SAND2009-0092C

ENERGY, RESOURCES and NONPROLIFERATION

energy, water, and security . . . enabled by science & technology

Implications from the Frontiers of Nano Science and Technology for the Energy Sector

Grace Hopper Celebration of Women in Computing

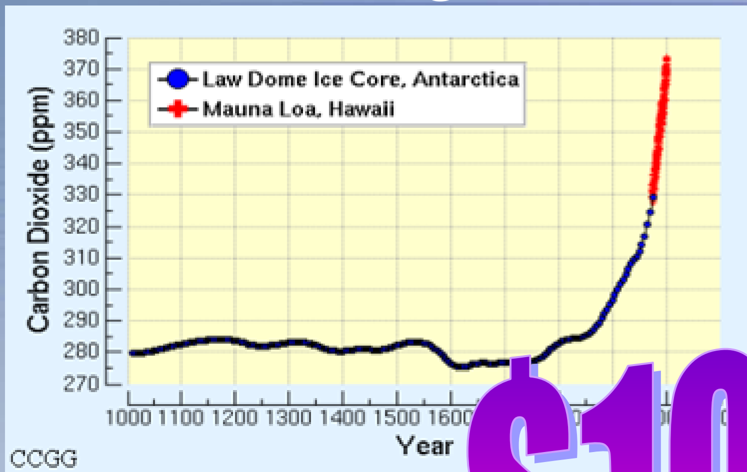
Ellen B. Stechel

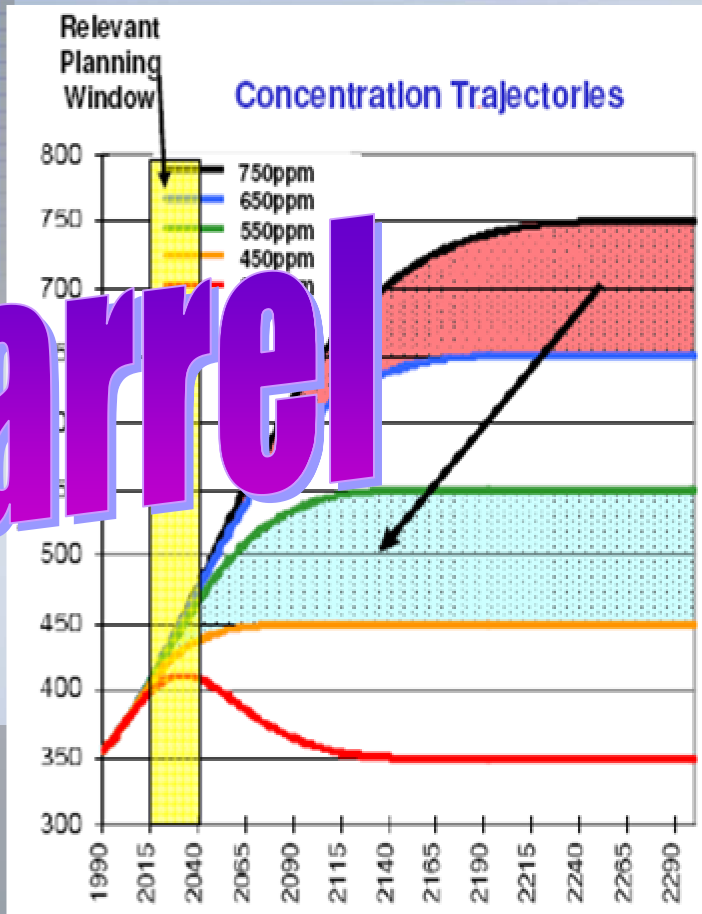
October 3, 2008

Sandia National Laboratories

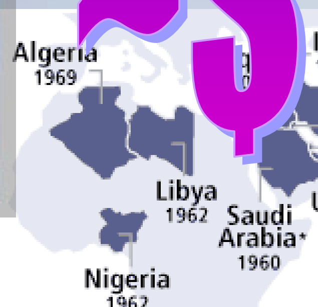
Energy and Climate Change are National Security Issues

Climate Change…





~$100/Barrel



Energy Security…

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Energy is the Forgotten Crisis: May 1996

“Our nation's complacency about the energy problem is dangerous. While the understandable result of currently abundant supplies of energy at low prices, such complacency is shortsighted and risky. “

The Council of the American Physical Society urges continued and diversified investments in energy research and development, as well as policies that promote efficiency and innovation throughout the energy system. Such investments and policies are essential to ensure an adequate range of options in the decades ahead. Our national security, our environmental well-being, and our standard of living are at stake.

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Our Actions are Not Commensur-ate with the Threat

- No obvious enemy threatening to kill us
- No abrupt event or wake-up call
  - At least not yet
- Snuck up on us as a series of continuous changes
  - Masking the overall magnitude of change
- Does not invoke visceral feelings of moral outrage

Unprecedented in Combination of Scale, Complexity, Importance, and Urgency

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And Stimulate a New, Long-Lasting Economic Boom

- **First must recognize and properly characterize the threat**
- **Then Commit to Rise to the Challenge**
- **Then Act Rapidly**
  - **Needs coordinated, and deliberate actions**
  - **From many actors**:
    - Governments (federal, state, international)
    - Non-Governmental Organizations
    - Industry

New low carbon economy, that can co-exist with the current fossil economy, permitting a smooth transition to sustain economic growth and prosperity

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We Must Rise to a Dual Challenge

- **Assuring Energy Security**
  - E.g., by increasing use of domestically available energy resources
- **Mitigating Climate Change**
  - E.g., Reducing the growth of atmospheric concen-trations of Green House Gases: mostly CO_2

		Climate Change		
		Makes Worse	Neutral	Mitigates
Energy Security	Assures			
	Neutral			
	Makes Worse			

Unprecedented combination of scale, complexity, importance, and urgency

Grasping the Scale of World Energy Consumption: Today

- **Average Rate ~15 Tera Watts**
  - **$1.5\ 10^{10}$ Kilo Watts**
  - **450 Quads/Year**
    - **1 Quad ≡ 10^9 BTU ≡ 172 Million BOE**
- **Population ≅ 6.65 Billion People**
- **Average per Capita Energy Consumption**
  - **~2.25 Kilo Watt/Person ≡ ~11.6 BOE/Person/Year**
- **~80-85% of energy comes from non-renewable energy sources**
- **A US vehicle uses on average ~10.8 BOE/Year**
  - **At 12500 Miles/Year and 25 mpg**
- **US Population ~300 Million persons**
  - **3.3 TW or ~100 Quad/Year or ~11 kW/person**
    - **15% for personal vehicles**

Slides 8-10

Slide 11

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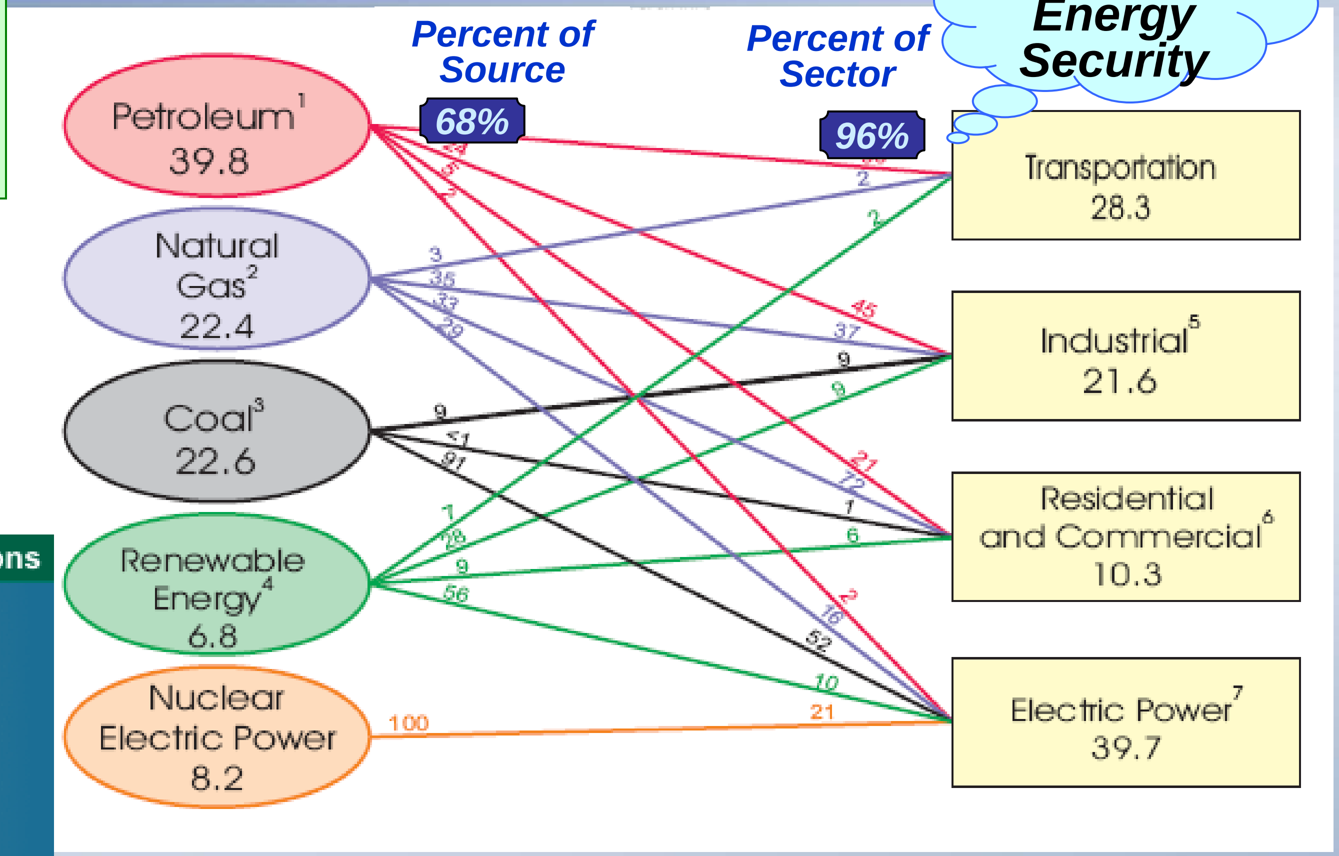
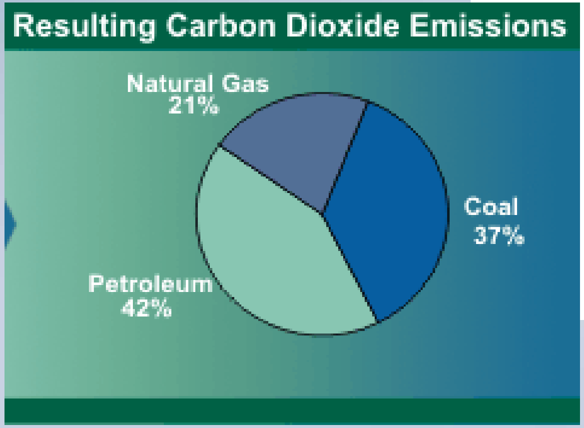
Decomposing Primary Energy Consumption in the US

US Primary Energy Consumption, 2006



Climate Change Concern



99.8 Quadrillion BTU/Year ~ 3.3 TW

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

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Transportation Sector Consumes a Great Deal of Petroleum

Every day the U.S. consumes ~20.6 million barrels of petroleum (2006) (that's ~10K gallons per second)

Over 2/3 (68%) of the petroleum consumed in the US is used for transportation

60% is imported

235M vehicles on the road in the US:

Median age ~8 yrs;
Median Lifetime of 1990 vehicles is ~17yrs

All Substitutes that meet the dual challenge face significant technical, economic, societal, political, & regulatory barriers, uncertainties, and risks

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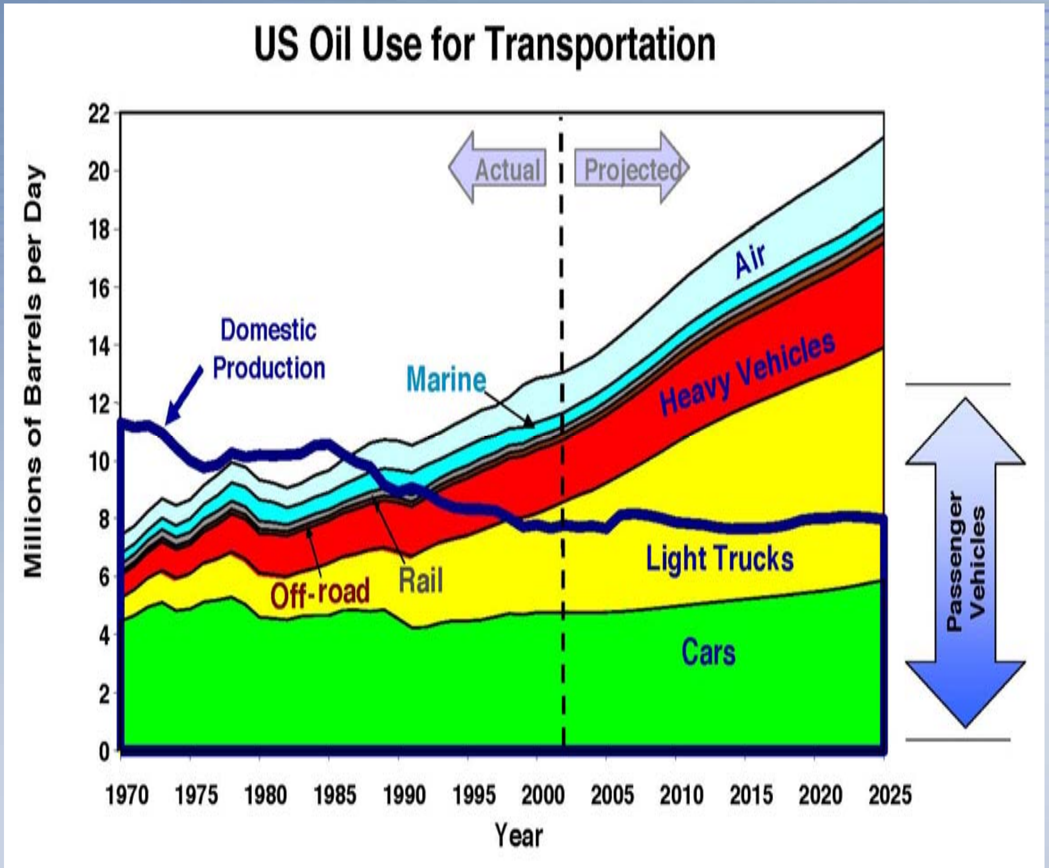
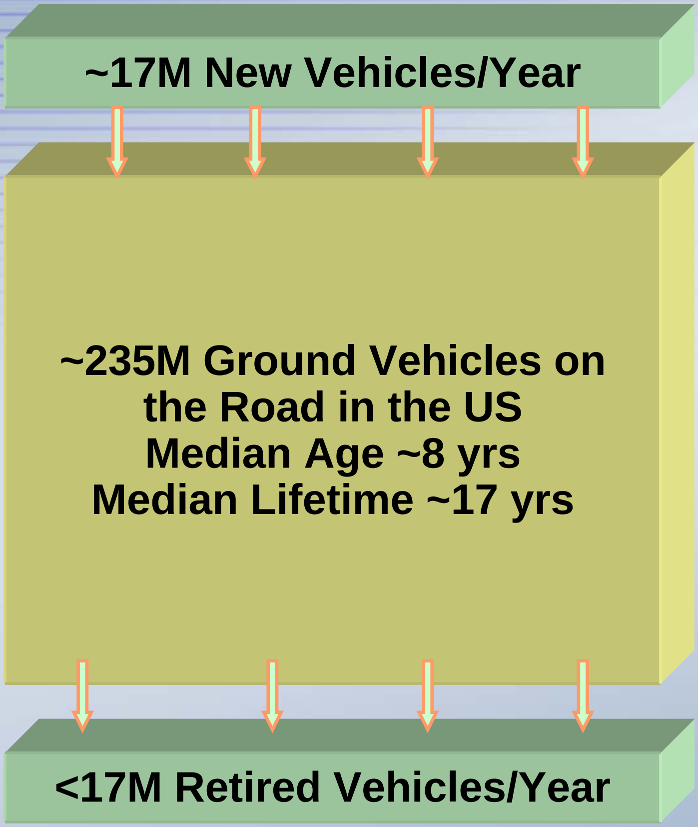
Petroleum Based Fuels are not Going Away Anytime Soon





