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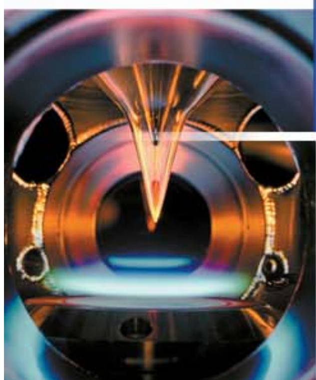
Moving Beyond a Fossil Fuel Dominated Electrical Grid:

Open and Transparent Policy Modeling Framework, A Critical Enabler

Fourth Annual Carnegie Mellon Conference on the Electricity Industry

FUTURE ENERGY SYSTEMS: EFFICIENCY, SECURITY, CONTROL

March 10th, 2008



Ellen B. Stechel

Energy Infrastructure Future Group

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Thank-you to the organizers for inviting me today and accommodating me off-schedule

- **External to SNL**
  - Ross Guttromson (PNL)
  - Bri-Mathias Hodge (Purdue student on-site at SNL)
  - Marija Ilic (CMU)
  - Lester Lave (CMU)
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  - Ken Hass (deceased)
  - Michael Kaericher (retired)
  - Irv Salmeen (retired)
  - John Sullivan (retired)
  - Debra Zemke (retired)

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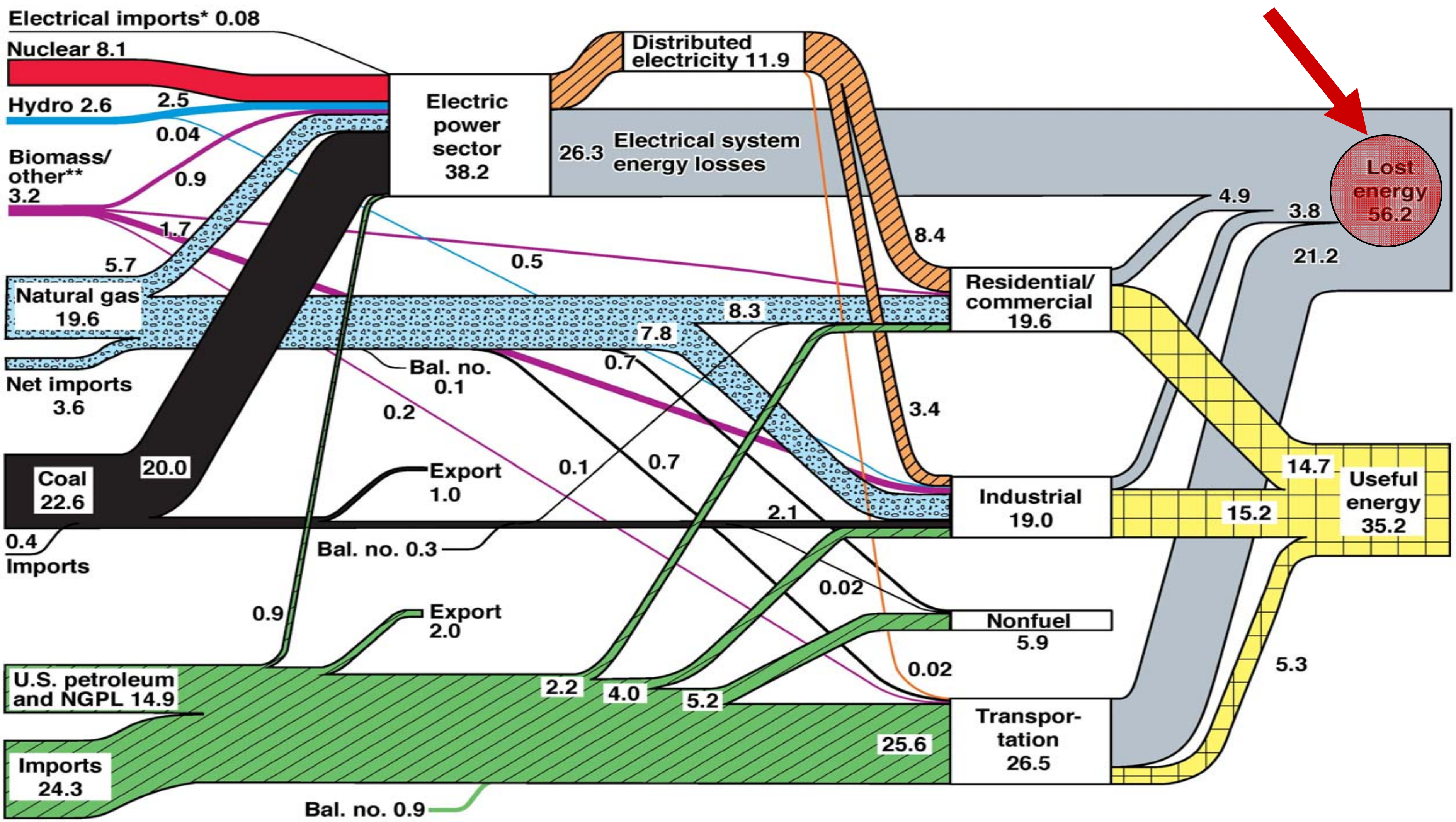
The U.S. Energy Flows

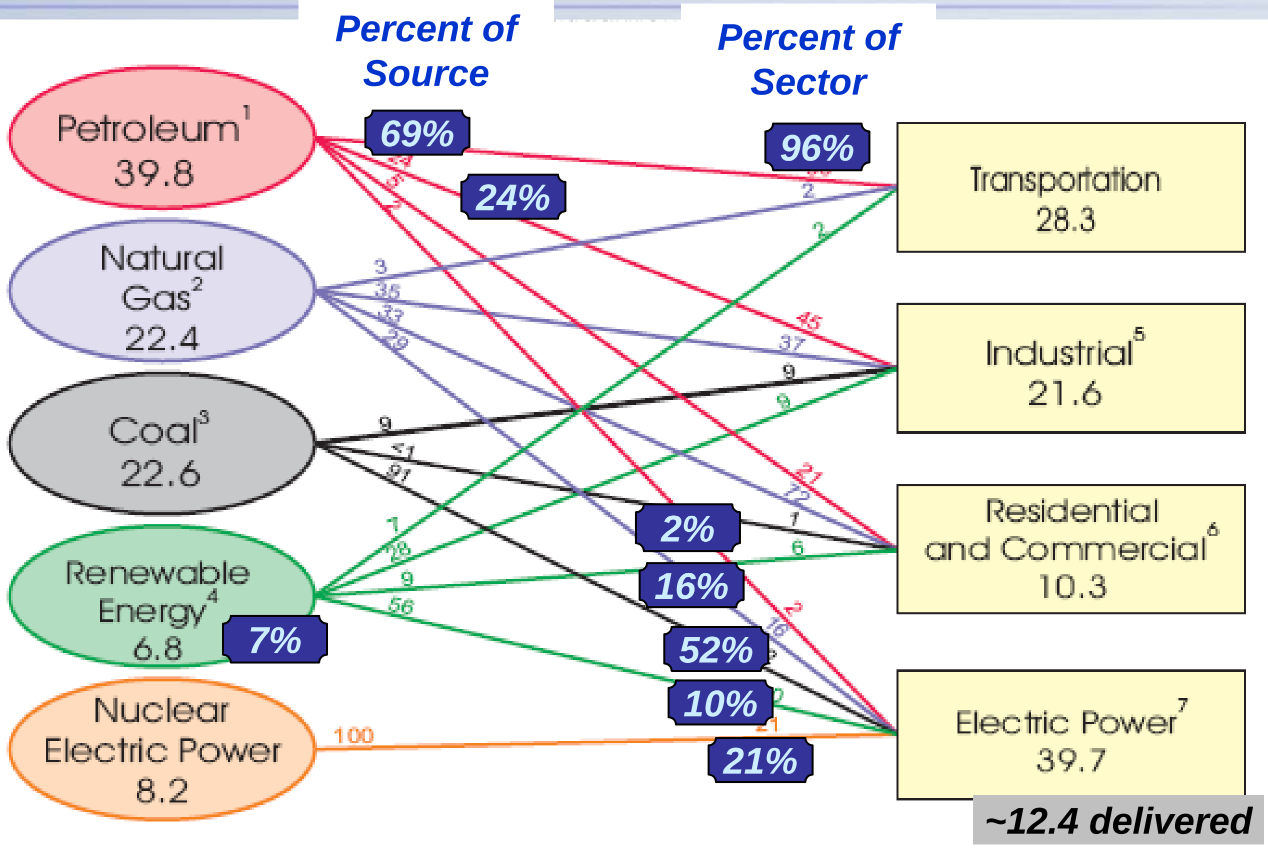


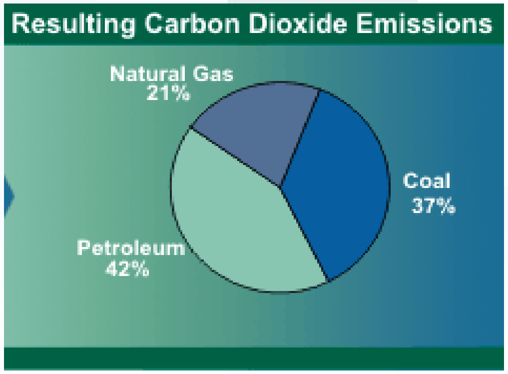
Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2002.*
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

June 2004
Lawrence Livermore
National Laboratory
http://eed.llnl.gov/flow

U.S Primary Energy Consumption Source and Sector, 2006

Not an Engineered System
Evolutionary Design
Dominated by Finite, Non-Sustainable Resources
Never has there been a forced transition; i.e., No precedent
Also no precedent for designing an engineered system of this complexity





99.8 Quadrillion BTU/Year ~ 3.3 TW
39.7 Quadrillion BTU/Year ~ 1.3 TW

http://www.eia.doe.gov/emeu/aer/pecss_diagram.html

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Unprecedented Transition

- **Not like a cold war race to send a man to the moon and back again safely**
  - **No new science – engineering feat**
- **Not the same as a Manhattan Project**
  - **Cannot be solved by a bunch of scientists in isolation and secrecy**
  - **Complexity was in the decision to drop it**
- **Neither the science nor business community <u>Knows</u> any <u>viable</u> way to <u>transition</u>**
  - **From a Fossil Energy-Based Energy System,**
    - **which is well recognized as unsustainable and vulnerable,**
  - **To a different energy system**
    - **One that would be <u>Sustainable, Robust, and Resilient</u>.**
- **The nature of the problem characterized by scale may not be unprecedented**
  - **But when characterized by <u>scale, complexity, importance, and urgency</u> is almost certainly is unprecedented.**

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Multitude of Concerns arising from the Fossil Fuel dominated energy system

- *National Security*
- *Energy Security*
- *Competition for Finite Resources*
- *Climate Change*
- *Economic Competitiveness & Economic Shocks*
- *Growing Trade Imbalance*
- *Price Escalation and Price Volatility in Strategic Resources*
- *…….*

Solution to one should not compound issues for another, address all or at least not exacerbate any

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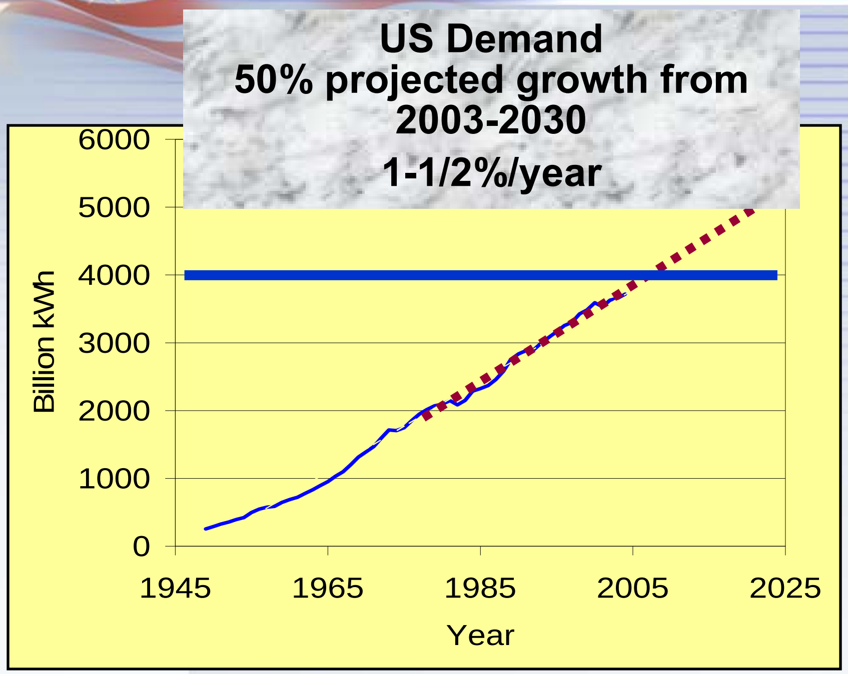
Punch-line

