SAND2008-1003C

Widespread Adoption of Renewable Energy: Challenges and Material Science Opportunities

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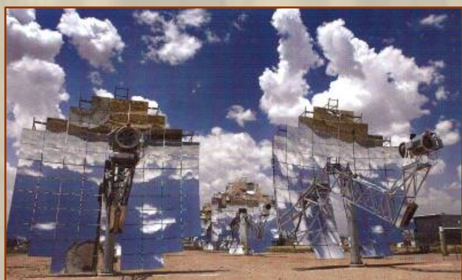
Energy & Infrastructure Future Group



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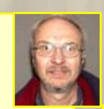

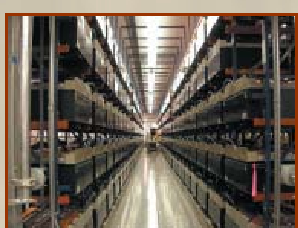

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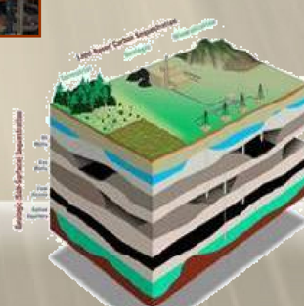

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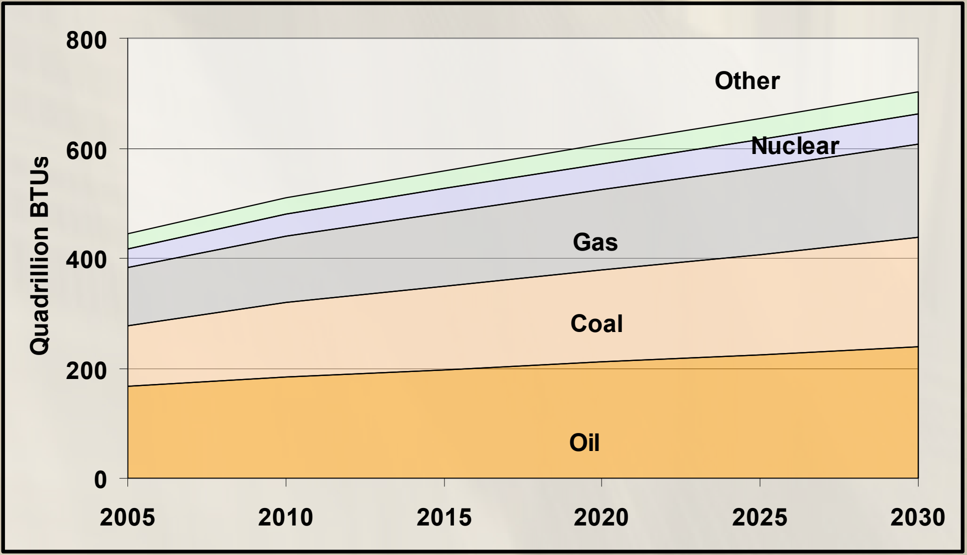
There is a *Gathering Storm* of Interest and Action Around Energy and Climate Issues

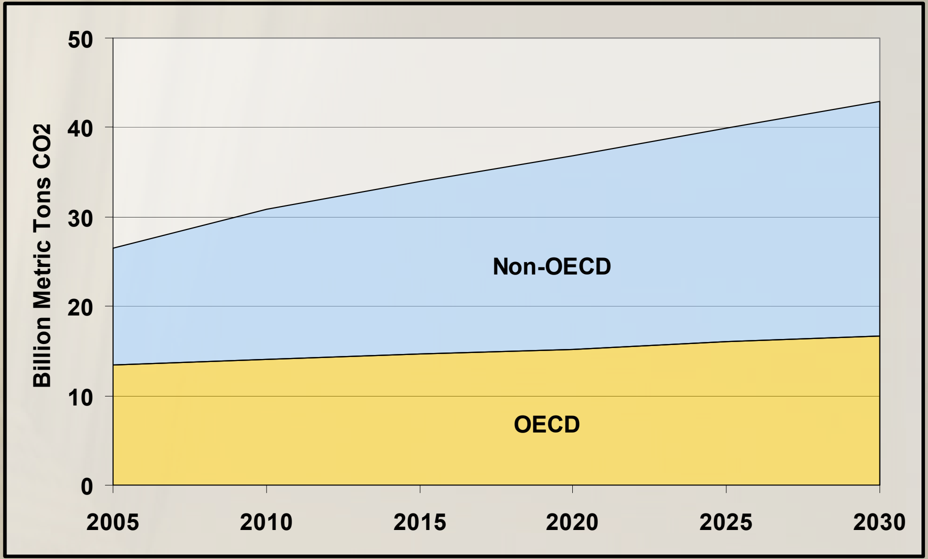
- People
- Financial Markets and Economists
- Politicians
- Scientists and Engineers
- Department of Energy
- Google (RE For $0.01-0.02 / KWhr)

Between Now and 2030, World Energy Demand and Carbon Emissions Will Grow ~65%

Global Energy Demand



Global Carbon Dioxide Emissions



Source: USDOE EIA IEO 2006 Reference Case (updated October 2007)

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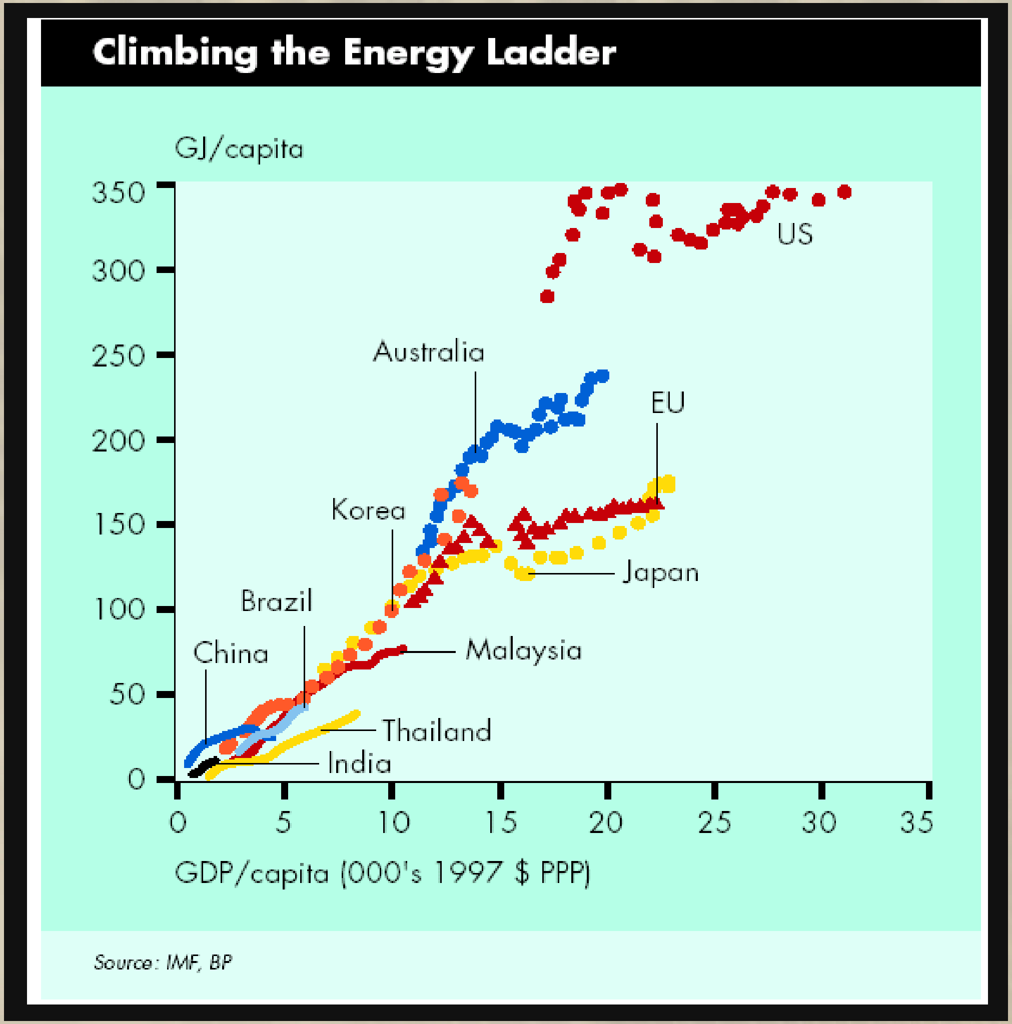
Economic Prosperity and Stability Require Access to Reliable and Affordable Energy



Electricity Consumption/person

- US – 800 KWh/mo
- India – 25 kwh/mo
- China – 15 kwh/mo

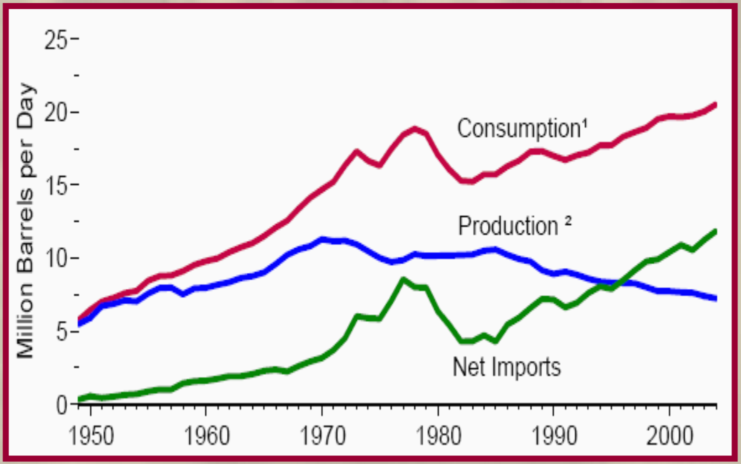
Transportation, vehicles/1000 people

- US – 800
- India – 60
- China – 70

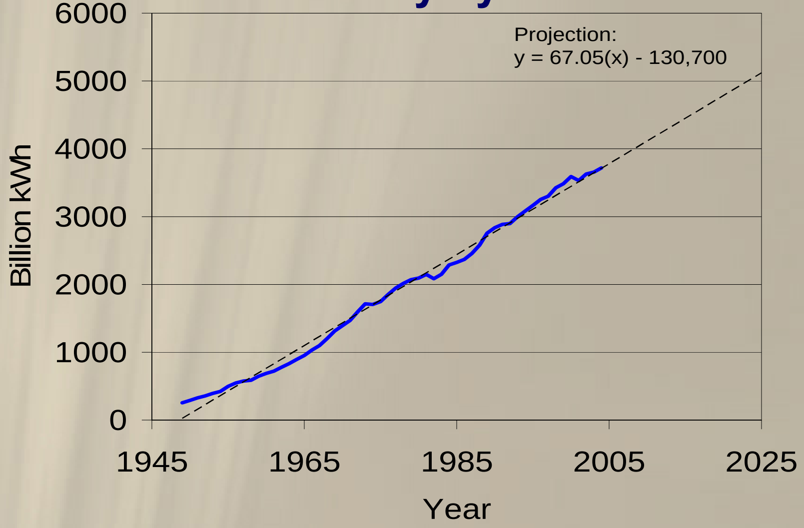
Source: Royal Dutch Shell, "Exploring the Future – Energy Needs, Choices and Possibilities"

U.S. Energy Needs Will Increase Through 2030

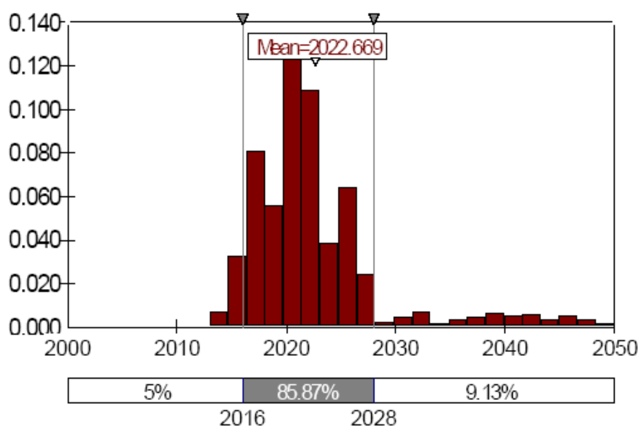
U.S. Will Need 30% more Transportation Fuels by 2030



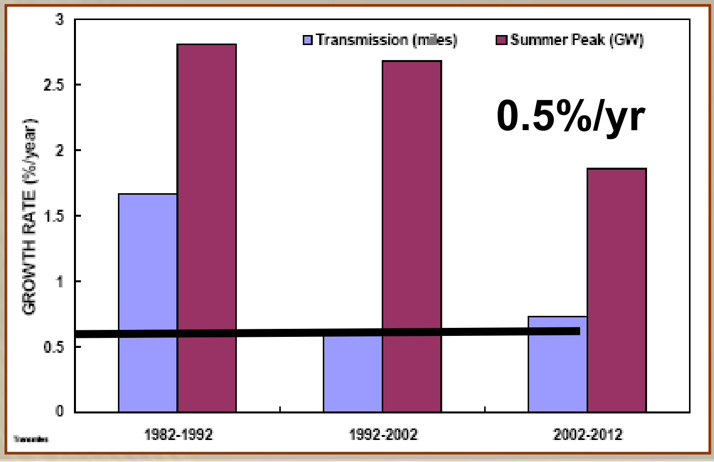
U.S. Will Need 50% more Electricity by 2030



Peak Year of ROW Conventional Oil Production: Reference/USGS



Generation and Transmission Growth



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

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World Proven Fossil Fuel Reserves and Consumption

Have's (% of Global Reserves)

Area/Share	Oil	Gas	Coal
Key M. E.*	65	33	0
Saudi	26	4	0
Iran	9	16	**
Iraq	11	2	0
Kuwait	9	1	0
UAE	10	4	0
Qatar	**	6	0
Russia	5	33	16
China	2	1	12
US	2	3	25
Australia	**	1	9
ROW	25	29	38
Total	100	100	100

* Sum of Saudi Arabia through UAE

** Less than 0.5 %

Have not's (% Global Consumption of Oil)

US	26%
Japan	7%
China	6%
Germany	4%
Russia	3%

Options & Challenges

- **Continue to Buy Fossil Fuels from our "Neighbors"**

- ***Energy Security and Economic Vulnerabilities***

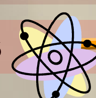
- **Begin Expanding our use of Unconventional Fossil Resources**