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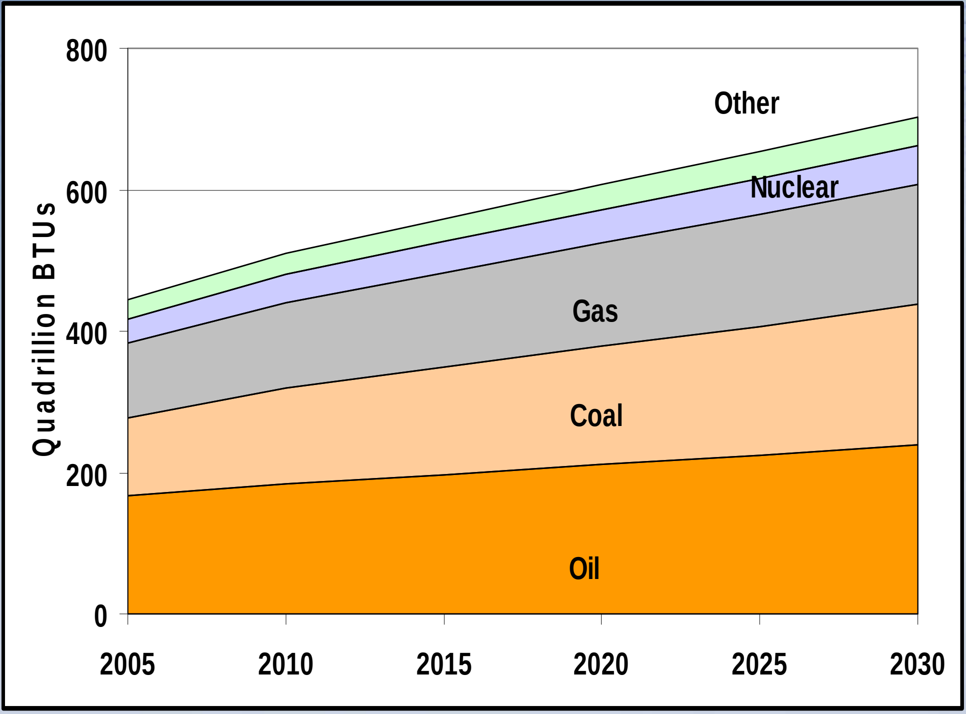
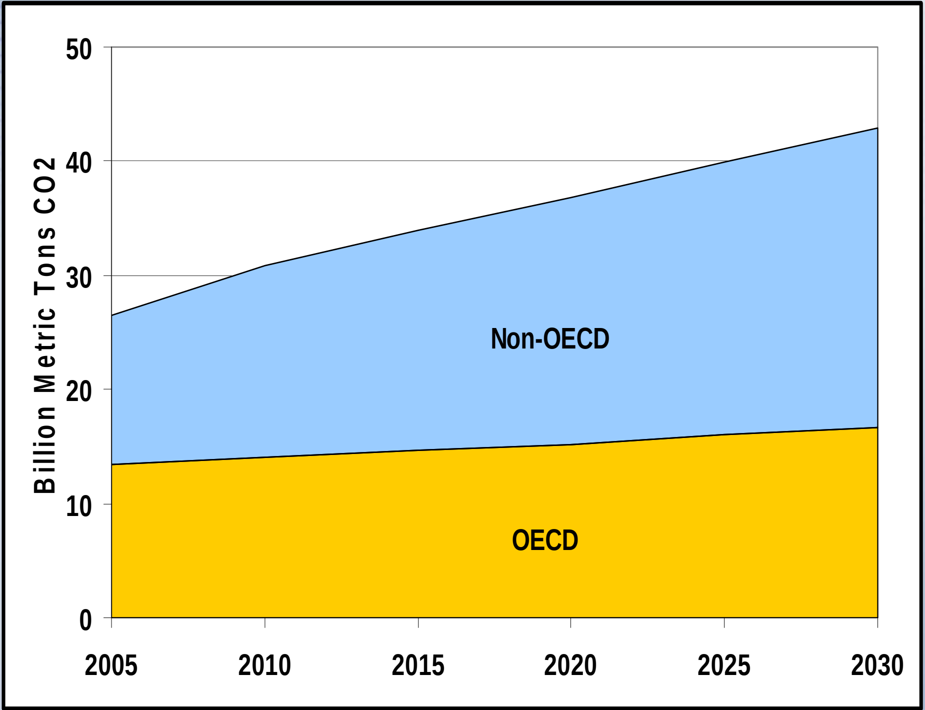
Between Now and 2030, World Energy Demand and Carbon Emissions Could Grow ~65%

Global Energy Demand



Global Carbon Dioxide Emissions



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

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Nanoscale Science, Engineering, and Technology as a Catalyst for Revolutionary Breakthroughs

"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."

Neal Lane, former Science Advisor

As revolutionary in transforming society as was:

Electricity
Transportation
Computing
Communications

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Grasping the Scale of World Energy Consumption: 2050

- **Population ~10-11 Billion People**
- **If 50% of today's US per capita**
  - **The Need is then ~60 TW (~4x today)**
  - **Most of the increase Carbon Neutral**
- **To Halve US Per Capita - ~1.5% yoy energy intensity reductions**
  - **More efficient production, distribution, end-use**
  - **Waste less along the way or at end use**
- **Expect demand will be more like 30 TW**
  - **~2.7 kW/person or ~21% more than today**
  - **Most likely – many have nots**
  - **To be equivalent to US Standard of Living today - ~3% yoy energy intensity gains**

Humanity's Top Ten Problems for the Next 50 years

- **ENERGY**
- **WATER**
- **FOOD**
- **ENVIRONMENT**
- **POVERTY**
- **TERRORISM & WAR**
- **DISEASE**
- **EDUCATION**
- **DEMOCRACY**
- **POPULATION**

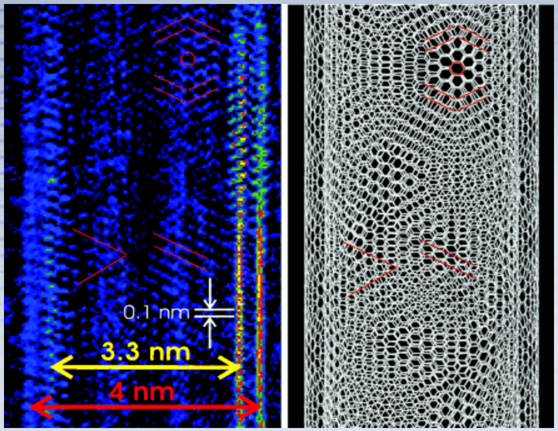
Slide 45

2004 6.5 Billion People
2050 ~10-12 Billion People

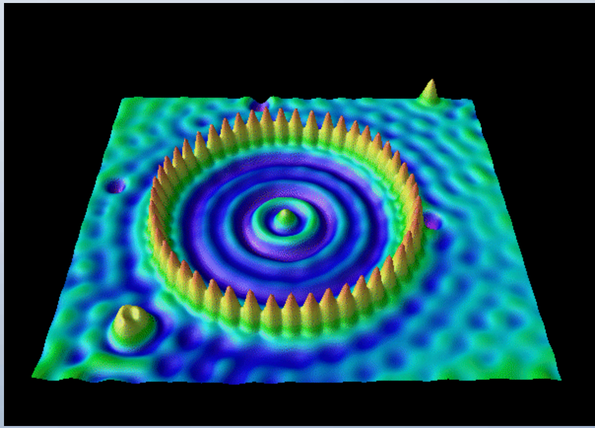
Borrowed from one of Smalley's numerous presentations

What Is Nanotechnology?

- Research and technology development aimed to work at atomic and molecular scales, in the length scale of approximately 1 - 100 nanometer range
- Ability to understand, create, and use structures, devices and systems that have fundamentally new properties and functions because of their nanoscale structure
- Ability to control – to see, measure, and manipulate – matter on the atomic scale to exploit those properties and functions
- Ability to integrate those properties and functions into systems spanning from nano- to macro-scopic scales



Nanoarea Electron Diffraction of DW Carbon Nanotube – Zuo, et.al



Corral of Fe Atoms – D. Eigler

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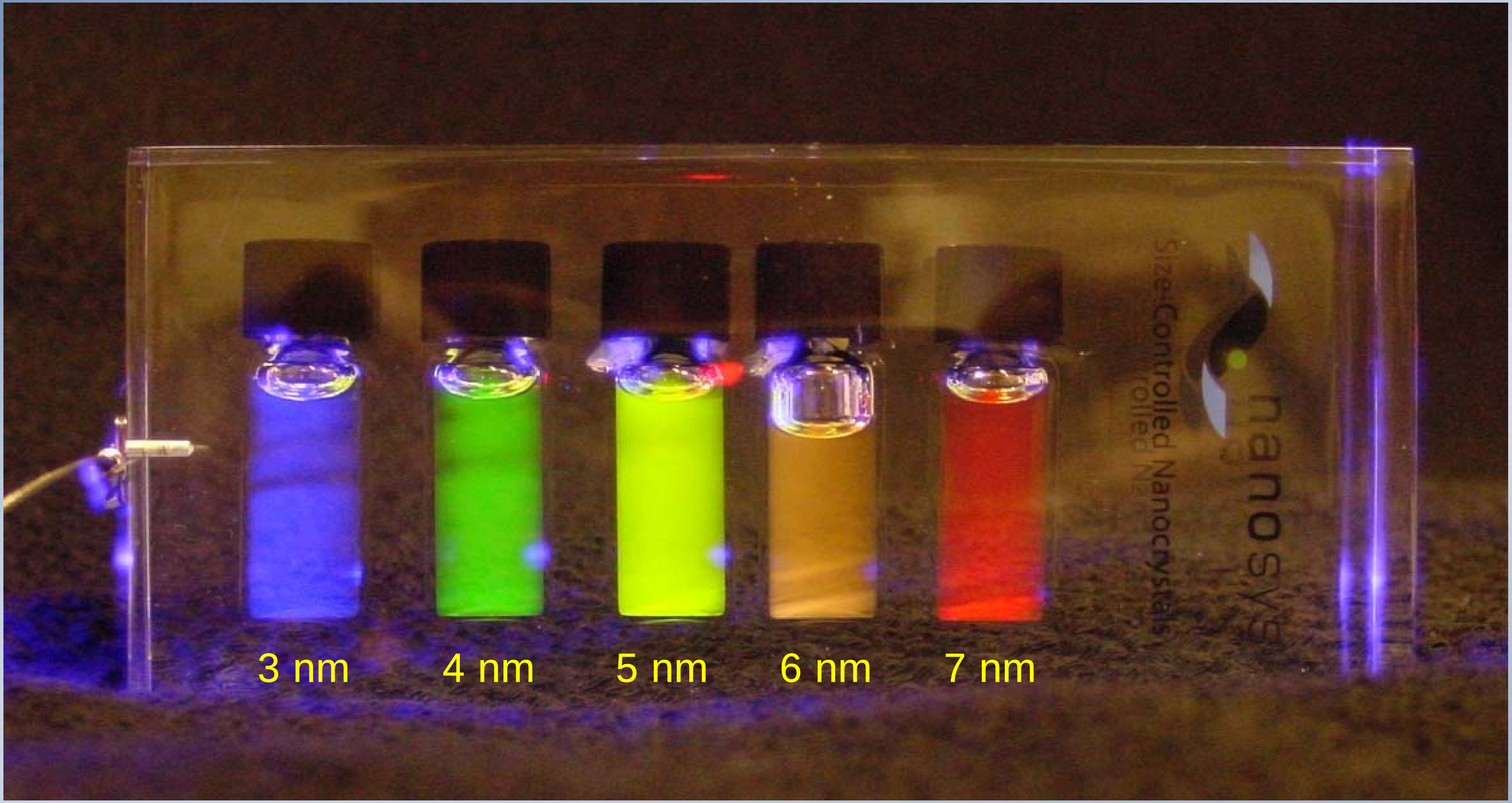
Unique Properties Derive From Nanoscale Dimensions

Illustration of Quantum Size Effect in Cadmium Selenide



Color of fluorescence determined by size of particles and type of material

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History of Nanotechnology

Richard Feynman After Dinner Talk APS
"why can we not write th
entire 24 volumes of th
Encyclopedia Brittannic
on the head of a pin?"