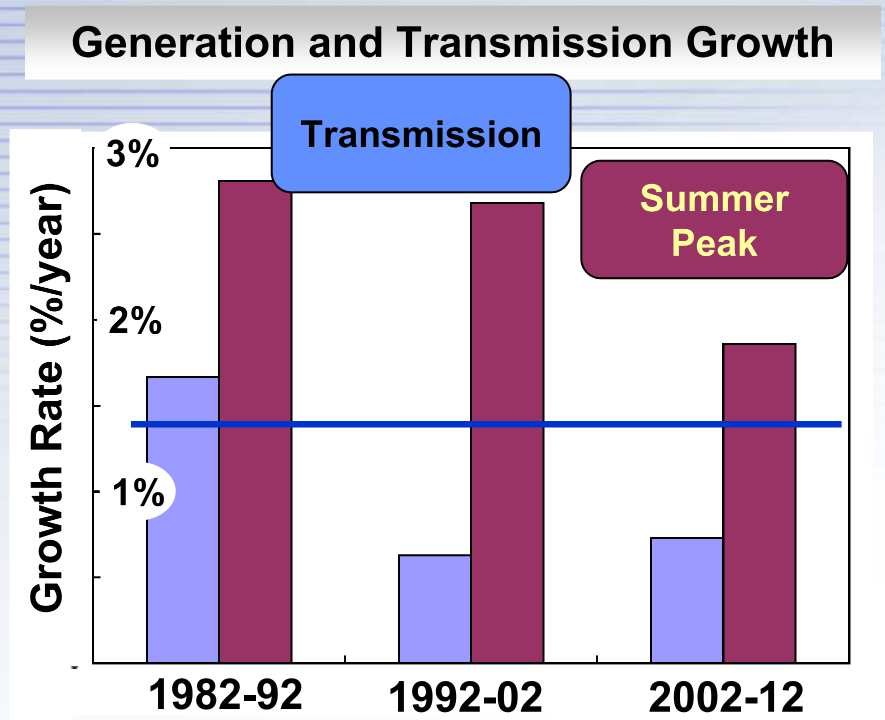
- What we Need: Sustained Commitment
- 1000 flowers blooming (best and most creative minds) but within one coordinated community framework (for coherence)
  - Full creativity of Bottom-up and clarity of direction of Top-down at the same time
  - Develop a Community-based Open and Transparent Policy Modeling Framework
- Mechanisms to guide the system with Appropriate policies
  - Help immature but viable technologies walk down the learning curve
- Consistent policies that do not lock-out alternative solutions prematurely or that have conflicting objectives
- Reinvigorate our nation’s excitement in Math, Quantitative Sciences, and Engineering Disciplines,
- Set an Apollo-like Race to the Moon-type Strategy and deliberately (guided self-assembly) move beyond the fossil age
- Science, Technology, Engineering, and Good Policy Decision-Making through Partnering and Innovation,
- Should Strengthen the Economy and Excite the Next Generation

Electricity Demand Will Increase Substantially Through 2030



1000 Billion kWh/yr ~ 114 GW~0.1 TW
2030 projects to ~618 GW (~5400B kWh)

In the face of increasing needs for power quality and power conditioning



2002-2012 ~6% increase in transmission is planned

Transmission Limited & Vulnerable
Load Leveling (narrow the Peak to Average load) could help

Source: DOE/EIA-0384 (2004) Sam Baldwin, DOE

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Challenges for the Electric Utility Industry

- **Aging Infrastructure**
- **Maintain (improve) reliability and security**
  - In the face of increasing regulator and customer demands
  - 36 major power outages occurred during the years 1997–2007
- **Expand the system to meet new demand**
  - Challenges for Transmission Siting
- **Reduce emissions (CO_2, SO_x, NO_x, Hg, ..)**
  - Driving Regulatory Uncertainty
- **Manage the cost**
  - Financial pressures
  - Price volatility

Electricity Demand has variable requirements?

- Value is created from electrically powered devices that deliver
  - Lighting
  - Comfort
  - Convenience
  - Security
  - Connectivity, access
  - Means for economic production
  - Enhanced quality of life

Value for the service and price for the service not really linked

- The "levelized" price per kWh depends on the energy conversion technology
  - different externalities,
  - different investment risks,
  - different timescales for construction,
  - none well-accounted for in the business models of today
    - or priced into the delivered cost
- The real cost incurred from outages also varies depending on where the power goes
  - But it can be quite large

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U.S. Electrical Grid Architecture

Currently:

- Grid designed for one way flow
- Designed around large-scale centralized power plants
- Distribution system designed with only loads in mind
- Not designed to handle intermittent generation on the distribution side

In the Future:

- Grid will need two way electrical and information flow (utility and customer/supplier)
- Accommodate
  - storage on generation and load side
  - intermittent, central and distributed generation
  - Net-metering and congestion pricing
- Enable micro-grid operations and Islanding

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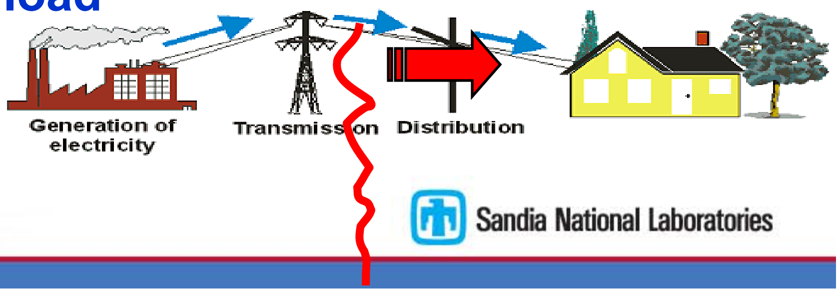
Why Micro-grids?

- What's the drivers
  - Increased Energy Reliability & Security
  - Meeting the growing electrical demand despite limitations on growth in Transmission Capacity
- Can also deliver major benefits (not particularly easy to quantify)
  - Shorter lead times, less financial risk, less regulatory risk
  - Less Siting Issues
  - Reduced Levelized Cost of delivered electricity
  - Reduced Variability in Cost
  - Energy Efficiency – more opportunities for cogeneration and other synergies
    - About as much heat is lost from centralized generation as is re-generated locally
    - About as much drinking water is consumed as would be the output of from a fuel cell generating the electric demand
  - Reduced Emissions
  - Revenues - Net Metering (Sell energy back to the grid)
  - Reduced variability from peak to average load
  - Service Differentiation
  - Power System Optimization
  - Renewables Integration



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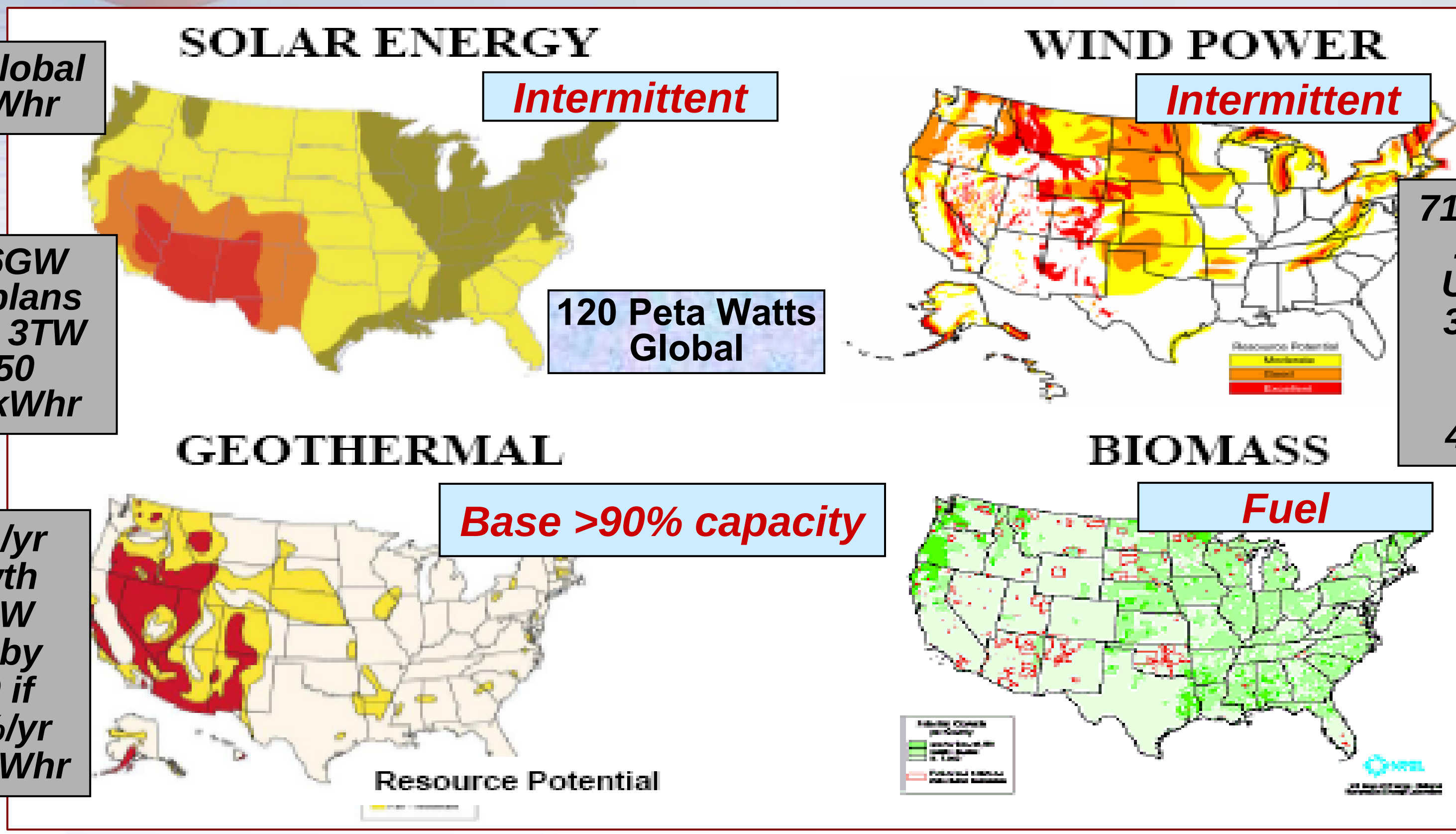
Renewable Energy Sources – No Lack of Resources, So what's the problem?

Geographic Diversity

PV 7GW Global 13-32¢/kWhr

CSP 4.6GW Global plans 16.8%/yr 3TW in 2050 12-15¢/kWhr

4½% /yr growth 2.8GW 1TW by 2050 if 11½%/yr 5-9 ¢/kWhr



71GW Global 14¼%/yr US growth 3.3TW US by 2050 4-6¢/kWhr

"Stranded" resources not necessarily close to major loads?

Renewable Transmission Lines? Or Make Fuel? Or Both?

Fuel: Stored Energy that can easily be used whenever and wherever

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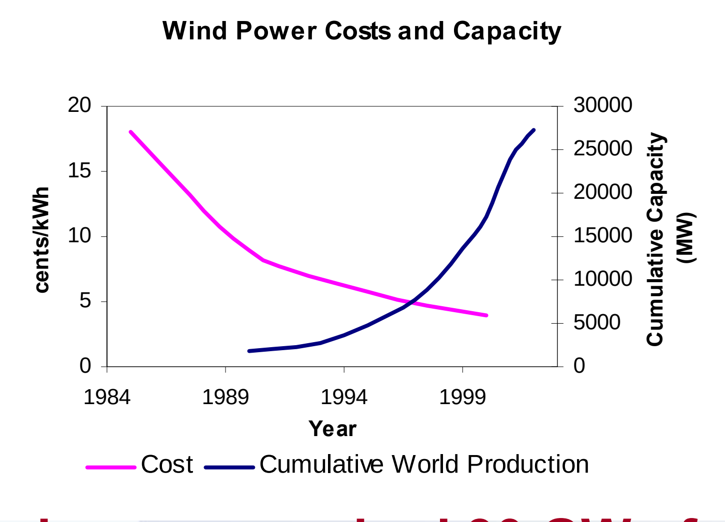
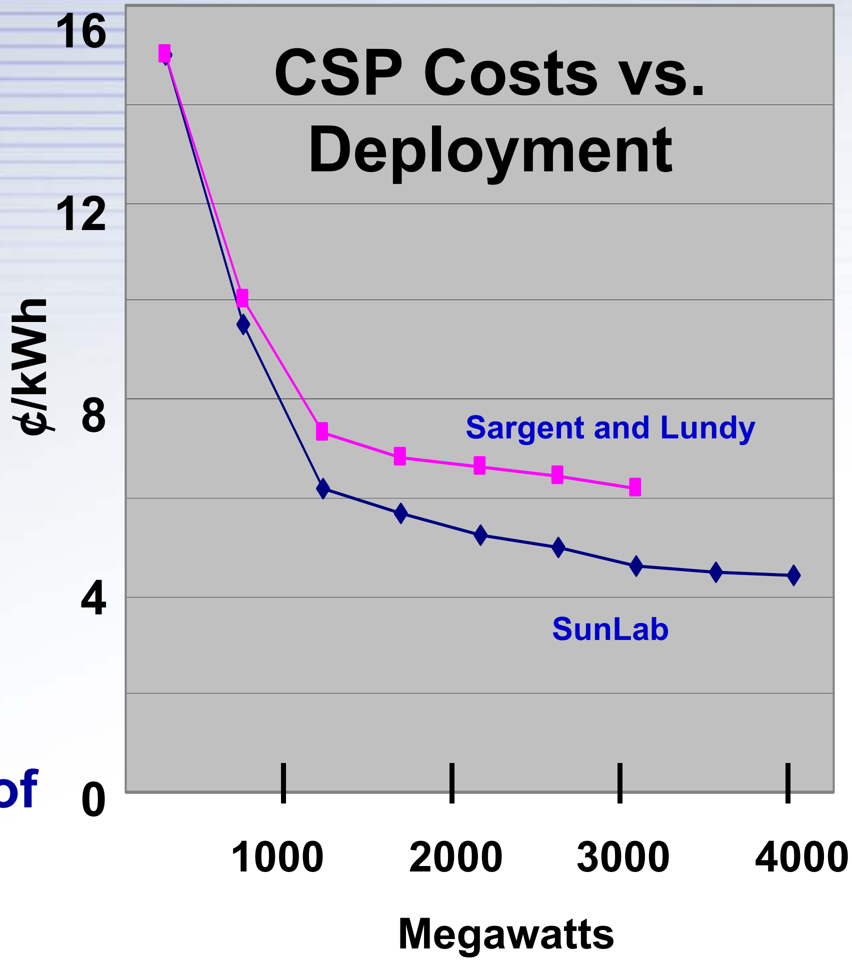
Learning: CSP Costs Will Decline with Deployment





