

Powering the Planet

Nathan S. Lewis, California Institute of Technology



Global Energy Perspective

- Present Energy Perspective
- Future Constraints Imposed by Sustainability
- Challenges in Exploiting Carbon-Neutral Energy Sources Economically on the Needed Scale

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Perspective

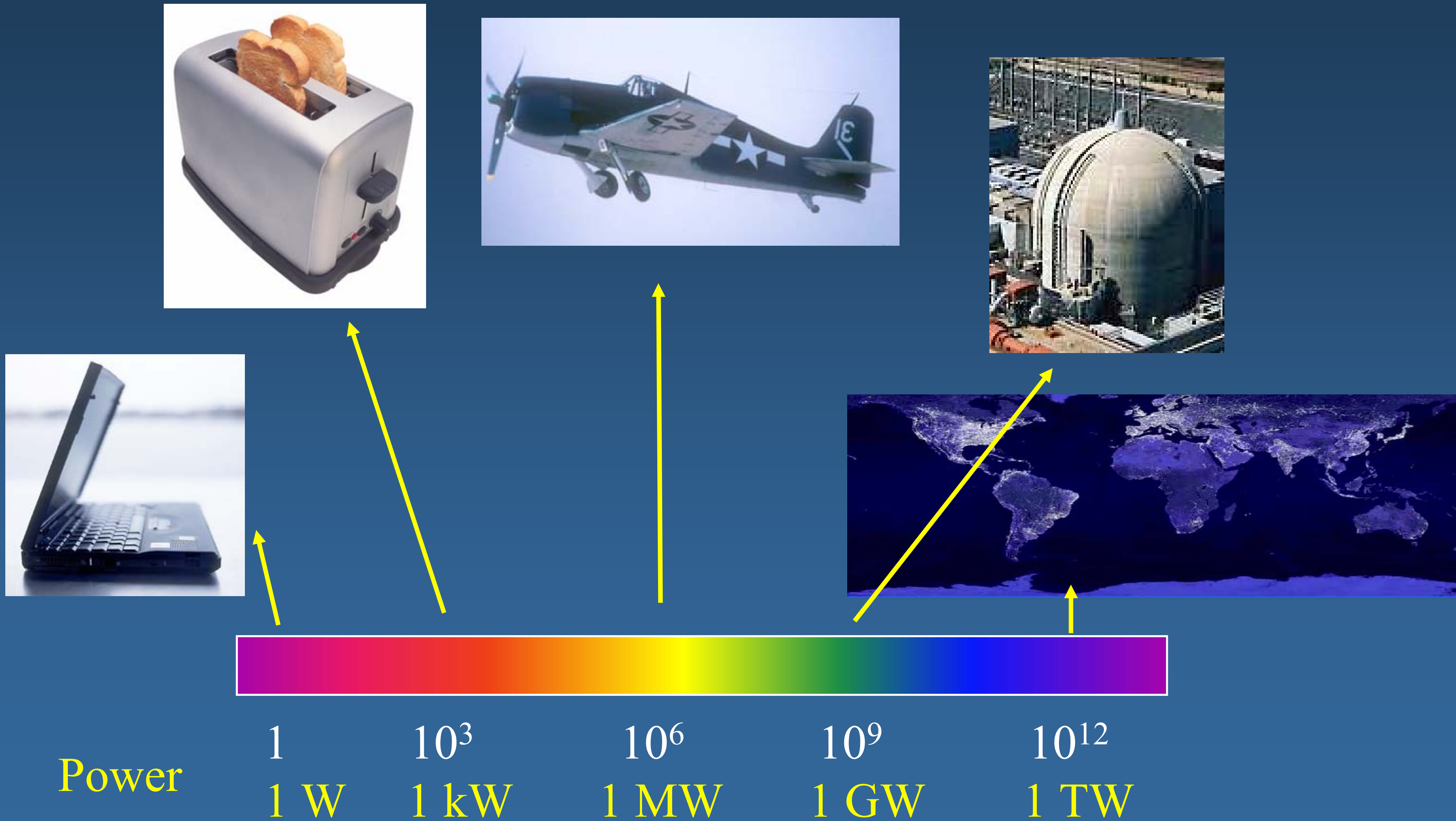
"Energy is the single most important challenge facing humanity today."
Nobel Laureate Rick Smalley, April 2004, Testimony to U.S. Senate

"..energy is the single most important scientific and technological challenge facing humanity in the 21st century..": Chemical and Engineering News, August 22, 2005.