Norio Taniguchi coined the term nanotechnology

First Nanotech Organization, Forsight was formed

Spelled out using individual Xenon atoms arranged using an STM

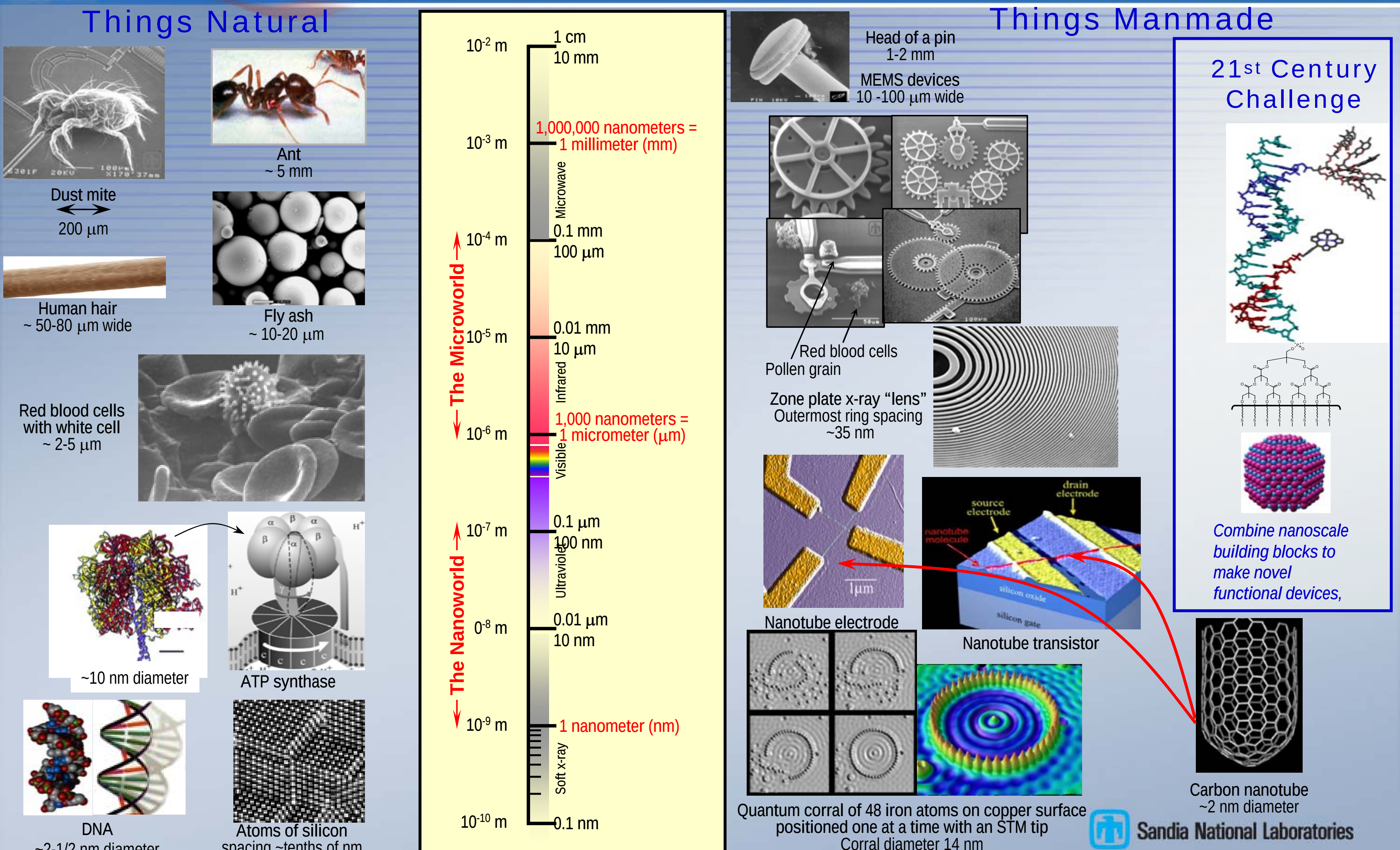
- 1959 — Start
- 1974 — Coined the Term
- 1981 — STM Invented
- 1985 — Buckeyball Discovery
- 1986 — AFM Invented
- 1987 — 1st Protein Engineered
- 1989 — IBM Logo
- 1990 — 1st Nanotech Journal
- 1991 — Nanotube Discovered

Slides 18-19

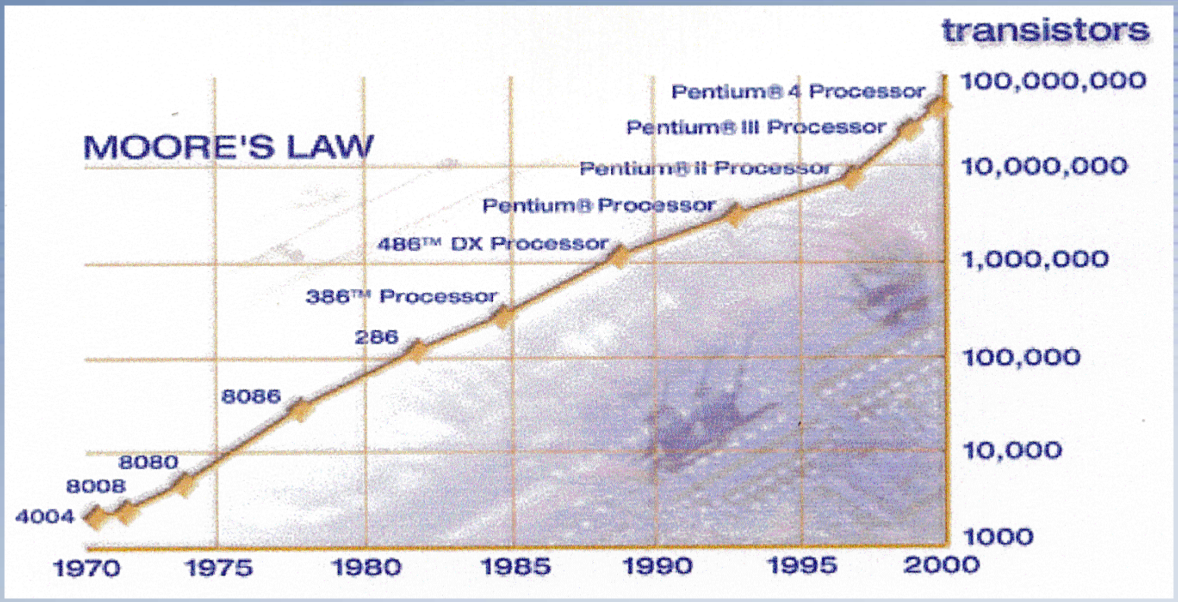
Slides 20-21

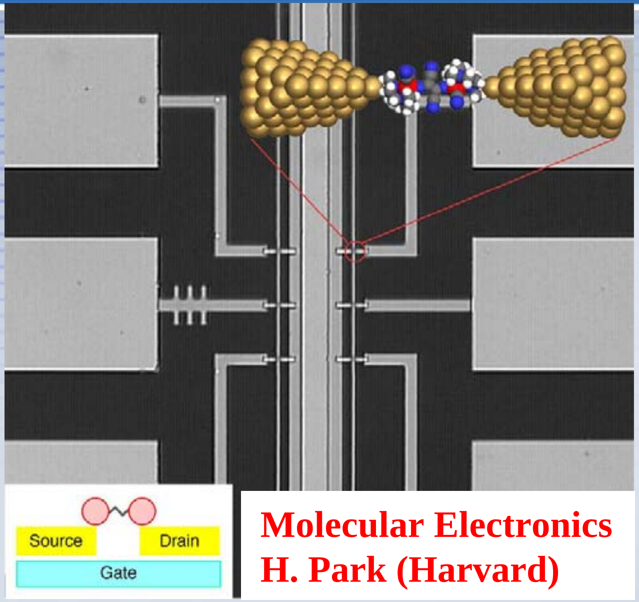
Slides 22-23

The Scale of Things -- Nanometers and More

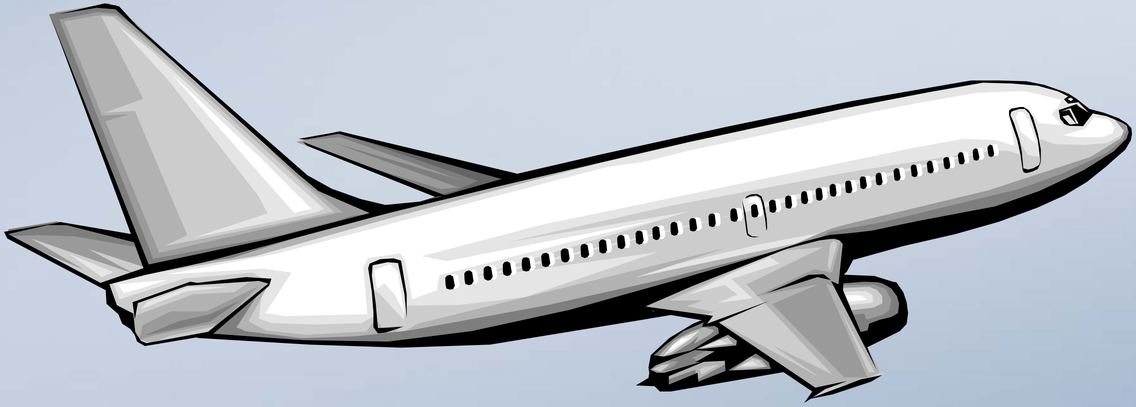


Nanoelectronics





Molecular Electronics
H. Park (Harvard)



If the aircraft industry had evolved at the same rate as the microelectronics industry in the last 25 years, a Boeing 777 today would cost $500, and circle the globe in 20 minutes on 5 gallons of fuel.

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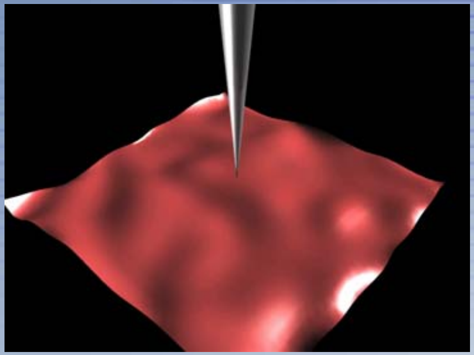
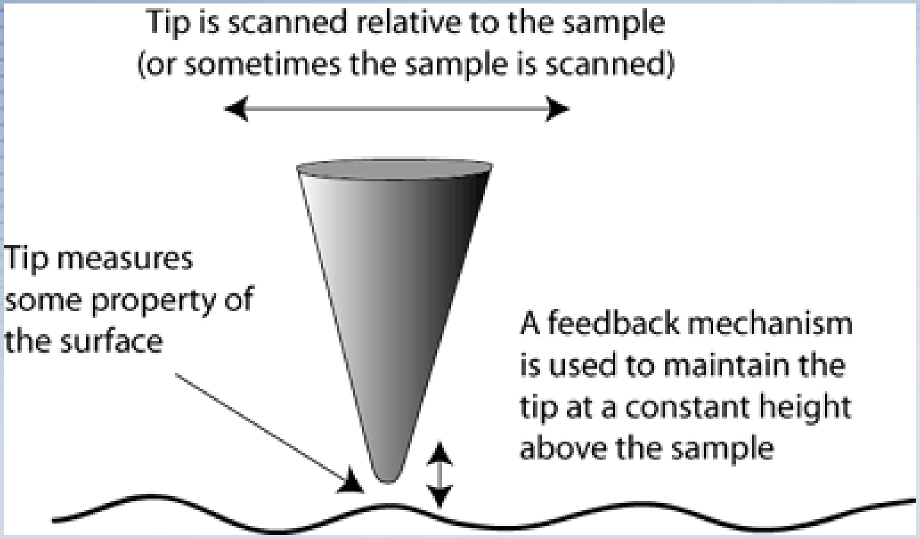
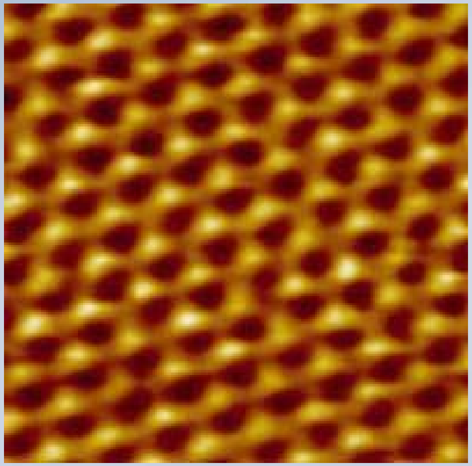
Scanning Tunneling Microscope







1981 STM invented by Binnig and Roher
1986 Nobel Prize in Physics

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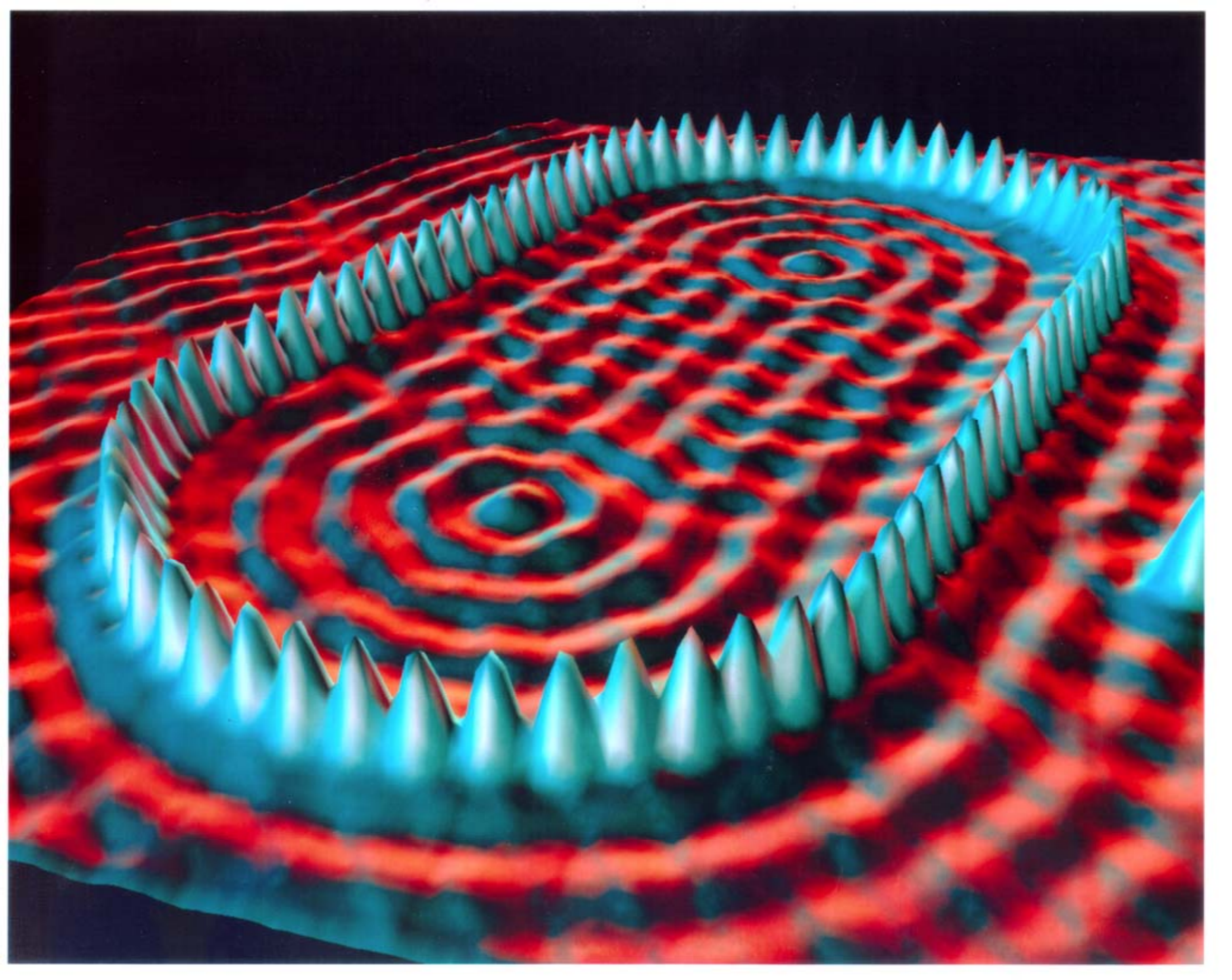
STM manipulation of atoms