- ***Increased Environmental Concerns***

- **Expand Biofuels Efforts**

- ***Land use; Water; Compatibility with existing infrastructure***

- **Expand Nuclear Power Efforts**



- ***Permitting; Waste Archival***

- **Hydrogen**

- ***R&D Advances Needed; Infrastructure***

- **Expand Renewable Energy Content of our Infrastructure**

- ***Intermittency; and Geographic Diversity;***

- **Fusion Energy**

- ***Fundamental materials and physics advances needed***

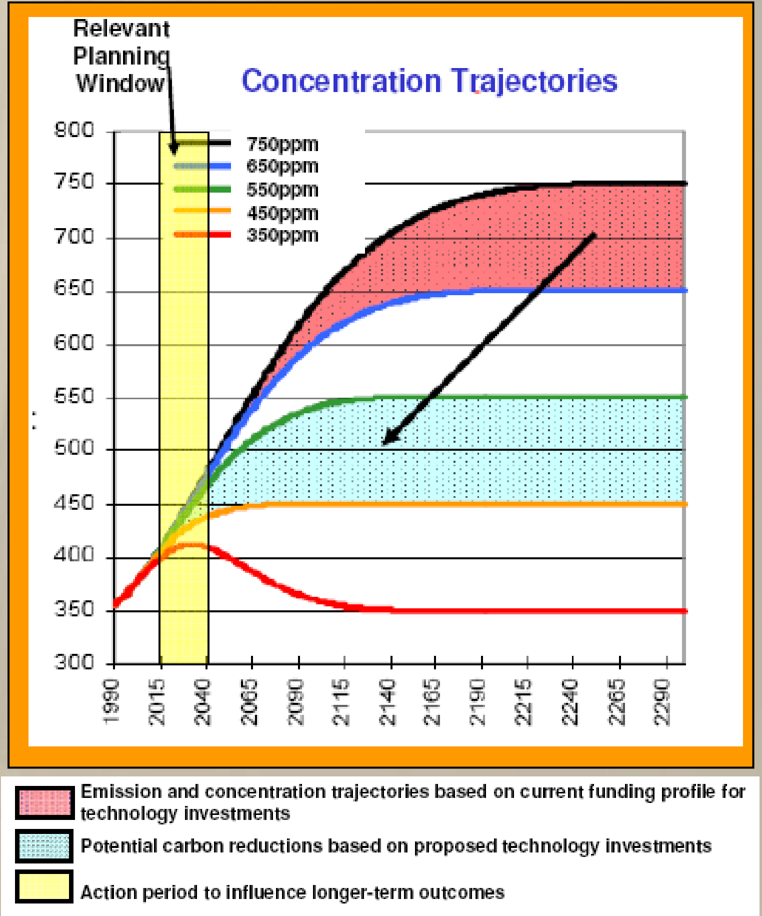
Whatever it is we need to get started!!!

(We will need all options, no silver bullets, and we must find ways to overcome challenges)

Time Constants

- Political consensus building ~ 3-20+ years
- Technical R&D ~10+
- Production model ~ 4+
- Financial ~ 2++
- Market penetration ~10++
- Capital stock turnover
  - Cars ~ 15
  - Appliances ~ 10-20
  - Industrial Equipment ~ 10-30/40+
  - Power plants ~ 40+
  - Buildings ~ 80
  - Urban form ~100's

- Lifetime of Greenhouse Gases ~100's-1000's
- Reversal of Land Use Change ~100's
- Reversal of Extinctions Never



Sam Baldwin, DOE

Bob Marlay, DOE

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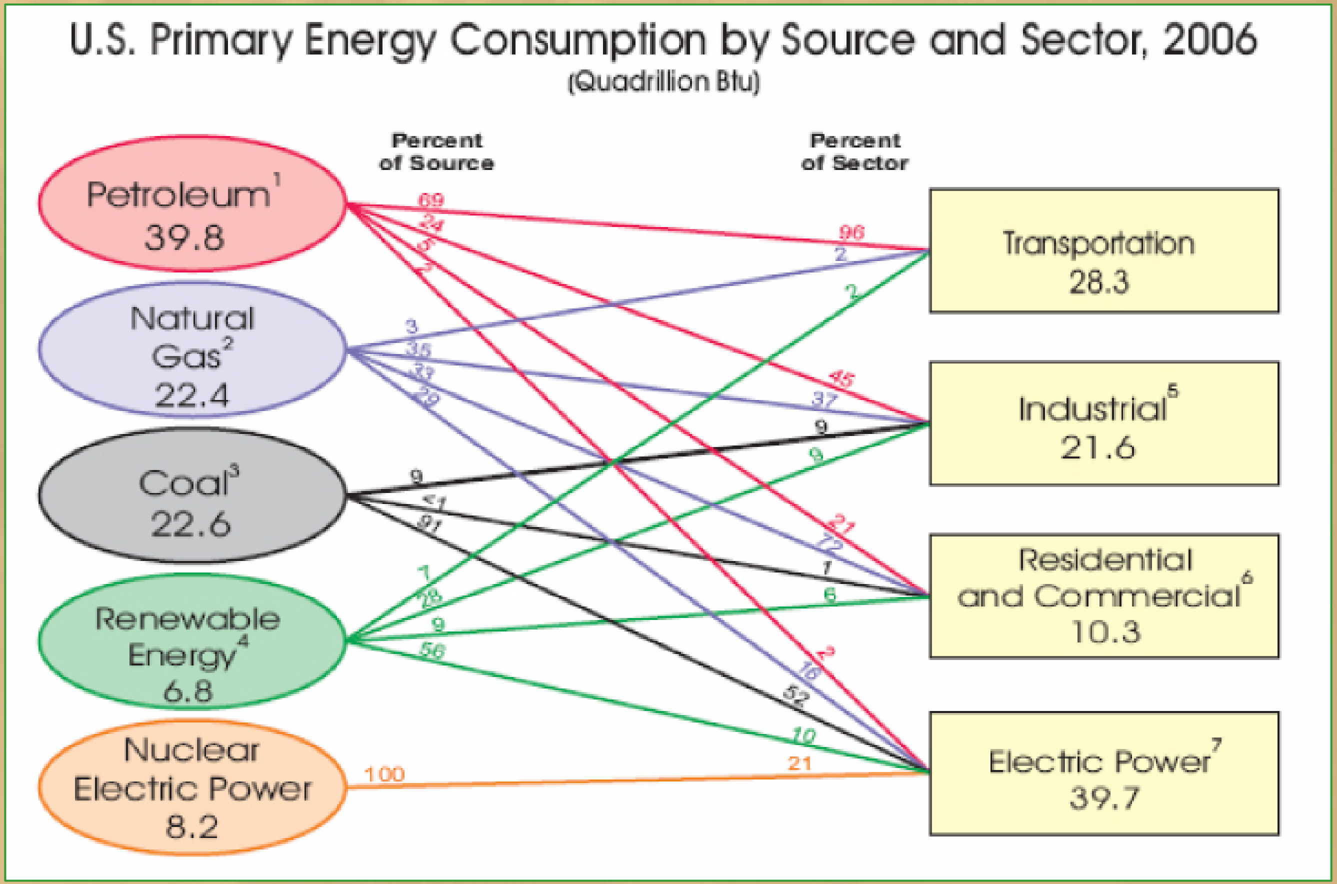
Energy Use By Sector



[1]Excludes 0.5 quadrillion Btu of ethanol, which is included in "Renewable Energy."
[2]Excludes supplemental gaseous fuels.
[3]Includes 0.1 quadrillion Btu of coal coke net imports.
[4]Conventional hydroelectric power, geothermal, solar/PV, wind, and biomass.
[5]Includes industrial combined-heat-and-power (CHP) and industrial electricity-only plants.
[6]Includes commercial combined-heat-and-power (CHP) and commercial electricity-only plants.
[7]Electricity-only and combined-heat-and-power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public.

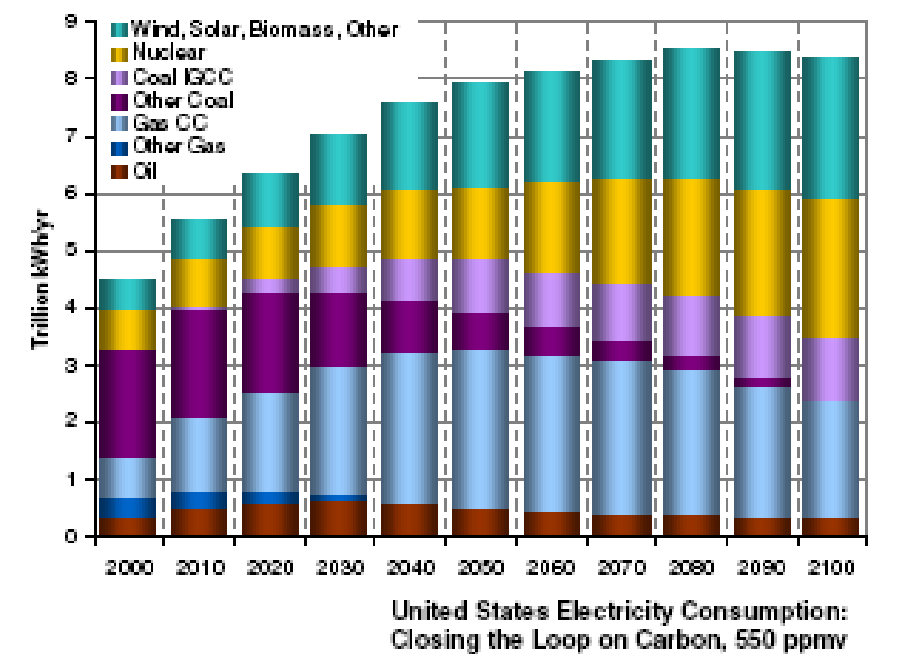
Note: Sum of components may not equal 100 percent due to independent rounding.

Sources: Energy Information Administration, *Annual Energy Review 2006*, Tables 1.3, 2.1b-2.1f, and 10.3.

Rapid De-Carbonization of Our Energy Infrastructure

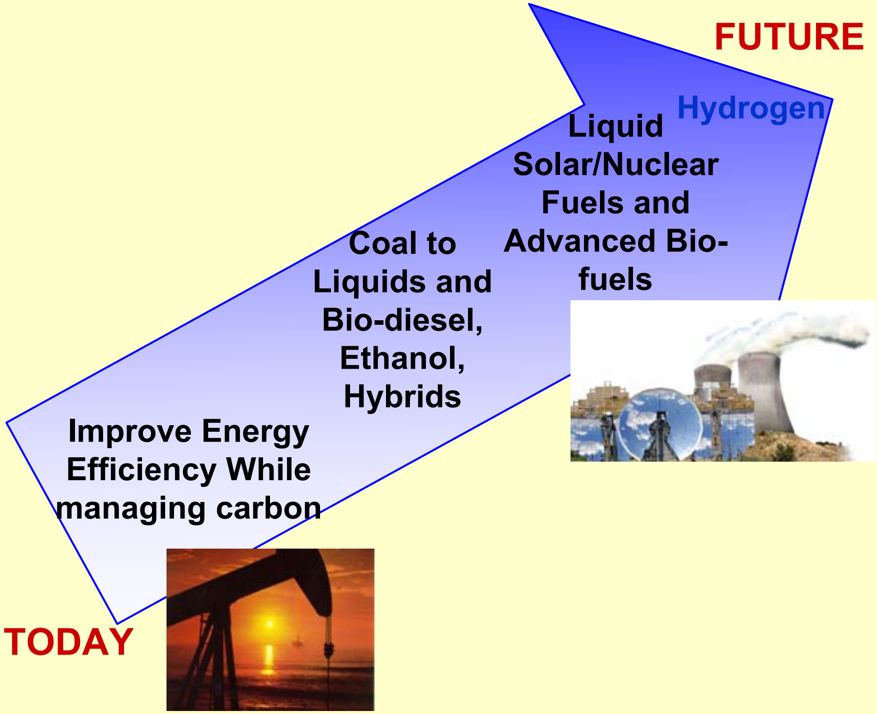
Electricity Sector

- De-carbonize Electricity Grid via Pervasive Use of Renewables, Nuclear and clean Gas/Coal Technologies



Transportation Sector

- Develop Renewable Liquid Transportation Fuel Sources



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More Than 10TW of Clean Energy are Needed by 2050 to "Stabilize" CO_2 Levels

- ***Is this even remotely possible?***

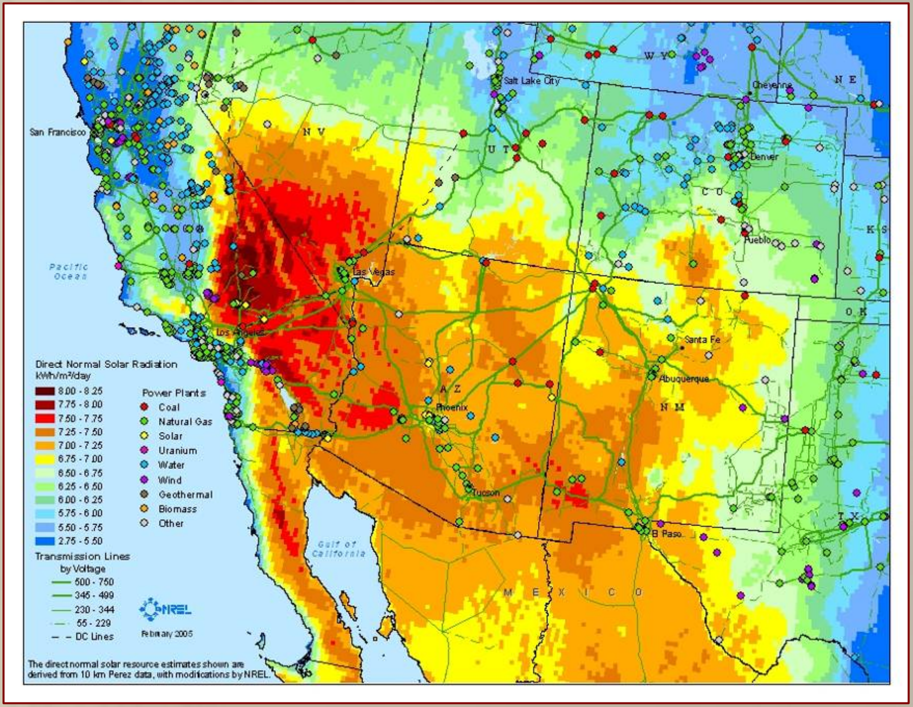
and

- ***What the heck is holding us back?***

Solar Resource in the Southwest

Filters applied:

- Direct-normal solar resource.
- Sites > 6.75 kwh/m^2/day.
- Exclude environmentally sensitive lands, major urban areas, etc.
- Remove land with slope > 1%.
- Only contiguous areas > 10 km^2