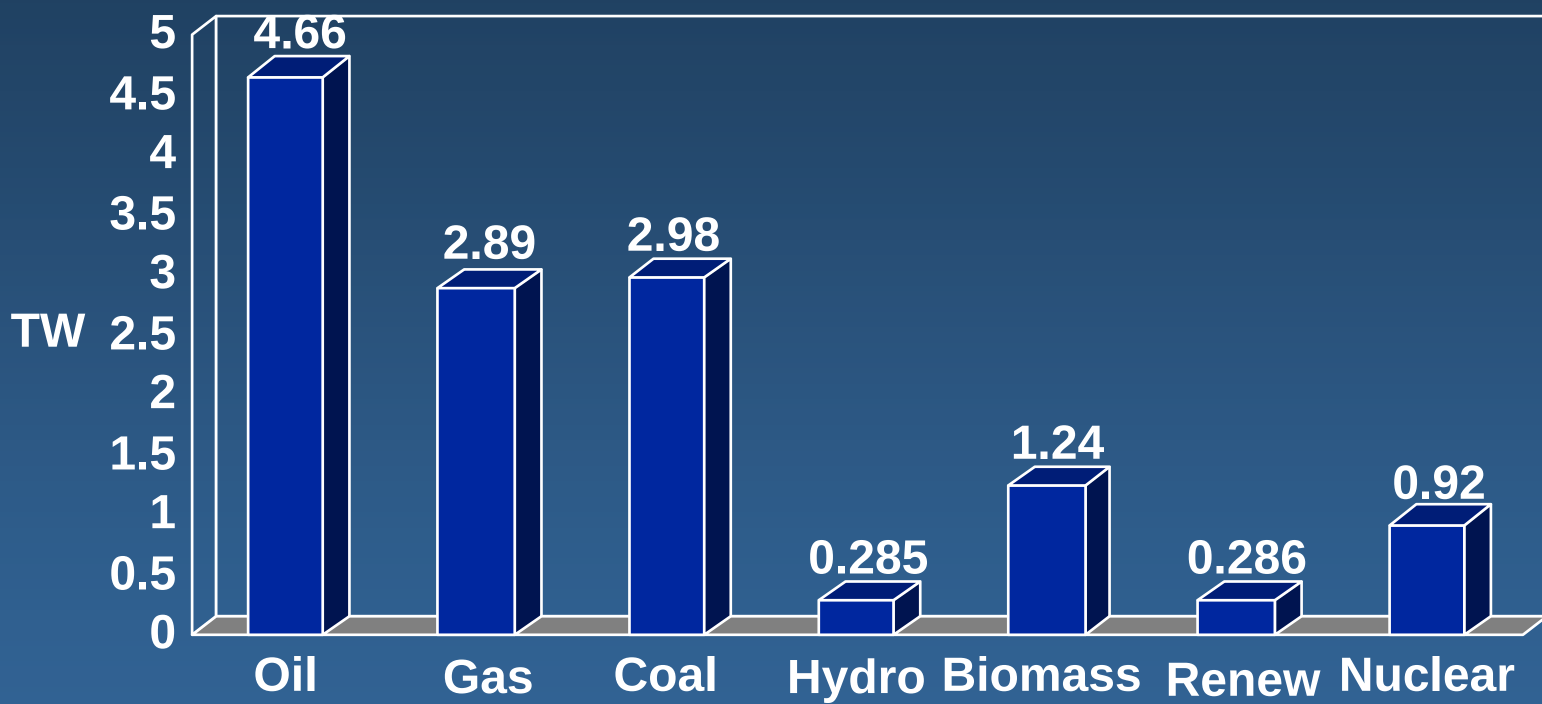
"What should be the centerpiece of a policy of American renewal is blindingly obvious: making a quest for energy independence the moon shot of our generation", Thomas L. Friedman, New York Times, Sept. 23, 2005.

