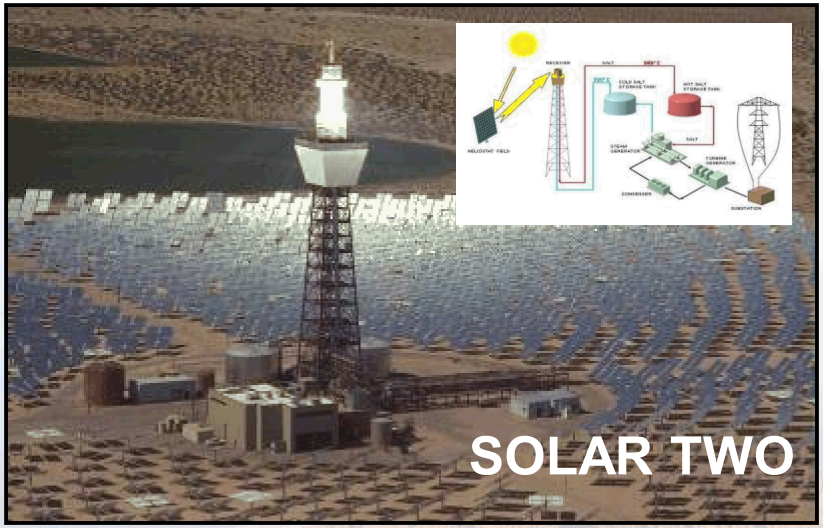
1 Hour thermal storage (steam)

1878 heliostats (120 m² each)

Towers height 100 m and 160 m

73 GWhr/annually





Solar Two Experiment (1995 – 1997)

10 MW Capacity

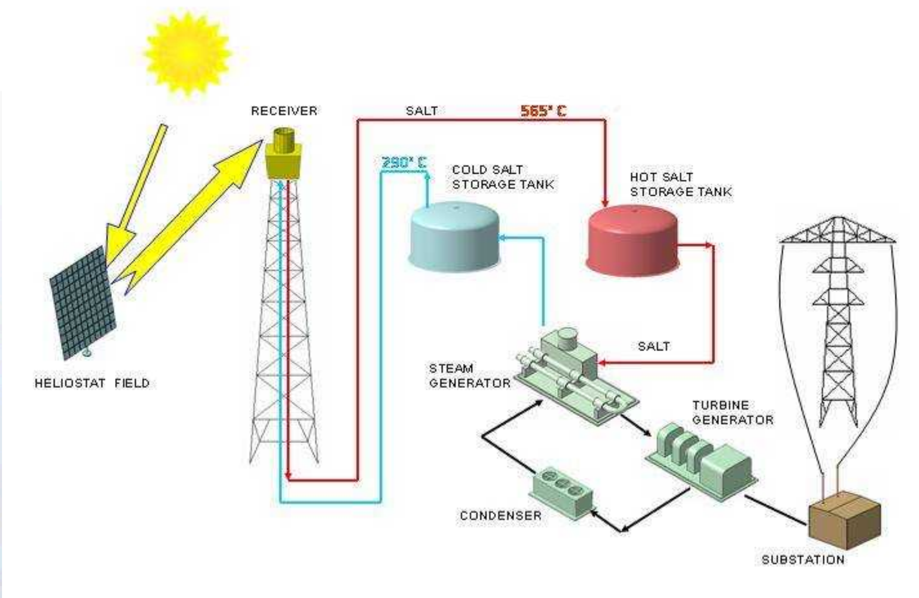
Molten Salt working fluid/thermal st.

Receiver η = 88%

η of Storage > 98%

Dispatchability demonstrated

Molten-Salt Power Tower



In a Molten Salt Tower

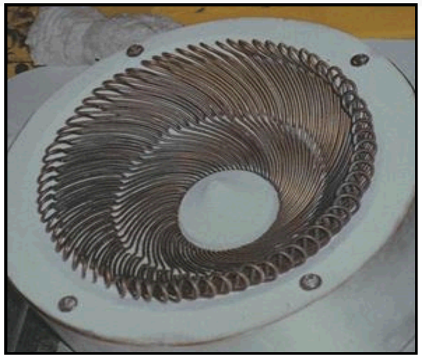
cold salt (265C) is pumped to the receiver, heated to 565 C, and returned to the Hot Tank

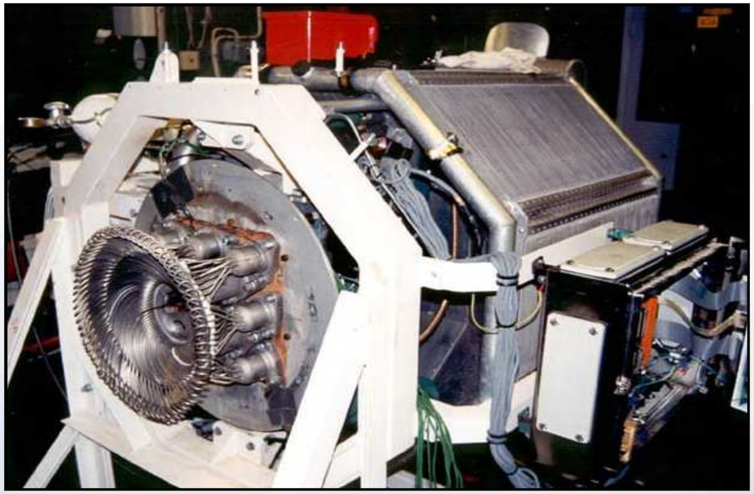
To generate power, hot salt is removed from the hot tank, passed through the steam generator, and returned as cold salt to the cold tank.

Energy collection is uncoupled from power production

Dish Stirling Components

Receiver

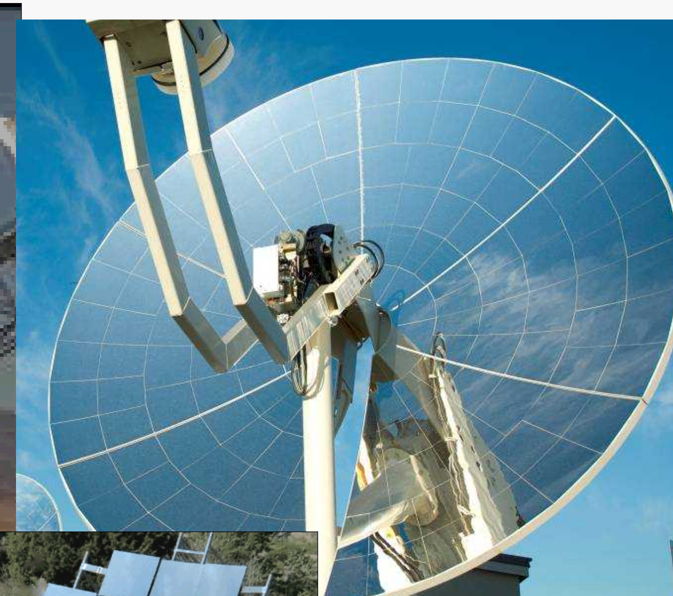




Engine/Generator

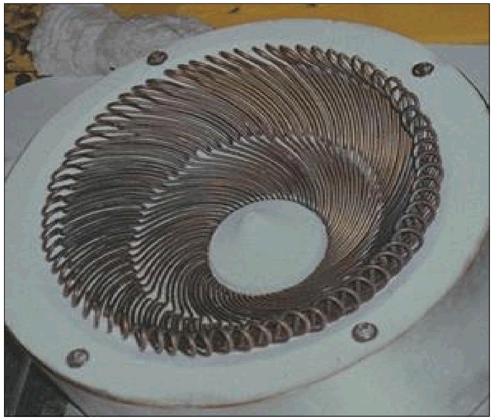
Dish

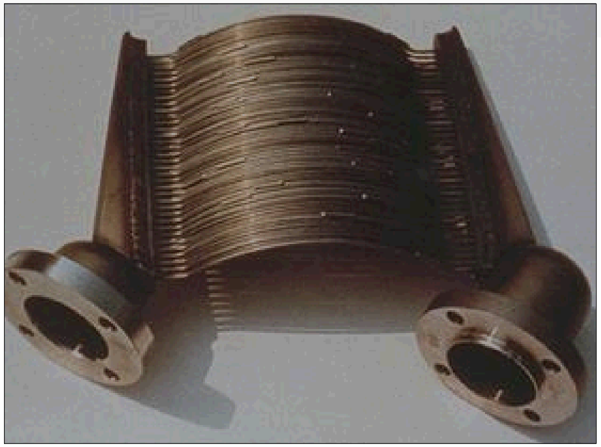
Dish Designs



Sizes range from about 10 m^2 to 300 m^2

Dish Stirling Receivers

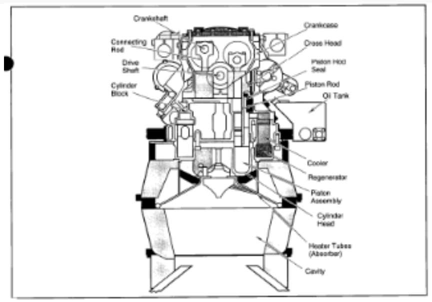


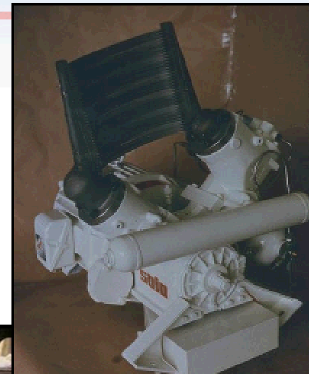


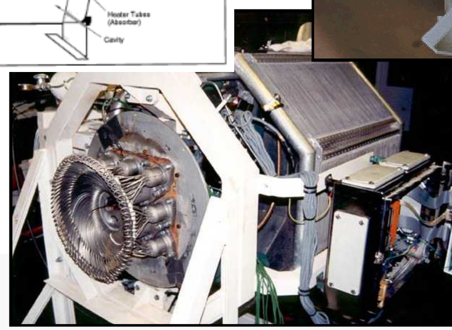
The receivers transfer the solar-generated heat to the engine. This is done indirectly; by heating tubes that transfer the heat to the engine working fluid (hydrogen or helium) or by transferring the heat to an intermediate fluid (like sodium) that heats the tubes.

CSP Dish Stirling Systems

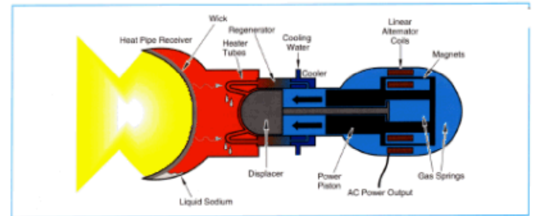
Kinematic







Free Piston



Kinematic engines operate similar to an automobile to produce mechanical power by moving pistons, driving a crankshaft, and spinning a generator.