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	19,279	2,467,663	5,836,517
CA	6,853	877,204	2,074,763
CO	2,124	271,903	643,105
NV	5,589	715,438	1,692,154
NM	15,156	1,939,970	4,588,417
TX	1,162	148,729	351,774
UT	3,564	456,147	1,078,879
Total	53,727	6,877,055	16,265,611

Bottom Line:
Almost 7 TW Available Resource
(Total U. S. Capacity is 1 TW)

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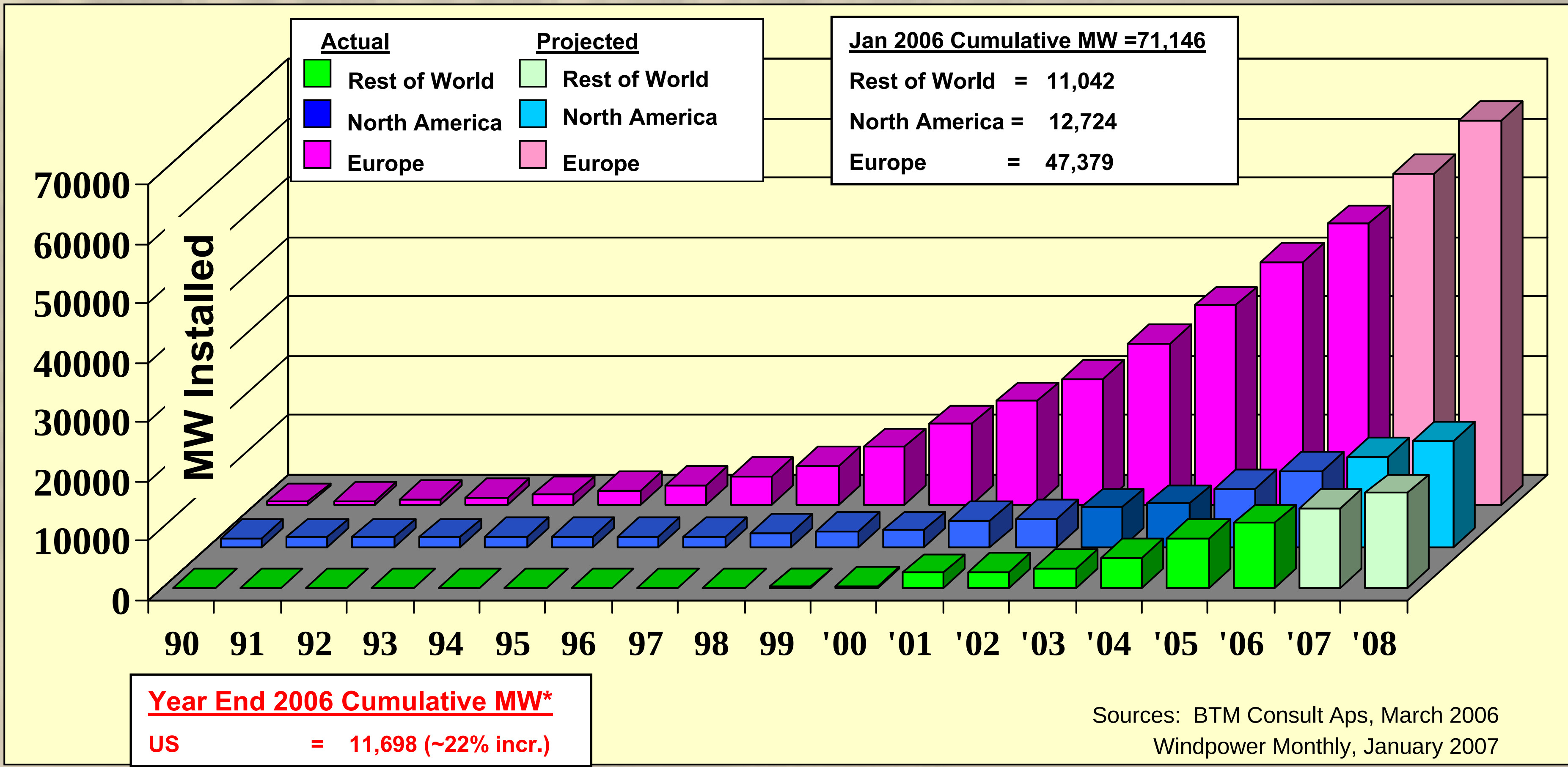
Wind Power Markets



10% US Growth Rate: ~ 1TW by 2050

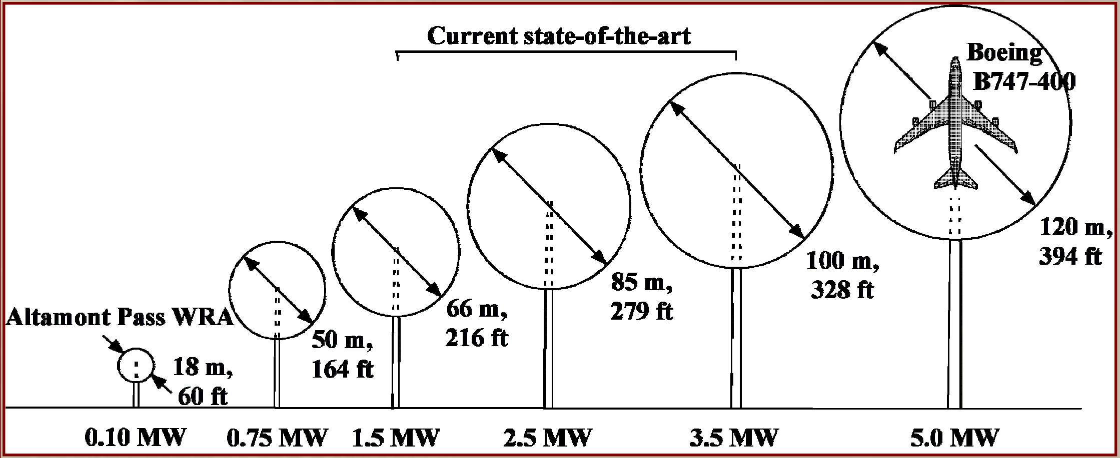
Major Challenges With Widespread Adoption of Renewable Energies

- **Cost**
  - → Not an issue in the near future, but major advances needed to continue adoption and reach ~$0.02 / KWhr
- **Intermittency**
  - → Major issue, and will require fundamental new approaches to grid management and storage
- **Geographic Diversity**
  - → Significant issue, but regional optimization coupled with liquid fuels or hydrogen could potentially minimize effect, or special purpose RE transmission lines
- **Infrastructure Evolution**
  - → Major issue, and solutions must take maximum advantage of 100 years of infrastructure investments

Wind Power Costs are Competitive with Fossil Generation

- Costs:
  - System < $3/lb
  - Blades < $5/lb
  - ~ $1.00/Watt

  - $0.04-0.06/kWh



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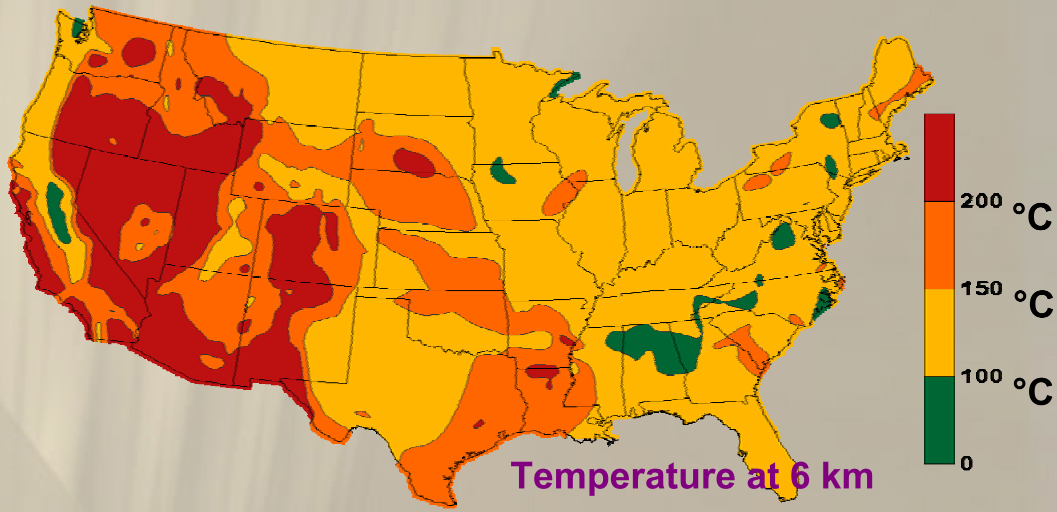
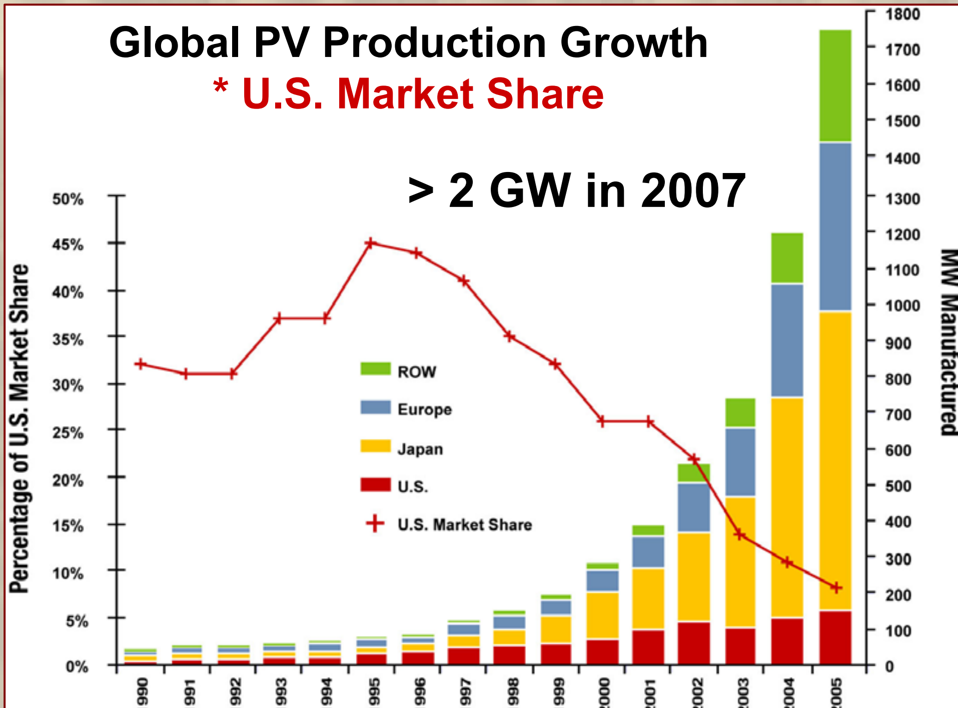
Geothermal Power Costs are Competitive With Fossil Generation



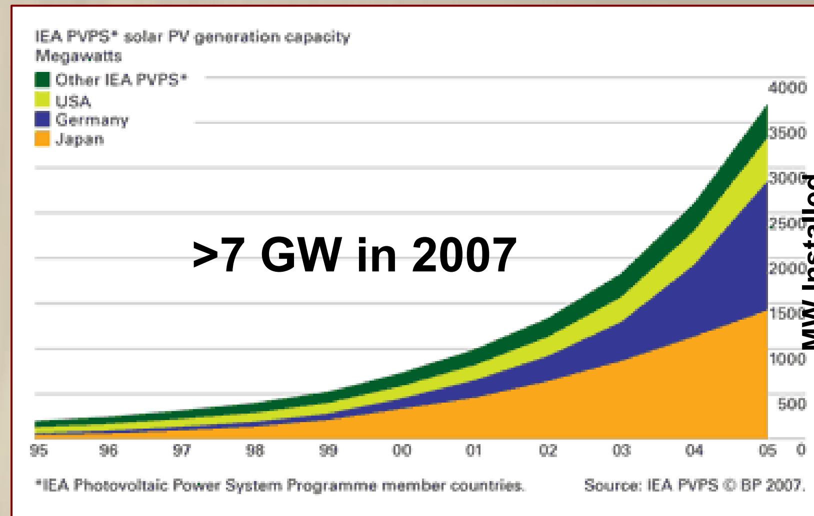
Installed Capacity: 2.8 GW (Capacity Factor >90%)

Cost of Energy: 5-9 cents/KWh

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 > $0.2 /KWhr
Europe > $0.15 / KWhr
CA ~ $0.1-0.2 / KWhr

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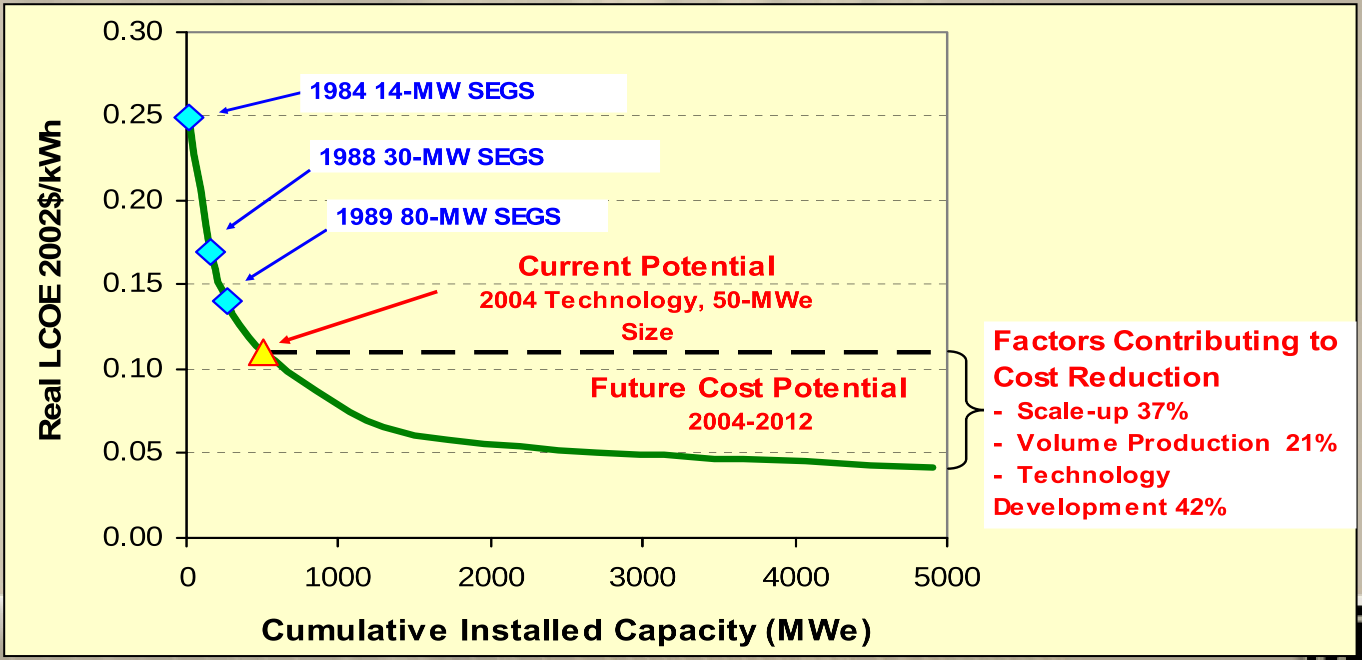
Concentrating Solar Power (CSP) Systems are a Leading Source of Renewable Utility Scale Power