"The time for progress is now. .. it is our responsibility to *lead* in this mission", Susan Hockfield, on energy, in her MIT Inauguration speech.

Power Units: The Terawatt Challenge

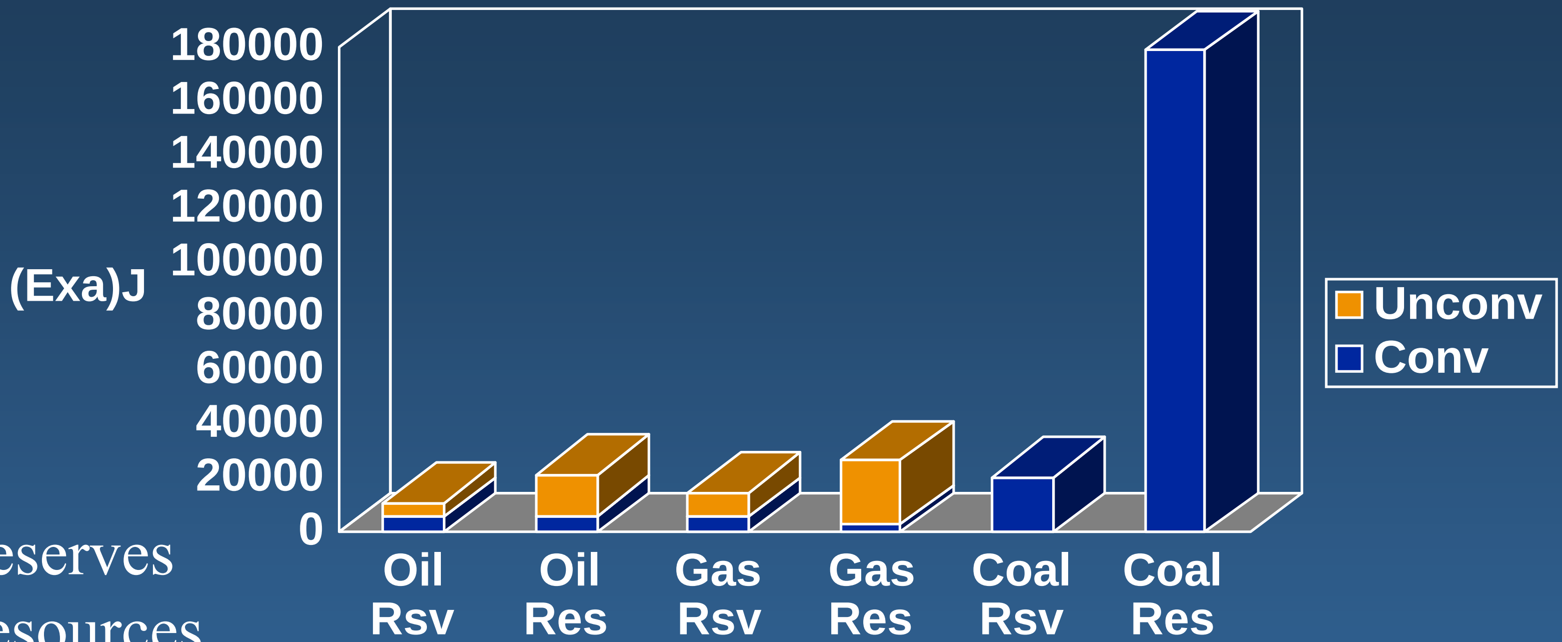


Global Energy Consumption, 2001



Total: 13.2 TW U.S.: 3.2 TW (96 Quads)

Energy Reserves and Resources



Rsv=Reserves
Res=Resources

Reserves/(1998 Consumption/yr)		Resource Base/(1998 Consumption/yr)
Oil	40-78	51-151
Gas	68-176	207-590
Coal	224	2160

Energy and Sustainability

- "It's hard to make predictions, especially about the future"