- Wind power required 30 GW of deployment to reach ~ 5 ¢/kWhr
- CSP may require only ~3 GW of deployment to reach this level.
- Should not underestimate the value of learning and scale-up
  - But as a community are not good at properly accounting for it in our models

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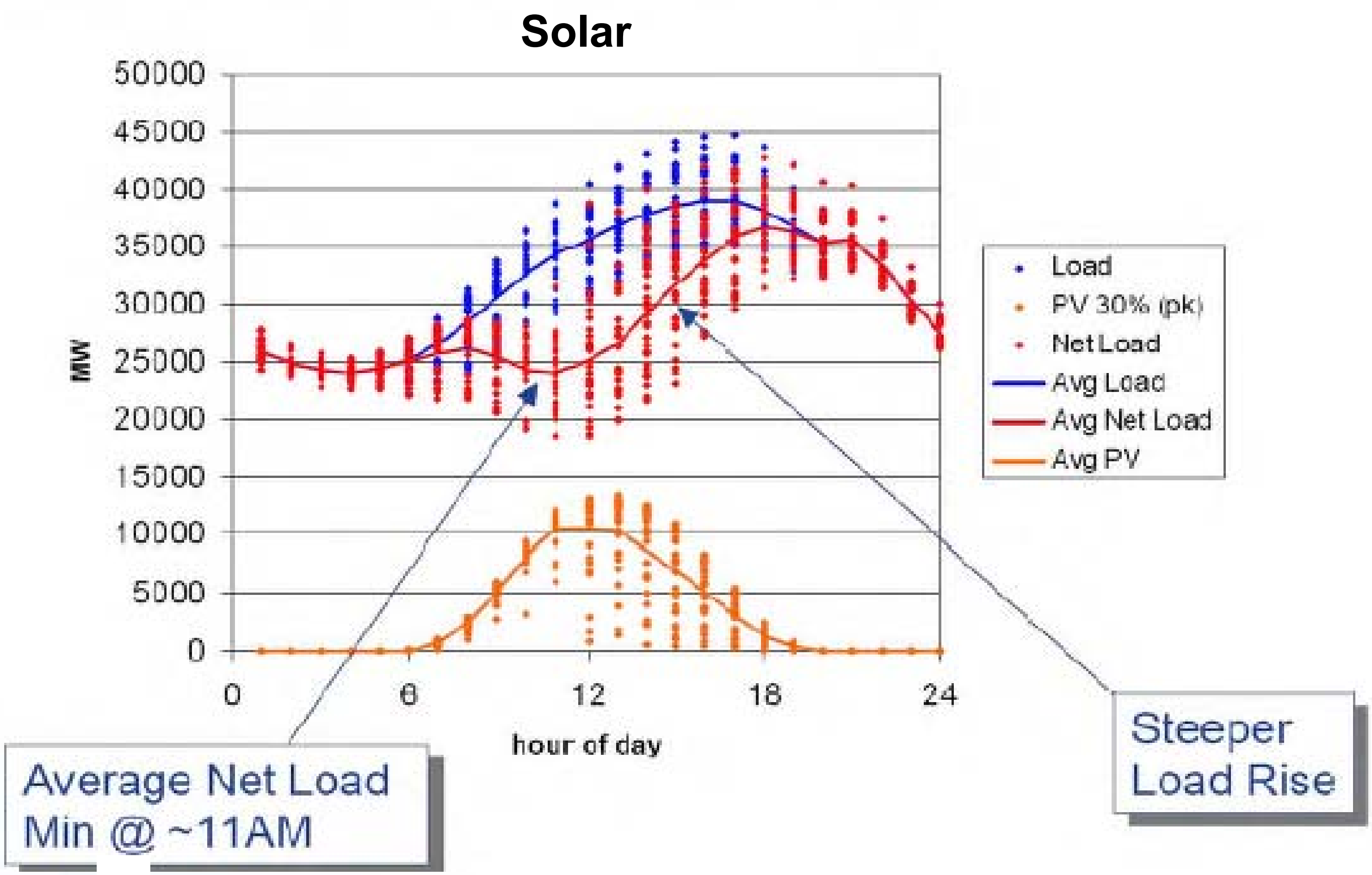
Solar Energy Doesn't Quite Match Typical Load Profiles



Source: GE

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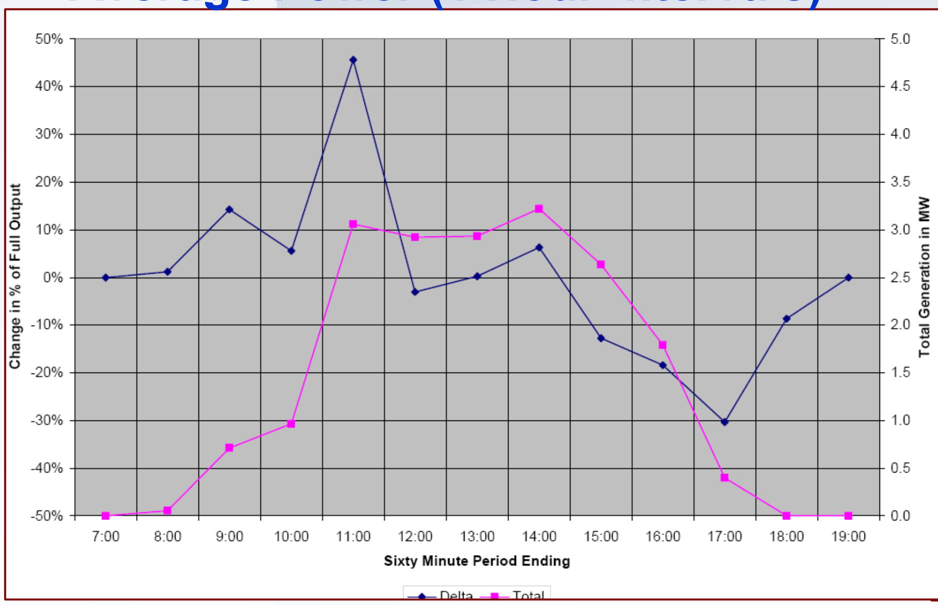
Solar Intermittency

Tucson Electric Power 4.5MW PV Plant

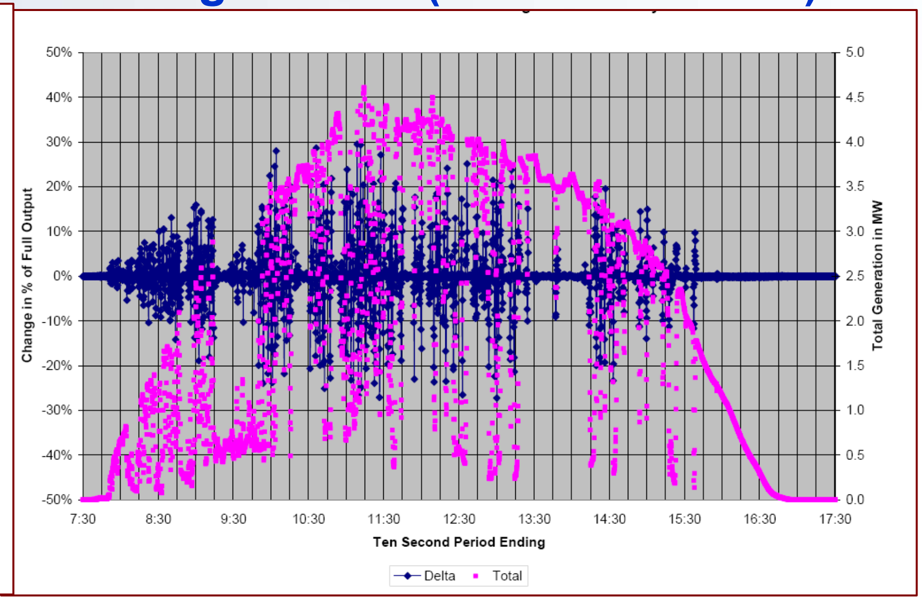
Blue: Delta

Pink: Total

Average Power (1 Hour Intervals)



Average Power (10 Sec Intervals)



Source: Tom Hansen, Tucson Electric Power

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Solar and Photovoltaics are <u>NOT</u> synonymous
What about Concentrating Solar Power?

<u>C</u>oncentrating <u>S</u>olar <u>P</u>ower or CSP:

Solar concentration allows tailored design approaches for central and distributed power and heat generation, thermal storage, <u>and</u> solar fuels production (with development.)

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Major Challenges With Widespread Adoption of Renewable Energies

- **Cost**
  - **Not necessarily an issue for the near future,**
    - **although major advances needed to continue adoption and reach a desired target ~$0.02 / KWhr**
- **Intermittency**
  - **→ Major issue, and will require fundamental new approaches to grid management and storage**
- **Geographic Diversity**
  - **Transmission constraints**
  - **→ Significant issue, but regional optimization coupled with storage perhaps in the form of liquid fuels or hydrogen could provide some solutions**
- **Infrastructure Evolution**
  - **→ Major issue, and solutions should take maximum advantage of 100 years of infrastructure investments**

Are RPS (Renewable Portfolio Standards) the answer to transition to large scale renewable energy generation; will it drive breakthroughs in storage or more spinning reserves?

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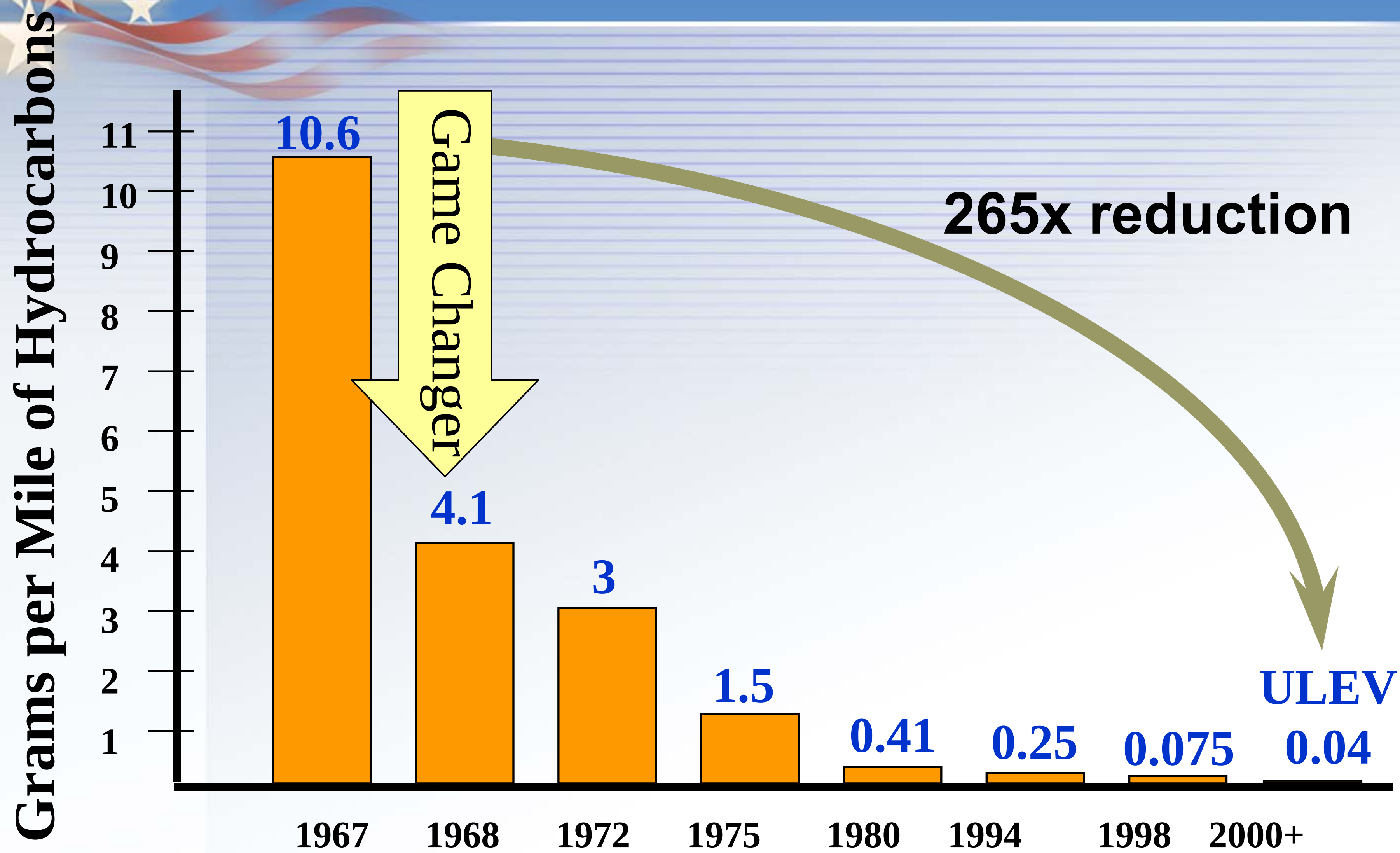
Renewable Portfolio Standards

- Renewable energy can help solve multiple problems:
  - increasing and volatile fossil fuel prices,
  - energy supply shortages and disruptions,
  - a growing dependence on natural gas,
  - a need for more domestic energy supplies, and
  - harmful air pollution.
- A national renewable energy standard for electricity, also called a Renewable Portfolio Standard (RPS), can
  - diversify our energy supply with clean, domestic resources.
  - help stabilize electricity prices through competition,
  - reduce natural gas prices,
  - reduce emissions of carbon dioxide and other harmful air pollutants,
  - create jobs—especially in rural areas—and
  - bring new income to farmers and ranchers.
- The RPS seems to be a market-based mechanism
  - requires utilities to gradually increase the portion of electricity produced from renewable resources such as wind, biomass, geothermal, and solar energy.
- Policy decisions, only indirectly connected to the goal, geerally lead to unintended consequences – shifting the burden.