Free-piston engines have only two moving parts – a power piston and a displacer piston. The power piston moves back and forth driving the displacer piston. The displacer piston has a permanent magnet that moves back and forth in coils located in the engine housing, operating as an alternator.

CSP Dish Stirling Systems

- High efficiency (Peak > 30% net solar-to-electric)
- Annual Efficiency ~ 22 – 25%
- Modular (3, 10, 25kW)
- Utility-scale plants would have 1000s
- Small system for DG applications
- No commercial plants built yet

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Summary

- Solar resource and potential is huge in all parts of the U.S.
- Many PV technology and design options
- Characterization and prediction of PV system performance needs improvement
- CSP offers options with energy storage, which makes integration easier, but costs are still high

RENEWABLE ENERGY OUTLOOK IN THE US AND THE WORLD

Joshua S. Stein Ph.D.
Photovoltaics and Grid Integration Department
Sandia National Laboratories

Renewable Energy Short Course, Burlington, VT
26 July, 2011

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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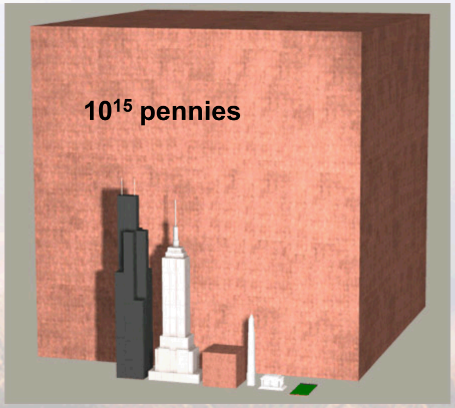
Outline and Goals

- How do we measuring energy use for a country or the world?
- Who measures energy for the U.S.
- Where does our energy originate and how is it used?
- How are states and governments influencing a switch to renewables?
- How reliable are future energy forecasts?
- What are the main barriers to renewable energy?
- What is happening in Europe?

Energy Units and Conventions

- **How do we measure energy?**
  - Joule (J) – 1 newton/meter *or* 1 Watt/sec (very small amount of energy)
    - Gigajoule (GJ) = 1 billion (10^9) Joules (~6 GJ per barrel of oil)
    - Zettajoule (ZJ) = 10^{21} Joules (Annual global energy consumption is about 0.5 ZJ)
  - BTU (British Thermal Units) = 1,055 J = Energy required to heat 1 pound of water from 39 to 40 deg F.
    - **Quad** = quadrillion BTUs (10^{15}) is the standard unit for measuring energy use by world economies.
    - U.S. used about 100 Quads of energy in 2005
      - **1 Q = 8 million gallons of gas**
      - **100 Q = PV energy potential**
        - ~13,000 mi^2
        - Land required = 25 years of coal mining



- The U.S. defines "quadrillion" differently from the rest of the world
  - The "British" quadrillion = 10^{24}

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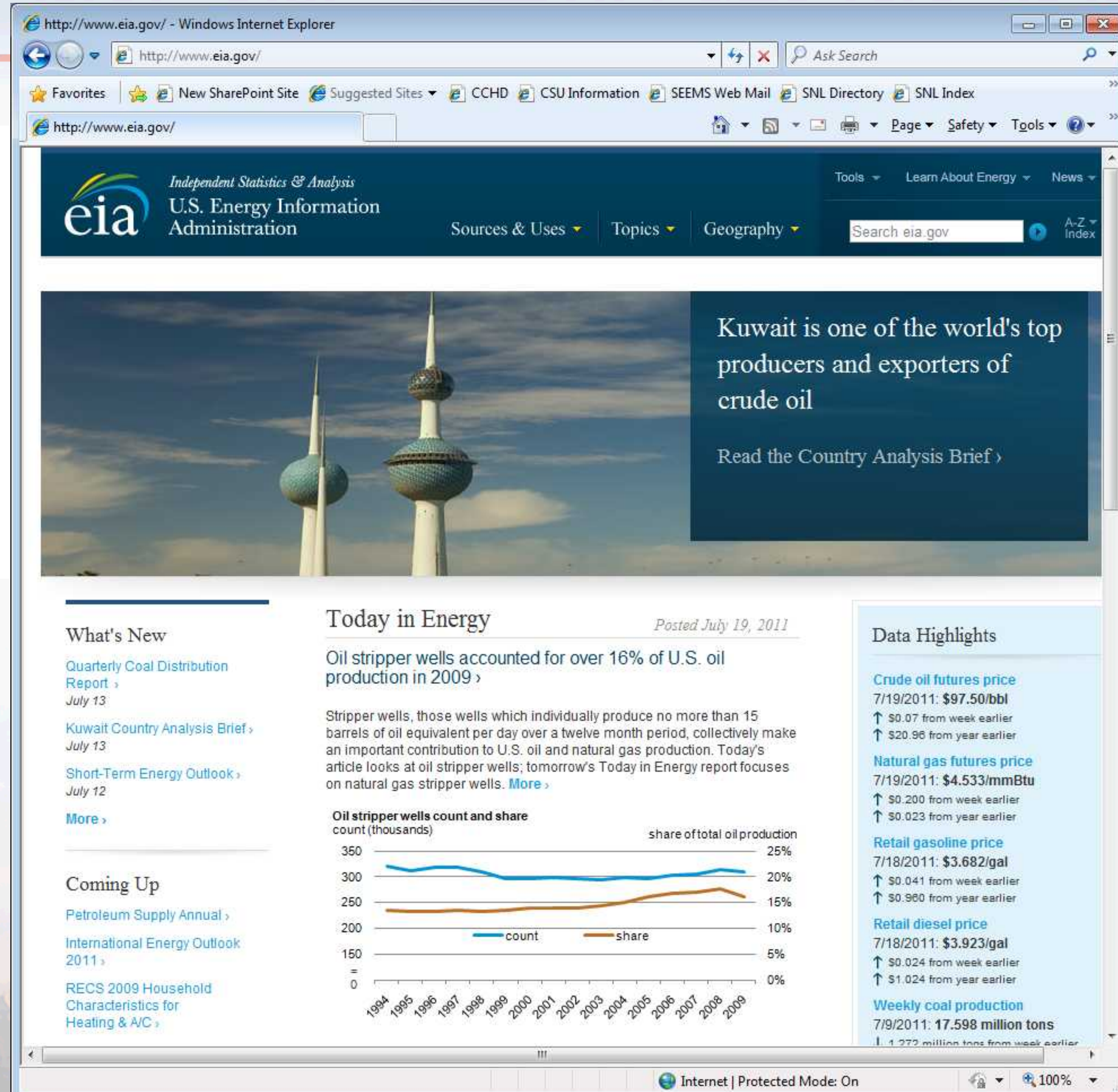
Who Measures Energy for the U.S. and World?

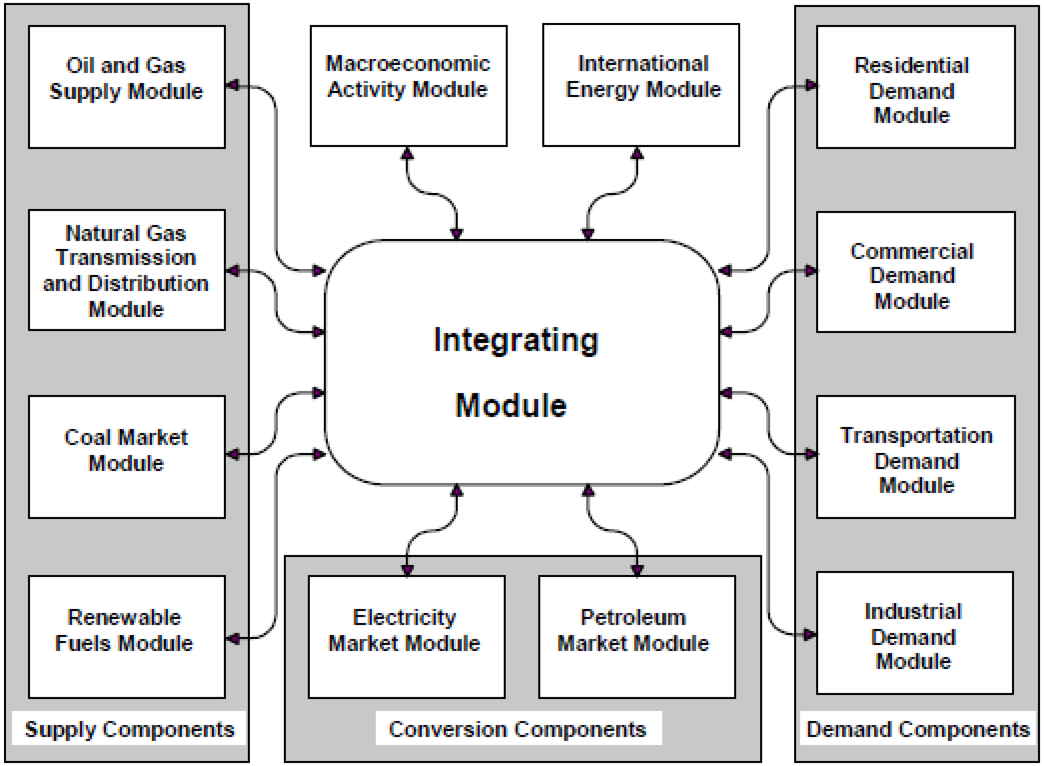
- **U.S. Energy Information Administration**
  - Statistical and analytical agency within DOE
  - Weekly, monthly, quarterly, and annual assessments and forecasts
  - Annual energy outlooks
  - Systems modeling (National Energy Modeling System (NEMS)
- **International Energy Agency**
  - 28 member countries