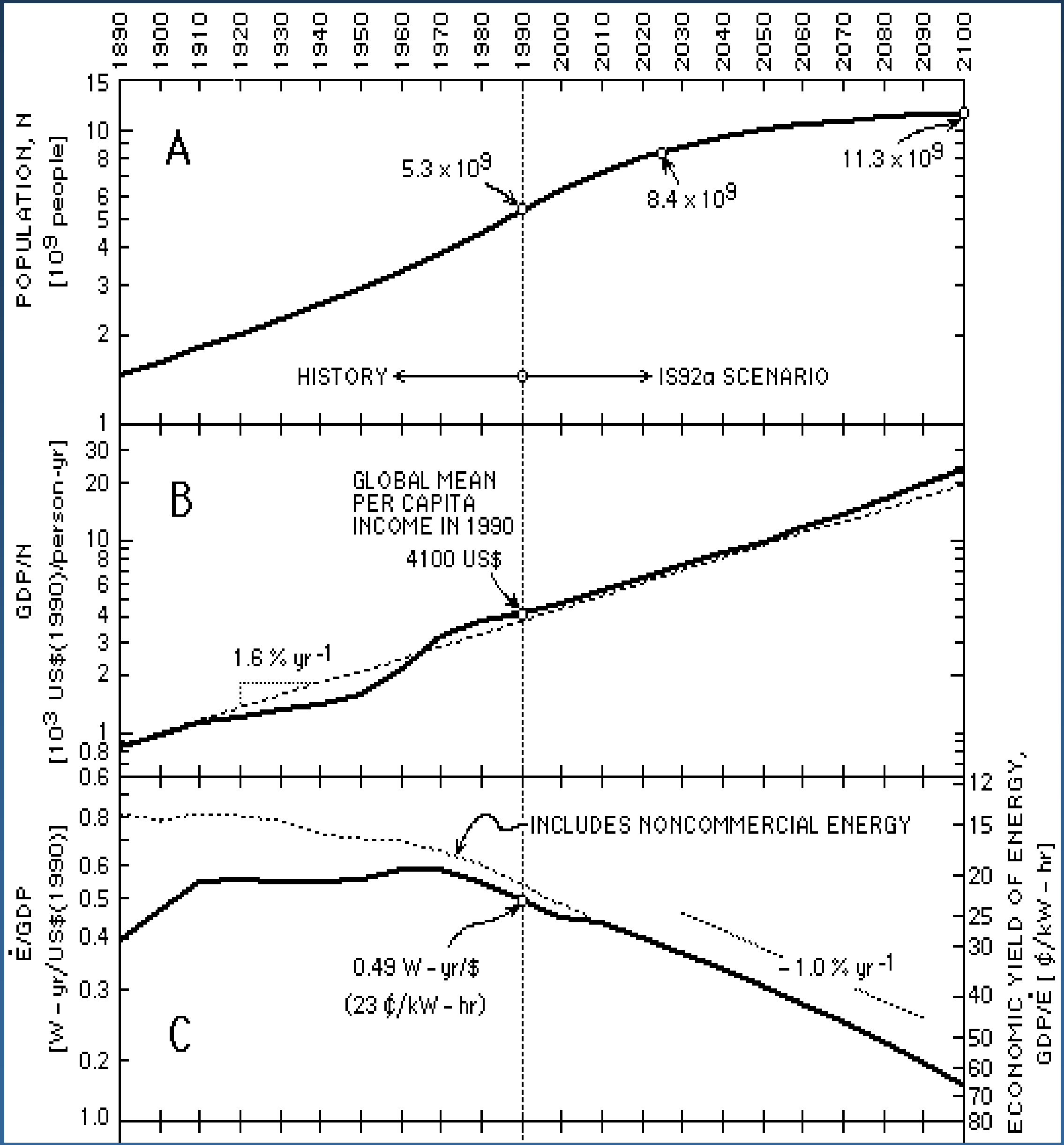
- M. I. Hoffert et. al., *Nature*, **1998**, *395*, 881, "Energy Implications of Future Atmospheric Stabilization of CO_2 Content

  adapted from IPCC 92 Report: Leggett, J. et. al. in Climate Change, The Supplementary Report to the Scientific IPCC Assessment, 69-95, Cambridge Univ. Press, 1992