There have been Reasonably Successful Policies

- Tailpipe emissions standards
  - Fairly transparent to the consumer
  - Little impact on the buying decision or driving patterns
    - No attempt to accelerate replacement of older vehicles with cleaner vehicles
  - Drove development of electronic feedback controls, adaptive learning, and after-treatment technology
  - More or less level playing field
  - New product segments (winners, no obvious losers)
- Oxone Depletion – CFC's phase-out
  - Same company produced the replacement product; No losers
- SOx Trading - efficient
- Leaded to Unleaded; Diesel to Low Sulfur Diesel
- Hallmarks of Successful Policy
  - Does not significantly transfer wealth
  - Reduces uncertainty and volatility
  - Does not constrain out better solutions or technologies
  - Self-correcting – avoids lock-in of adverse unintended consequences
- Seems to be more an art than a science: How can we know?

History of Tailpipe Emissions



SULEV II & PZEV are 10mg/mile NMOG

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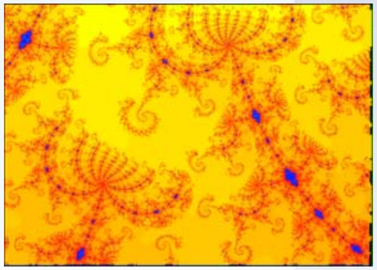
There are also been some on-going Policy debates

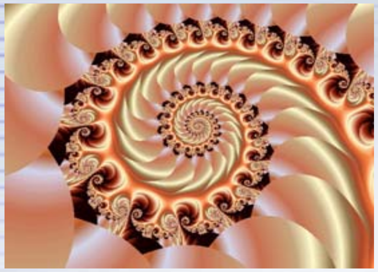
- **Issues**
  - CAFÉ standards vs. Trading Credits vs. Fuel Tax
    - Studies show Fuel Tax most effective and CAFÉ least
  - Day Light Savings
    - Does not save energy
  - Recycling percentages
    - Can impede material substitutions that would reduce the amount of material going to landfill
      - 1600 kG at 90% recycled → 160 kG not-recycled
      - 800 kG at 85% recycled → 120 kG not-recycled
  - Ethanol Standard
    - Depending on how the ethanol is made – it may or may not reduce petroleum usage
  - Carbon Cap & Trade vs. Carbon Tax (in debate)

In general policy analysis and debate are stymied by:

- Low resolution models
- Non-comparable models
- “Blackbox” models”
- Incomplete models
- Unexposed assumptions
- Proprietary models
- Cost of doing the modeling
- Lack of Data
- Pessimistic on mature technologies, optimistic on immature technologies (or reverse)
- Rarely account for system adaptation or feedback
- Usually modeled as discrete events or continuous flows – rarely both
- Cannot capture the essential complexity

Complexity Frontier





- Requires Balanced Perspective

Reductionist	↔	Holistic
Linear	↔	Nonlinear
Equilibrium	↔	Non-equilibrium
Mechanical	↔	Organic, Evolutionary
Predictable	↔	Contingent, Emergent
Optimizable	↔	Robust, Adaptive, Strategic
Centralized	↔	Distributed, Self-Organized
Quantitative	↔	Qualitative, Patterns
Simple Laws	↔	Complex Behaviors

- Dominance of worldview on left (in science, engineering, and business) impedes understanding of complex systems, complex adaptive systems, and system of systems

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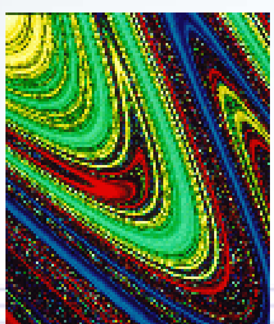
Complex Systems Have the following characteristics:

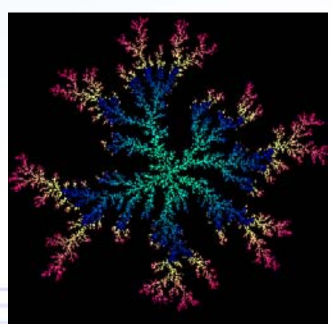
- Multiple interactions between many components
- Nonlinear Relationships
- Experimental domain is large
- Underlying model is generally unknown
- No analytic formula for the response surface, maybe patterns are what matters
- Whole ≠ sum of parts (behavior derived from interactions – defies simplification)

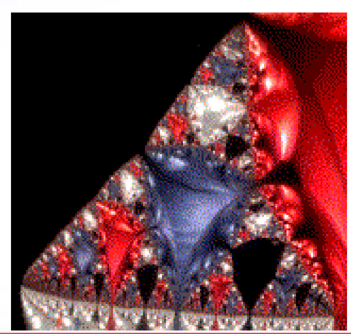
Ordered —— **“Complex”** (“Edge of Chaos”) —— **Chaotic** →

Increasing randomness

Deterministic







Statistical

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Complex Adaptive Systems (CAS)

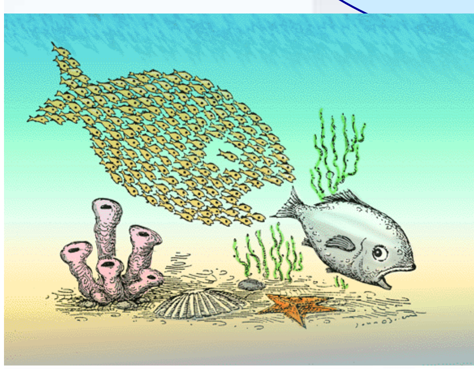
- Individual components ("agents") change their rules based on experience

Alien concept in physics and engineering, but central in biology and social sciences

Agents adapt to environment

Co-evolution

Adaptation changes environment



No Central Controller!
Autonomy + Connectivity!
Self-Organizing

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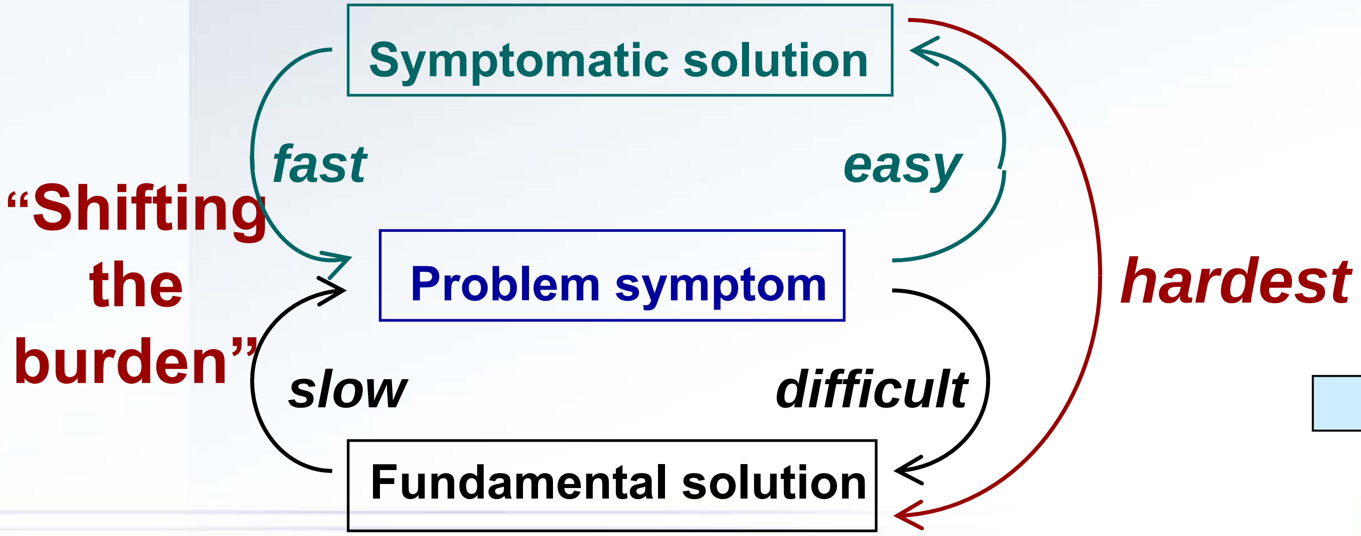
Complex Systems Dynamics

- Conventional forecasting, planning, and analysis methods are not equipped to deal with dynamic complexity (cause and effect are distant in time and/or space)
  - Every influence is both Cause and Effect.
- Today's problems come from yesterday's "solutions”
  - “We cannot solve problems by using the same kind of thinking we used when we created them.”
- Leverage points in a system --where the smallest efforts can make the biggest differences, but the areas of highest leverage are often the least obvious
  - Systems thinking is a discipline for seeing the "structures" that underlie complex situations, and for discerning high from low leverage points.



Peter Senge

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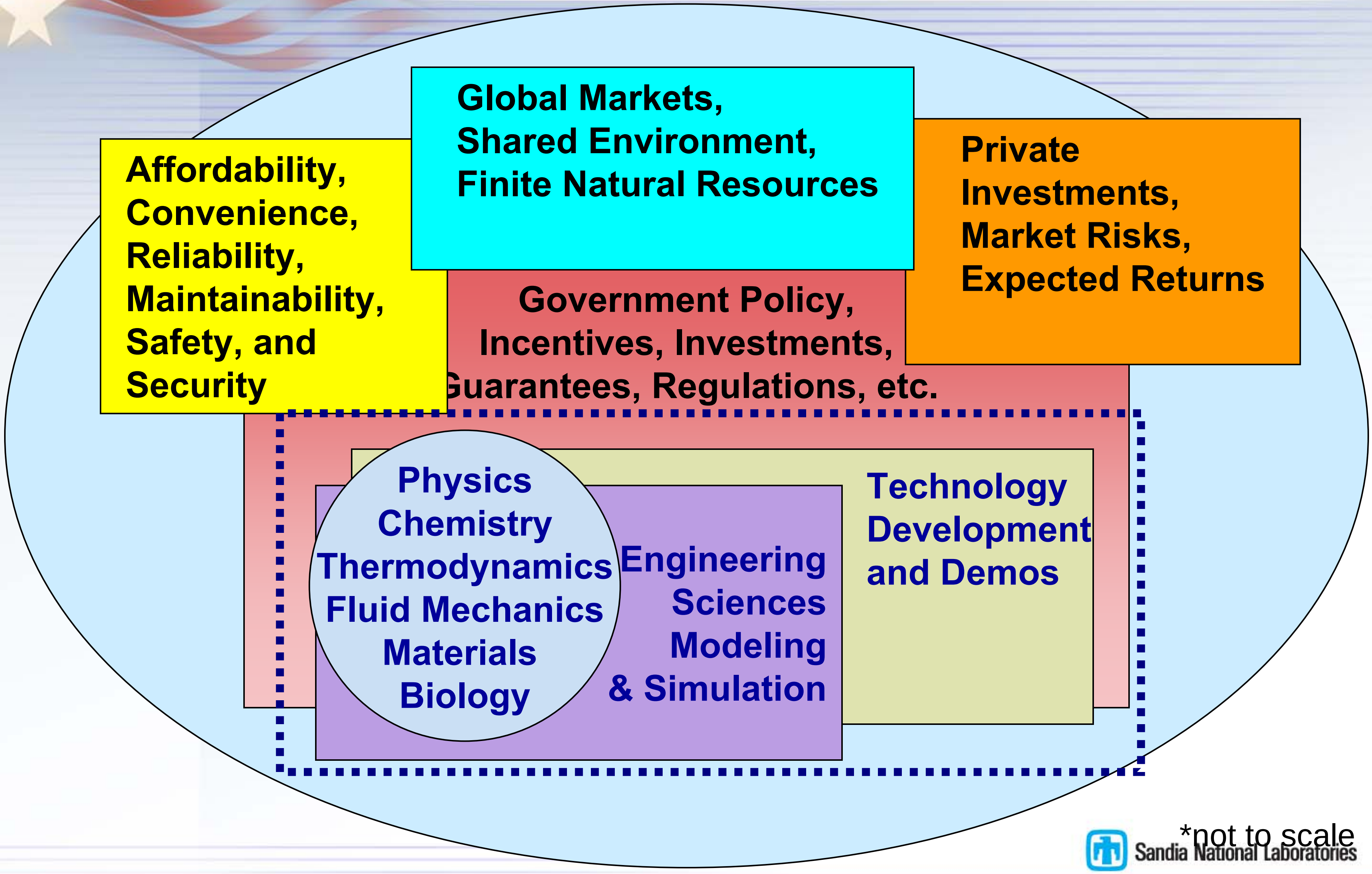
System of Systems Typically Exhibit the Behaviors of Complex Adaptive Systems

- Operational Independence of Elements
- Managerial Independence of Elements
- Evolutionary Development
- Geographical Distribution
- Multi and Inter-disciplinary
- Heterogeneity of Systems
- System of Networks
- Emergent Behavior

System of Systems Science is an emerging discipline

See for example: Carlock, P.G., and R.E. Fenton. "System-of-Systems (SoS) Enterprise Systems for Information-Intensive Organizations," Systems Engineering, Vol. 4, No. 4 (2001), pp. 242-261.