National Energy Modeling System

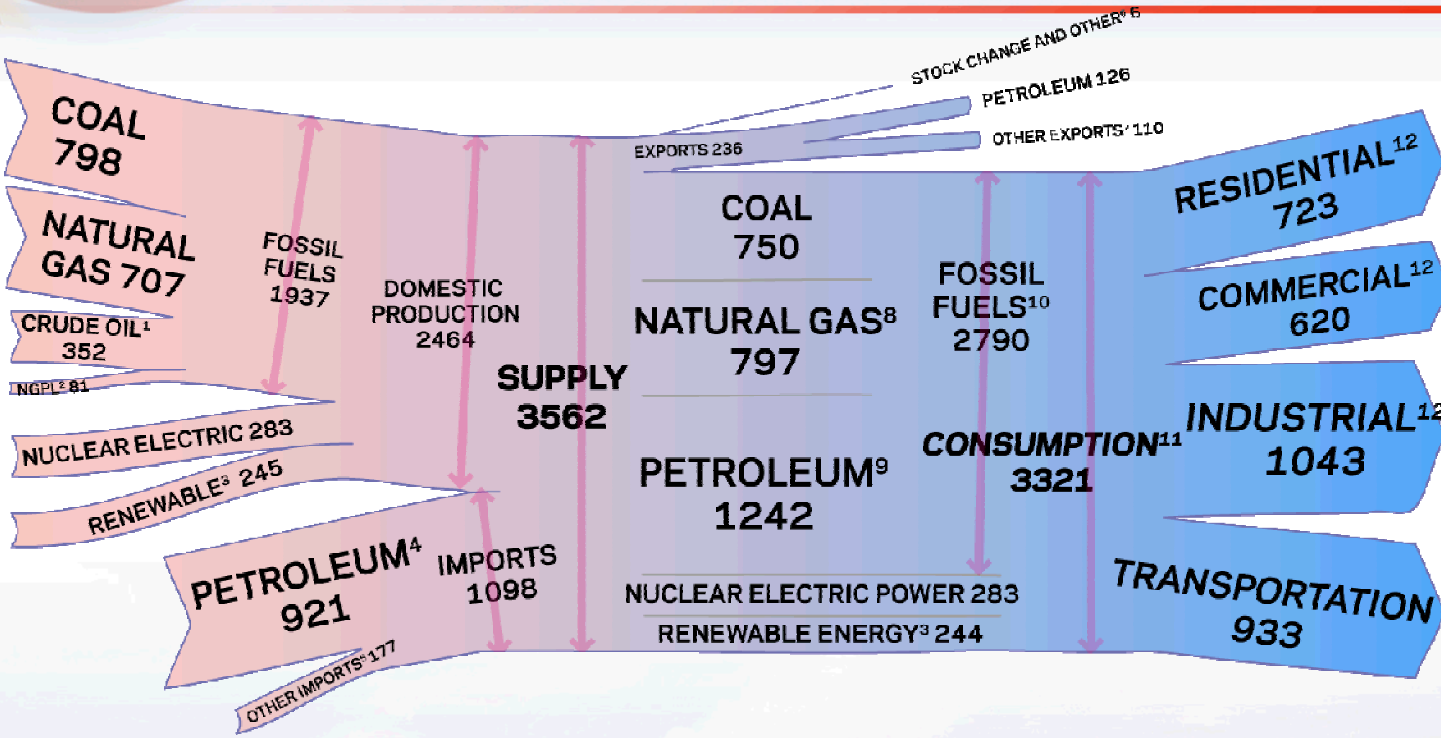
- **Global optimization problem with multiple constraints**
  - Supply and demand are balanced for the minimum price
  - Capital expenditures, international prices, and economic activity are also considered
  - Regional divisions are considered
  - Current incentives included

Figure 1. Basic NEMS Structure and Information Flow



U.S. Energy Flow by Source and Sector

US TOTAL Energy Flow, 2008
(Gigawatts)



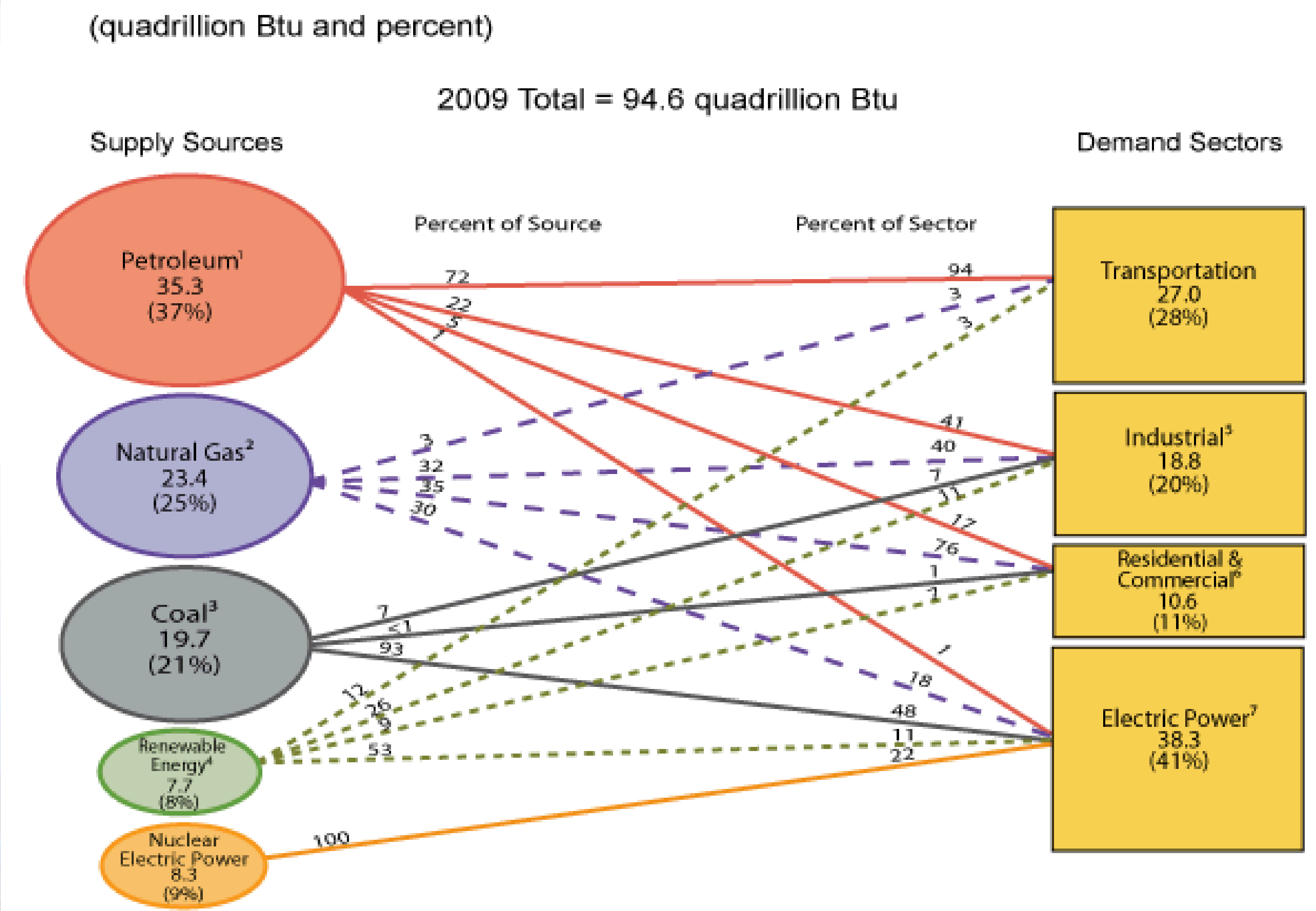
[1] Includes lease condensate.
[2] Natural gas plant liquids.
[3] Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.
[4] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[5] Natural gas, coal, coal coke, fuel ethanol, and electricity.
[6] Adjustments, losses, and unaccounted for.
[7] Coal, natural gas, coal coke, and electricity.
[8] Natural gas only; excludes supplemental gaseous fuels.
[9] Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.
[10] Includes 0.04 quadrillion Btu of coal coke net imports.
[11] Includes 0.11 quadrillion Btu of electricity net imports.
[12] Primary consumption, electricity retail sales, and electrical system energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note, "Electrical Systems Energy Losses," at end of Section 2.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.