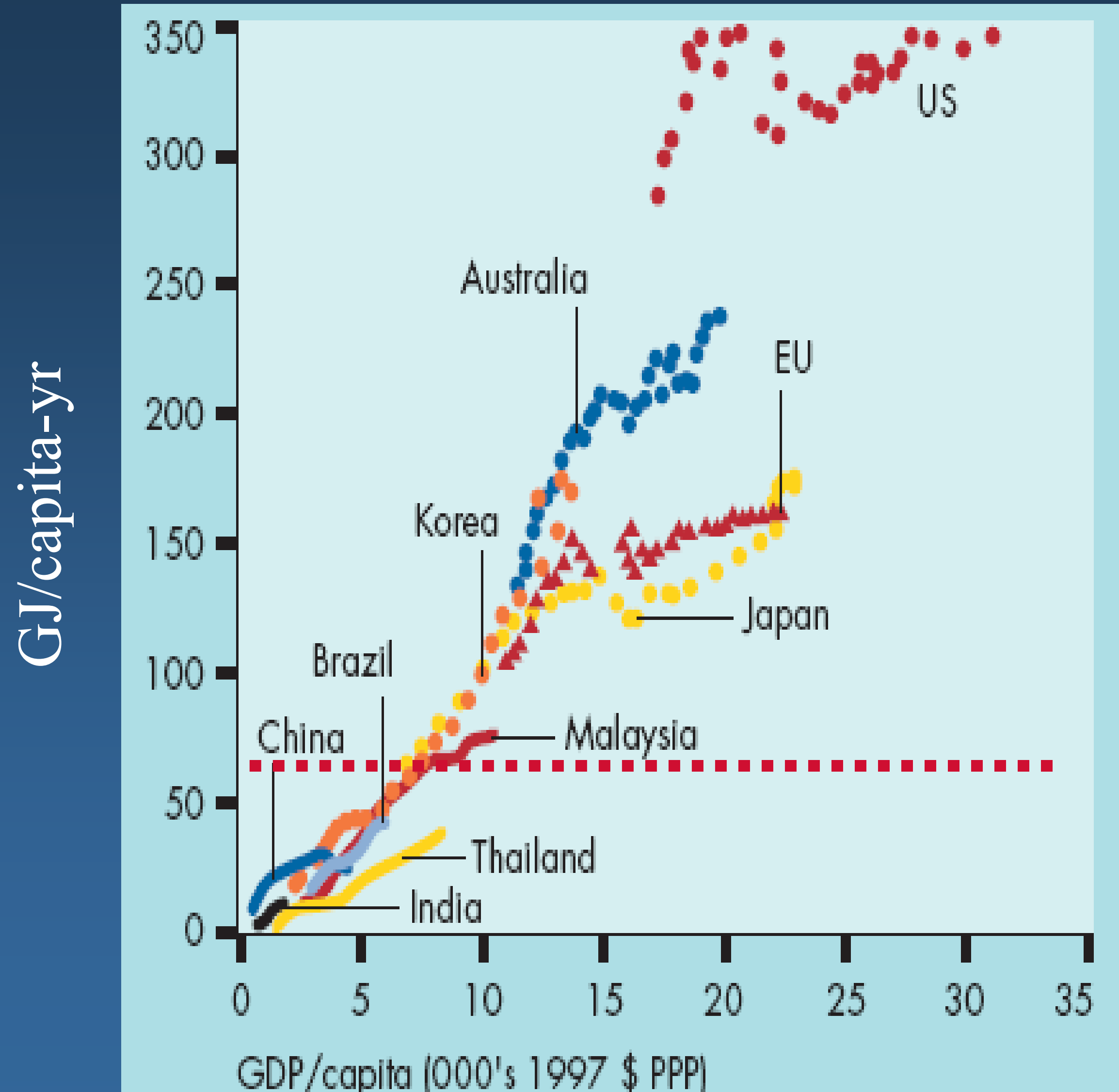
Population Growth to 10 - 11 Billion People in 2050