Trough

Dishes

Towers



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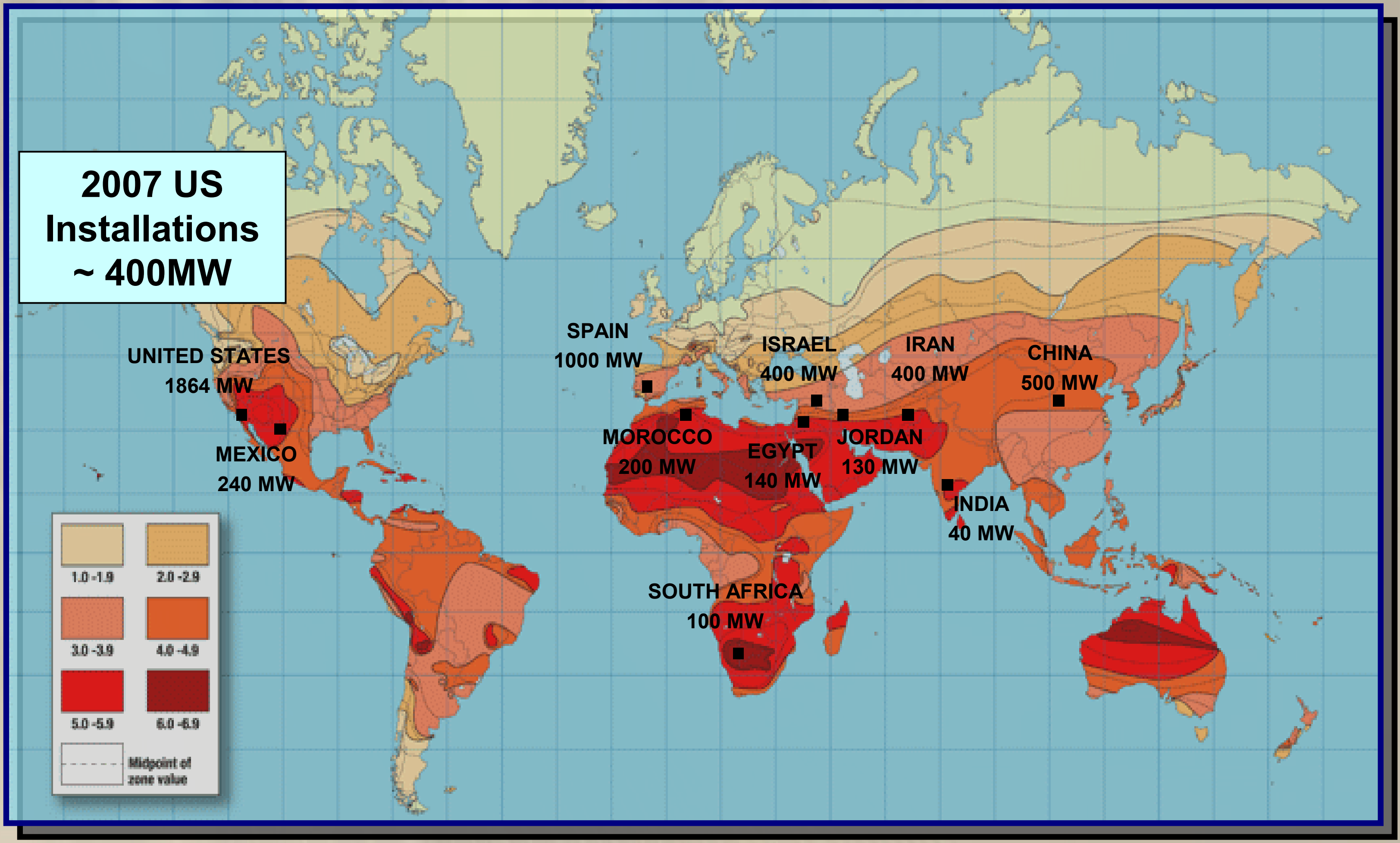
CSP Worldwide Deployment Plans (~5GW)
(Active Projects: Broke Ground, PPA, Announcements)



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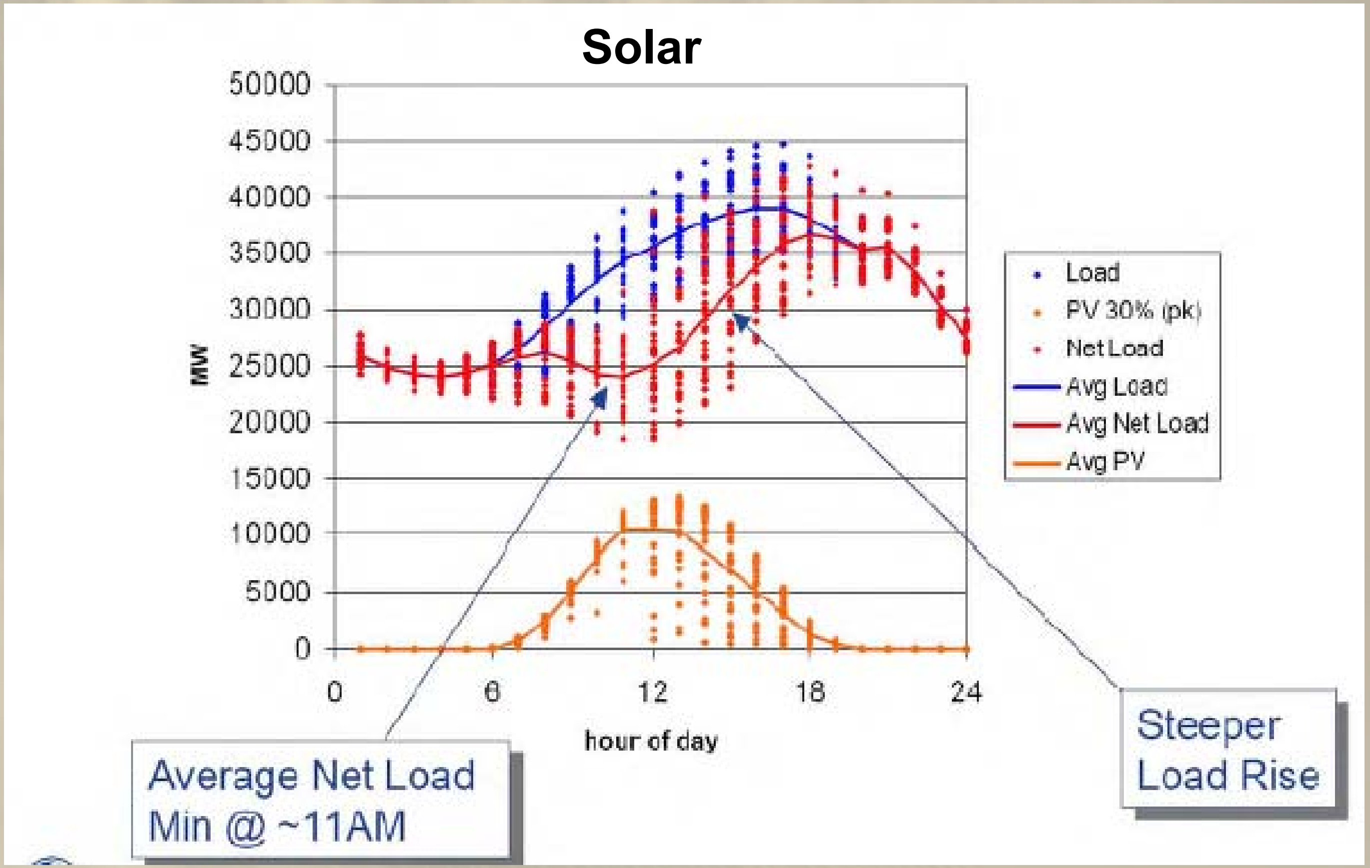
Wind and Solar Energy Profiles Don't Match Typical Utility Load Profiles

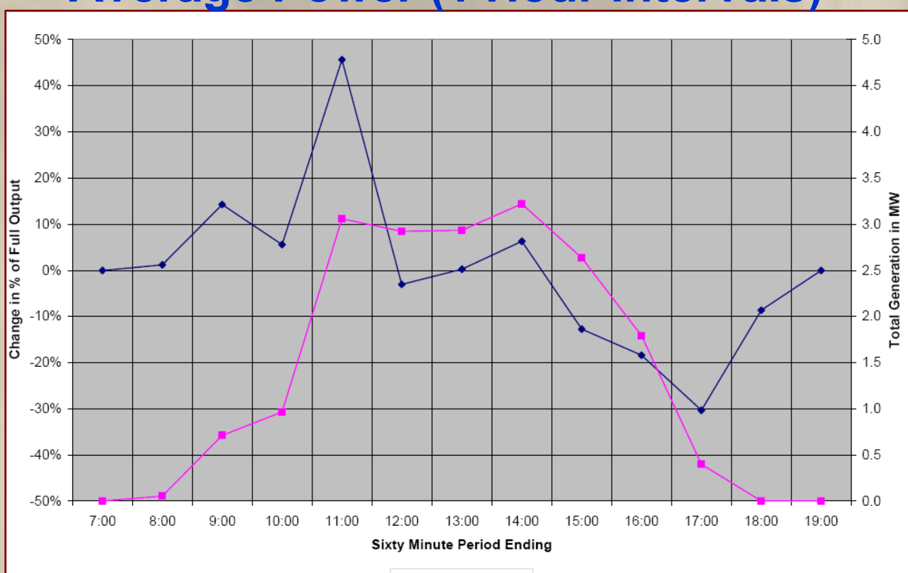


Source: GE

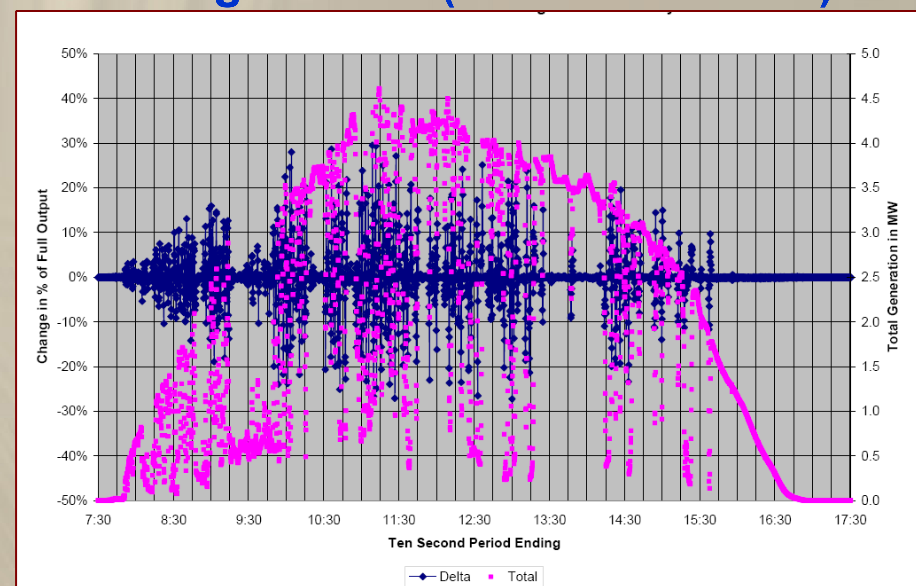
Solar Intermittency

Tucson Electric Power 4.5MW PV Plant

Average Power (1 Hour Intervals)

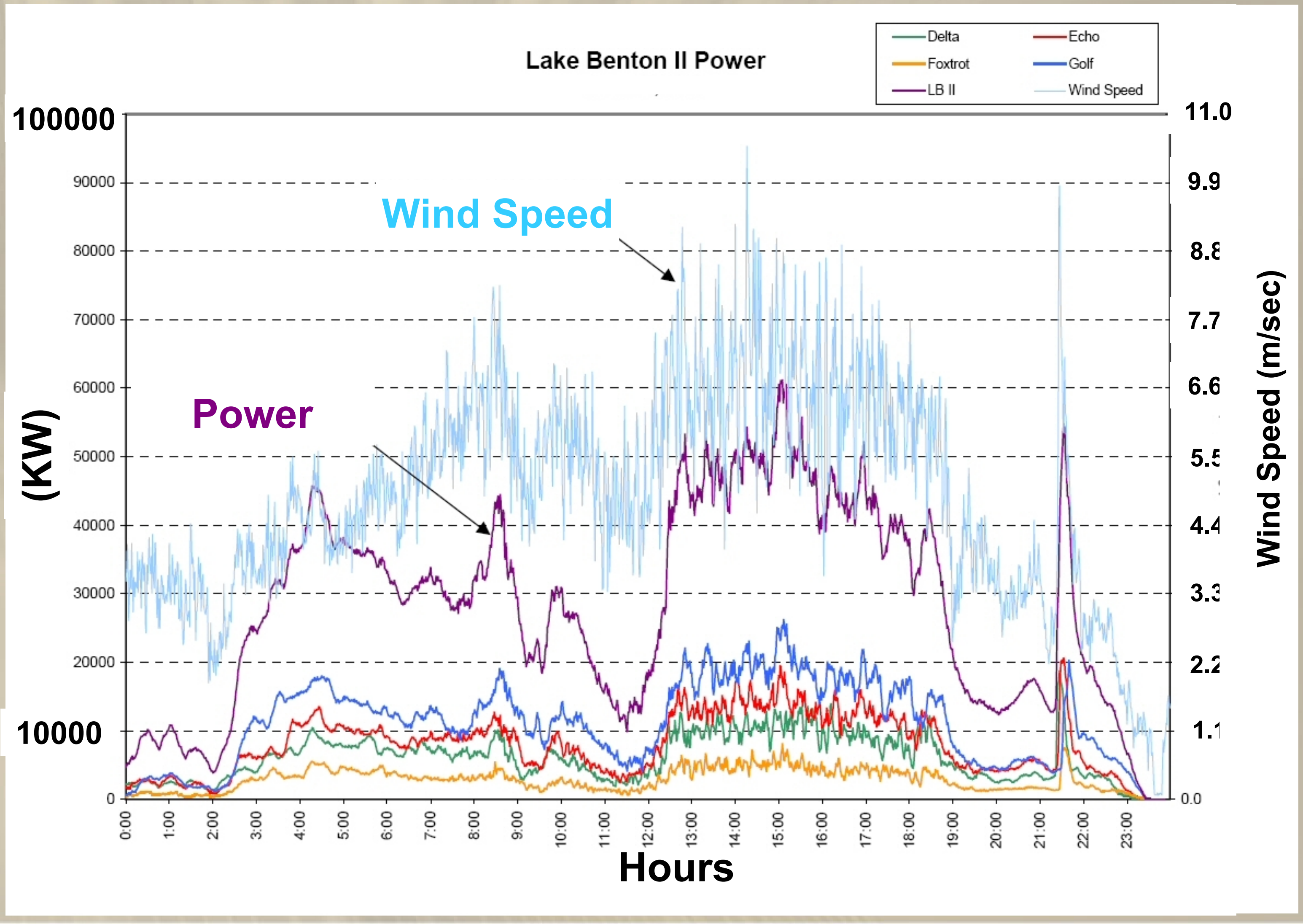


Average Power (10 Sec Intervals)