MODIFIED FROM: Energy Information Administration / Annual Energy Review 2008

U.S. Primary Energy Flow by Source



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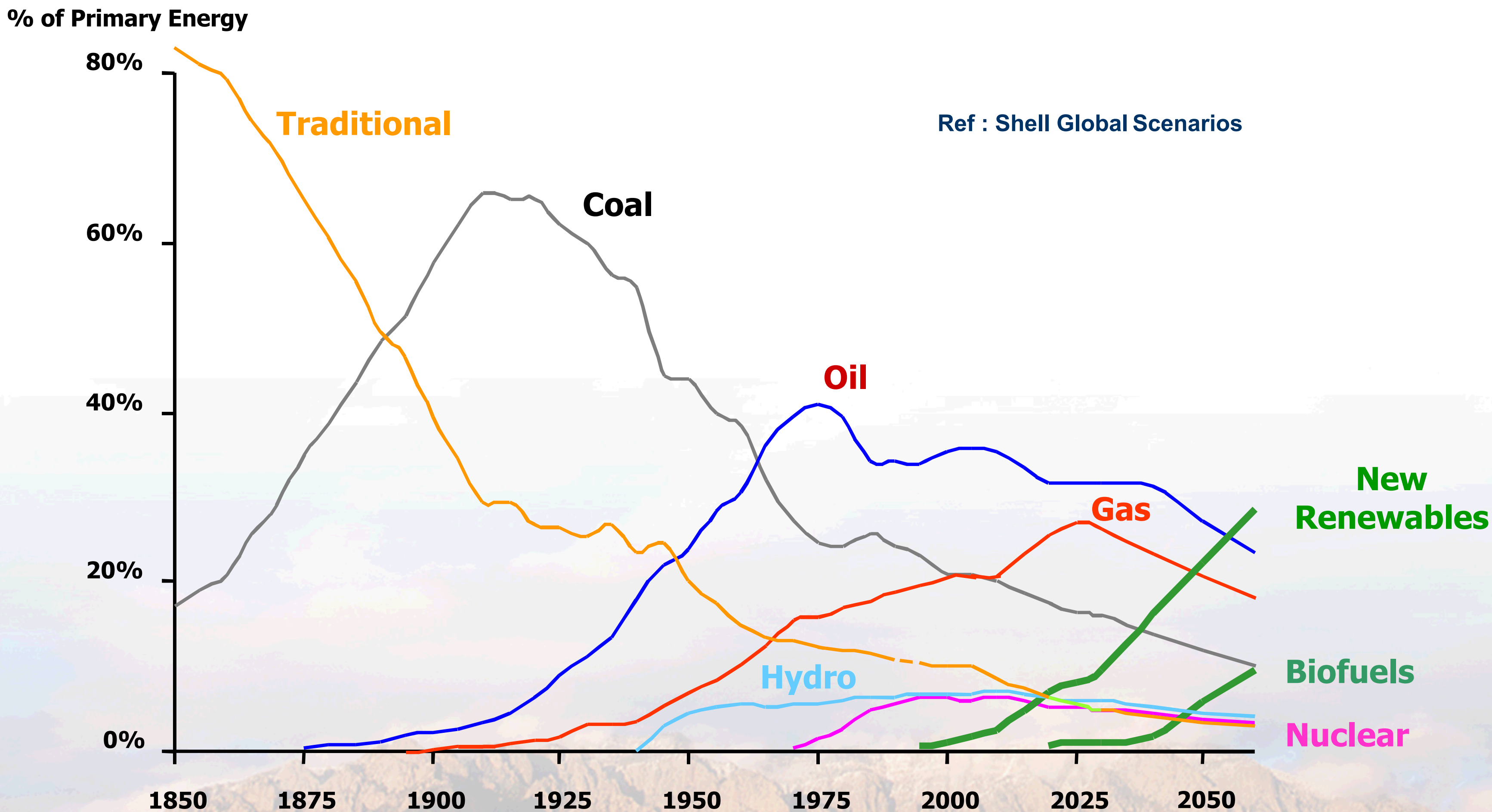
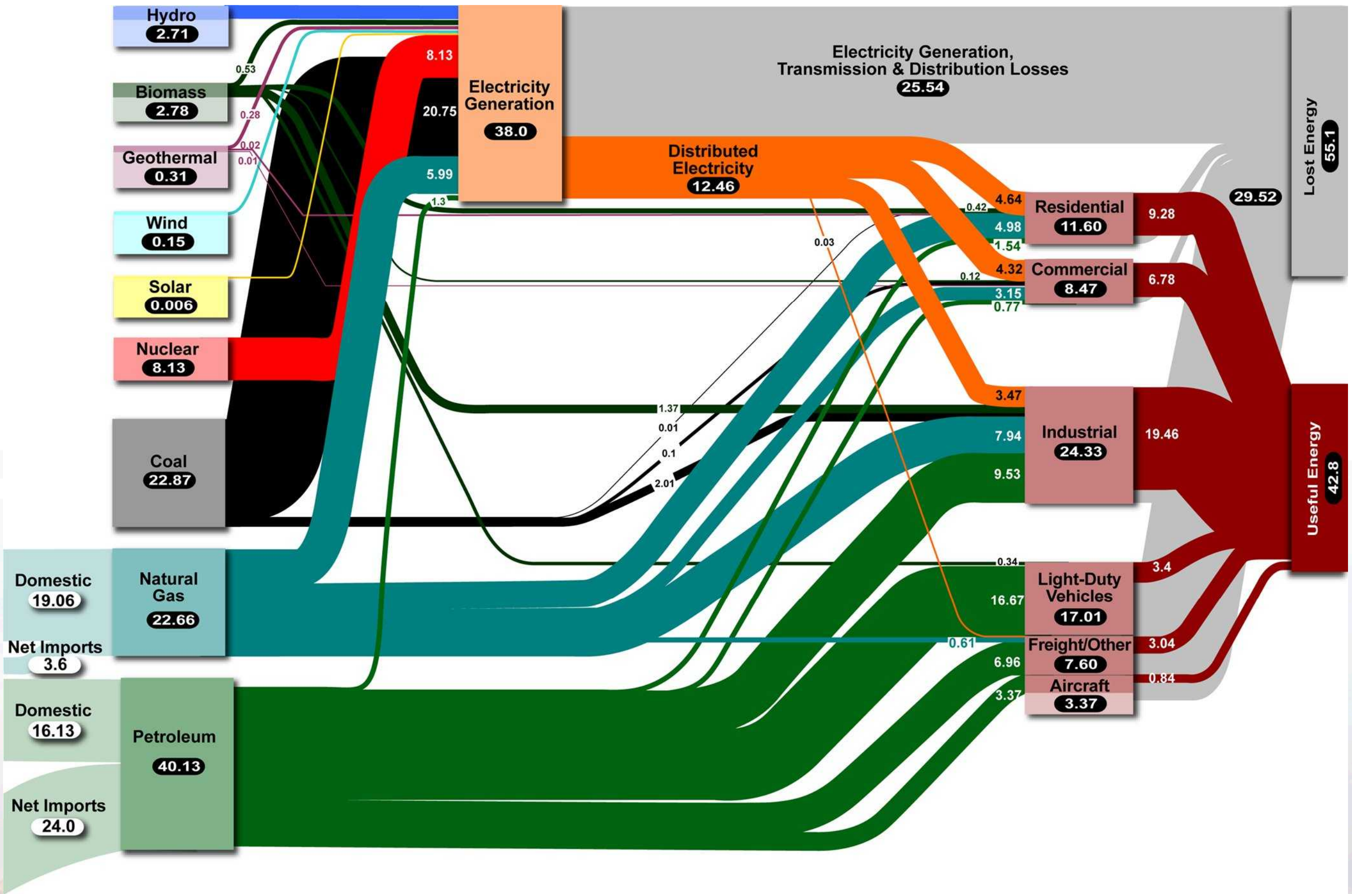
The Evolving Energy Mix



U.S. Electricity Flow

- Increasing efficiency is important
- Conversion losses (technology)
- Transmission and distribution losses (system design)

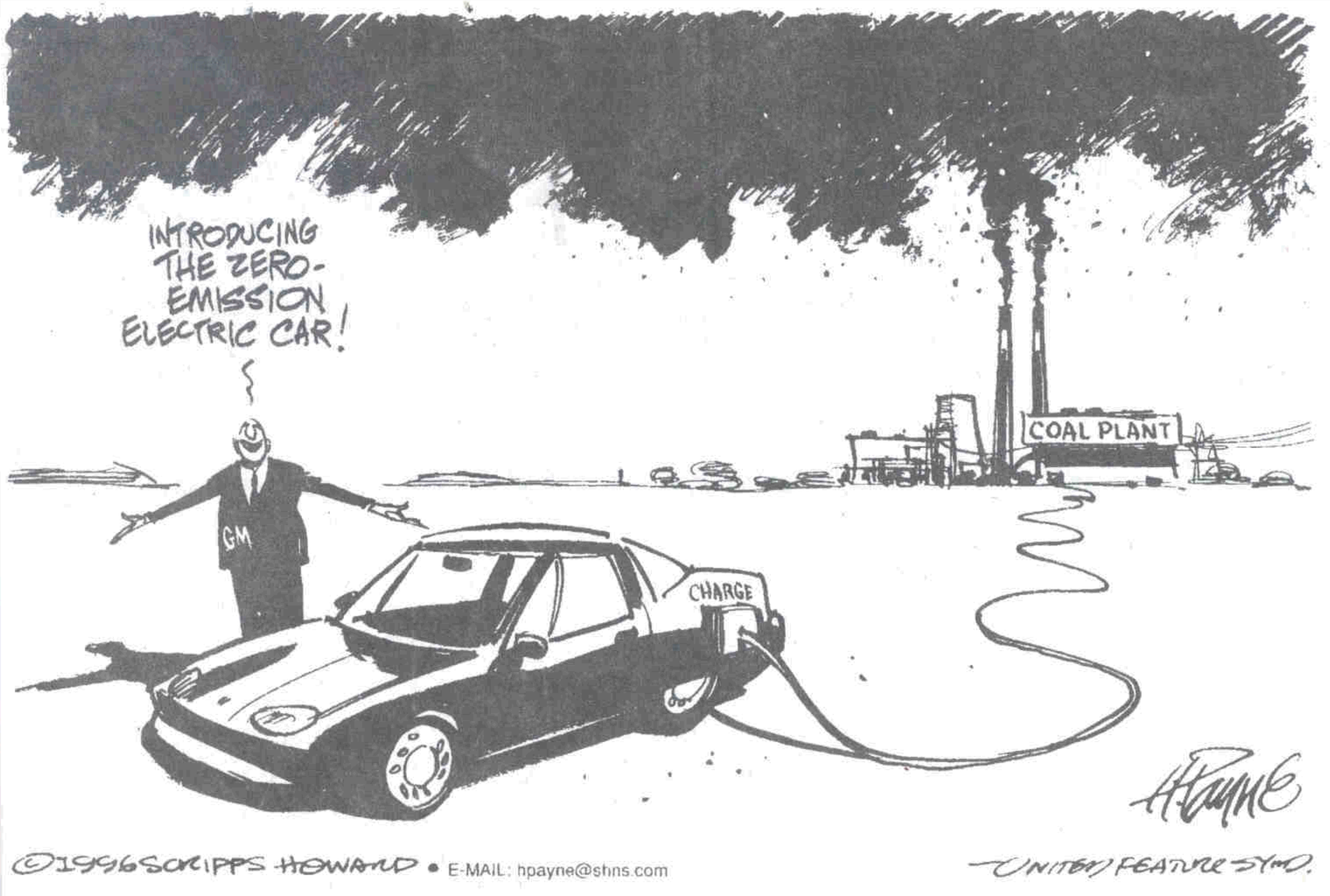
- Does not include wasted energy
  - E.g., consumer electronics on standby, lighting, A/C, …



Using the “Spaghetti Chart” to Understand Energy Issues

- Nuclear energy role in U.S. energy supply and in electric energy production?
- Is the U.S energy supply vulnerable, how much is imported and for what?
- Benefits of solid-state lighting on oil imports? On energy efficiency and future power plant needs?
- Are there benefits of higher fuel efficiency standards for cars? For cars and trucks?
- Where are energy efficiency technology improvements most productive?

Growing Environmental and Ecological Issues (Carbon Footprint)



HYDROGEN FUEL CELL – $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$

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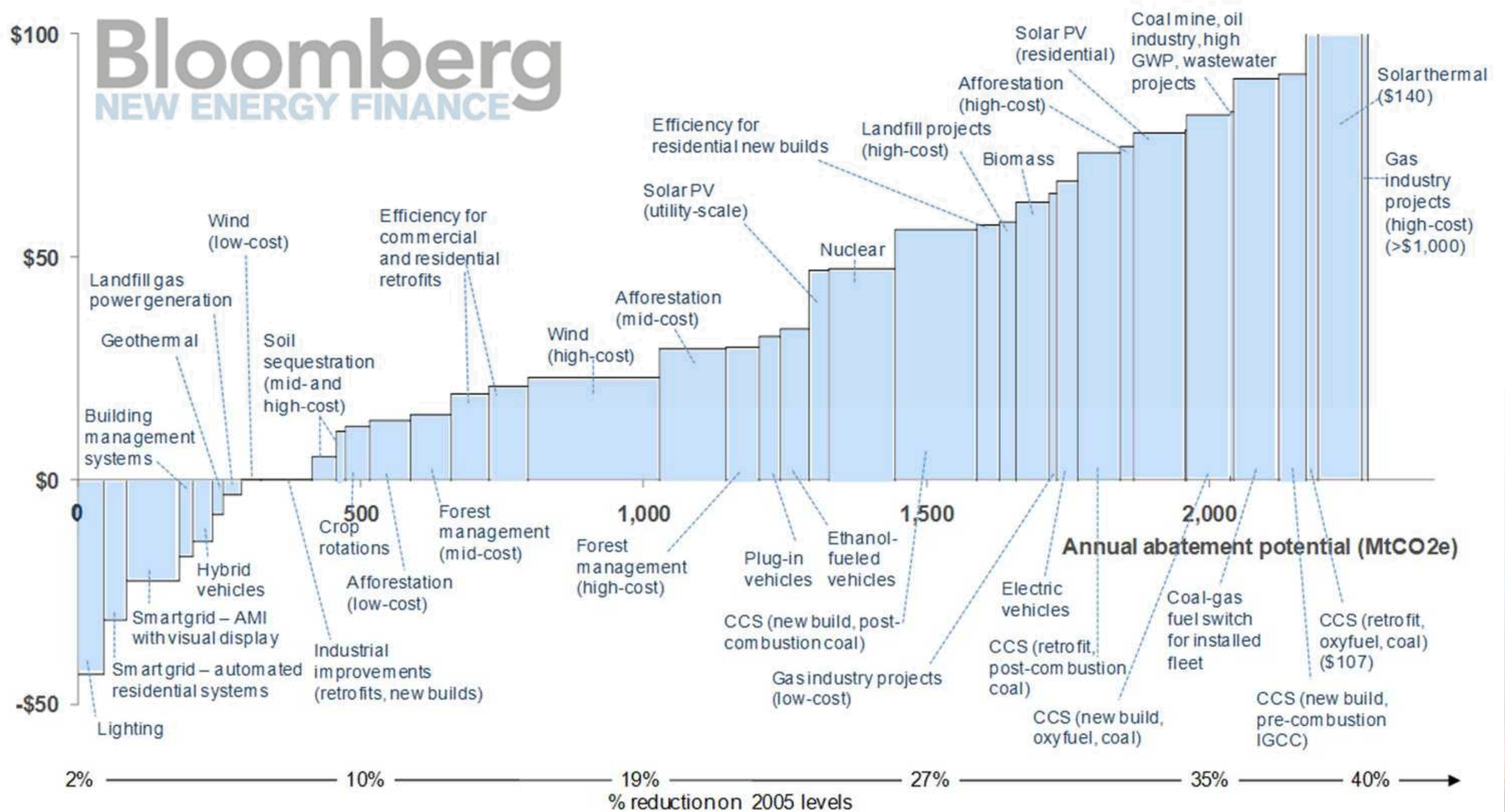
Cost of Reducing CO^2