Slide from D. Eigler

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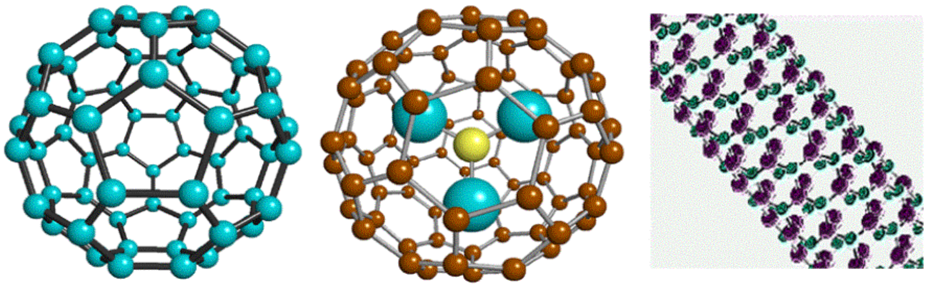
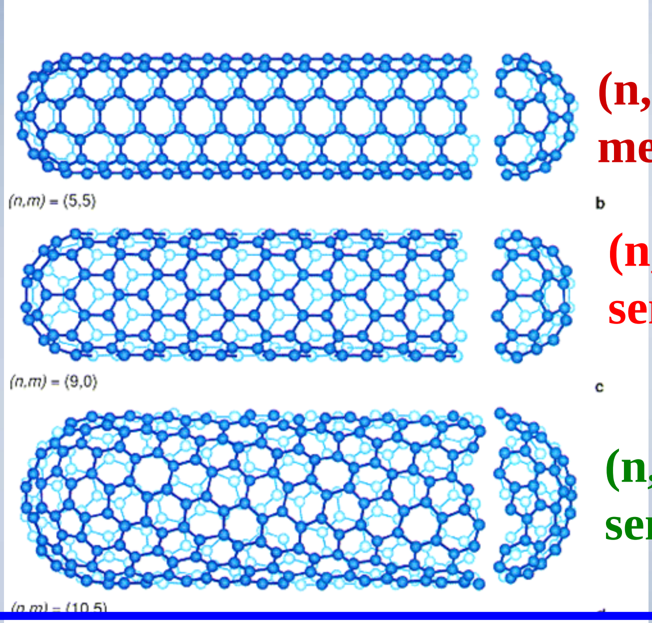
Carbon Nanomaterials



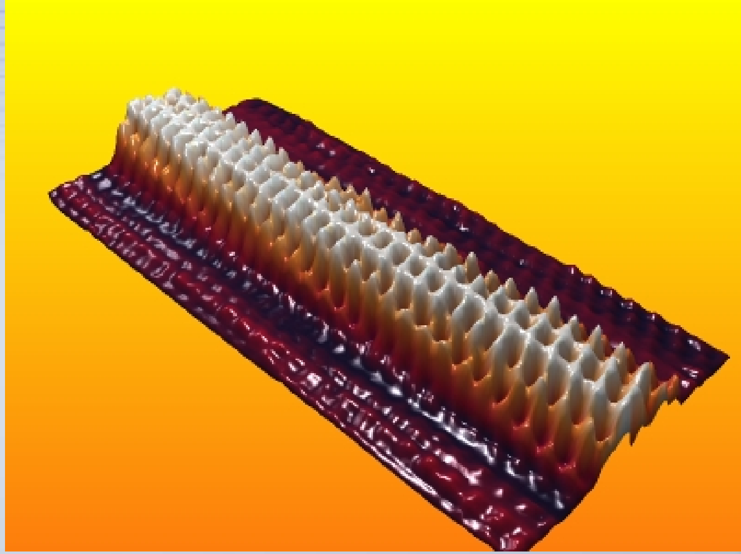
C_{60} Fullerene | $Sc_3N@C_{80}$ Metallofullerene | Carbon Nanotube



(n,m) = (5,5)
metal

(n,m) = (9,0)
semimetal

(n,m) = (10,0)
semiconductor



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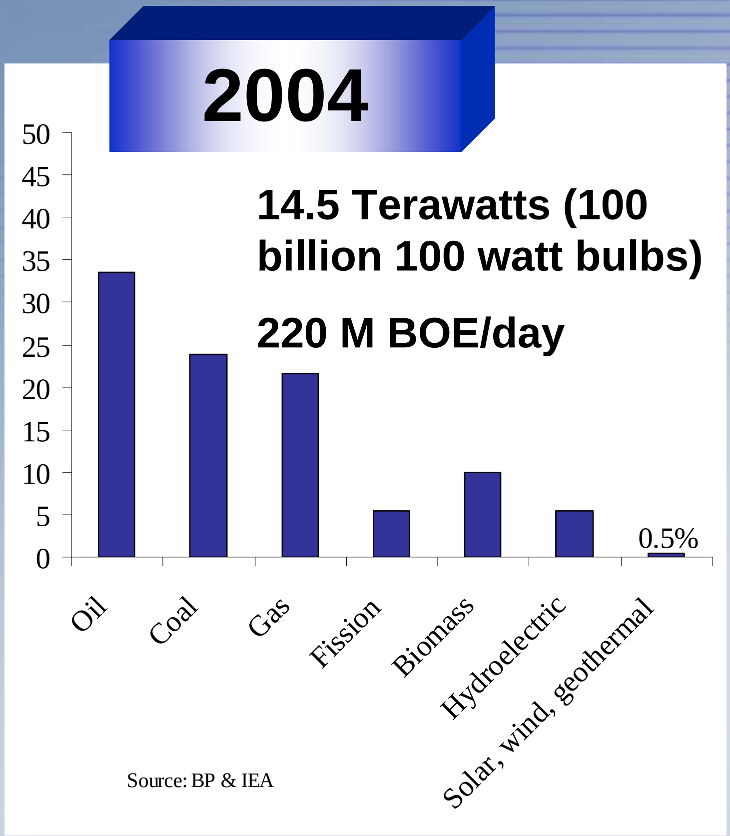
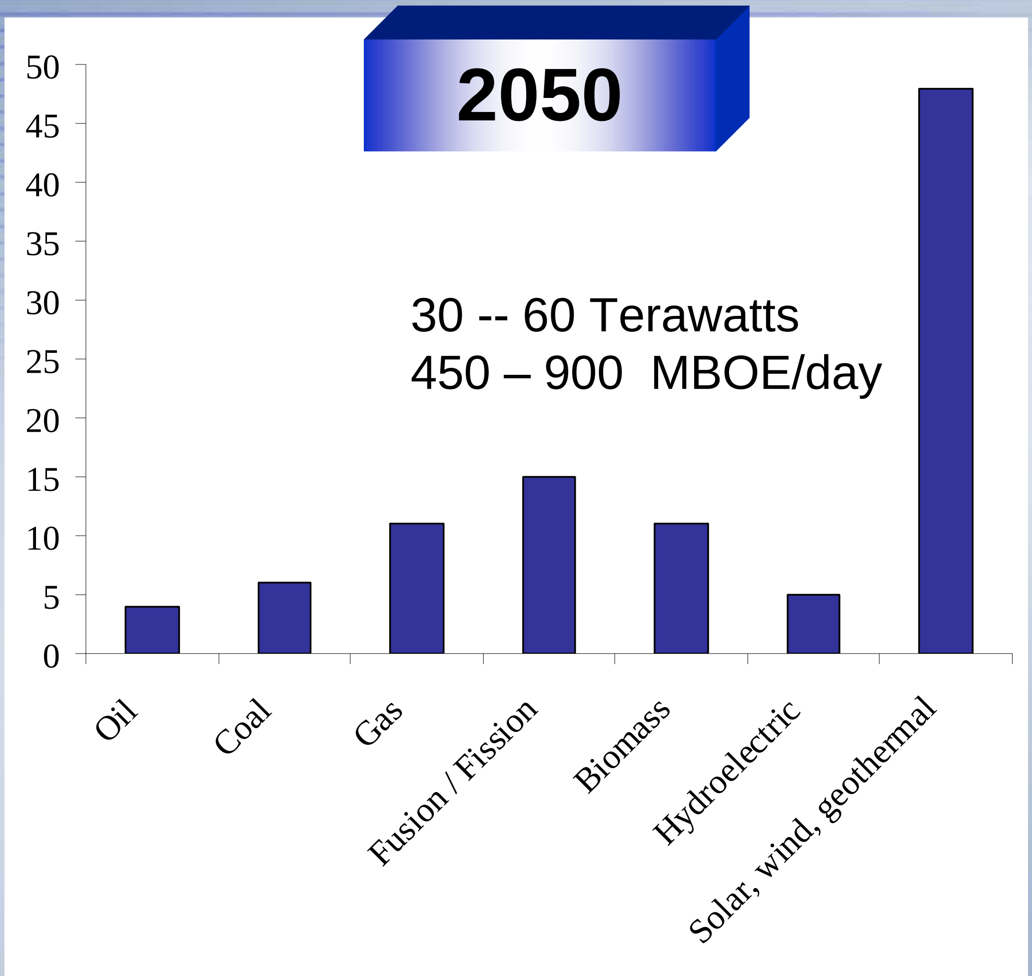
Use "Magical" Properties of Nanotubes

- **Ten times tensile strength of steel with about 1/6 the mass density**
- **Up to 20 times electrical conductivity of copper with about 1/6 the mass density**
- **Thermal conductivity close to that of diamond, the current champ**

Property	SWNT	Copper	Aluminum	Steel
Electrical Conductivity	1- 20	1	0.63	0.1
Mass Density	0.16	1	0.3	0.88
Thermal Expansion	- 0.125	1	1.4	0.7
Thermal Conductivity	0.05 - 5	1	0.3 – 0.6	0.11
Tensile Strength	15	1	0.8	1.6
Bulk Modulus	10 - 20	1	2.7	5

We do Need an Energy Revolution





The Basis of Prosperity

20st Century = OIL

21st Century = ??

Slide modified from R.E. Smalley

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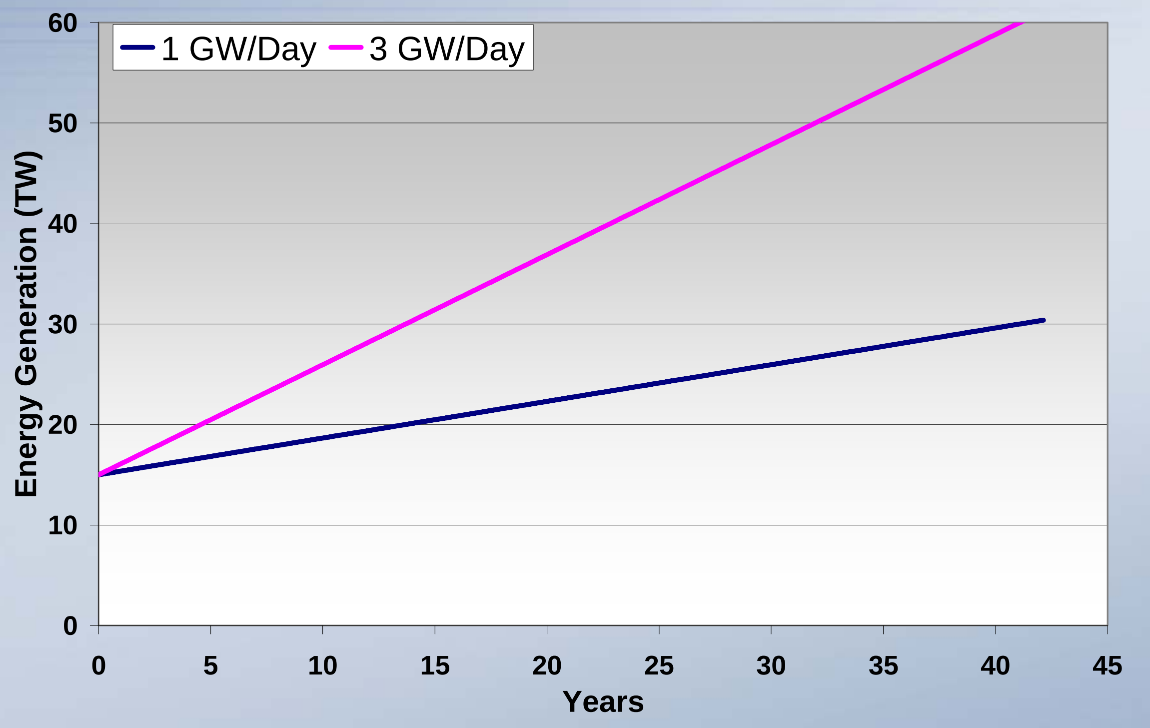
But it is a Daunting Challenge

- Installing daily 1 GW/day of new energy generation to get to 30 TW by 2050 and 3 GW/day to get to 60 TW
- 15% Efficient PV would require ~10 sq-miles/day to generate 1 GW/day