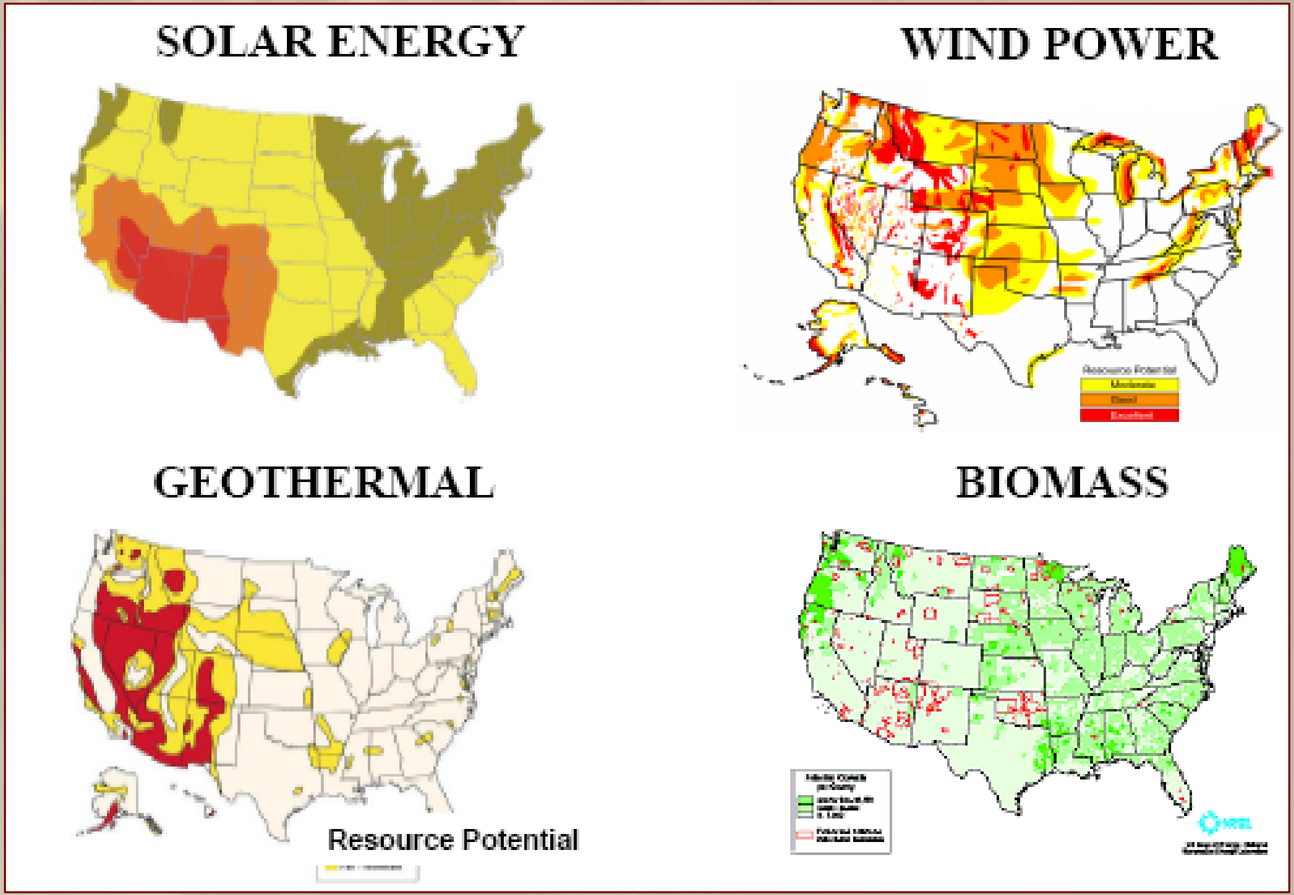


Source: Tom Hansen, Tucson Electric Power

Wind Intermittency



Geographic Diversity of Renewables



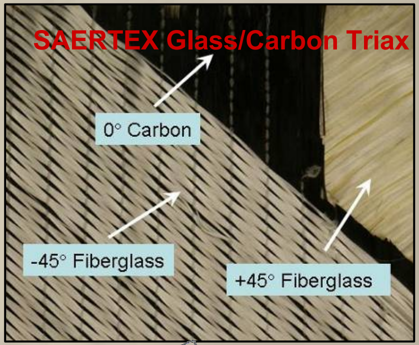
What is best way to move "stranded" resources to use centers ?

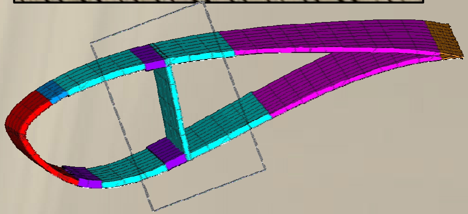
Renewable Fuels?

Renewable Transmission Lines?

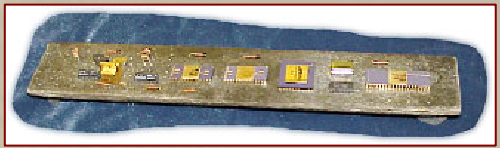
Wind and Geothermal Power Materials Needs

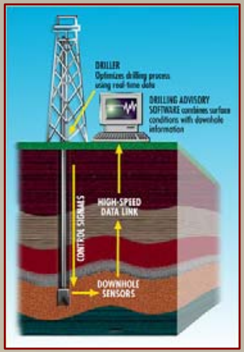
- **Wind Technology**
  - **Engineered *Composites Materials* that can be manufactured to reduce the weight and increase the strength of wind turbine blades**



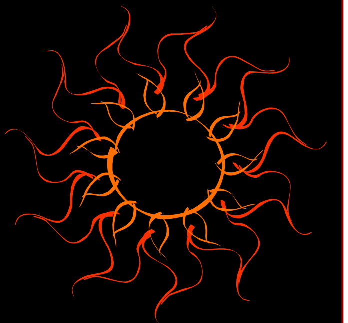


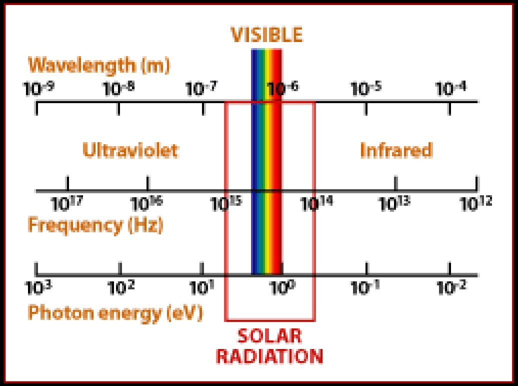
- **Geothermal Technology:**
  - ***Materials for Extreme Environments*, to improve Hard-Rock Drilling, High Temperature Instrumentation, and Diagnostics while drilling.**

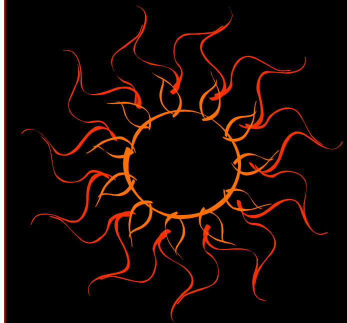




Solar Energy Technologies

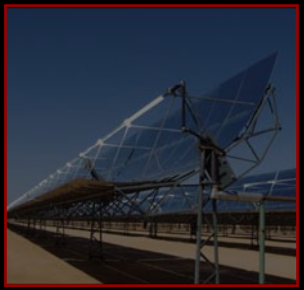






- **Solar Hot Water**

  Solar -> Hot H_2O -> Use



- **Solar Thermal (Concentrating Solar Power)**

  Solar -> Hot Fluid -> Steam Turbine -> Electricity -> Use

- **Solar Electric (Photovoltaics or PV)**

  Solar -> Electrons -> DC-AC Conversion -> Electricity -> Use

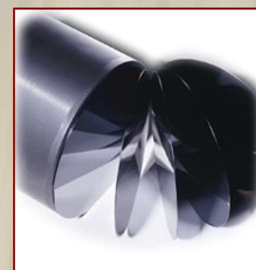
Solar Energy Material Science Needs

- Energy Conversion
- Solar Liquid Transportation Fuels
- Energy Storage
- Energy Routing (Power Electronics)

PV Conversion Materials and Markets

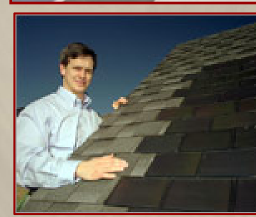
Polycrystalline Si ~63%

Crystalline Si ~27%



TF CdTe ~6%

TF Si (a-Si, ribbon) ~4%



(Organic, Dye, CIGS, III-V, Nano) ~0%

Wafers

Decreased Raw Materials Usage

Decreased Efficiency

Thin-Films

Systems Integration

Material Science

% Market Share

CdTe R&D Roadmap

Parameter	Present Status (2007)	Future Goal (2015)	Approach
Champion device efficiency	16.5%	18%-20%	Improved modeling & device understanding
Commercial module efficiency	9%	13%	Controlled carrier concentrations and improved back-contacts
Module cost ($/Wp)	1.25	0.70	Maturing deposition techniques/alternative absorber layer processes

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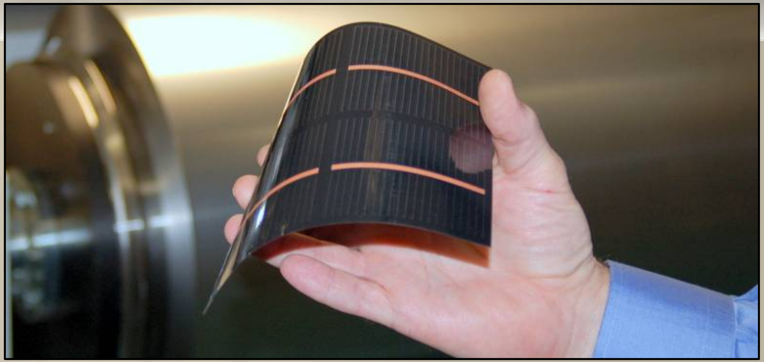
CIGS R&D Roadmap



Parameter	Present Status (2007)	Future Goal (2015)	Approach
Champion device efficiency	19.5%	21-23%	Defect analysis and device physics
Commercial module efficiency	5%-11%	10%-15%	Characterization and improved processes
Module cost ($\$/W_p$)	Not established, estimated <$\$2/W_p$	$\$1/W_p$	Thinner absorbing layers
Overall Process Yield	Not available	>95%	Uniformity and control

Concentrating PV R&D Roadmap

Parameter	Present Status (2007)	Future Goal (2015)	Approach
Champion device efficiency	40.7%	44%	Improved metamorphic junction architecture
Commercial device efficiency	33%-37% (III-V) 25% (Si)	36%-40%	Optimize thermal and spectral packaging of III-V
Optical efficiency	75%-85%	80%-90%	Increase acceptance angle and improved design
Commercial System efficiency	17%	29%-33%	Optimized module design and cell packaging

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Organic PV R&D Roadmap

Parameter	Present Status (2007)	Future Goal (2020)	Approach
Champion device efficiency	5.2%	12%	Identify candidate materials whose fundamental properties, such as optical absorption, band structure, carrier mobility that allow for high efficiencies.
Cell degradation	< 5% per 1000 hours, research-scale	< 2% per 1000 hours, module	Fundamental device analysis including photo-oxidation, interfacial instability and delamination, interdiffusion, and morphology changes

Stability, Stability, Stability, …

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Solar Fuels: Sunshine to Petrol

Vision: To directly, efficiently, and cost effectively produce infrastructure compatible liquid fuels employing the same resources as nature (Sunlight, CO_2 and H_2O).