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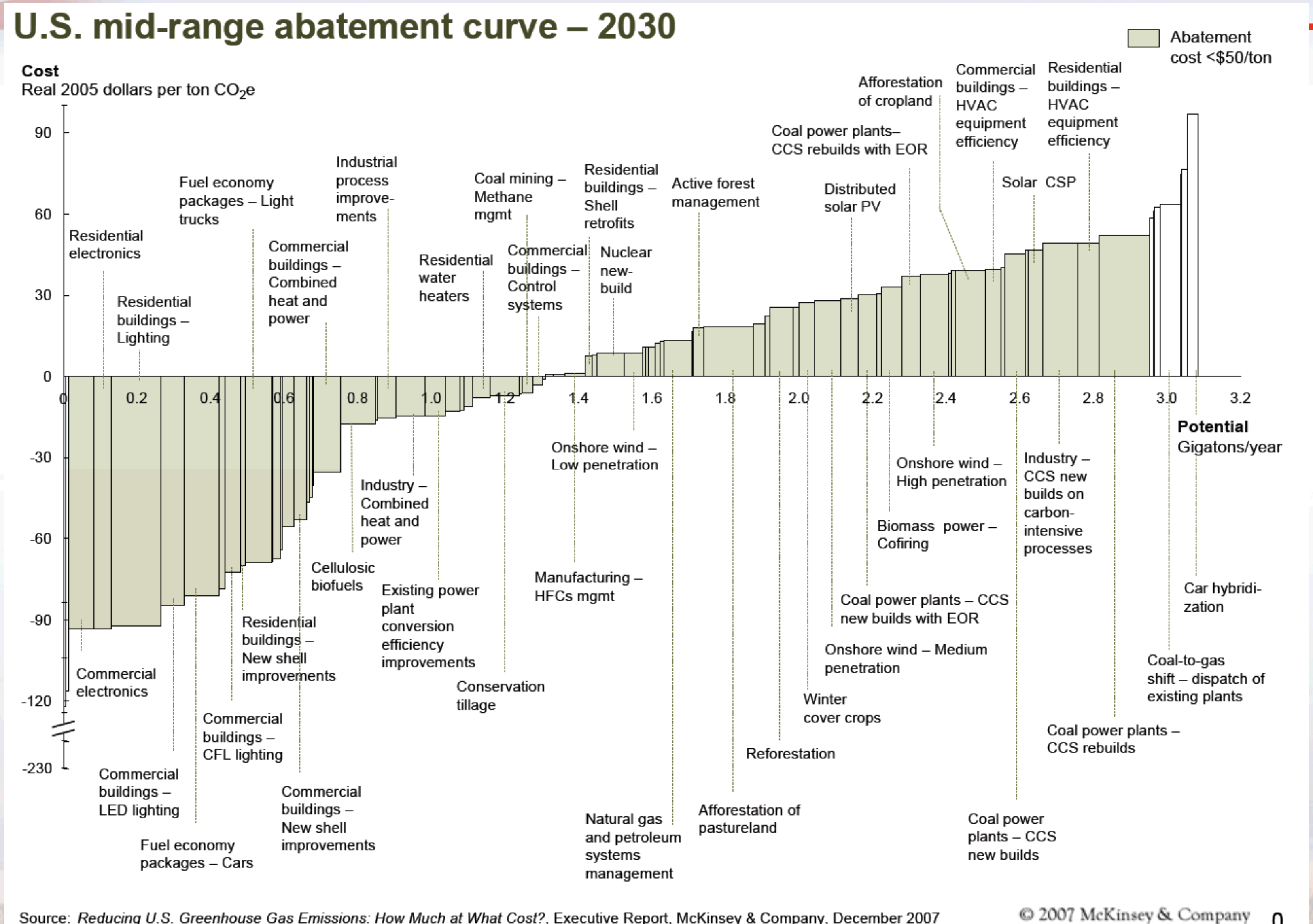
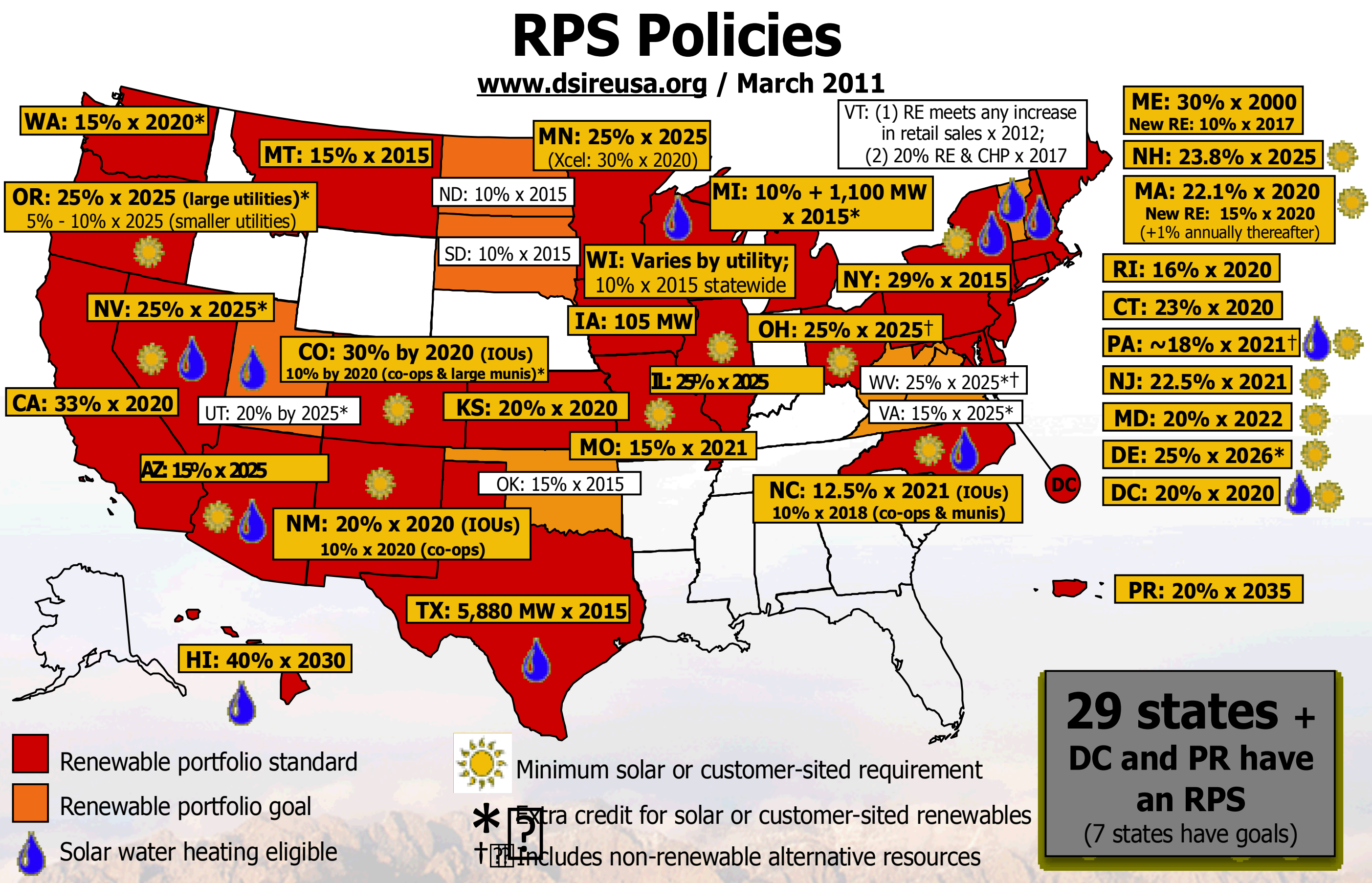
Cost of Reducing CO_2



Renewable Portfolio Standards Are Gaining Ground Across the US

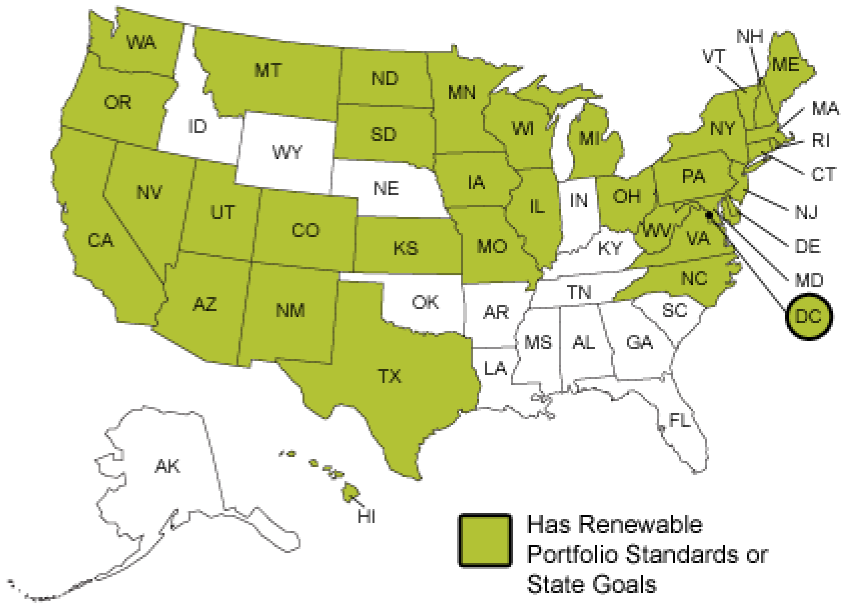
New Market Scenario: Climate change concerns, renewable portfolio standards, incentives, and accelerated cost reduction driving steep growth in U.S. renewable energy system installations.