Per Capita GDP Growth at 1.6% yr^{-1}

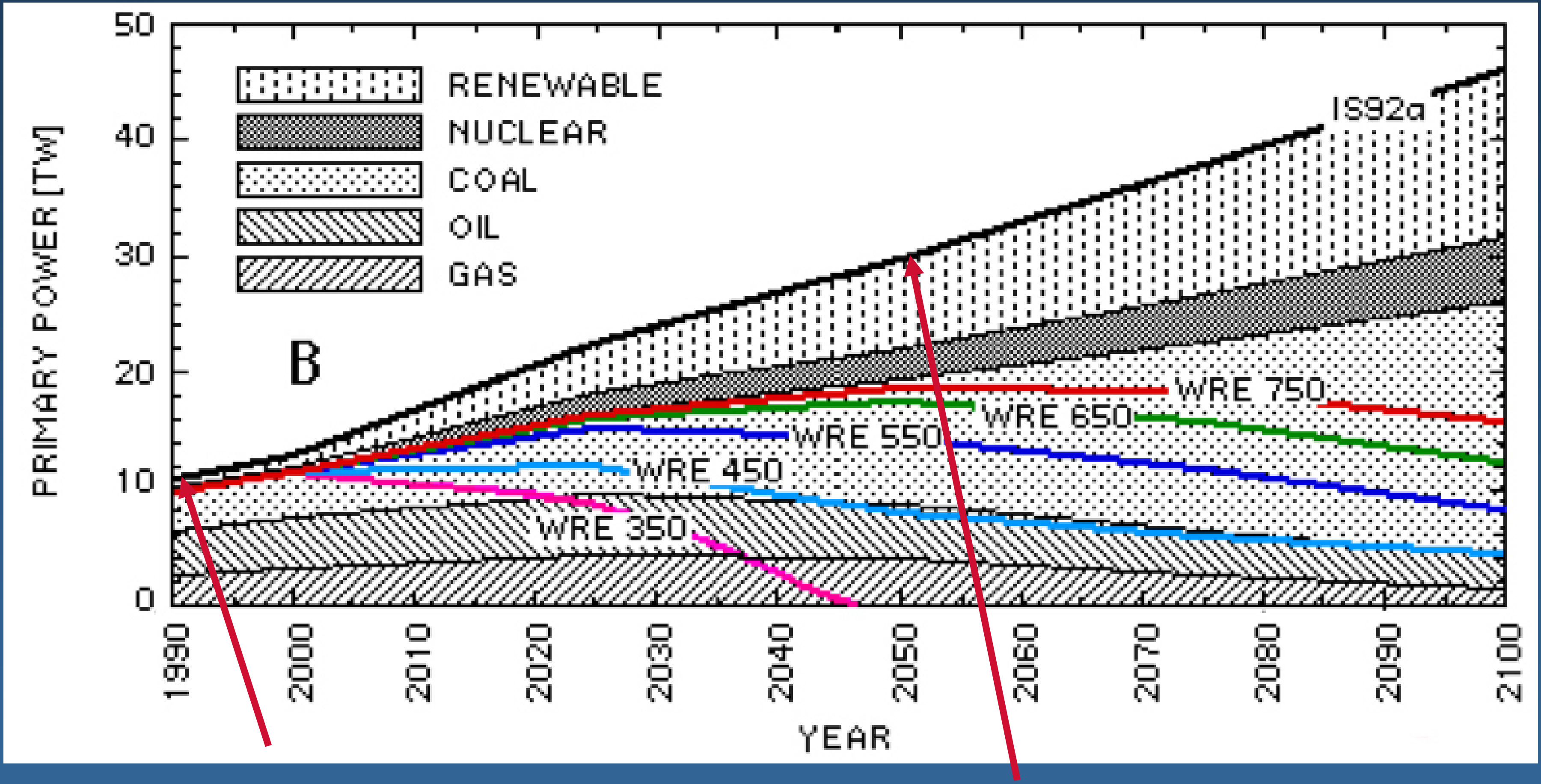
Energy consumption per Unit of GDP declines at 1.0% yr^{-1}