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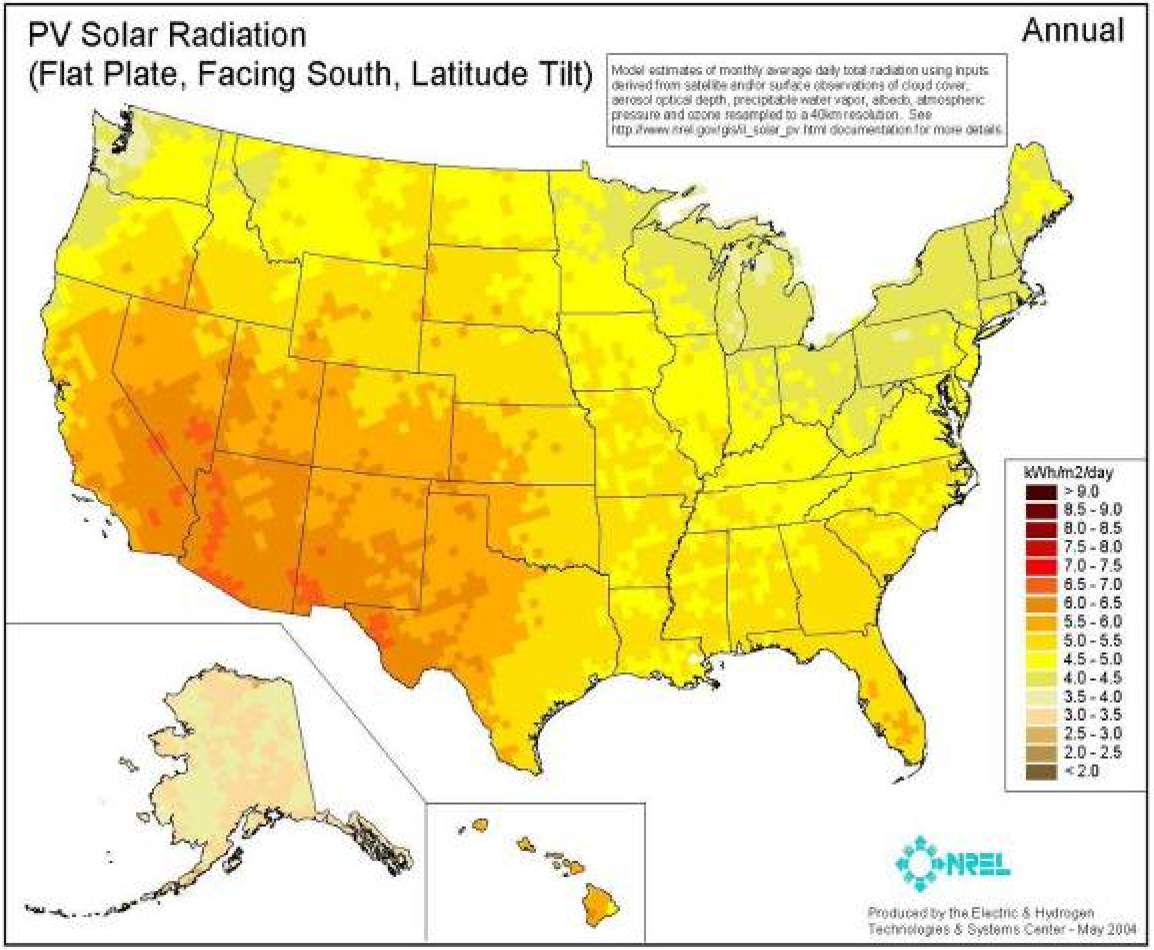
U.S. and World-Wide Solar Resources Greatly Outweigh the Energy Used

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.
- ✓ Covering the same amount of land on the earth (115K sq-mi) with 10%-efficient solar to fuels technology would provide the equivalent of today's world's production of petroleum.

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Nanotechnology Enabled Breakthroughs Needed

- **Scalable technologies to use sunlight to split water and/or CO_2 to produce a renewable form of liquid hydrocarbons** Slides 30-32
- **Highly selective catalysts for clean and energy-efficient, minimum waste, manufacturing, processing, and refining** Slide 33
  - Nature does it with 100% selectivity
- **Scalable technologies to harvest the sunlight with 20% conversion efficiency to electricity and 10-100 times lower cost, with greater durability and flexibility** Slide 34
- **Solid state lighting everywhere to provide greater than 50% savings in the energy demand for lighting** Slide 35
- **Super strong and lightweight materials to greatly reduce energy demand for transportation**
  - Also enable space solar energy in geo-synchronous orbit – 24/7/265 solar beamed back to earth
- **Reversible hydrogen or carbon dioxide storage materials with low energy penalty to release the stored gases**
- **Low loss and high power transmission lines, possibly based on carbon nanotubes** Slide 34
- **Low cost and high efficiency fuel cells with very little or even no precious metals** Slide 36
- **High energy and high power density batteries and ultra-capacitors to store electrical energy providing the capability to load level the demand and buffer intermittent renewable energy sources (such as solar and wind.)** Slides 38-41

More Nanotechnology Enabled Breakthroughs Needed

- **Efficient thermoelectrics that can convert low-grade waste heat to electricity**
- **Efficient separation technologies including mining CO_2 from the air at near the thermodynamic minimum energy** Slide 42
  - or creating new water from salt water or waste streams
- **Actinide separation technologies for revolutionizing nuclear fuel reprocessing and maybe even mining uranium from the ocean**
  - and other rare materials
- **Materials that can withstand extreme environments**
  - nuclear fission and fusion reactors
  - for deep drilling to mine geothermal heat from the earth Slide 43

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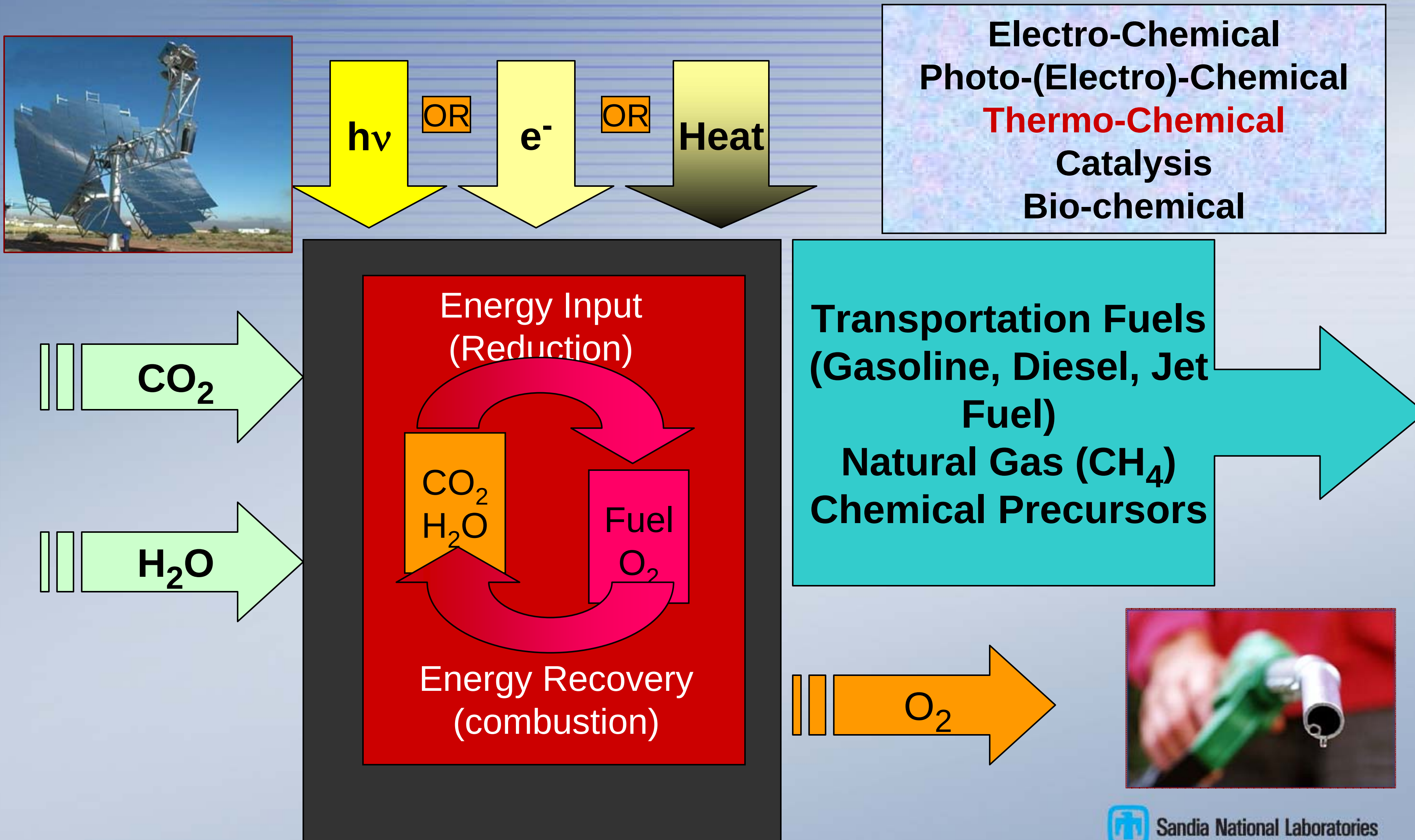
Solar Driven CO2 to Fuel and Back
Biofuels Without the Biology



All Fuels are Essentially Stored Sunshine
Fossil Fuels – Stored Buried Sunshine

- Each gallon of gasoline is equivalent to 100 tons* of prehistoric biomass, processed at low temperature for millions of years
  - Ancient stored solar energy
- Effective Conversion Efficiency ~2×10^{-4} %
  - We don't have millions of years to make what we are burning in centuries
- Corn Ethanol Conversion Efficiency ~0.1%
  - Lot better
- But can we improve on that efficiency even more by using chemical processes? 10%?
  - E.g. Solar driven thermo-chemical processes

*JEFFREY S. DUKES, *Climatic Change* **61:** 31–44, 2003.

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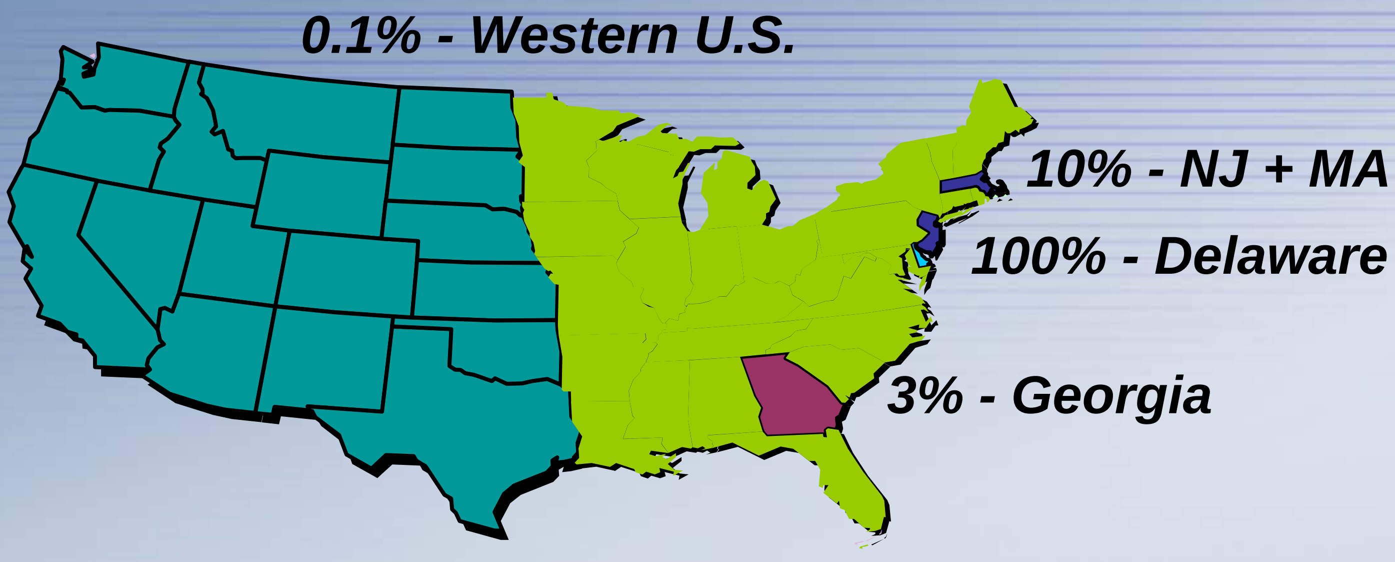
Energy Efficiency (Sunlight to Fuel) is the Key Consideration



Nominal Equivalent Land Area Required to Produce 20 mbpd at a given efficiency.

Sunlight to fuel efficiency assuming solar resource equivalent to Albuquerque – 2600 kWh/m^2/yr.
U.S. Petroleum consumption - 20 million bbls/day

Bio-ethanol routes currently < < 1%.

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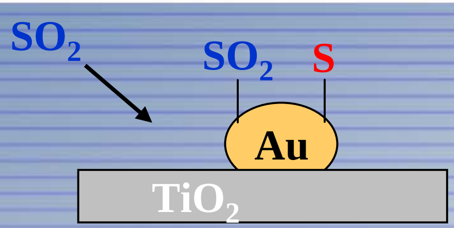
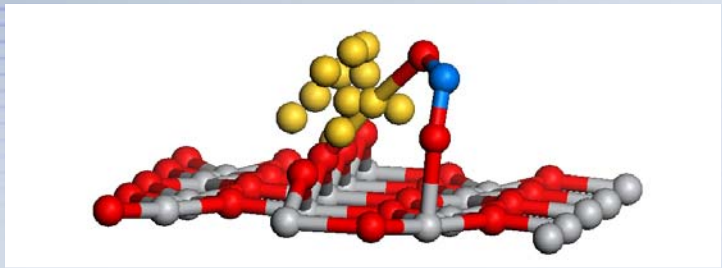
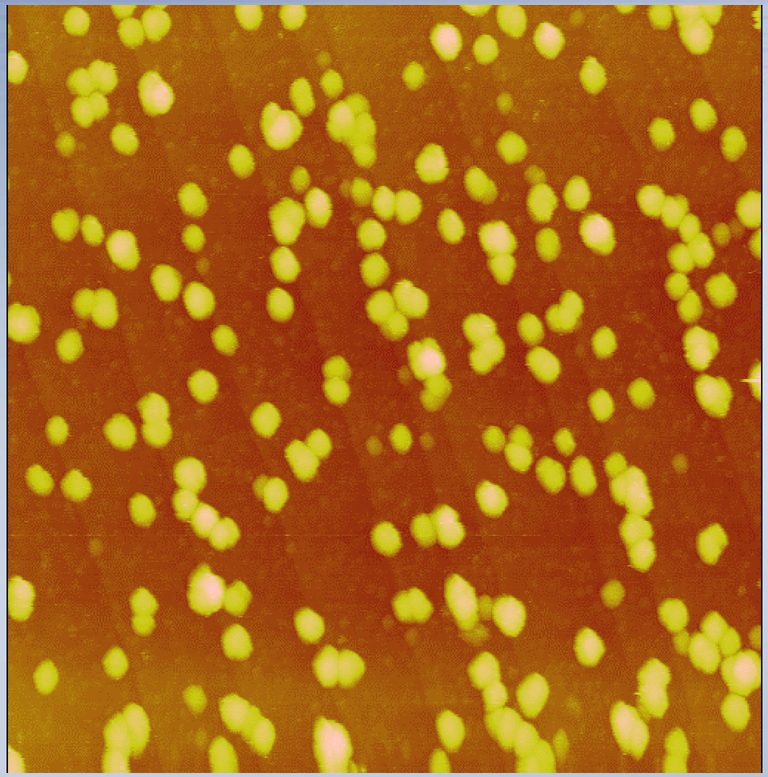
Nanoparticle Catalysts

Supported metal nanoparticles can exhibit reactivity not characteristic of the bulk metal or support



Calculations show that SO_2 binds to both Au particle and TiO_2 support





Au/TiO_2 catalyst is 7-10 times more active than commercial catalyst.