Most States have Renewable Portfolio Standards

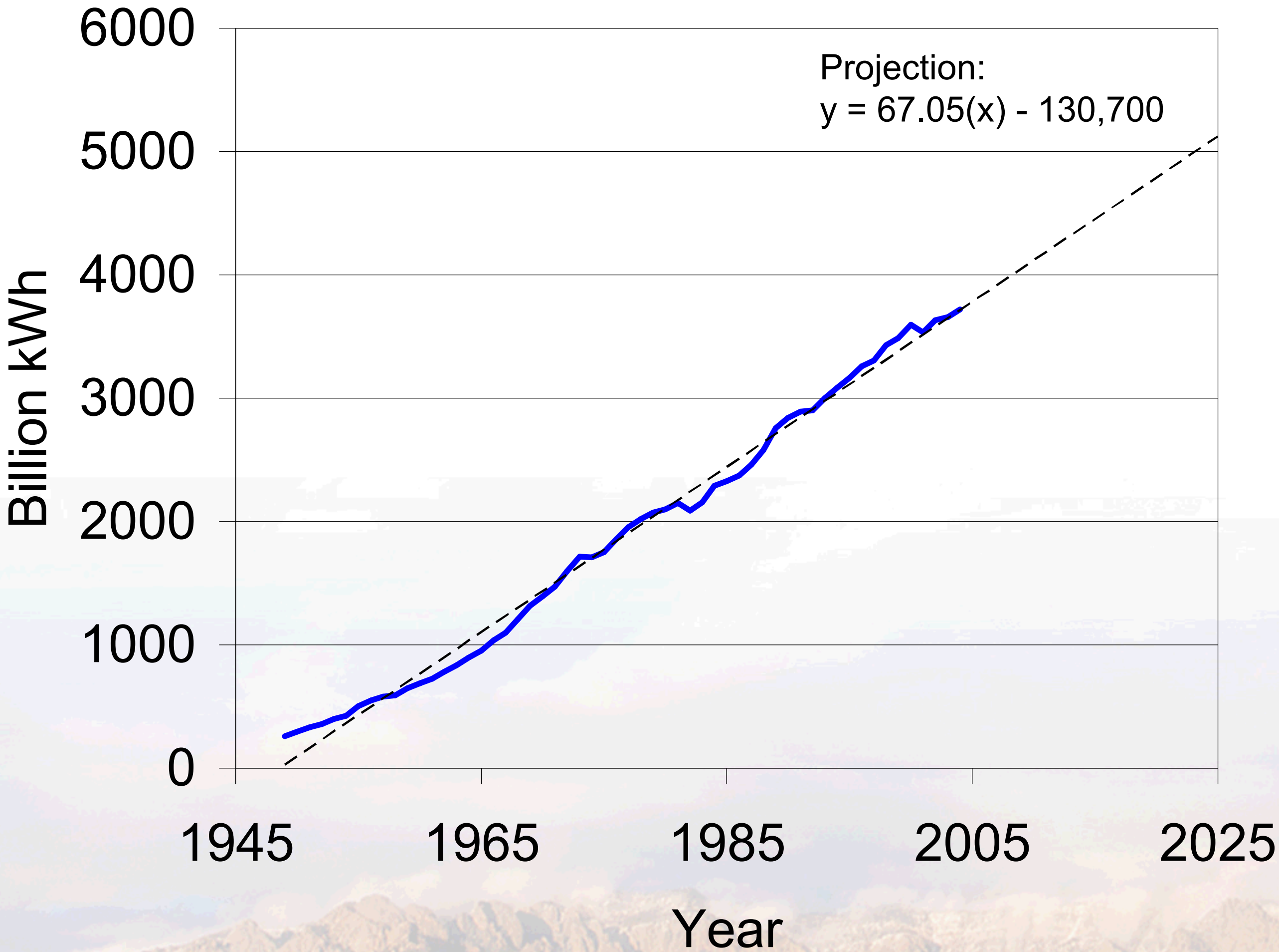
- 2007 EIA examined 15% Federal RPS
- Result was tripling of electricity generated from biomass as well as large increases in wind and solar
- Price for electricity increased by 0.9%
- Natural gas prices fell as a result of decreased demand
- RPS can have significant and sometimes unintentional effects on other economic sectors

Most States Have Renewable Portfolio Standards, Mandates, or Goals, 2010



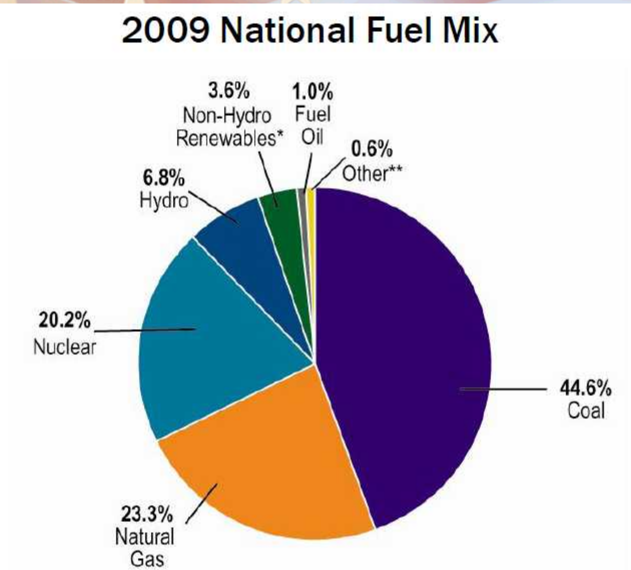
Source: Database of State Incentives for Renewables & Efficiency (accessed January 2010).

Forecasting: The U.S. electrical energy demand only increases

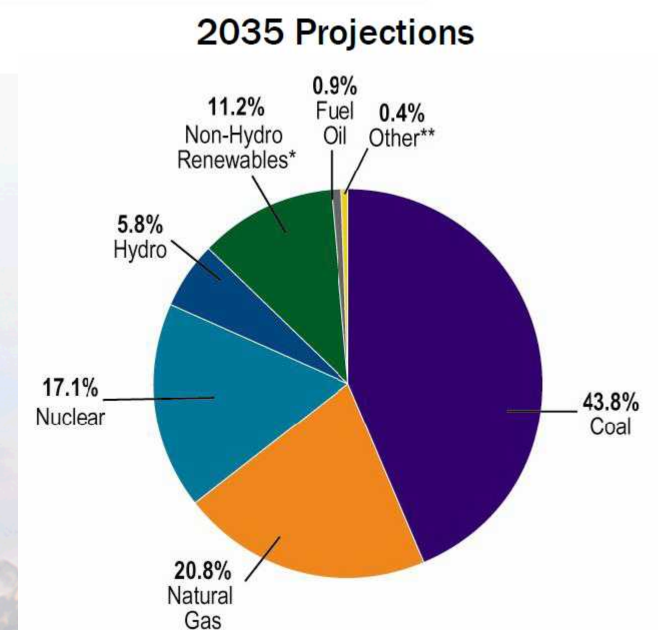


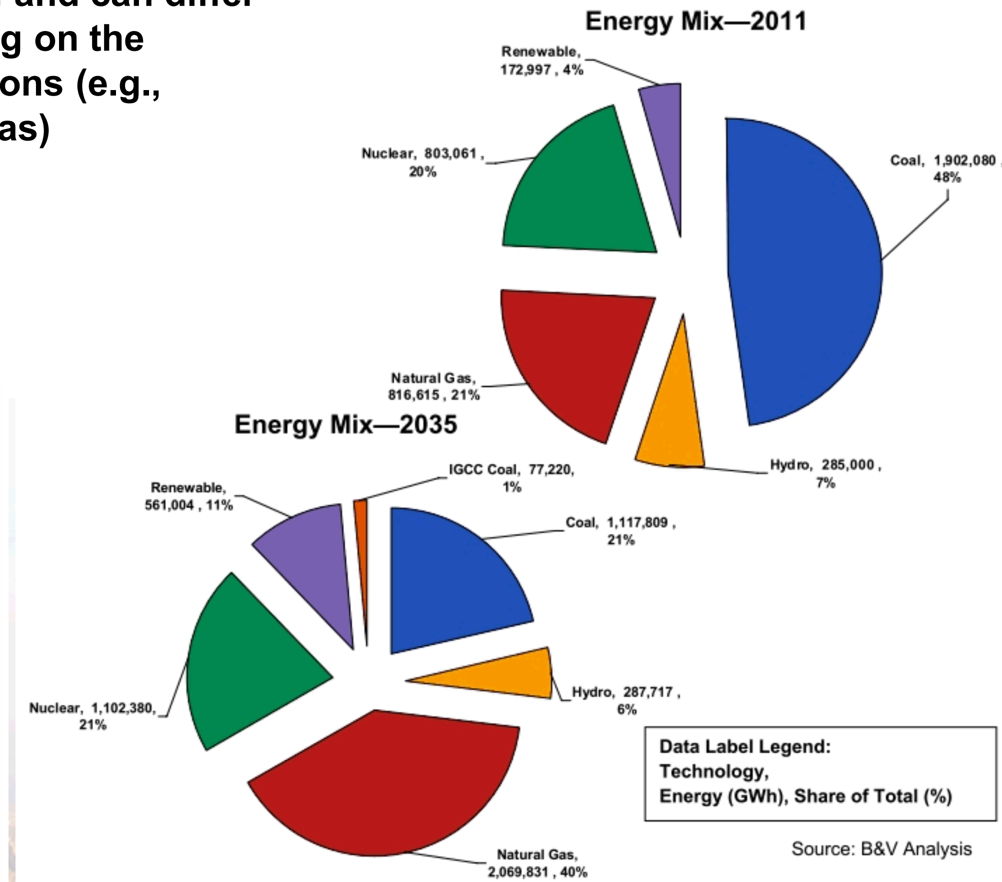
Source: DOE/EIA-0384(2004)

Electrical Energy Forecasts (IEA and B&V)