Multi perspectives to capture in the Systems Framework Well outside the Normal "Comfort Zone"



*not to scale

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Multi-scales – generally temporal and spatial:

Challenging but Key to Scalability

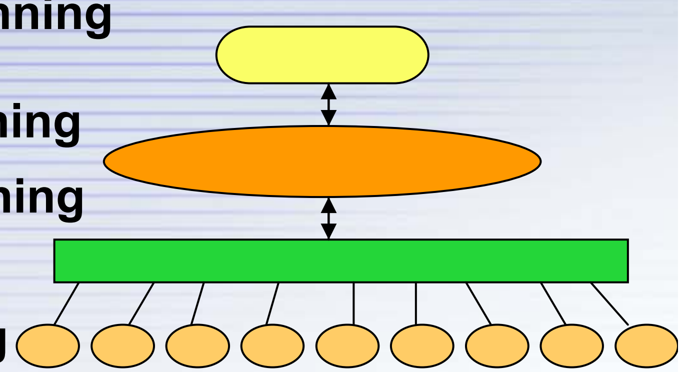
Long Term Planning

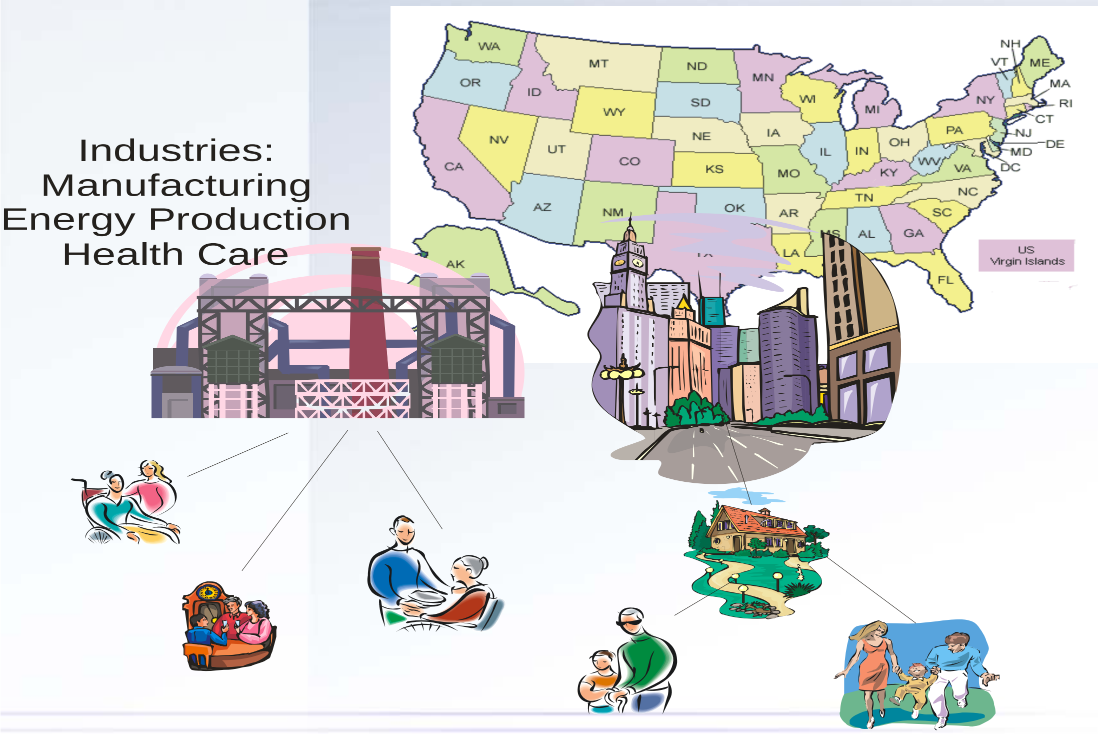
Annual Planning

Monthly Planning

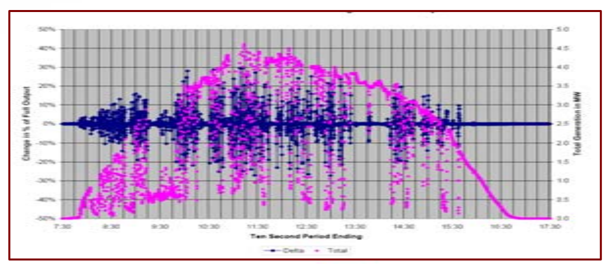
Daily Planning

Hourly Planning





- **Due to the size of the system there are different levels of granularity that are required to accurately represent the entities within the system**



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Believability, Uncertainty, and Validation

- Decision makers need to trust the model.
  - Uncertainties must be measured, calculated, and propagated through the model.
  - Believable codes cannot rely on "fudge factors" and non-transparent "knobs".
  - All assumptions need to be transparently exposed
- Believable, transparent descriptive/predictive capabilities simply do not currently exist in the policy arena.
  - Complexity of interactions limited
  - Inability to measure uncertainties
  - Mostly expert based – "trust me I know what I am talking about"
  - Trust but Verify very limited
- But Is it feasible to validate contingent and emergent behaviors starting from primitive inputs?

Building a Community of Practice across the full range of stakeholders

- Wikipedia Style with Strict Quality Control
- Open and Transparent
- Free Licensing (freely accessible)
- Modular
- Common “Language”
- Careful management of Data sources
  - Acquiring data
  - Redistributing data
  - Repurposing data
  - Credentialing data
  - Archiving data
- User Friendly (low barrier for participation)
  - Developers (novice to masters)
  - Users (novice to masters)

Community-based Open and Transparent Policy Modeling Framework

Strategy

- Multi-scale model, capable of modeling at household, neighborhood, city, state, regional, and national scales from microseconds to years
- High degree of transparency in model and information
  - Well developed taxonomies for both information and modules
- Open and free access
- Community effort
  - Wikipedia style with strict quality control
- Major thrusts in validation and quantification of uncertainties and sensitivities
  - Exposing known unknowns
- Major efforts to expose
  - What we think we know that isn't so
  - What we don't know that we don't know
- Scalable, agent-based and dynamic simulation modeling approaches for execution on platforms from PC to high performance computing platforms
- Phased implementation
  - Early, testable modules – not "all or nothing" after many years.

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Punch-line & Summary

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- Reinvigorate our nation's excitement in Math, Quantitative Sciences, and Engineering Disciplines,
- Set an Apollo-like Race to the Moon-type Strategy and deliberately (guided self-assembly) move beyond the fossil age
- Science, Technology, Engineering, and Good Policy Decision-Making through Partnering and Innovation,
- Should Strengthen the Economy and Excite the Next Generation

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Thank-you for your Attention

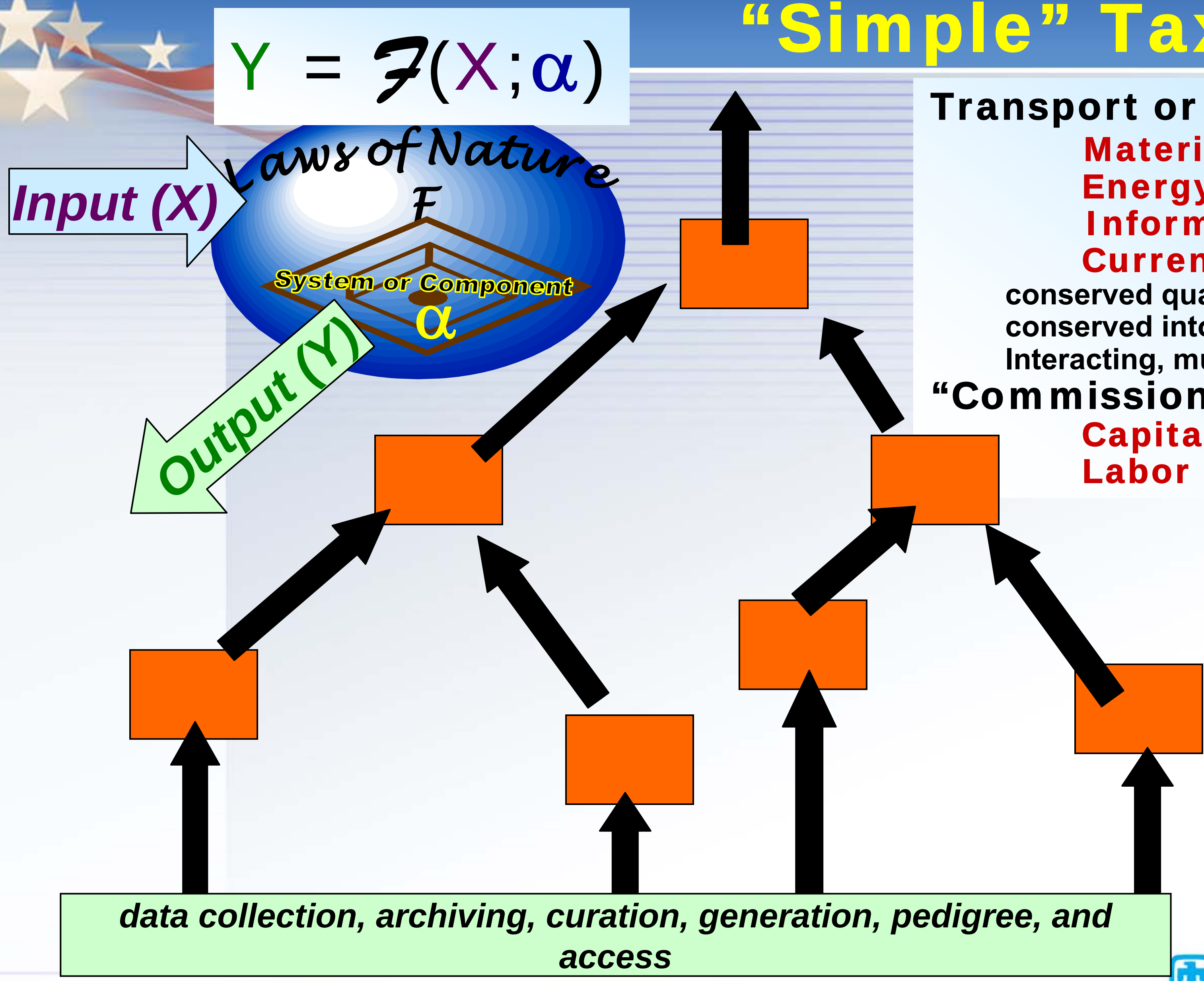
Questions

Backup Slides

Reality Check: Change Agents

Dimensions	Respond to Climate Change & Energy Security Drivers	Community Based Policy Modeling Framework
SHOULD we CHANGE		
Risk from BAU	HIGH	HIGH
Consequence of BAU	HIGH	HIGH
SHOULD we CHANGE NOW		
Urgent	MEDIUM or UNCERTAIN	NOT OBVIOUS
Important	HIGH	NOT OBVIOUS
CAN we MAKE the CHANGE		
Practical	HARD	HARD
Impact	HIGH	HIGH but NOT OBVIOUS
WILL we MAKE the CHANGE		
Recognized Imperative to Act	HIGH – tipping point likely past in 2007	LIKELY LOW
Will to Act	MAYBE	LOW

Modular, Networked, Adaptive, "Simple" Taxonomy



Transport or Transform

- **Materials**
- **Energy**
- **Information**
- **Currency**

conserved quantities (but not conserved into function)

Interacting, multiple network flows

"Commission" Resources

- **Capital**
- **Labor**

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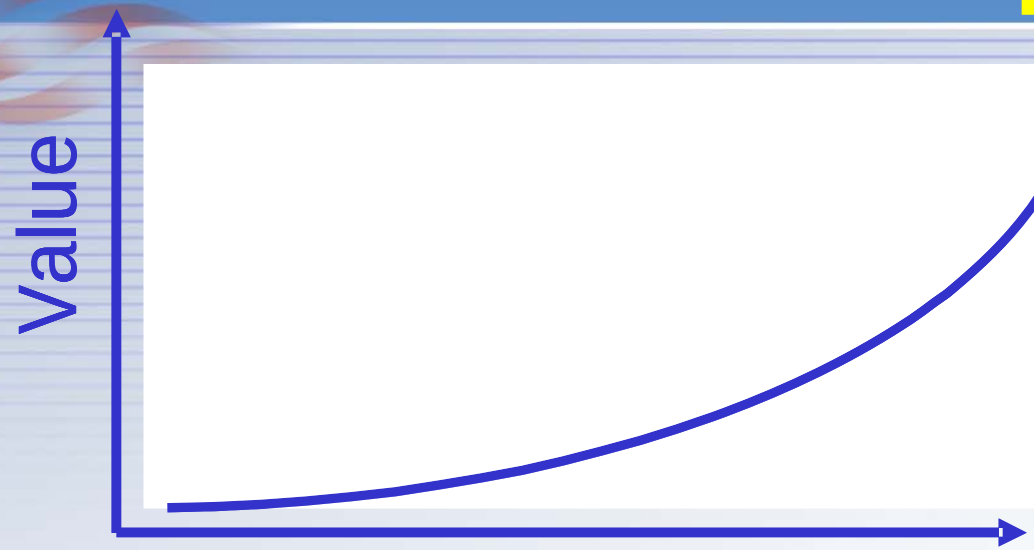
Information Transforms into Decisions



Data Information Knowledge Decision Action

Relationships Patterns Commitment of Resources

Decision: Commitment to Expend Resources and to take Action
Strategy: Set of Decisions to achieve a goal
Want: Robust Decisions and
Strategies to evolve the system to resiliency

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Energy Challenge - Harvest, Transform, and Control Delivery of Available Energy

Energy & Material Resources

Limited Fossil (coal, oil, gas)

Solar (and derivative wind and hydro)

Geothermal

Nuclear (small-scale)

Plant, animal and human waste

CO_2 & other energy conversion byproducts

Energy Processing

Harvest, transform, and deliver exergy* at the necessary amount and rate.