Sunlight + CO_2 + H_2O = Fuel + O_2

Sunlight + CO_2 + $2H_2O \rightarrow CO + 2H_2 + (3/2)O_2 \rightarrow CH_3OH$ (Methanol)

Target

>10x sunlight to fuel efficiency than biomass

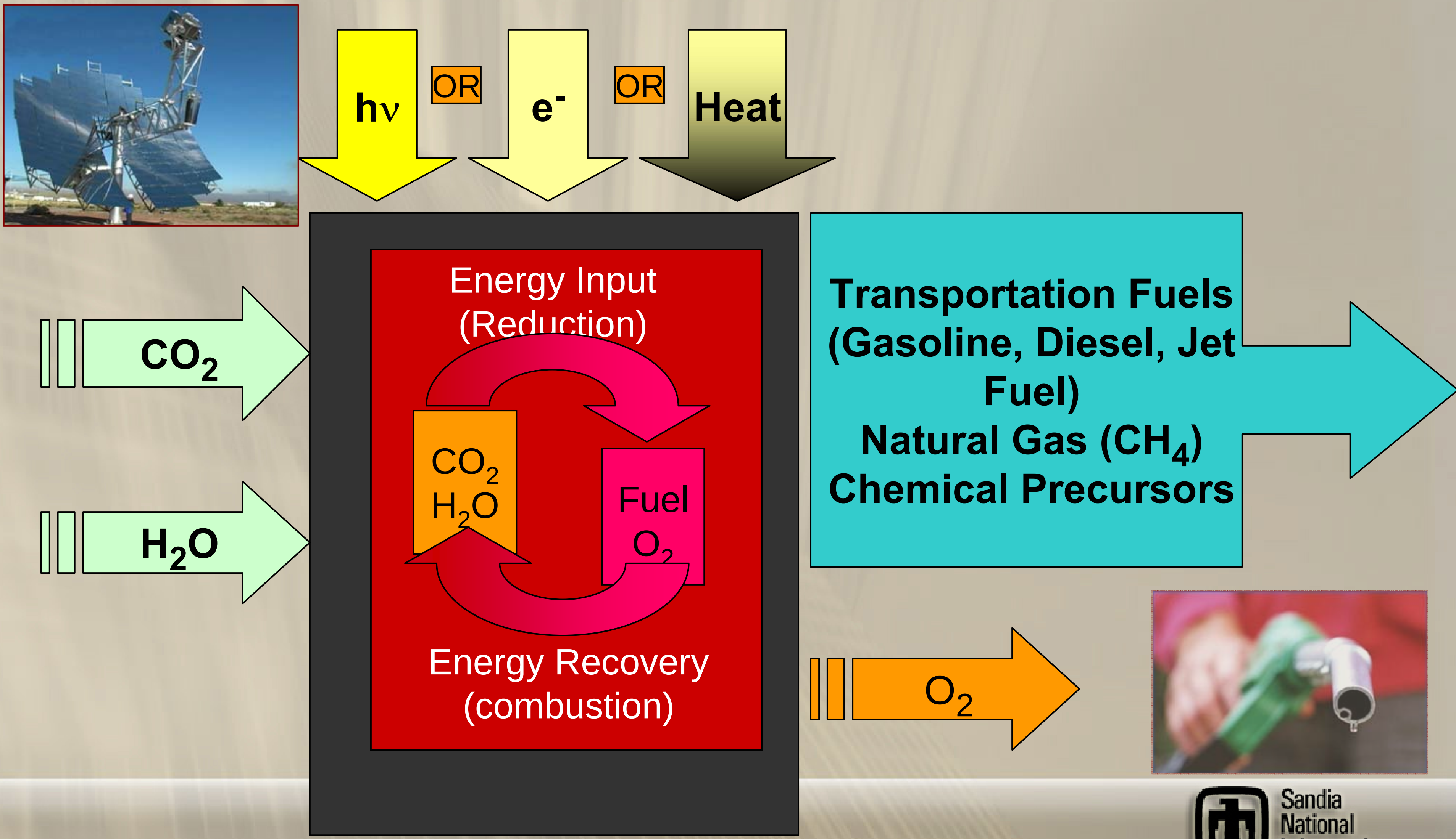
Nature Has Helped Us in the Past

- Each gallon of gasoline is equivalent to 100 tons of prehistoric biomass, processed at low temperature for millions of years (ancient stored solar energy)

- We need to speed up the process, via solar driven high temperature thermochemistry-

→ we only have 25-75 years to get this right.

Solar Driven CO_2 to Fuel
Biofuels Without the Biology



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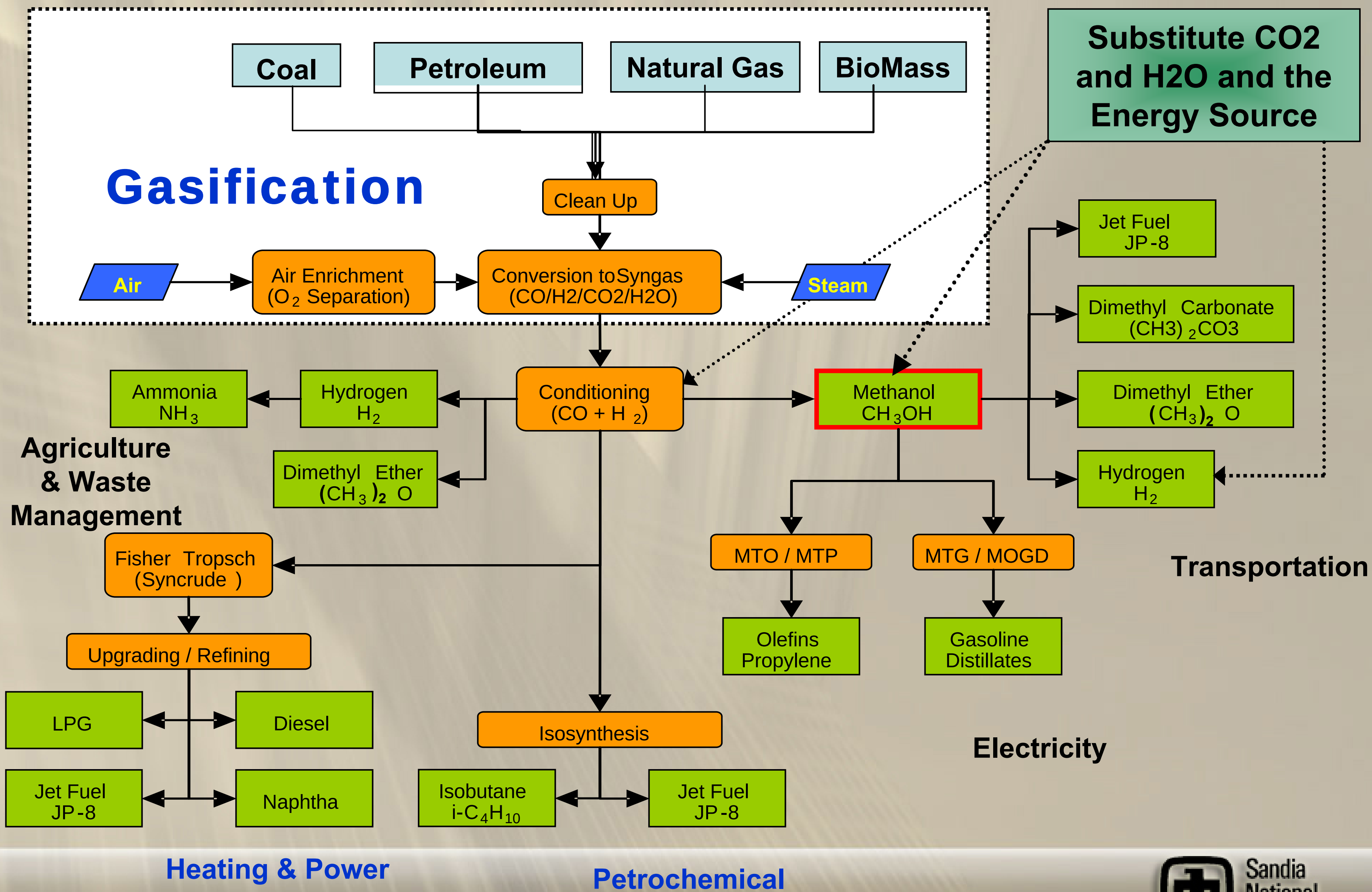
There are Known Pathways to Most Anything Desirable to Synthesize



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Thermodynamic Analysis: Efficiencies
Sunlight to Fuel (Methanol)

	CO_2 from a Concentrated Source such as Flue Gas		
			Thermal (%)
H_2 by PV electrolysis CO by TC			10.1
H_2 and CO by TC			17.9

PV: Photovoltaics, TC: Thermochemical

Photosynthesis	~ 1-3%
Ethanol Production	< PS
Biodiesel Production	< PS

Proven/known

S2P Experiments at the NSTFF

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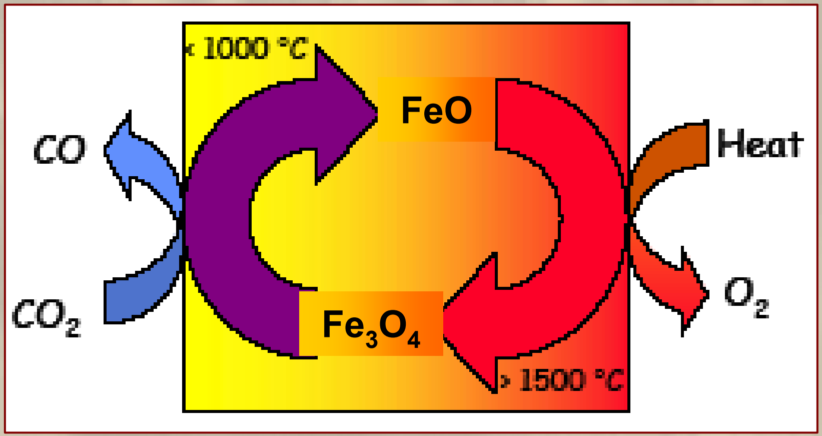
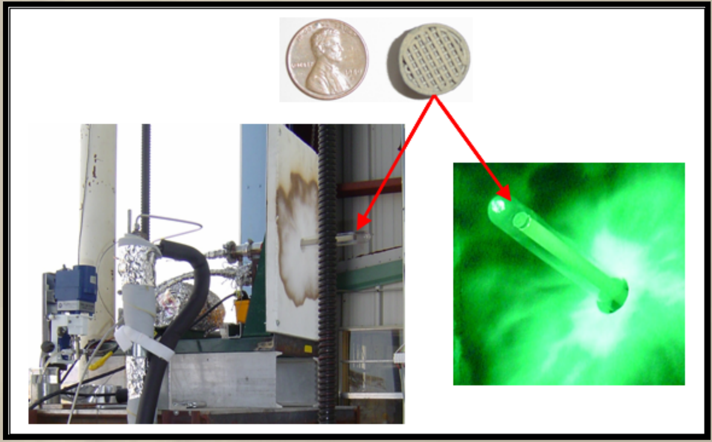
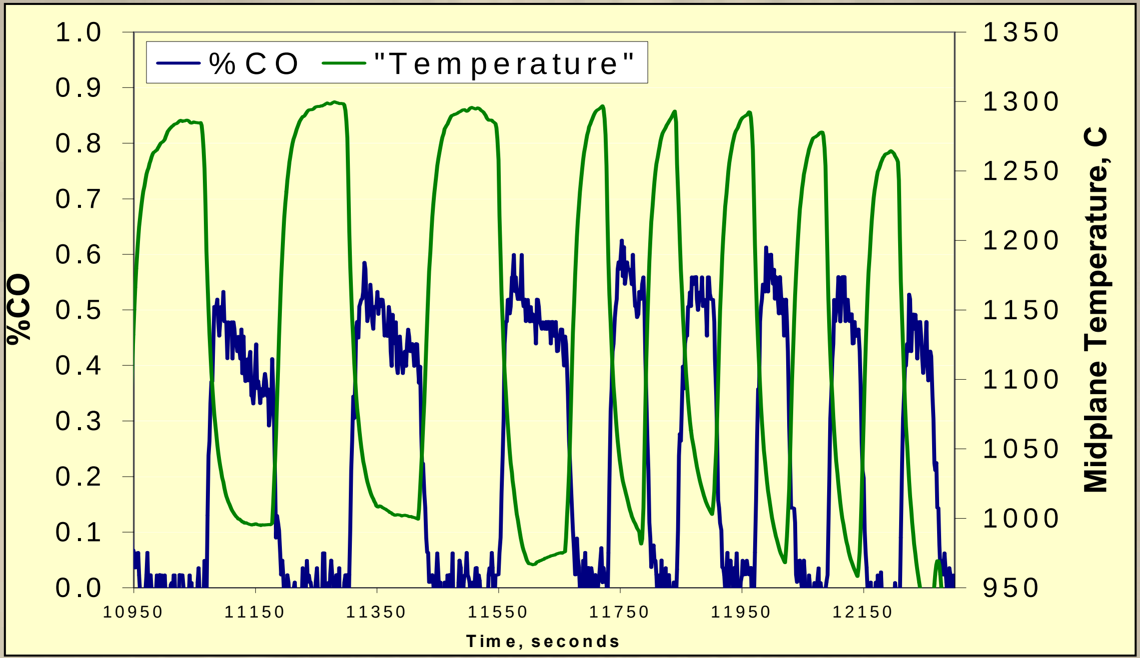
NATIONAL SOLAR THERMAL TEST FACILITY

CO2 Splitting at the NSTTF

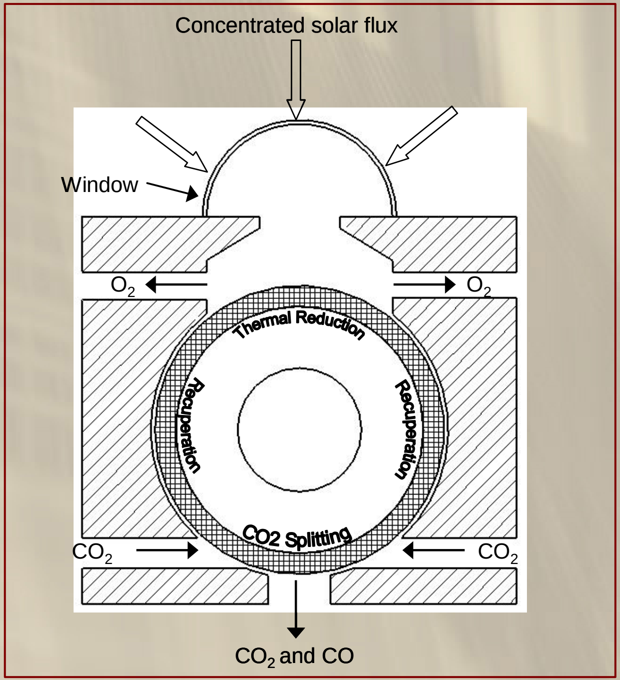


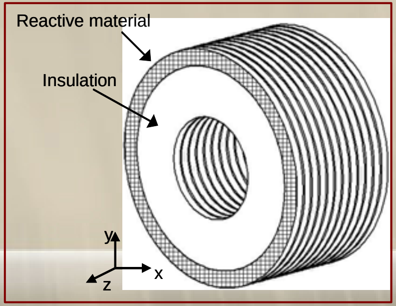




Solar Fuels Production with the CR5

- Practical CO (or H_2) production in the CR5 requires:
  - *Target: ~24% sunlight to CO conversion*
  - *Check back in a few months*





So what might be the Impact?
Does it scale to the size of the Problem?

- What do we need?