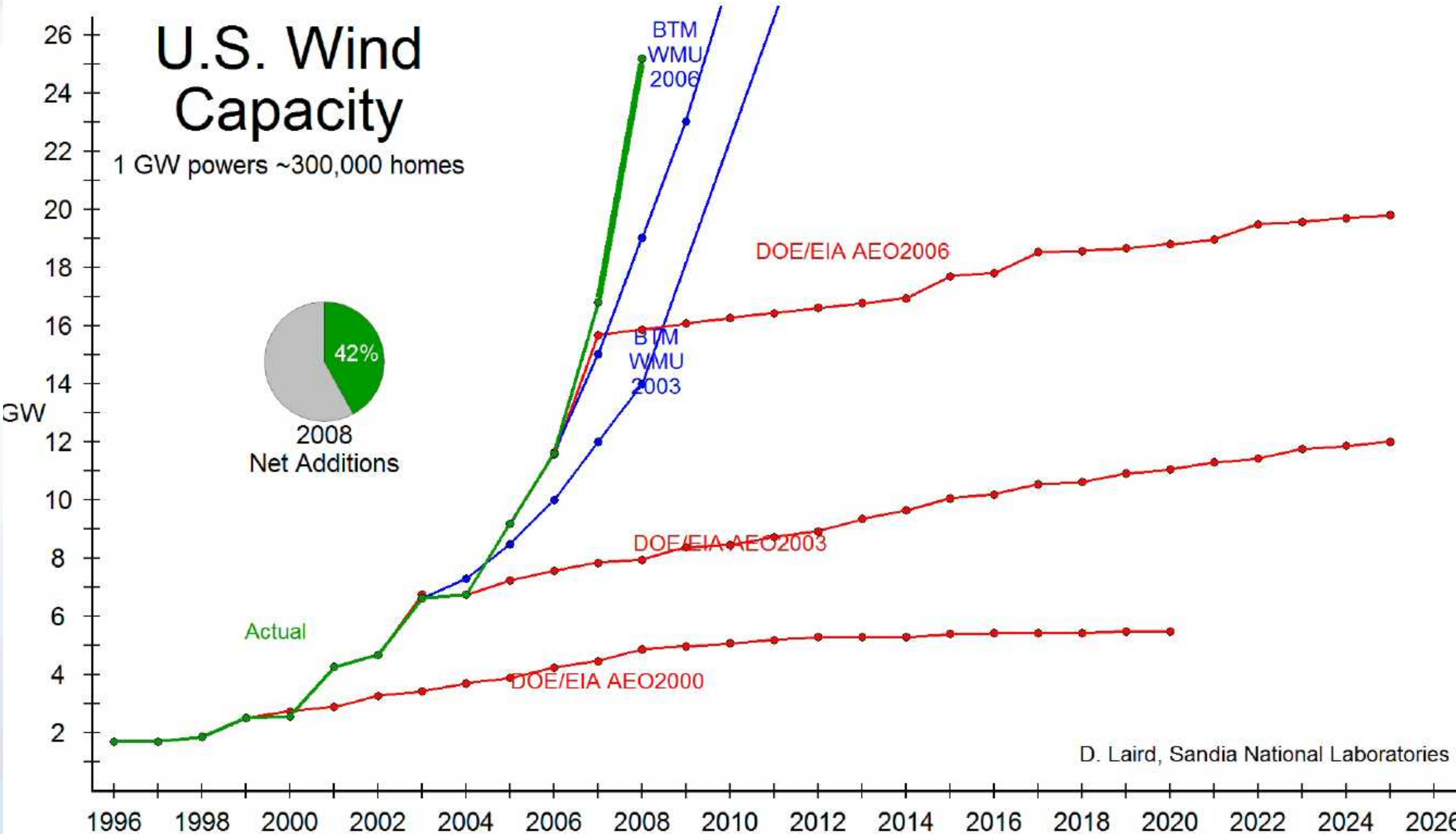


Forecasts are quite uncertain and can differ depending on the assumptions (e.g., Natural gas)





Growth Forecasts for Wind



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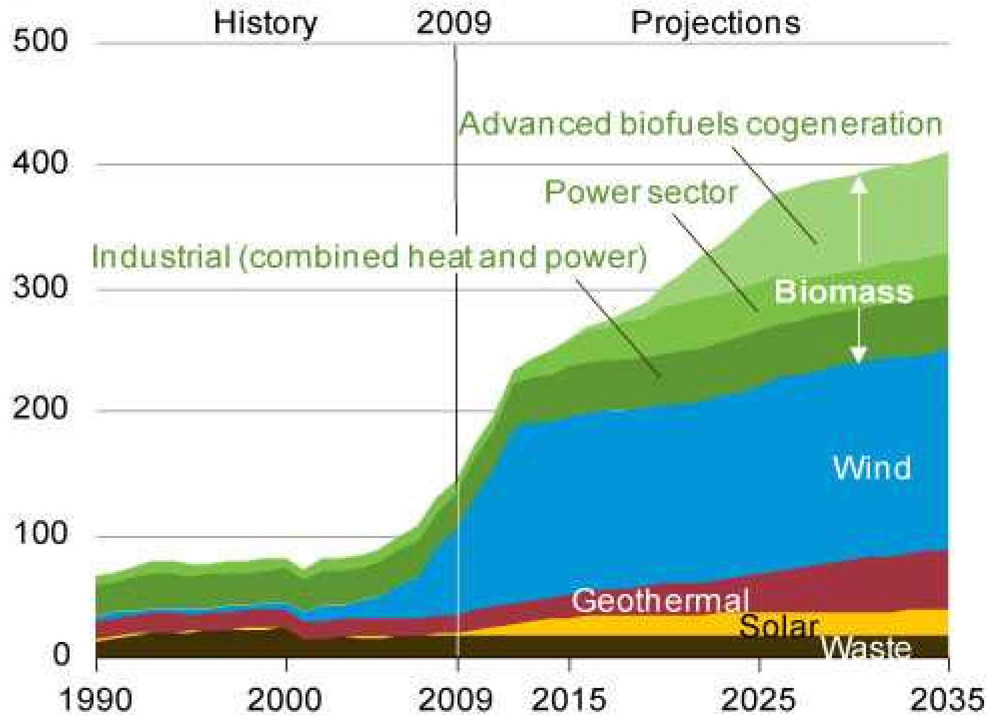
Projected Growth in Renewable Energy to 2035

- **EIA predicts that biomass and wind will increase the most**
- **These projections assume modest price reductions for solar**
- **DOE SunShot Initiative aims to reduce installed cost of solar to below $1/W (5-6 cents per kWh LCOE)**
  - This would be a major game changer of successful

Figure 3. U.S. nonhydropower renewable electricity generation, 1990-2035
(billion kilowatts per year)



Why is Renewable Energy Such a Minor Component of the Total Mix Going Forward?

- **First, natural gas is cheap (now)**
- **Answer depends on technology**
  - **Wind**: public opposition, transmission, and variability
  - **Solar**: price and variability
  - **Hydro**: environmental

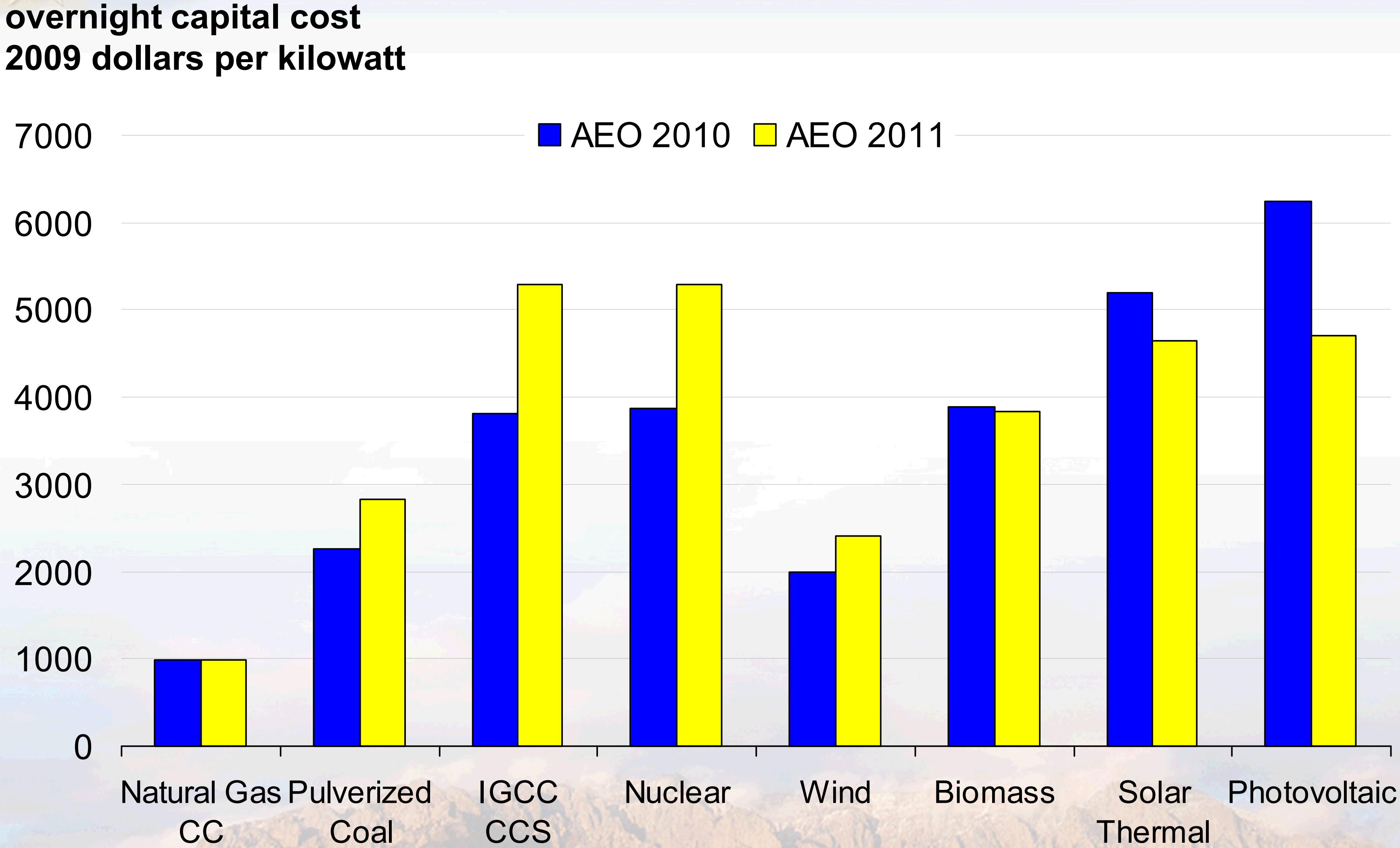
Table 1. Estimated Levelized Cost of New Generation Resources, 2016.