J. Rodriguez, BNL

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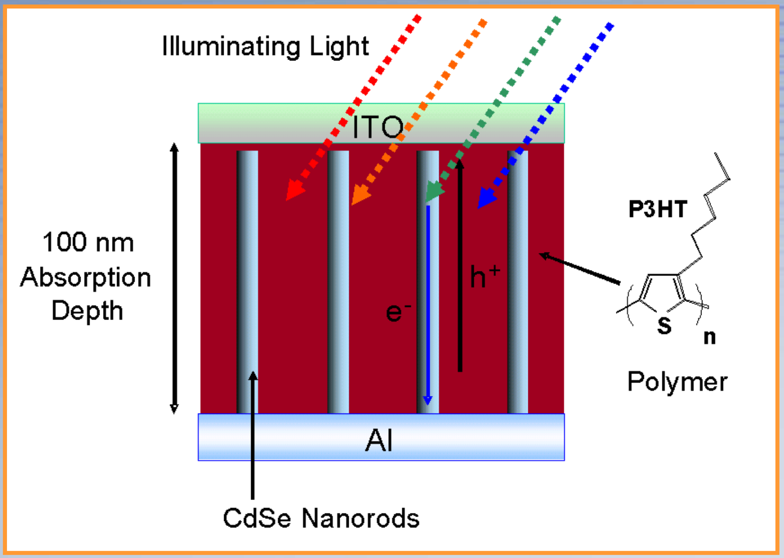
High Efficiency, Inexpensive Solar Cells

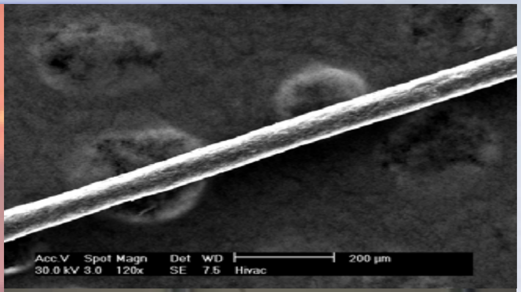
Sunlight conversion



Tune nanorods to absorb different wavelengths of solar spectrum just by changing their diameters

From P. Alivisatos,

Electricity transmission



Spinning carbon nanotubes can be the transmission lines of the future

From R.E. Smalley

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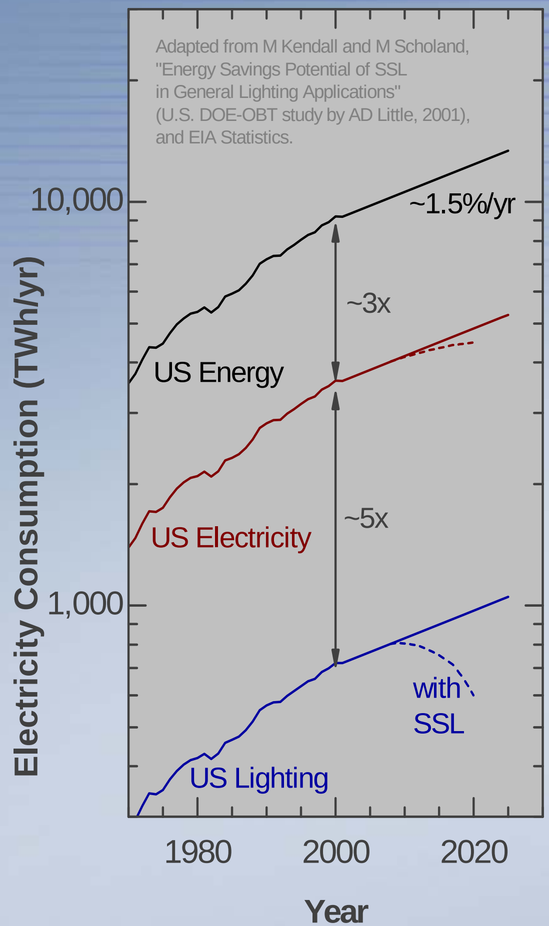
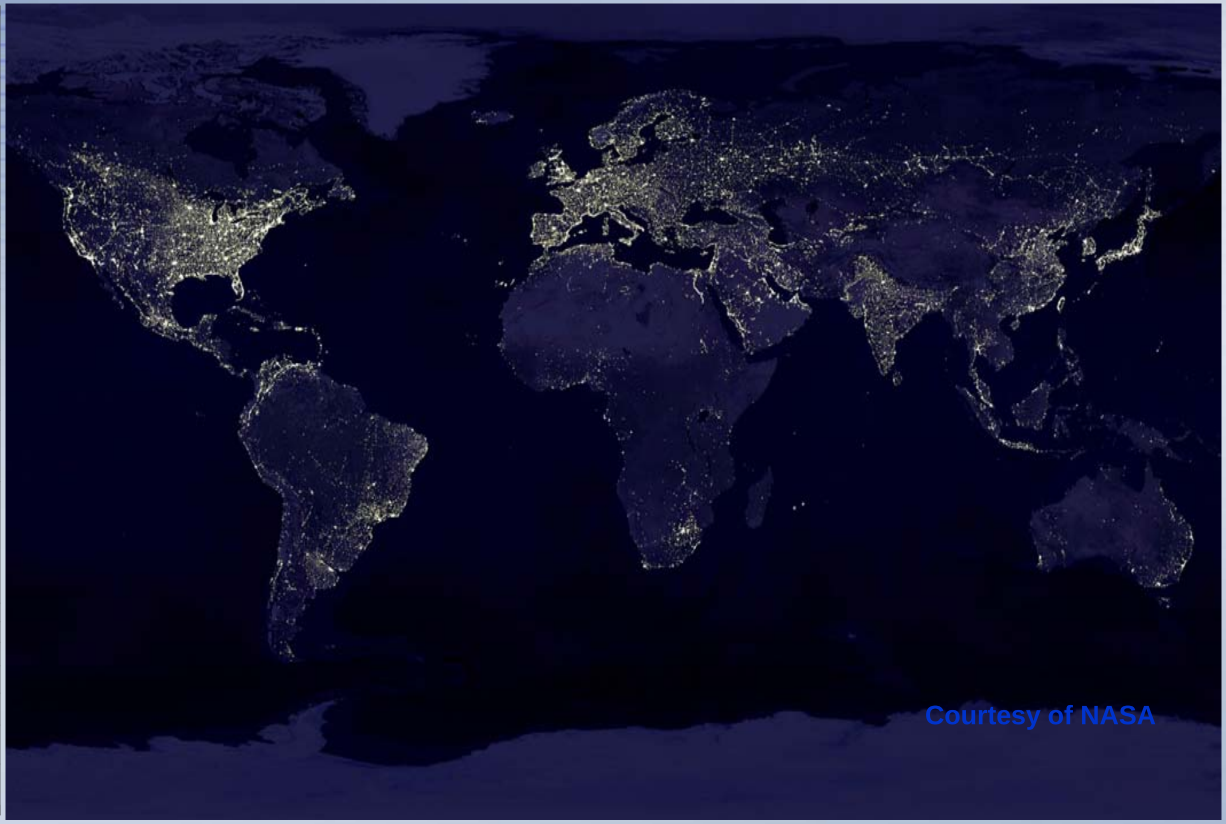
Lighting and Energy Consumption





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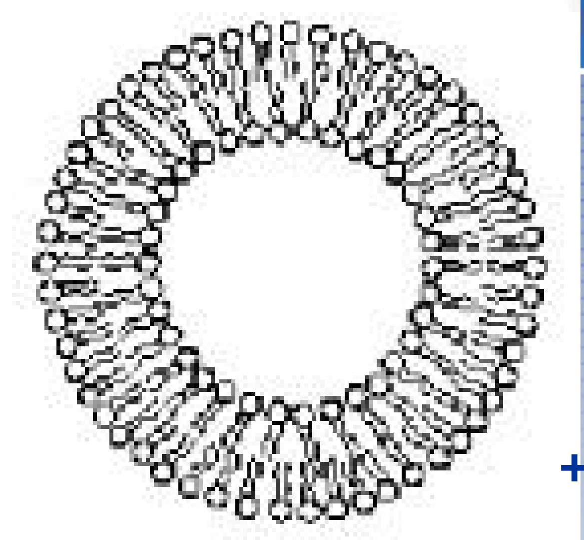
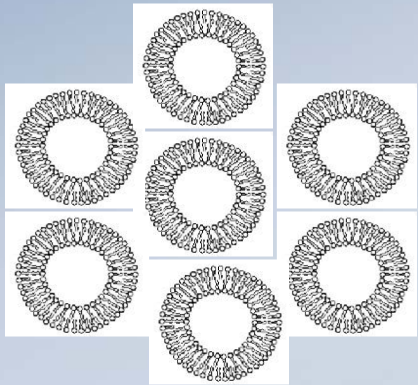
Examples: Liposomes for Shape Control Over Pt Nanostructures



Cross-section of a liposome

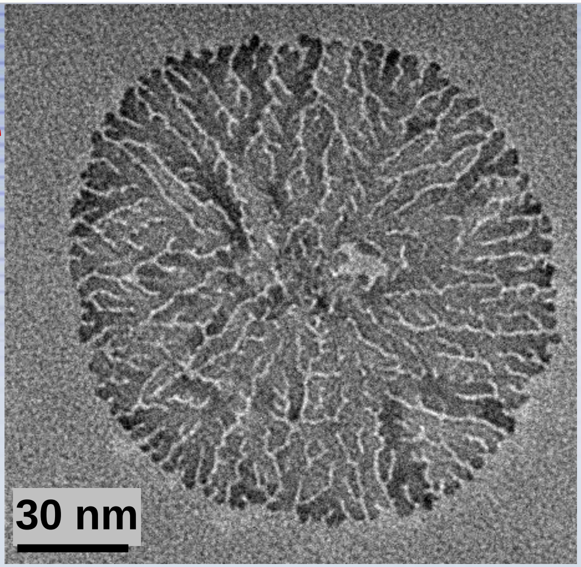


Aggregated liposomes

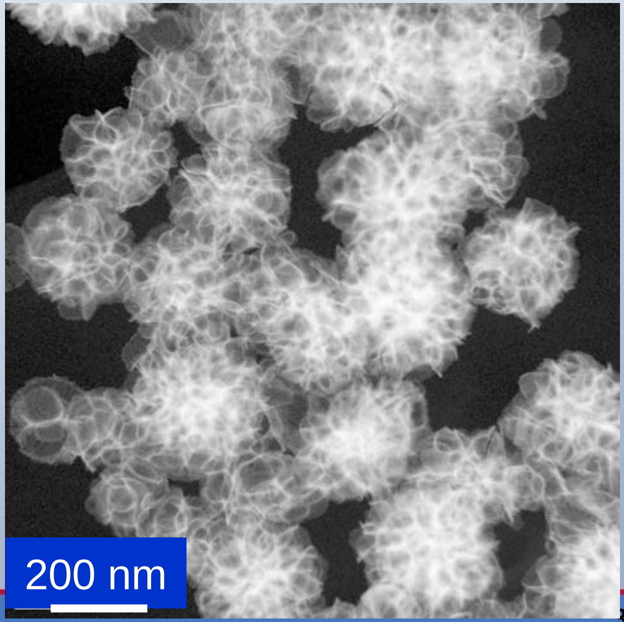
+ K_2PtCl_4 (aq.)

+Ascorbic acid (aq.)

Transmission Electron Microscope (TEM) image



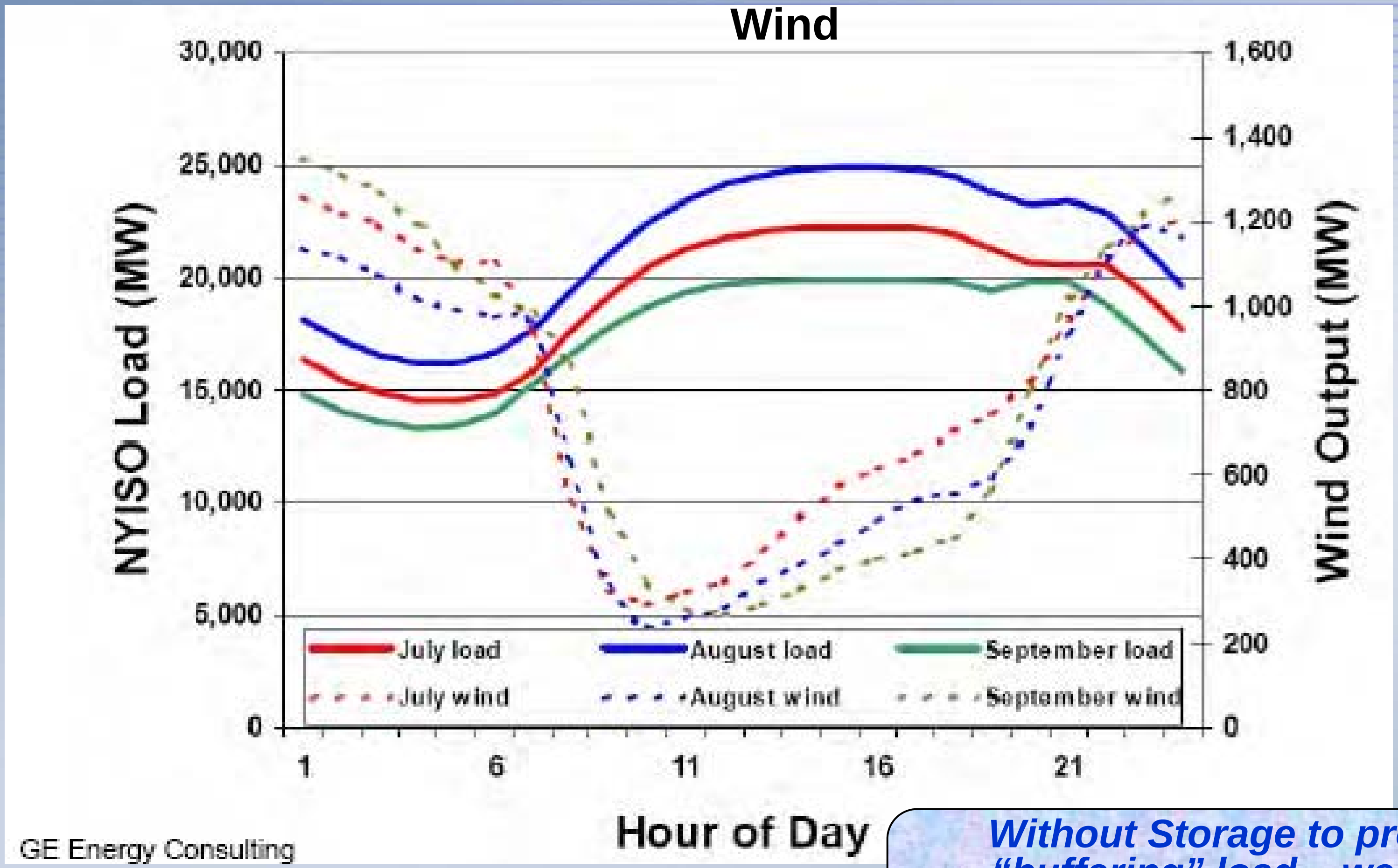
High-Angle Annular Dark-Field (HAADF) Scanning TEM image