1. Land and Sunshine – How much?
   - Estimates indicate little impact on land usage
     - < 25 FT x 25 Ft per vehicle of sunny land or <27 Ft x 27 Ft of average sunshine

     15% US penetration – 0.7M Acres (<1% of New Mexico)
     70% US penetration – 4.6M Acres (~4% of New Mexico)

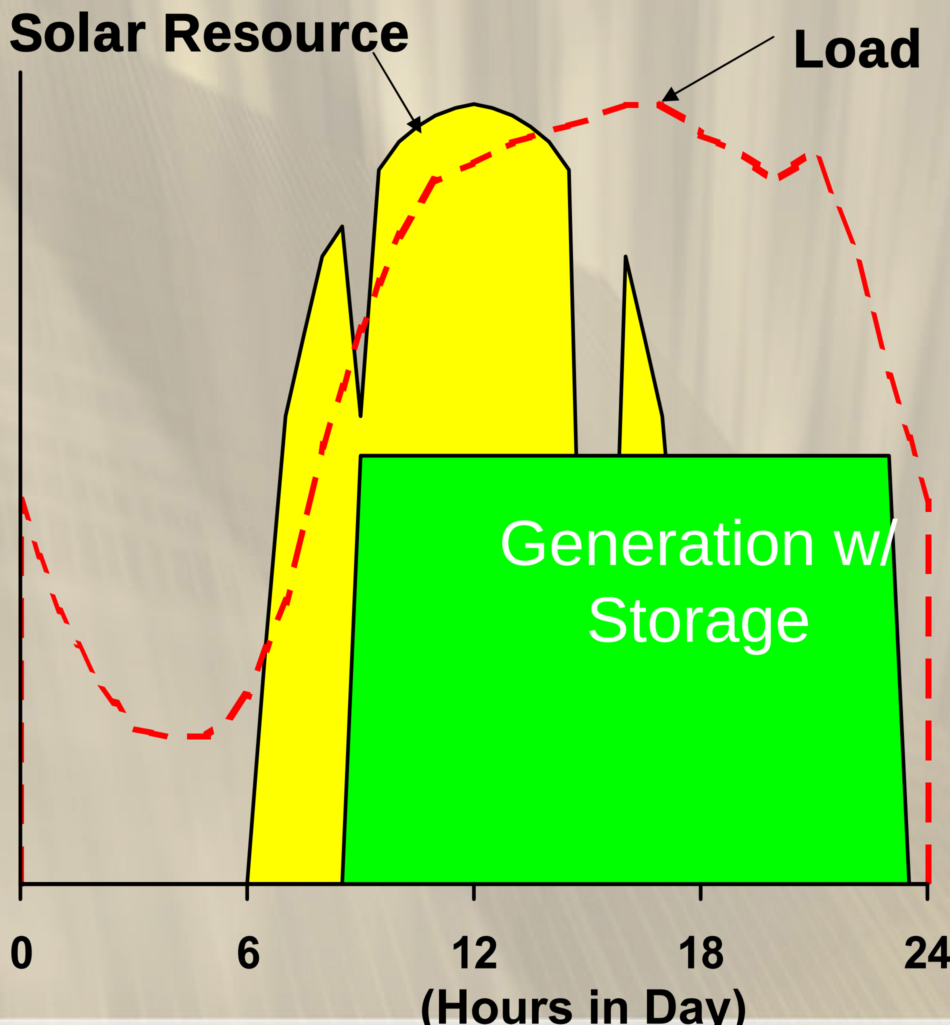
2. CO_2 – Is there enough?
   - More than enough CO_2 – Coal emitted 580 MMT-Carbon in 2006

     15% penetration – requires ~105 MMT-Carbon/Year*
     70% penetration – requires ~490 MMT-Carbon/Year*

3. H_2O – Is there enough?
   - Less than 1% of current domestic use of water

MMT: Million Metric Tons, * Based on 2006 emissions

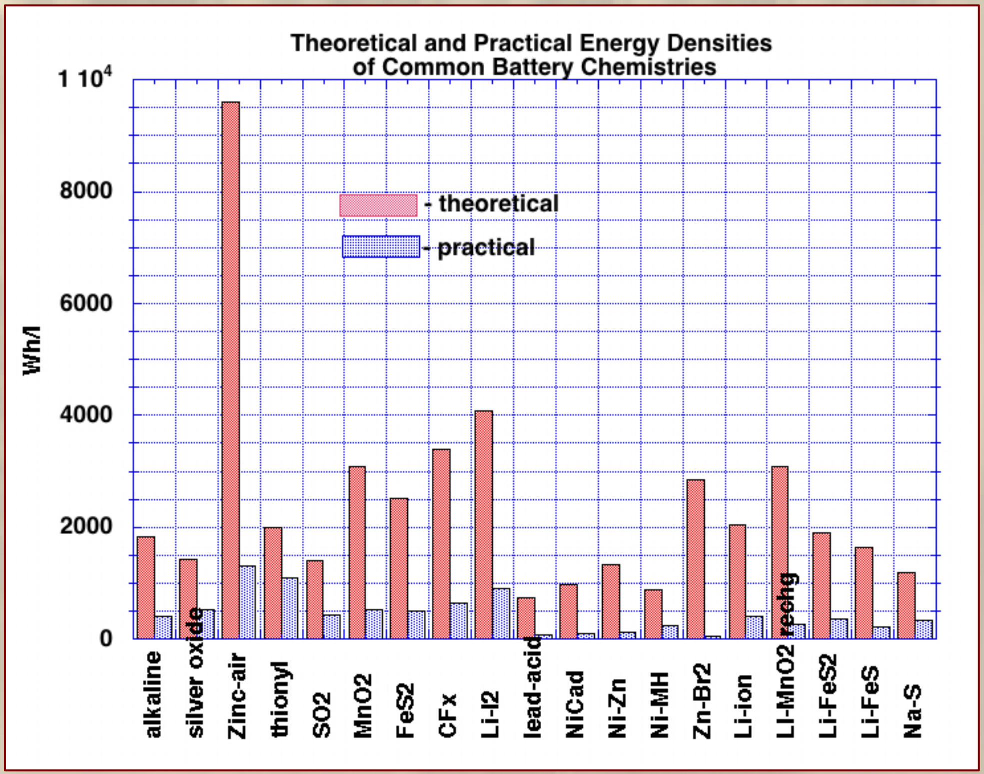
Storage Will Be a Key Component in Realizing Widespread Adoption of RE

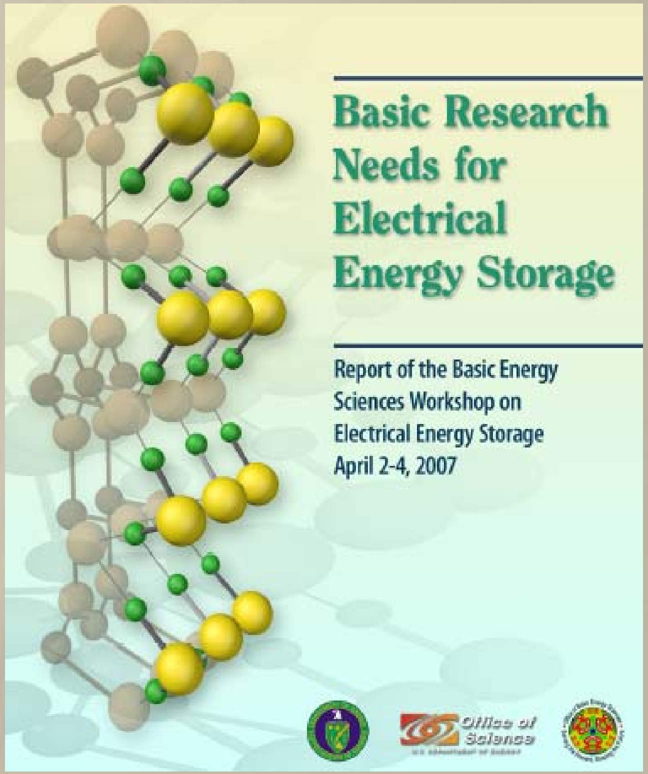


- Storage/hybridization provide
  - Decoupling of energy collection and generation
  - Respond to intermittent Solar resources
  - Higher value because power production can match utility needs

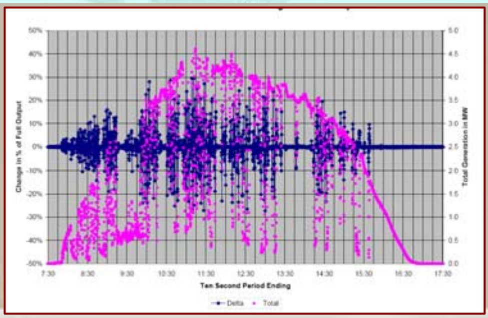
Photovoltaics →	Electrochemical Capacitors Flywheel, …
CSP →	Molten Salt

Advances in Energy Storage Materials-Devices are 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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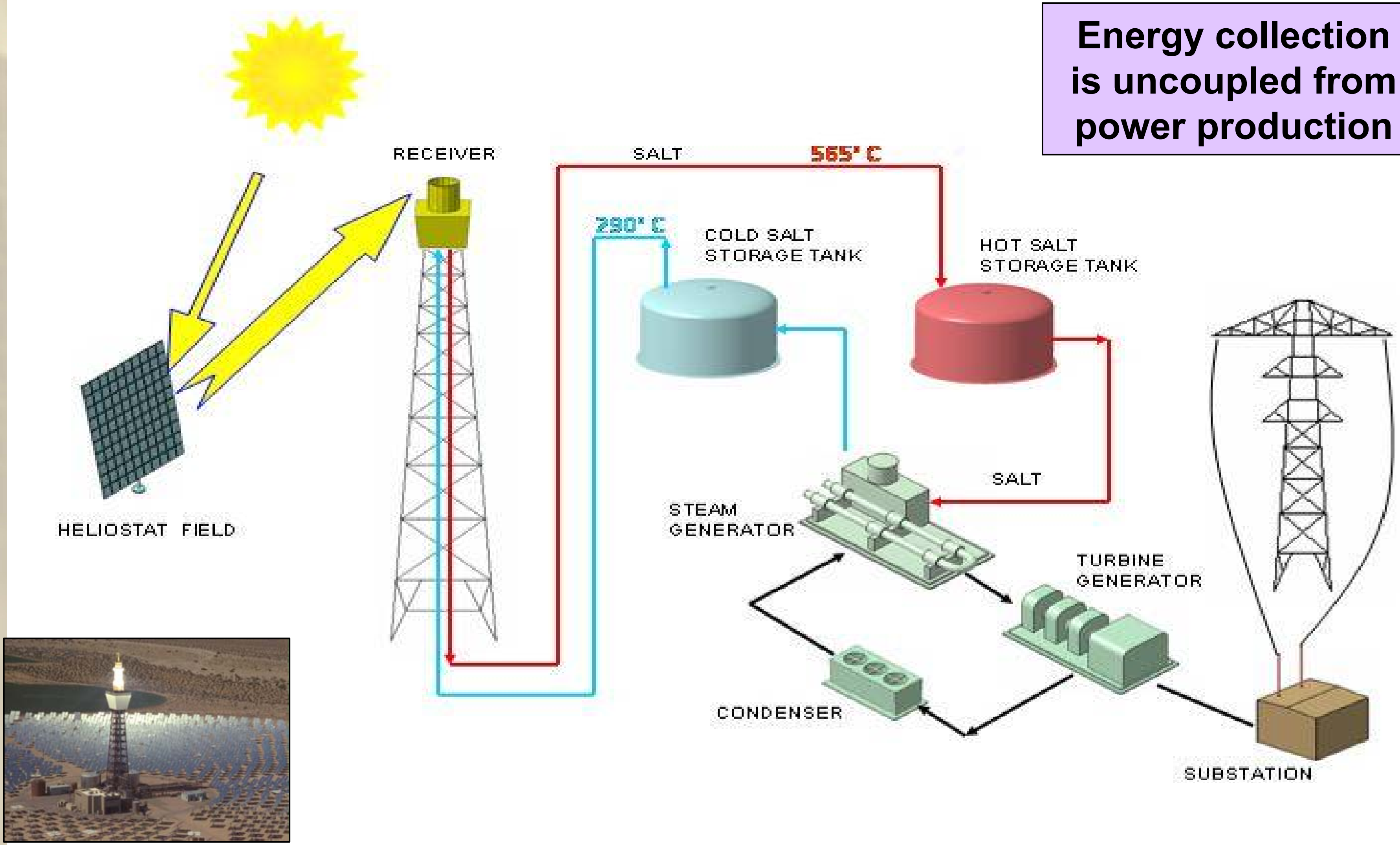
Molten-Salt Power Towers

Energy collection is uncoupled from power production



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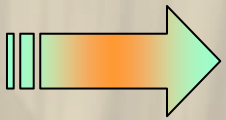
New Molten-Salt Materials are Needed for CSP Trough Systems

Receiver and Fluid Localized in Tower



Receiver and Fluid Distributed Over Field

- η of Storage > 98%
- Dispatchability demonstrated for > 6 days

CSP Storage With Molten Salts

KNO_3–$NaNO_3$–$Ca(NO_3)_2$

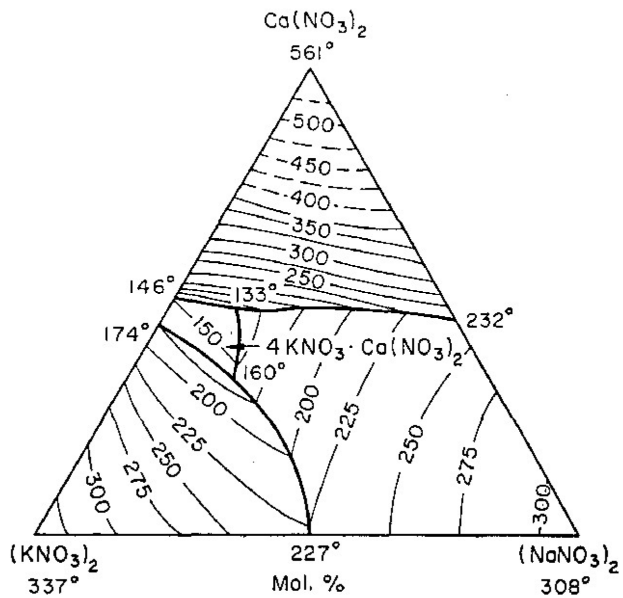


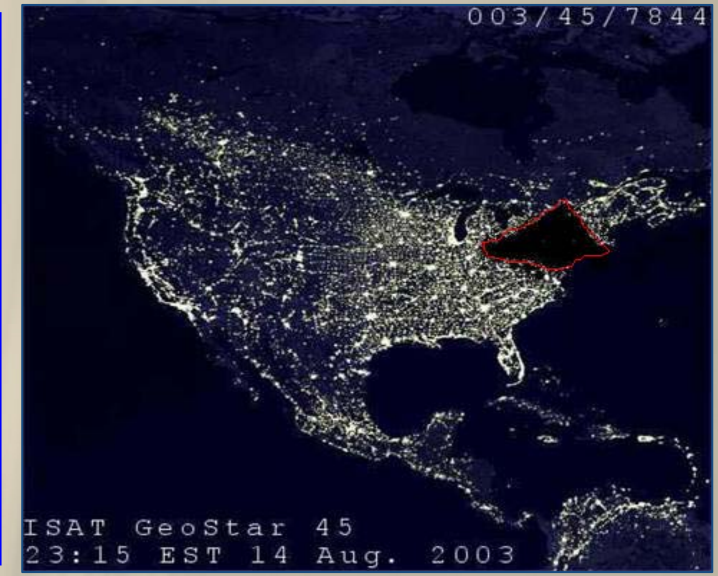
FIG. 1074.—System $(KNO_3)_2$–$(NaNO_3)_2$–$Ca(NO_3)_2$.