Plant Type	Capacity Factor (%)	U.S. Average Levelized Costs (2009 $/megawatthour) for Plants Entering Service in 2016				
		Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System Levelized Cost
Conventional Coal	85	65.3	3.9	24.3	1.2	94.8
Advanced Coal	85	74.6	7.9	25.7	1.2	109.4
Advanced Coal with CCS	85	92.7	9.2	33.1	1.2	136.2
Natural Gas-fired						
Conventional Combined Cycle	87	17.5	1.9	45.6	1.2	66.1
Advanced Combined Cycle	87	17.9	1.9	42.1	1.2	63.1
Advanced CC with CCS	87	34.6	3.9	49.6	1.2	89.3
Conventional Combustion Turbine	30	45.8	3.7	71.5	3.5	124.5
Advanced Combustion Turbine	30	31.6	5.5	62.9	3.5	103.5
Advanced Nuclear	90	90.1	11.1	11.7	1.0	113.9
Wind	34	83.9	9.6	0.0	3.5	97.0
Wind – Offshore	34	209.3	28.1	0.0	5.9	243.2
Solar PV[1]	25	194.6	12.1	0.0	4.0	210.7
Solar Thermal	18	259.4	46.6	0.0	5.8	311.8
Geothermal	92	79.3	11.9	9.5	1.0	101.7
Biomass	83	55.3	13.7	42.3	1.3	112.5
Hydro	52	74.5	3.8	6.3	1.9	86.4

[1] Costs are expressed in terms of net AC power available to the grid for the installed capacity.

Source: Energy Information Administration, Annual Energy Outlook 2011, December 2010, DOE/EIA-0383(2010)

Recent Price Trends for Generation Sources



Source: EIA, *Annual Energy Outlook 2011*

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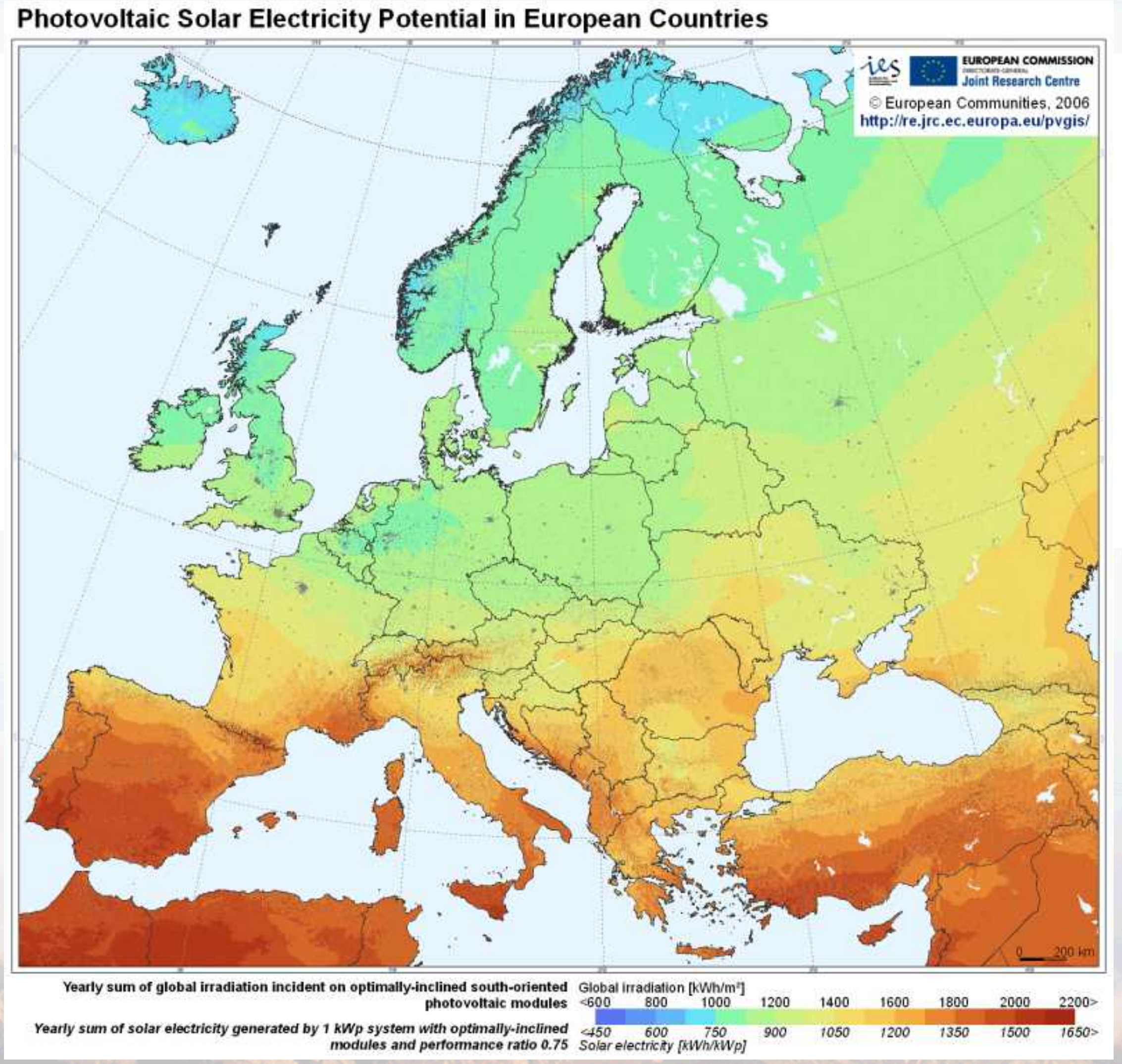
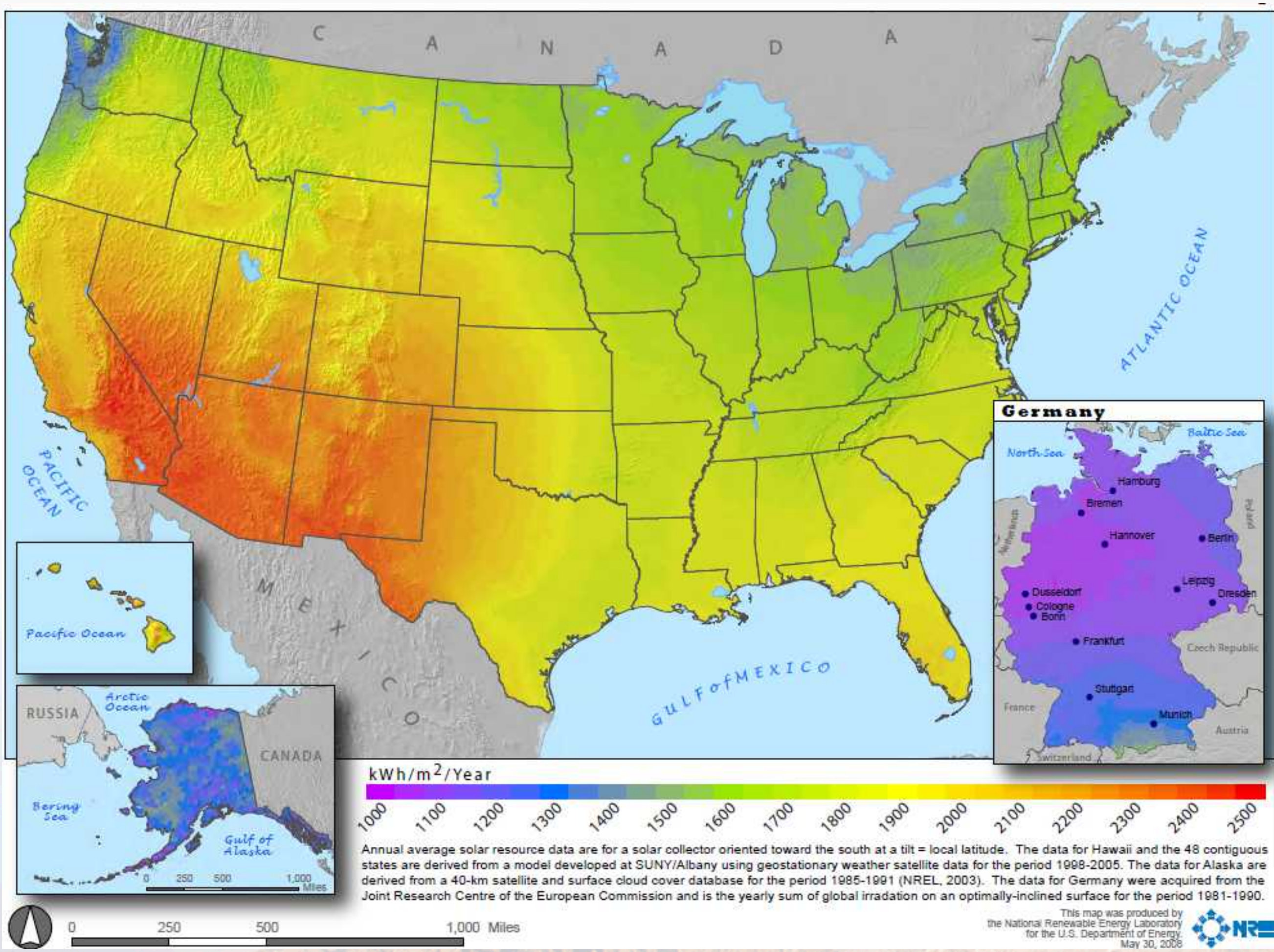
European Solar Experience

- Northern Europe is at a very high latitude
- Significant portion of Europe has solar resource lower than anywhere in the U.S.
- Vermont has a better solar resource than Germany!
- Germany is the world leader in solar power



U.S. Has Great Opportunities for Increased Solar Energy Applications



All of the electricity in the U.S. could be provided using:

- **Less than 2% of the land dedicated to cropland and grazing.**
- **Less than the current amount of land used for corn ethanol production.**

2009 PV Installs
Germany: 3.87GW
US: 485MW

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Germany Facts

- **Target: Renewable electricity 35% by 2020 and 80% by 2050**
- **Renewable energy has increased from 6.3% in 2000 to 17% in 2010**
- **Solar: as of 2010, Germany has 17 GW solar installed**
  - 7.4 GW (250,000 systems) installed in 2010 (U.S. installed 956 MW)
  - Market analysts predict this could reach 25% by 2050.
  - Growth driven by feed-in-tarif
    - July 2011: subsidies being cut
      - **Rooftop solar cut by 16%, Ground mount solar cut by 15%, Brown field PV cut by 11%, Large PV on arable land cut by 100% (eliminated)**
- **Wind: as of 2010, Germany has 27.2 GW wind capacity**
- **Electricity price = $0.31 /kWh (compared with $0.11 /kWh for U.S.)**
- **2010: Total RE = 101.7 TWh (36.5 TWh wind, 33.5 TWh biomass, 19.7 TWh hydro, and 12 TWhr solar PV)**
- **2009 study concluded that electricity rates increased 3%, utility profits reduced by 8%, PV market going to Asia**

Summary

- **Energy flows are measured in very large quantities**
  - Hard to measure accurately (need lots of information)
  - DOE has entire agency devoted to keeping track of this information
- **Energy flows need to be considered when making policy decisions**
  - CO_2 Emissions and pollution reduction policies
  - Regional differences are very significant
- **Renewable Energy Incentives**
- **Renewable Energy Forecasts**
- **Renewable Energy Costs**
- **Why so much Renewable Energy in Europe?**

- **Next… What is the renewable energy situation in Vermont?**

Questions and Discussion

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