Energy Consumption vs GDP

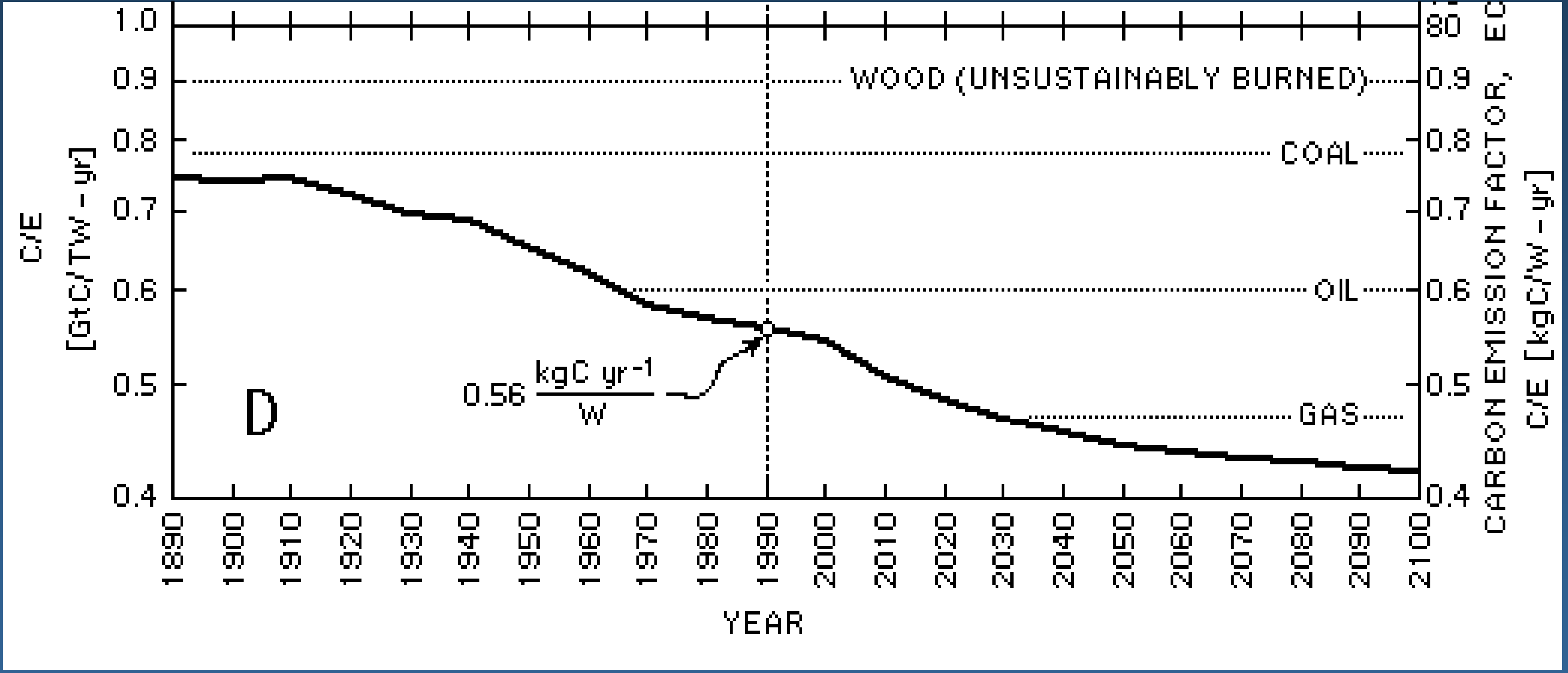


Total Primary Power vs Year