Y. J. Song, *et al., J. Am. Chem. Soc.* **2004**, *126*, 635.

Y. J. Song, *et al., Chem. Mater.* **2006,** *18*, 2335.

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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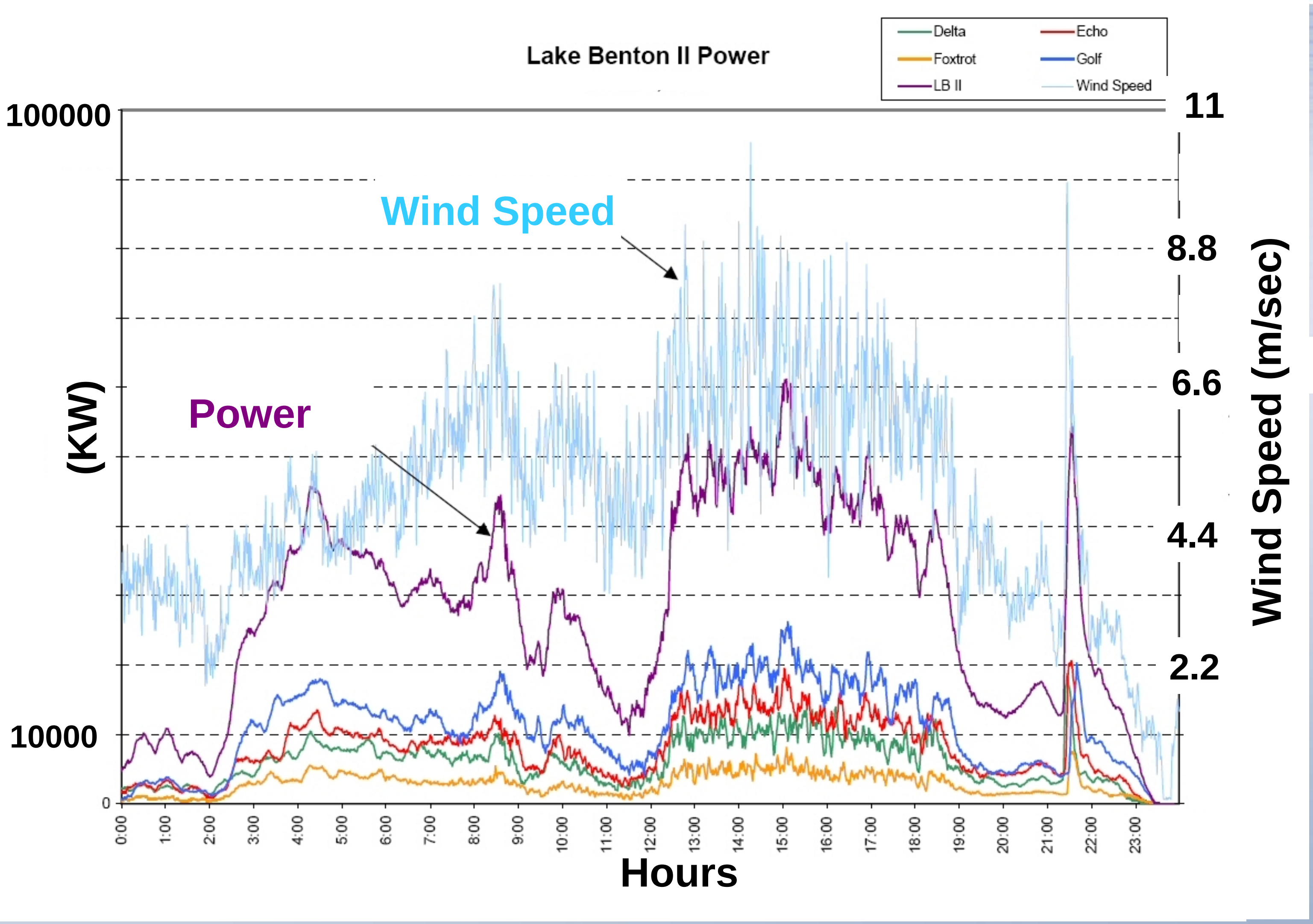
Wind Intermittency



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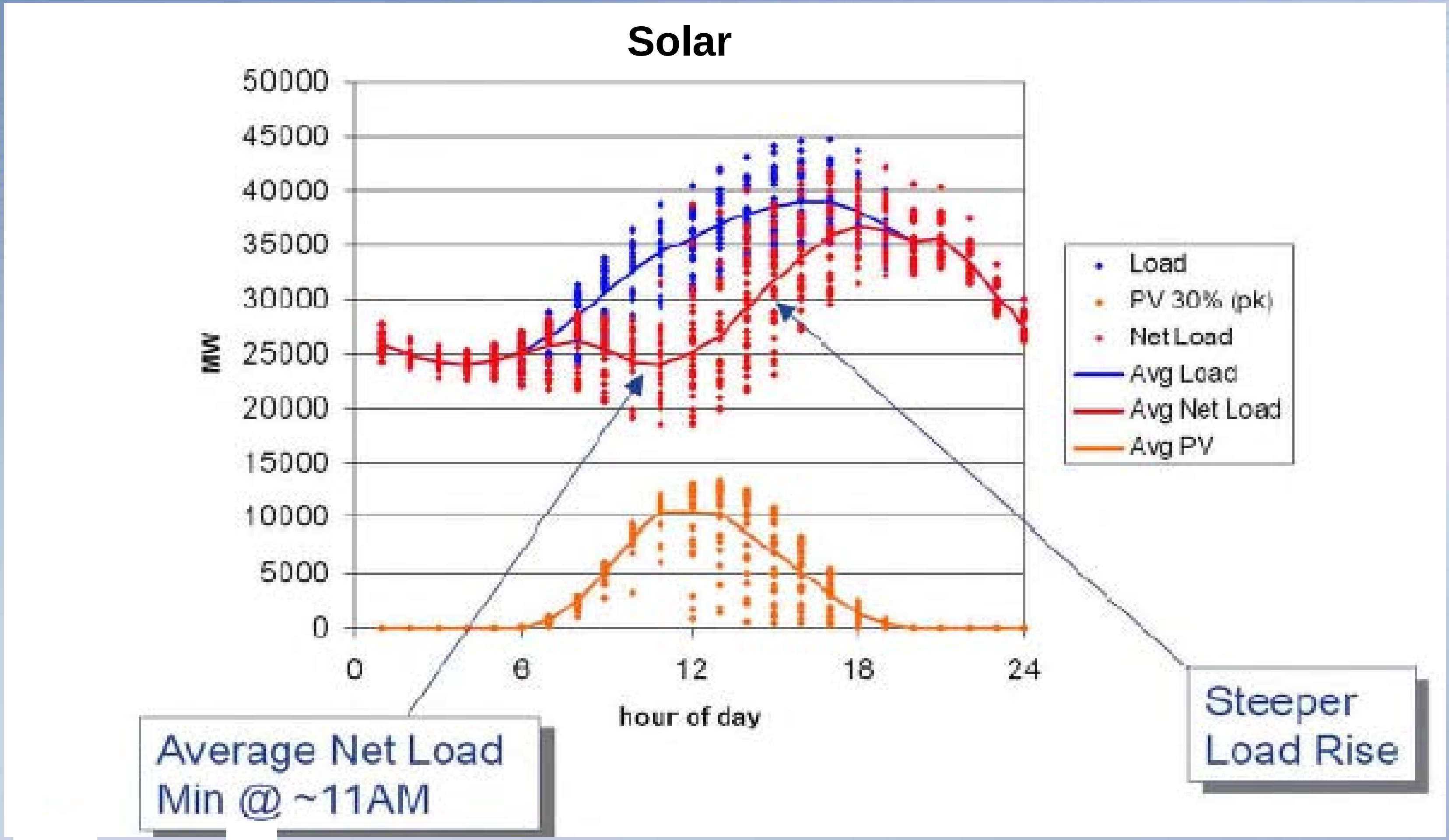
Solar Energy Profile Better Match than Wind but still Doesn't Match Typical Load Profiles



Source: GE

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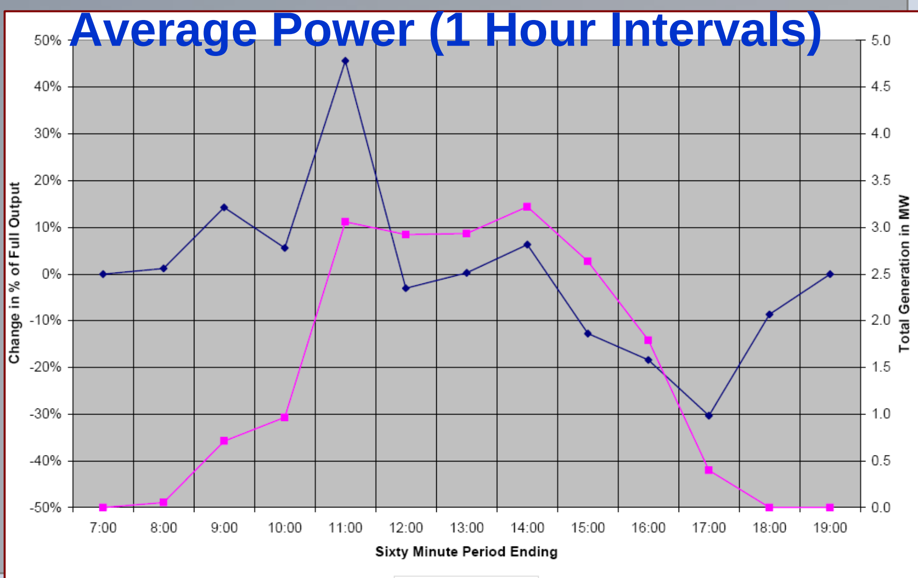
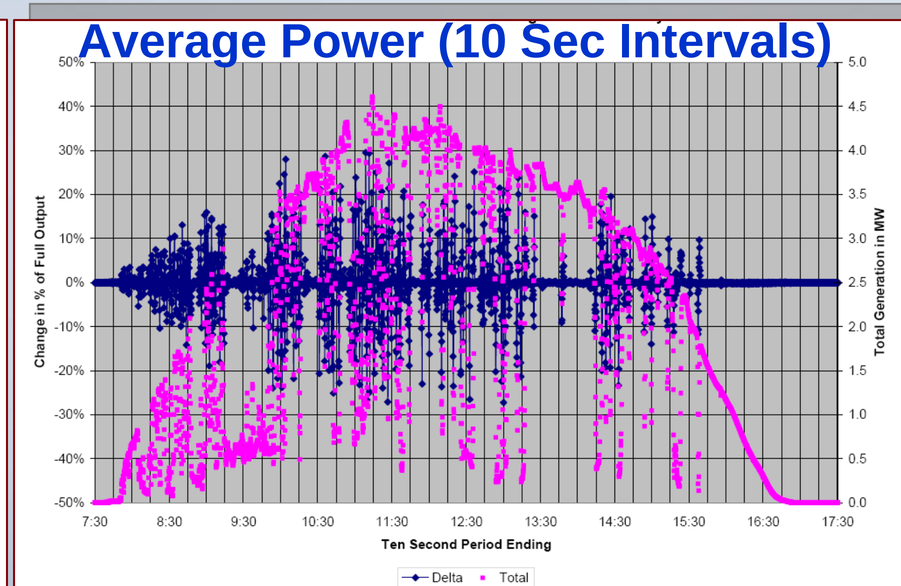
Solar Intermittency

Tucson Electric Power 4.5MW PV Plant

Blue: Delta
Pink: Total





Source: Tom Hansen, Tucson Electric Power

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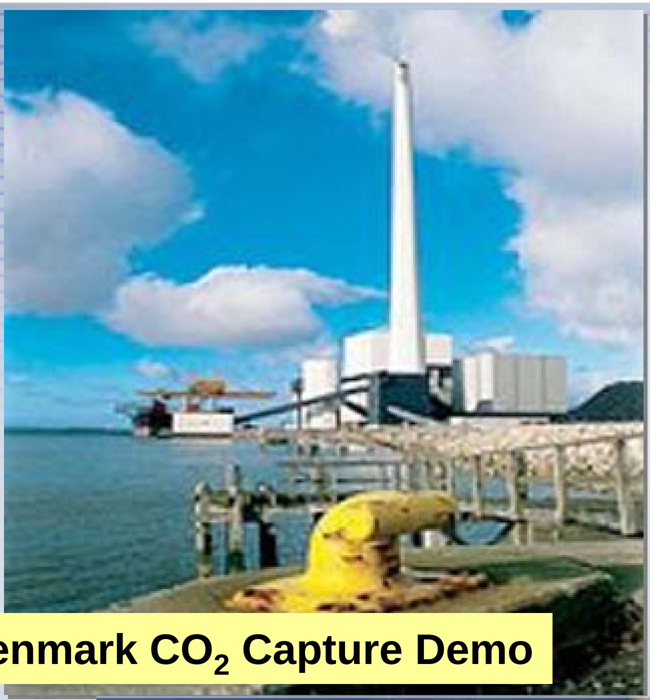
Capturing the CO_2 for Re-use rather than waste management or burial?