Primary Energy Needs or Services

Electricity

Fuel

Space Heat

Hot Water

Cooling

Clean Water

*EXERGY = AVAILABLE ENERGY = useful portion of energy that allows one to do work and perform energy services

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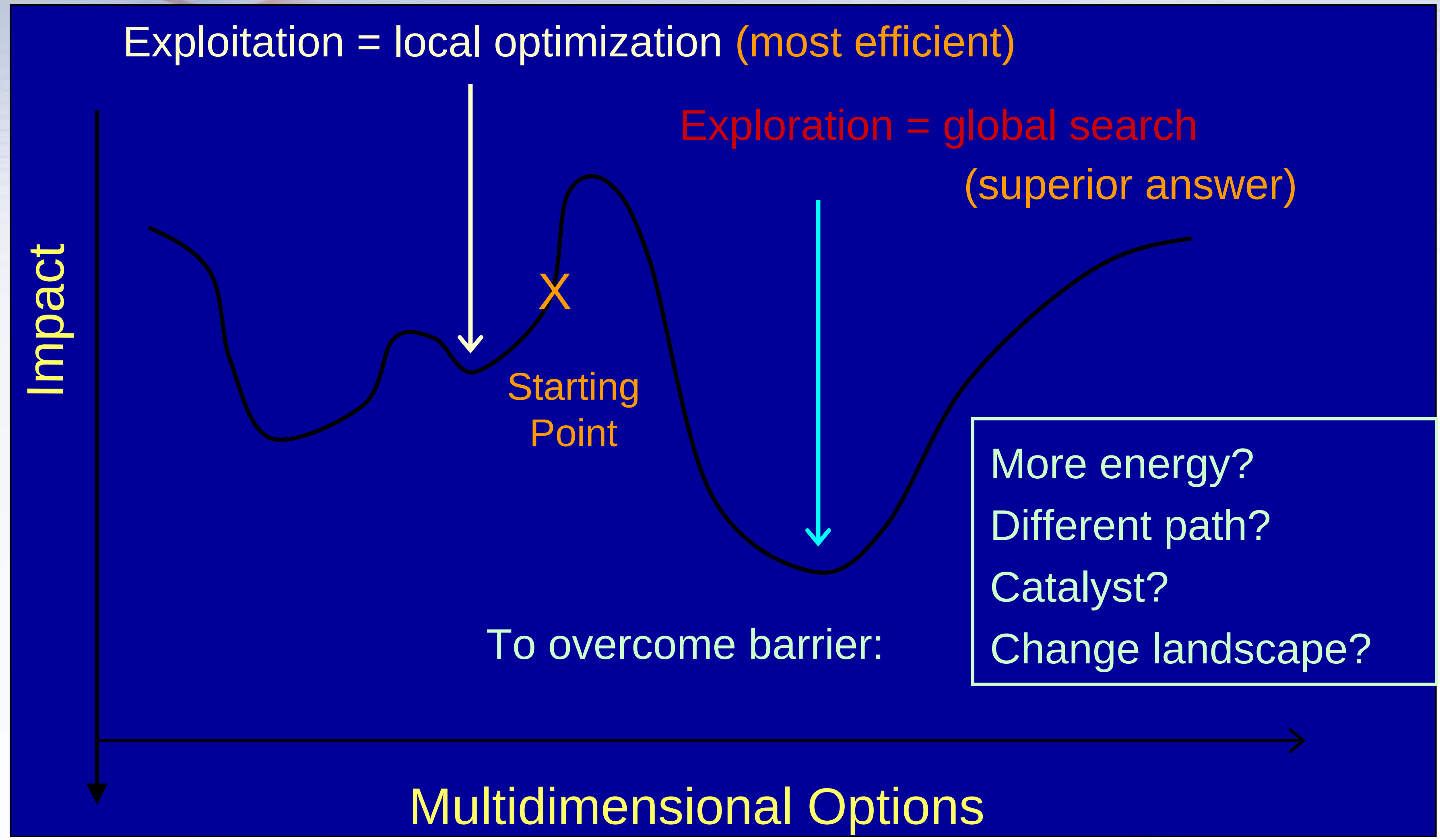
Landscape Metaphor



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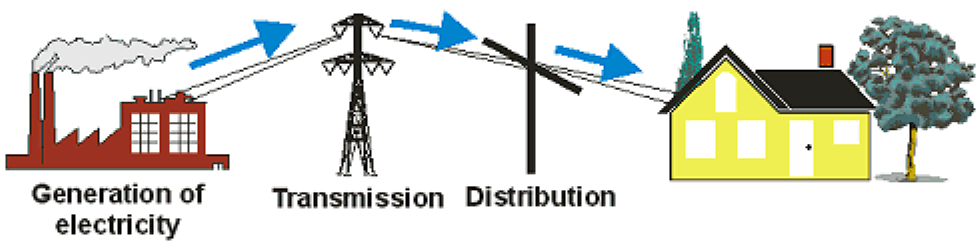
Increasing Generation from Micro-grids?

- An integrated energy system that consists of
  - Interconnected loads and distributed energy resources
  - Can operate in parallel with the grid or in an intentional "island" mode
    - Independent controls
    - Can island and reconnect with minimal to no service disruption
- Contrast
  - Distributed Generation
    - A single fuel cell, diesel generator, or micro-turbine in a building
- Centralized



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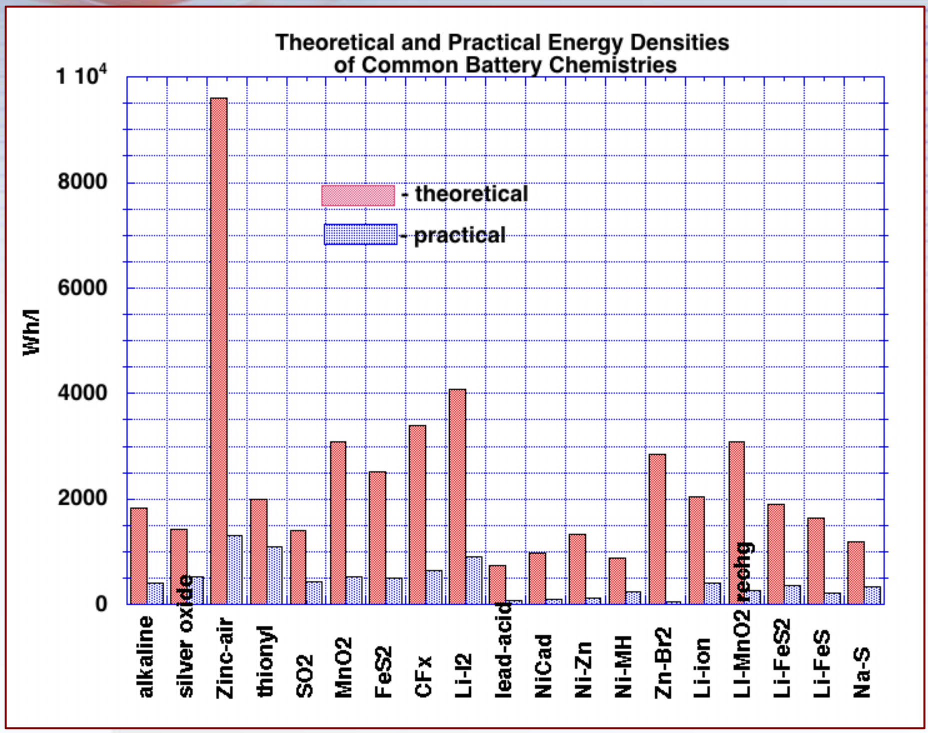
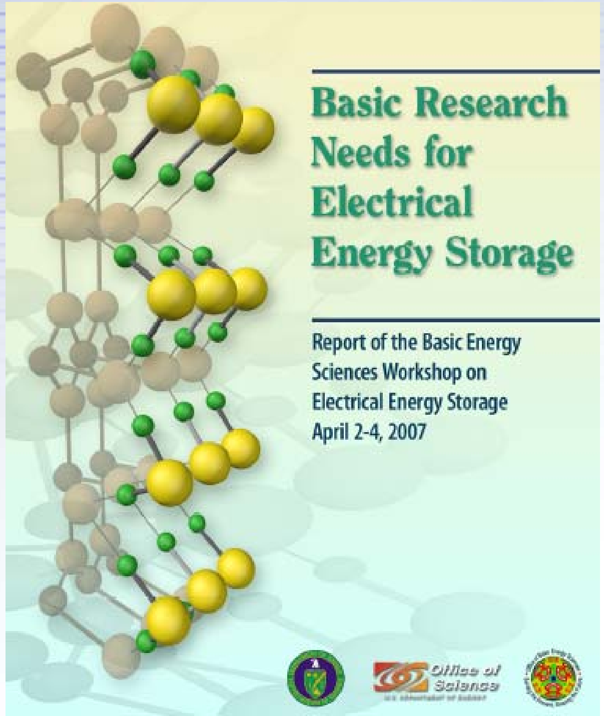
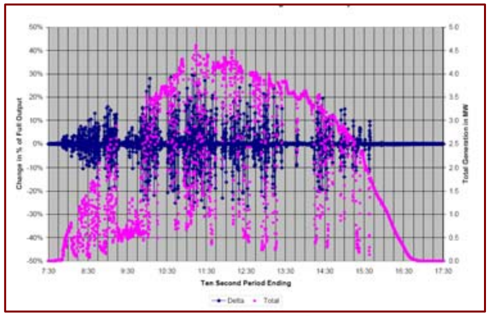
Advances in Energy Storage Needed for Widespread Adoption of Photovoltaics





- Cost
- Power and Energy Density
- Lifetime
- Faster Charge-Discharge Times
- Safe and Reliable Operation through 1000-10,000 Rapid Charge-Discharge Cycles



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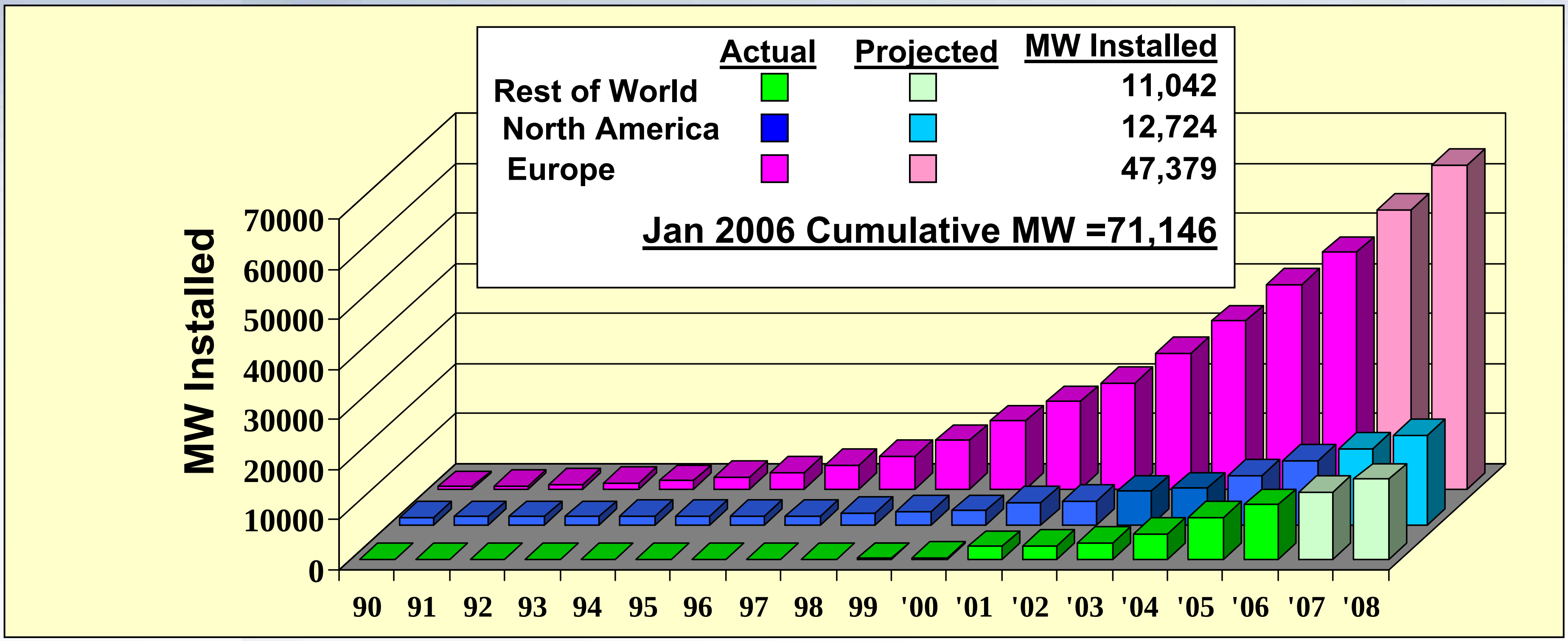
Wind Power Markets