A. G. Bergman, I. S. Rassonskaya, and N. E. Shmidt, *Izvest. Sektora Fiz.-Khim. Anal., Inst. Obshchei Neorg. Khim., Akad. Nauk S.S.S.R.*, **26**, 156 (1955).

- Freeze point and freeze/thaw behavior
- Salt disassociation
- Thermal stability
- Viscosity vs temperature
- Thermal conductivity
- Heat capacity

T_f ~ 225 C (current)
T_f ~ 100-150 C (goal)

U.S. Electrical Grid Architecture

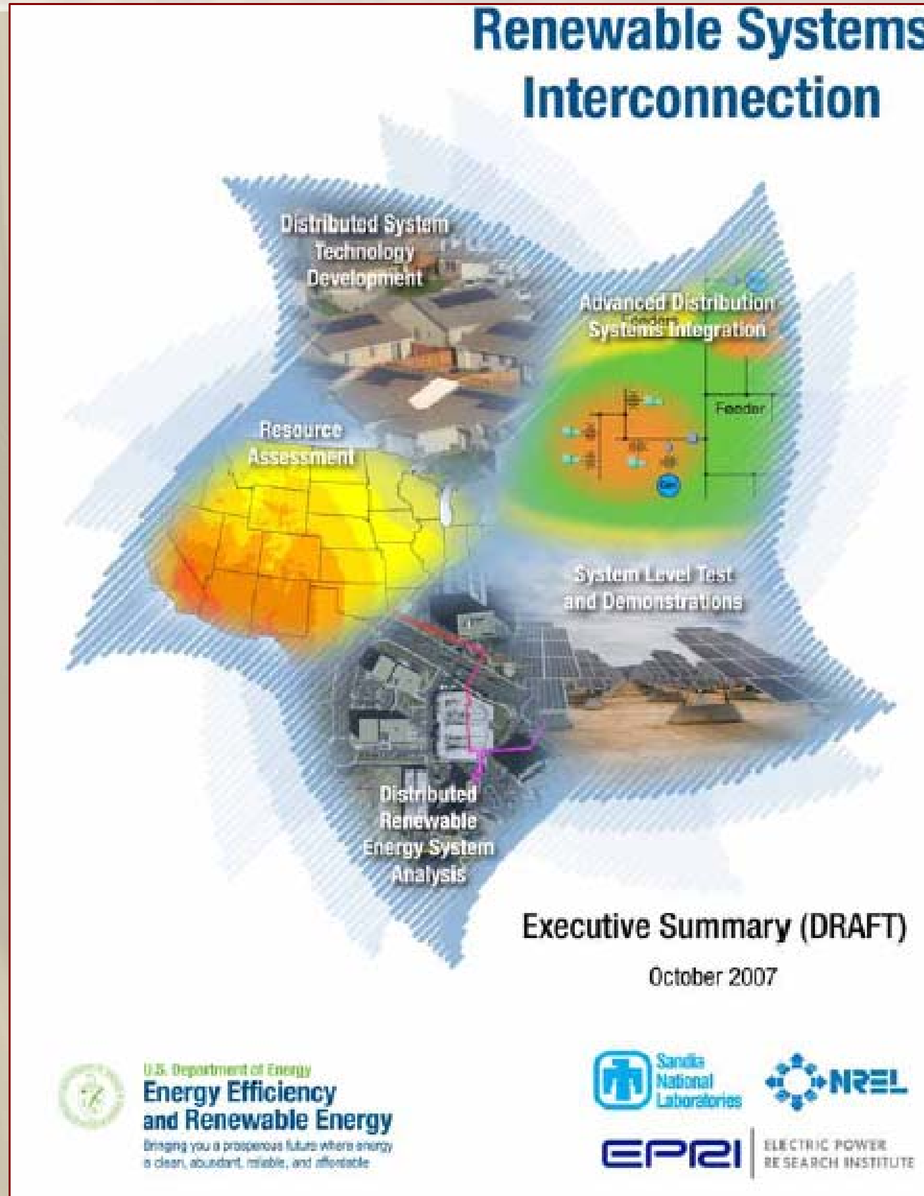


Currently:

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

In the Future:

- Grid will need two way information flow (utility and customer/supplier)
- Storage on generation and load side
- Accomodate intermittent central and distributed generation
- Enable microgrid operations and Islanding



Renewable Systems Interconnection

Executive Summary (DRAFT)

October 2007

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

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NREL
EPRI ELECTRIC POWER RESEARCH INSTITUTE

http://www1.eere.energy.gov/solar/solar_america/rsi.html

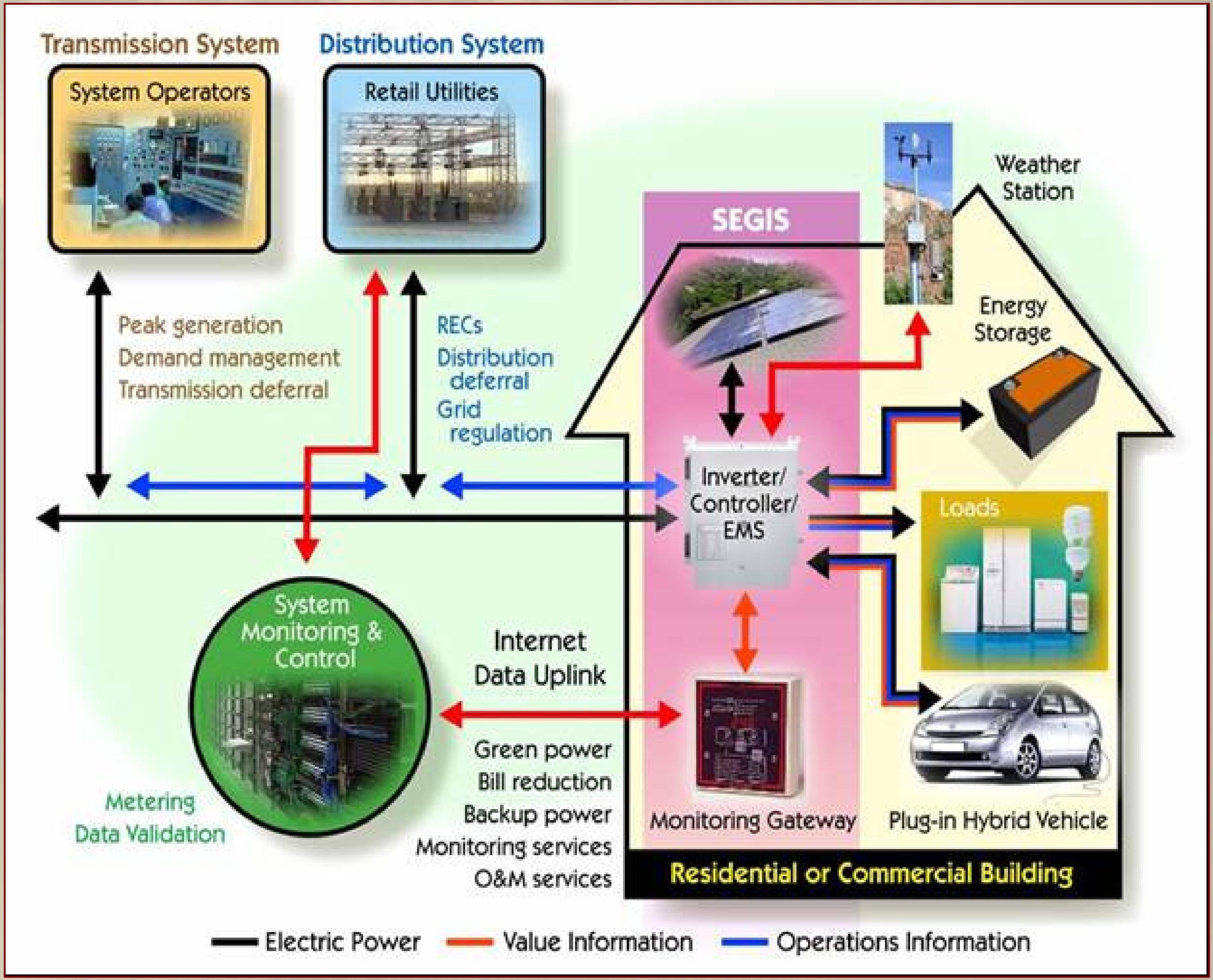
For Further Details Reading, Please See


BASIC RESEARCH NEEDS
TO ASSURE
A SECURE ENERGY FUTURE

A Report from the
Basic Energy Sciences Advisory Committee

**** Other DOE Documents within Each Program Office***

Solar Energy (PV) Grid Integration Systems

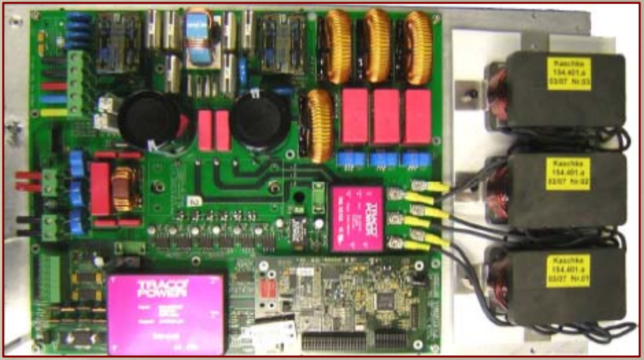


DOE New Initiative 2008 Sandia Led Program

SiC Materials and Devices Will Be Critical For High Reliability Inverters, Grid Control and Energy Management Electronics

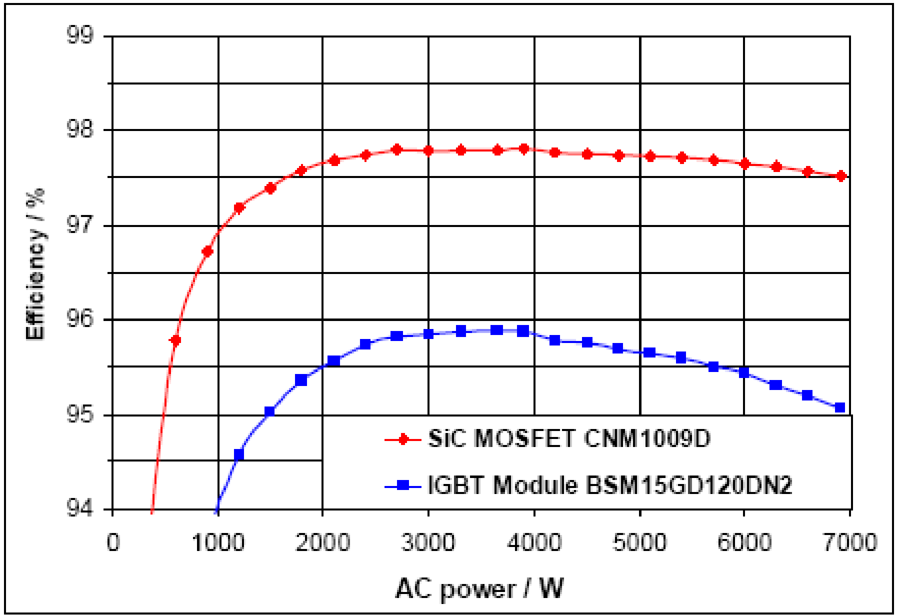
Photovoltaic Inverters with SiC MOSFETs

B. Burger, D. Kranzer, O. Stalter, S. Lehrmann
Fraunhofer Institute for Solar Energy Systems (ISE)
Heidenhofstraße 2
Freiburg, Germany



	1200 V IGBT	1200 V SiC MOSFET	Gain
Max efficiency	95.89 %	97.80 %	+ 1.91 %
Euro efficiency	95.10 %	97.46 %	+ 2.36 %
Mean efficiency	93.95 %	96.77 %	+ 2.82 %
P_{loss}@7kW	350 W	175 W	- 175 W
$T_{Heatsink}$	93 °C	50 °C	- 43 °C
Fit: P_{0_total}	45.6 W	19.1 W	- 26.5 W
Fit: $V_{F/phase}$	3.35 V	2.62 V	- 0.73 V
Fit: $R_{S/phase}$	0.7 Ω	0.255 Ω	- 0.445 Ω

- All measurements including on-board power supply, control electronics and DSP



High Efficiency Multijunction Solar Cells for Concentration

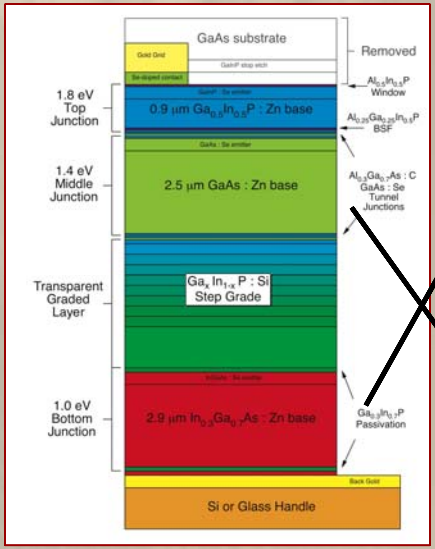
Challenge: Practically use optimal band gaps for 3 or more junctions

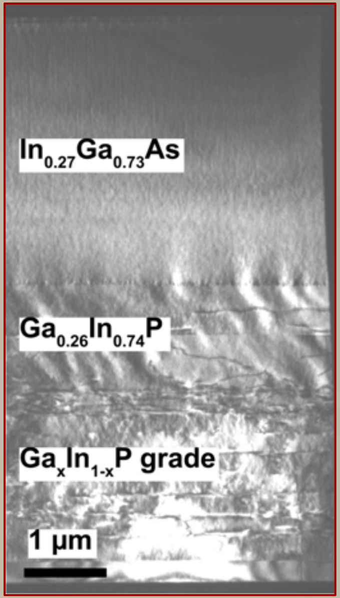
- Spectrum splitting (optics)
- Mechanical stacks (economics)
- New materials such as GaInNAs (understand intrinsic defects that cause efficiency lose)
- Lattice mis-matched materials (strain and dislocation control)

1.8 eV

1.4 eV

1.0 eV





39% efficiency

Inverted growth using graded buffer

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Let's Not Forget Energy Efficiency Efforts

- **Appliances and Equipment**

- **High Performance Buildings**

- **Zero Energy Buildings**

- **Lighting**

- **Advanced Combustion, Hybrids, and Light Weight Materials**

- **…**

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