- **Two major possibilities**
  - Capture it at the source (initially)
    - Most practical for stationary sources
    - Easiest with pure oxygen combustion
    - Demonstrations now underway
  - Remove it from the atmosphere
    - Challenging, but not impossible
    - Wind naturally moves vast quantities of air
    - Feasible to build scrubbers that pull CO_2 directly from air
    - Potential to disconnect capture from source
    - Not yet demonstrated at scale or in field



Denmark CO_2 Capture Demo

GRT LLC Synthetic Trees Concept

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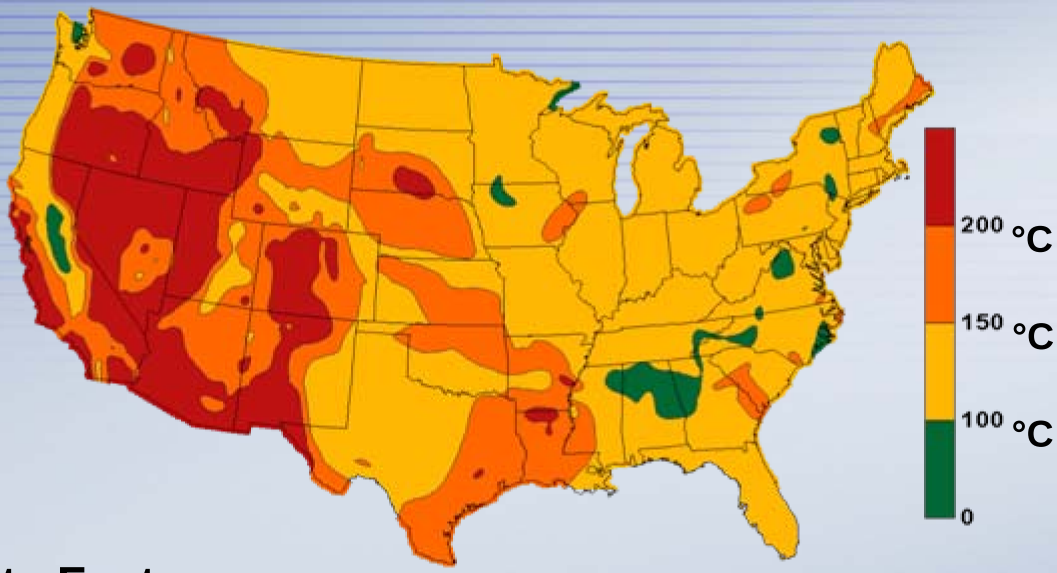
Geothermal Power Costs are Competitive With Fossil Generation



Temperature at 6 km

- Installed Capacity: 2.8 GW (Capacity Factor >90%)
- Cost of Energy: 5-10 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

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Use "Magical" Properties of Nanotubes

- Ten times tensile strength of steel with about 1/6 the mass density
- Up to 20 times electrical conductivity of copper with about 1/6 the mass density
- Thermal conductivity close to that of diamond, the current champ

Property	SWNT	Copper	Aluminum	Steel
Electrical Conductivity	1- 20	1	0.63	0.1
Mass Density	0.16	1	0.3	0.88
Thermal Expansion	- 0.125	1	1.4	0.7
Thermal Conductivity	0.05 - 5	1	0.3 – 0.6	0.11
Tensile Strength	15	1	0.8	1.6
Bulk Modulus	10 - 20	1	2.7	5

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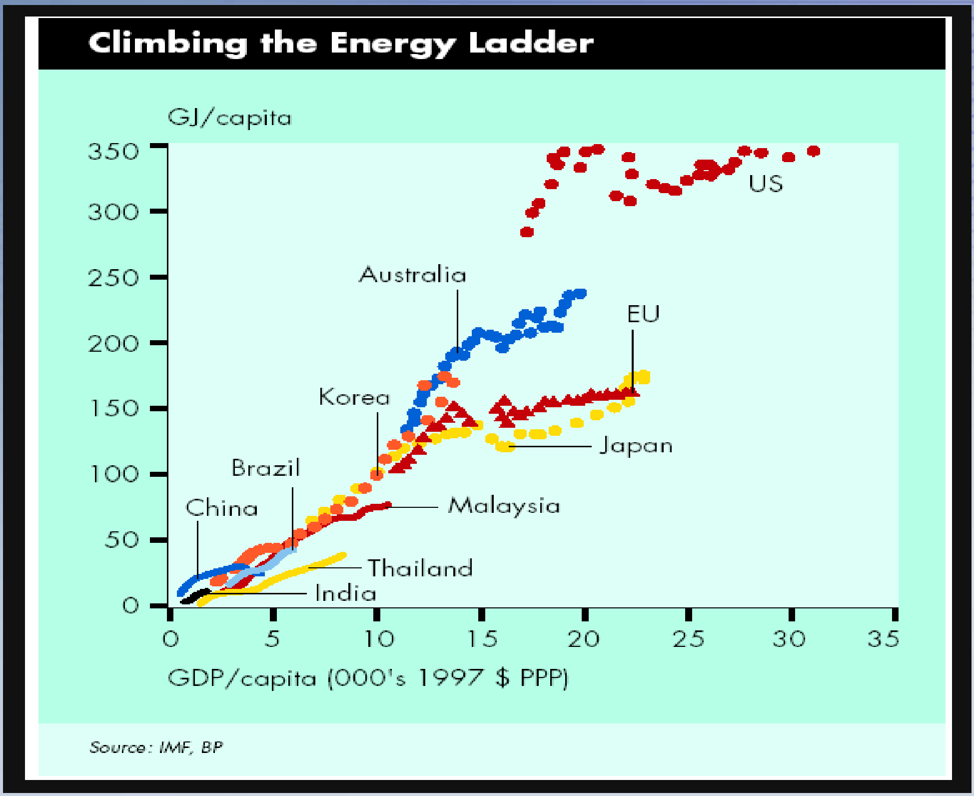
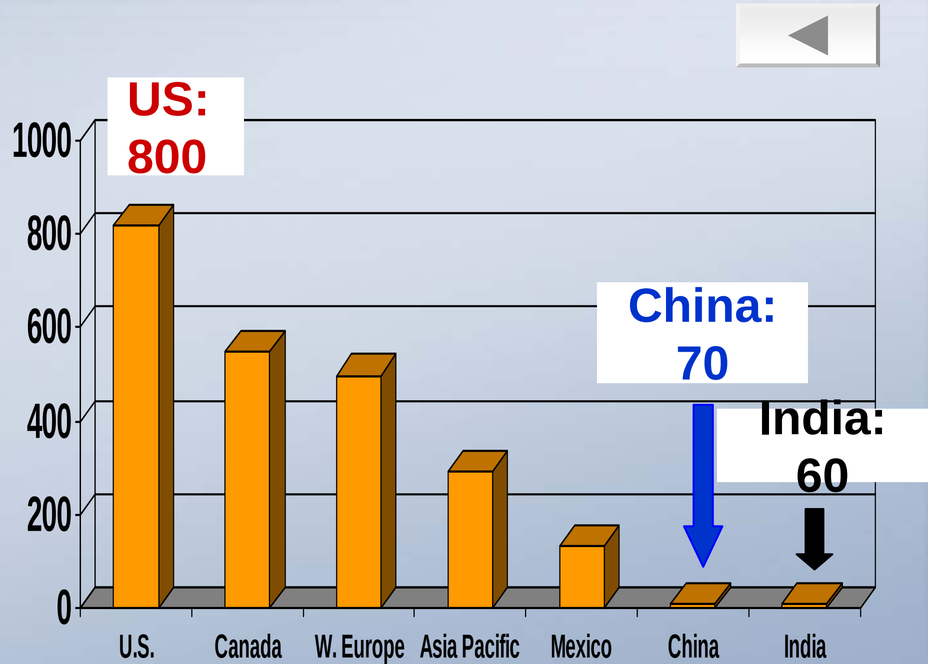
Economic Prosperity and Stability Require Access to Reliable and Affordable Energy

- **Electricity Consumption/person**
  - US – 9600 kWh/yr, *1100 W*, 22600 Calories/Day
  - India – 300 kWh/yr, *34 W,* 700 Calories/Day
  - China – 180 kWh/yr, *21 W*, 425 Calories/Day
- **Personal vehicles/1000 people**





- **Economic Growth (%/yr)**
  - US – 3.4%
  - China – 10.5%
  - India – 8.5%

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

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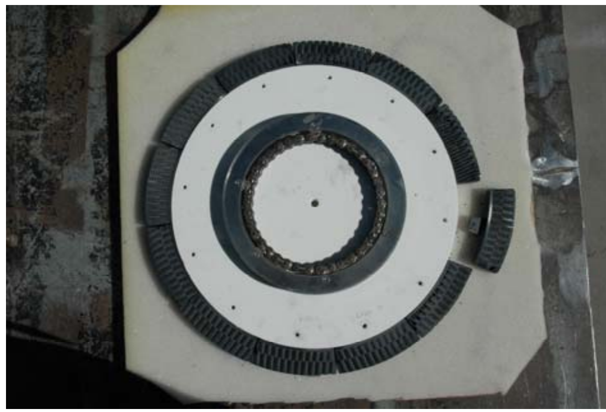
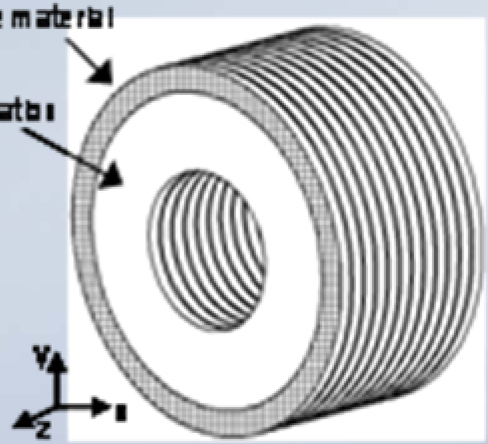
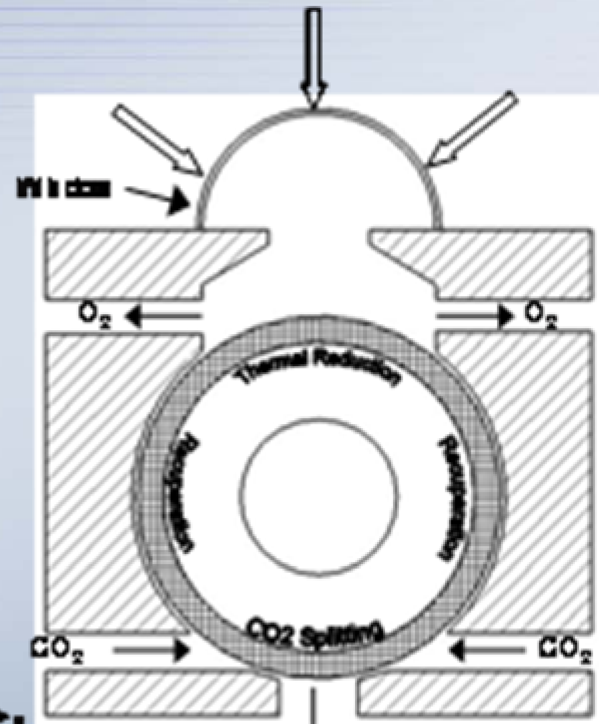
What is the Enabling Technical Innovation?
A "Thermo-Chemical Heat Engine"





Cross-Section Illustration

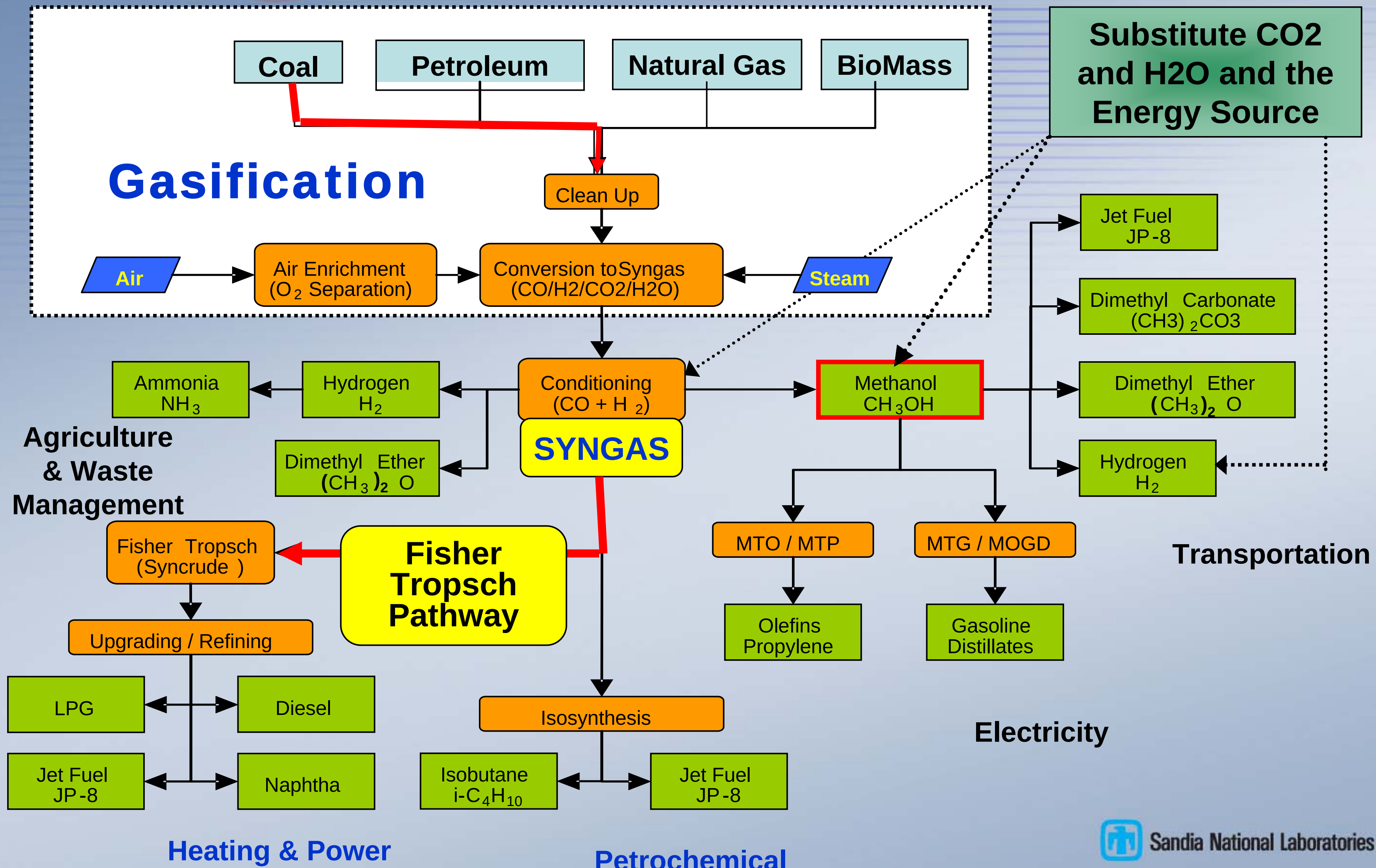


Enabling Attributes

- Thermal recuperation
- Reaction separation
- Continuous flow

Solar thermal to Chemical Work
Prototype in Build Phase

There are Known Pathways to Most Anything Desirable to Synthesize



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Thank-you for your Attention

Questions