Year End 2006 Cumulative MW* **US = 9149**

14¼% US Growth Rate: ~ 3.3TW installed by 2050, 1 TW net generation at 31% capacity
Estimated Potential is ~4TW installed

Source: American Wind Energy Association

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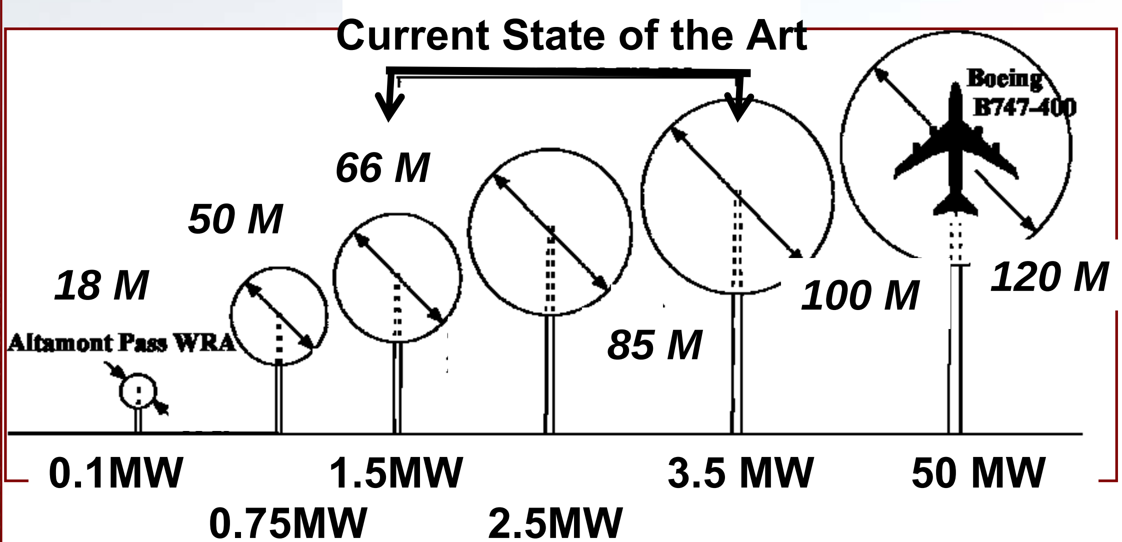
Wind Power Costs are Competitive with Fossil Generation

- **Costs:**
  - System < $3/lb
  - Blades < $5/lb
  - ~ $1.00/Watt installed
  - $0.04-0.06/kWh



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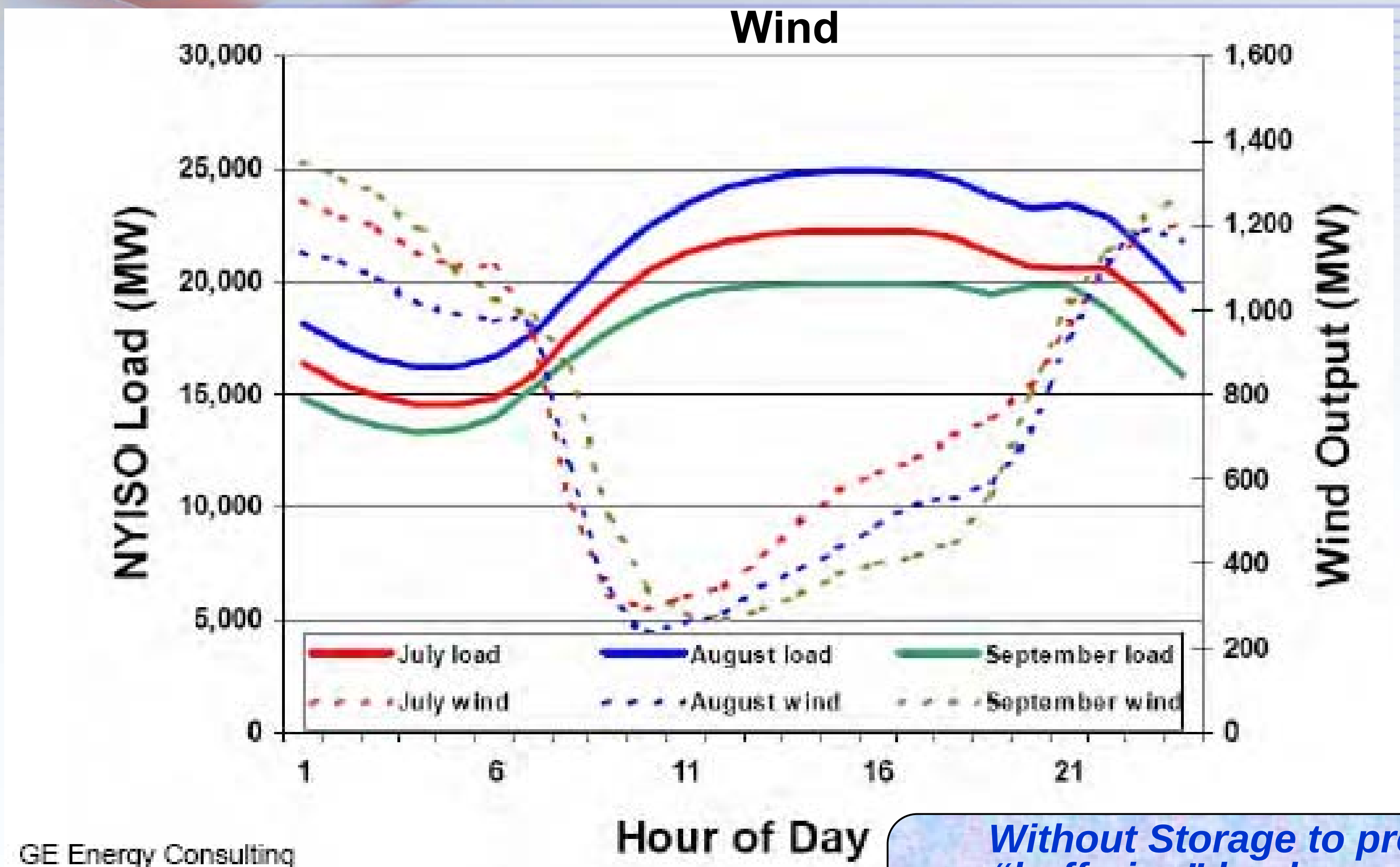
Wind Energy Profile Doesn't Match Typical Load Profiles



Without Storage to provide a "buffering" load – we have a constraint violation

Generation ≠ Load

Source: GE

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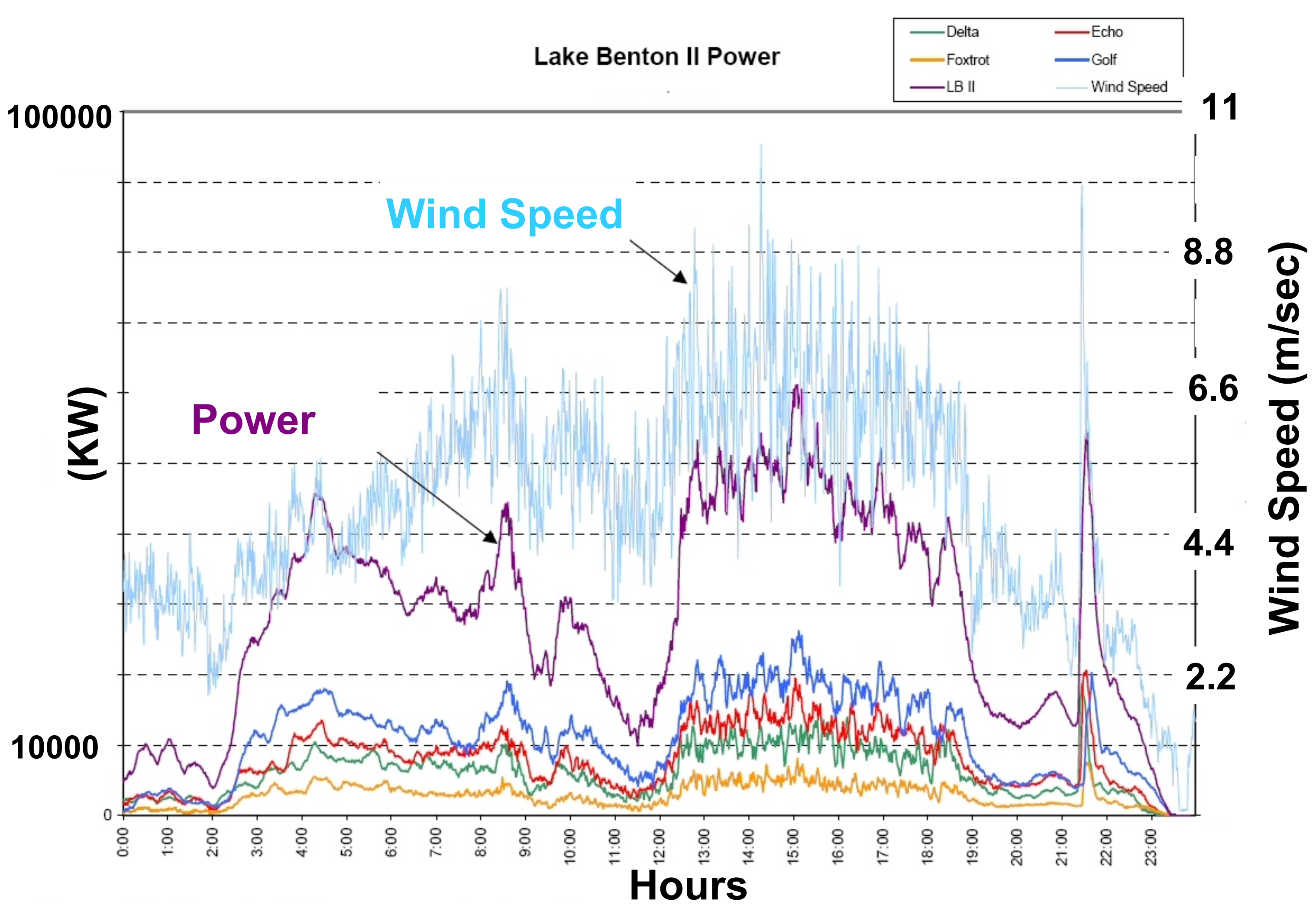
Wind Intermittency



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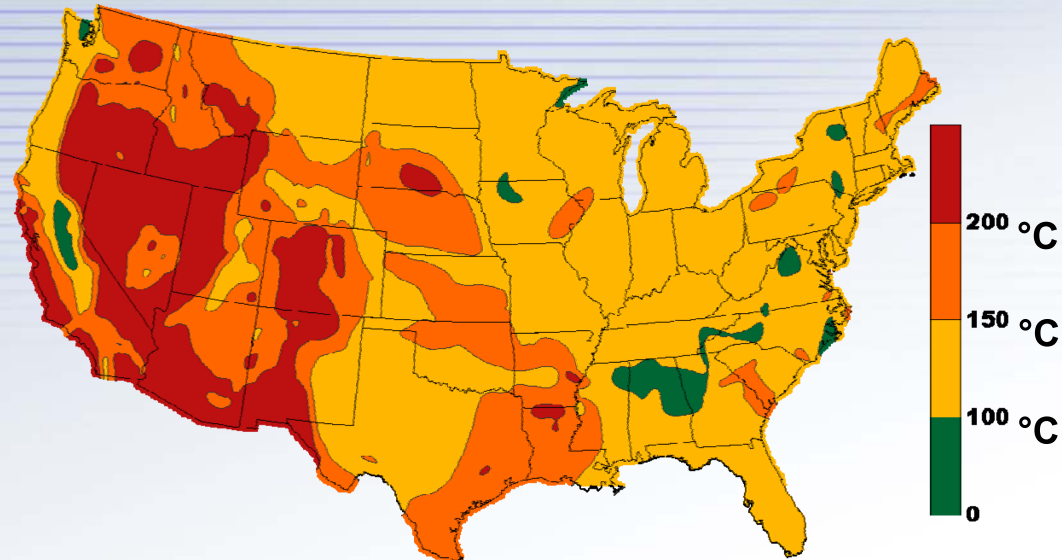
Geothermal Power Costs are Competitive With Fossil Generation



Temperature at 6 km

Installed Capacity: 2.8 GW (Capacity Factor >90%)

Cost of Energy: 5-9 cents/KWh

Extracting 0.01% of estimated resource > 300 TW world-wide is very substantial

Growing at ~4.5%/year – needs to accelerate to 11.4% to make 1 TW installed by 2050

Geo means **Earth**
Thermal means **Heat**

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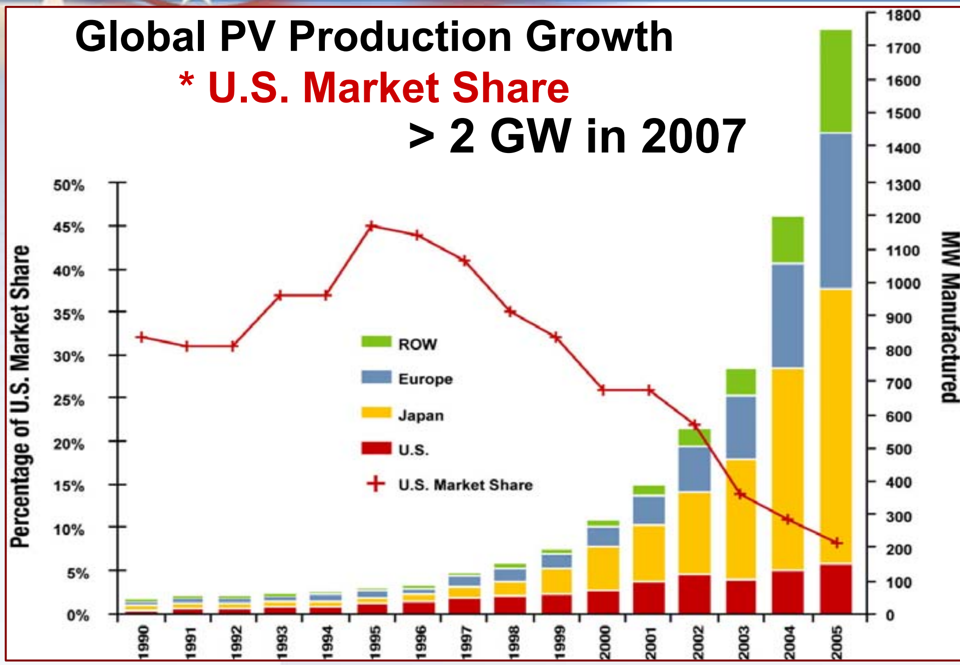
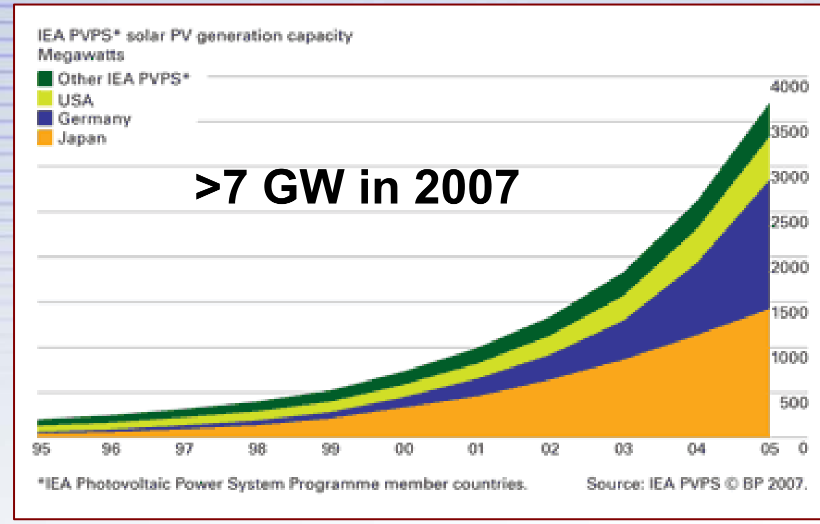
World-Wide Growth of Photovoltaic Energy Capacity



Global Installations



DOE Market Sector	Current U.S. Market Price Range (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

Japan > $0.20 /KWhr
Europe > $0.15 / KWhr
CA ~ $0.10-0.20 / KWhr
PV can be cost competitive especially with policy incentives – also remember it off-sets PEAK loads

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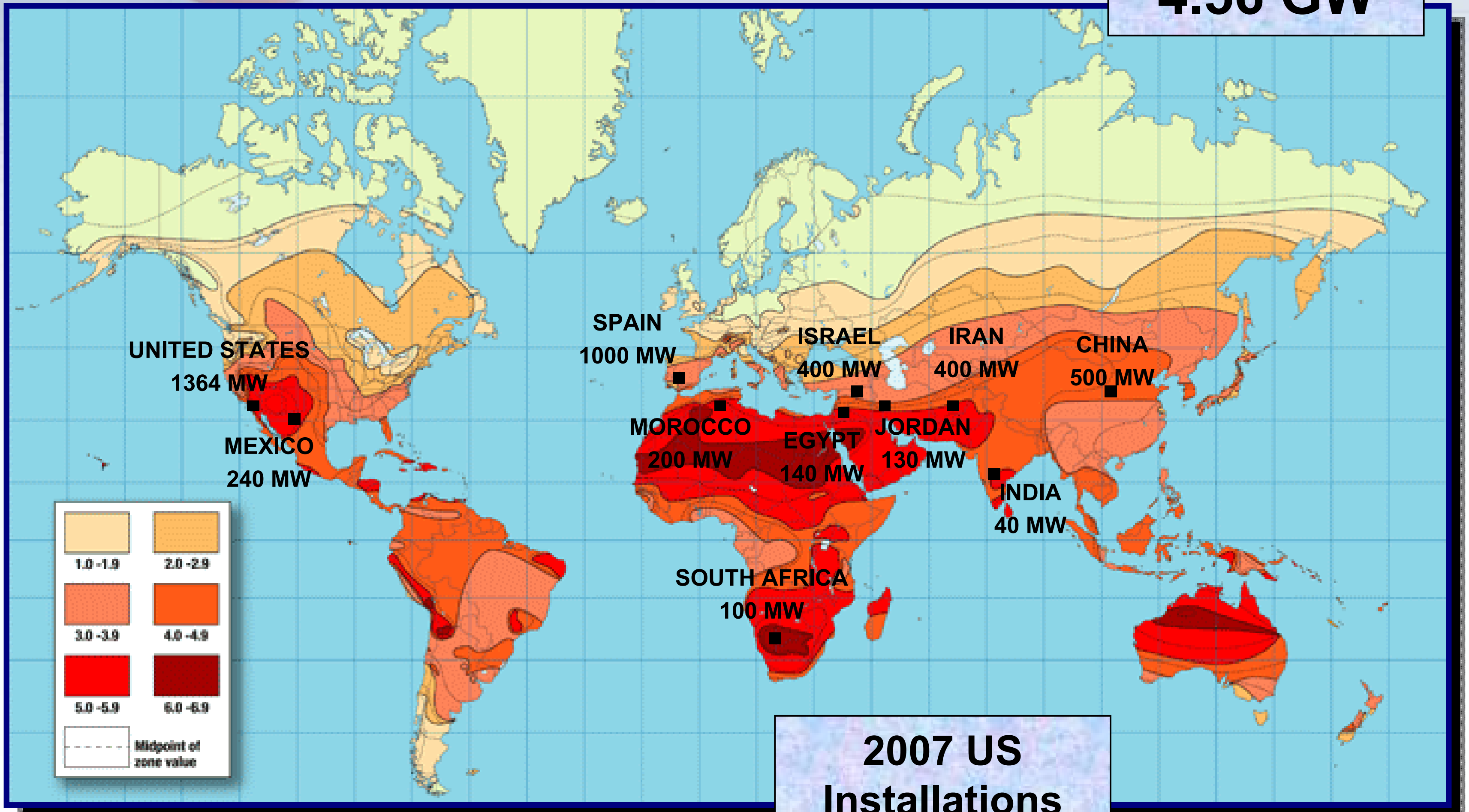
CSP Worldwide Deployment Plans

4.56 GW



2007 US Installations ~ 400MW

16.8%/yr provides 3 TW in 2050 Worldwide

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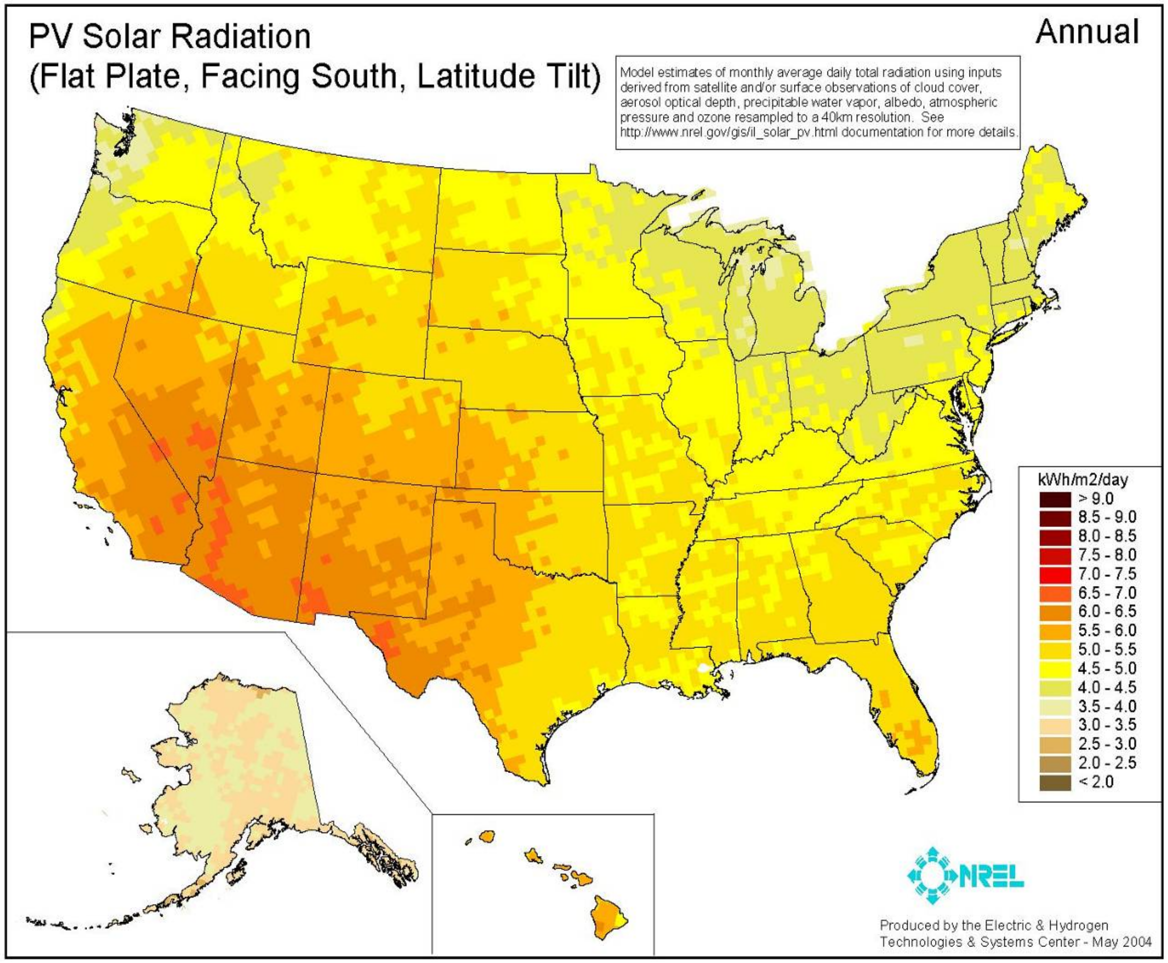
U.S. and World-Wide Solar Resources Greatly Outweigh the Energy Used



120 Peta Watts

- ✓ **Currently, solar provides less than 0.1% of the electricity used in the U.S.**
- ✓ **Covering less than 0.2% of the land on the earth (115K sq-mi) with 10%-efficient solar cells would provide (~6 TW) twice the power used by the world.**
- ✓ **For the U.S., a 100-mi by 100-mi area in the Southwest could generate as much electricity as we use.**
- ✓ **The same amount of area could provide all the US transportation fuels with 10% efficient Solar to a transportation fuel.**

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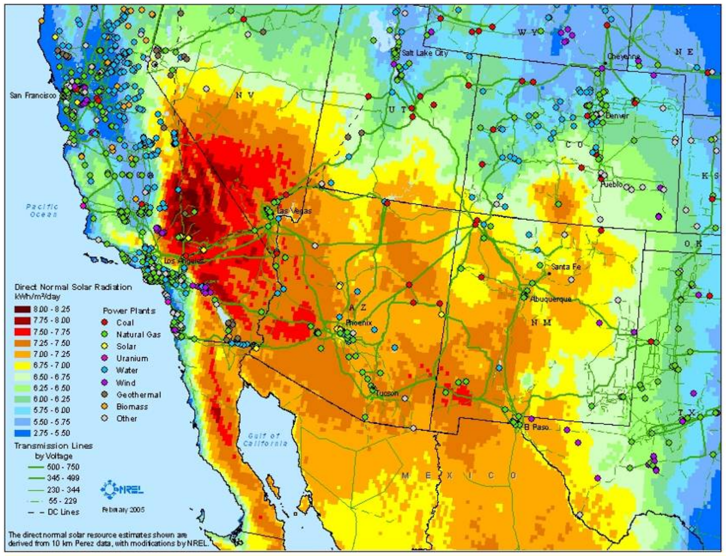
Direct Normal Incidence Solar Resource in the Southwest

Filters applied:

- **Direct-normal solar resource.**
- **Sites > 6.75 kwh/m²/day.**
- **Exclude environmentally sensitive lands, major urban areas, etc.**
- **Remove land with slope > 1%.**
- **Only contiguous areas > 10 km² or > 500MW**
  - **~2500 Acres or 4 sq-Mile**
- **5 Acre/MW or ~18% to MW Solar Capacity**
- **27% to Generation Capacity, Net is ~5%**



Data and maps from the Renewable Resources Data Center

at the National Renewable Energy Laboratory

State		Land Area (mi^2)	Solar Capacity (MW)	Solar Generation Capacity GWh
AZ	17%	19,279	2,467,663	5,836,517
CA	4%	6,853	877,204	2,074,763
CO	2%	2,124	271,903	643,105
NV	5%	5,589	715,438	1,692,154
NM	12%	15,156	1,939,970	4,588,417
TX	<1%	1,162	148,729	351,774
UT	4%	3,564	456,147	1,078,879
Total	6%	53,727	6,877,055	16,265,611

Bottom Line:
Conservative ~7 TW (Peak) Available Resource
>16000 Tera Watt Hours/Year
US Energy Consumed ~29000 TWh/yr

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