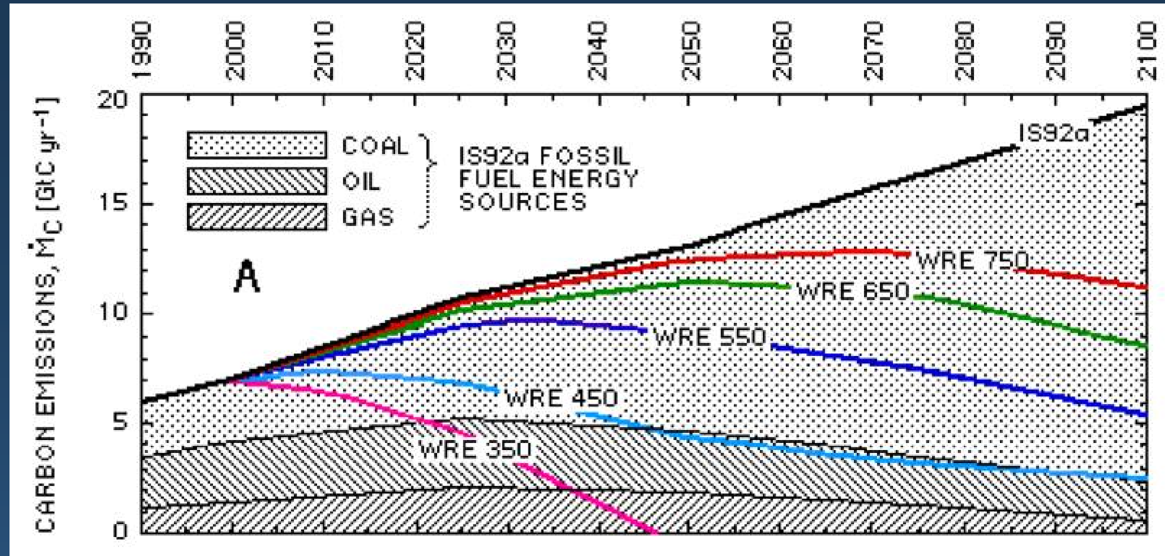
1990: 12 TW 2050: 28 TW

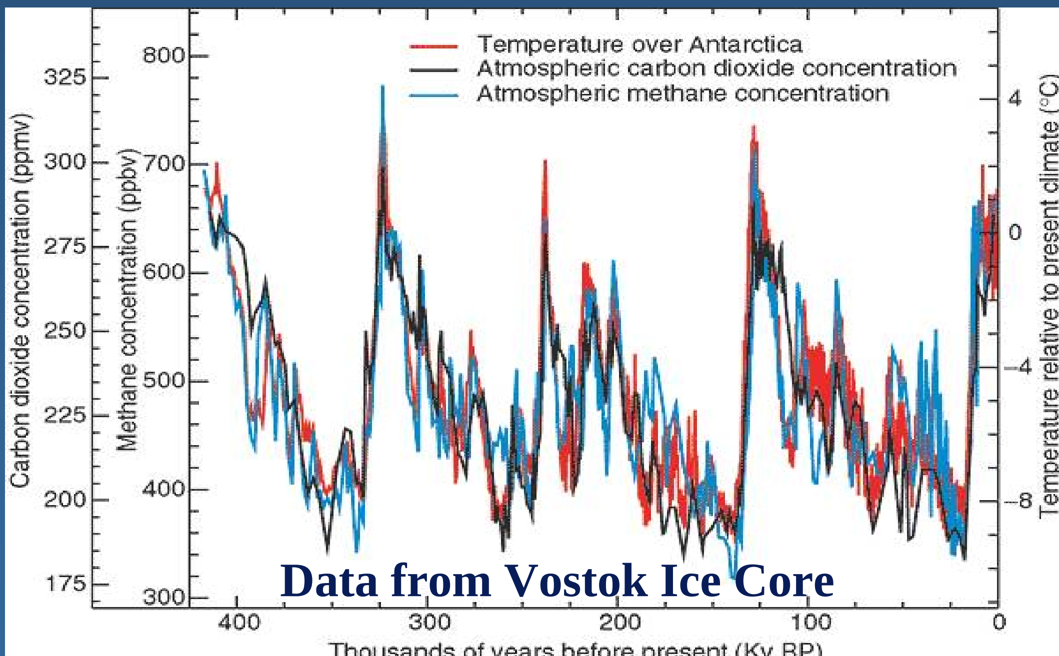
Carbon Intensity of Energy Mix

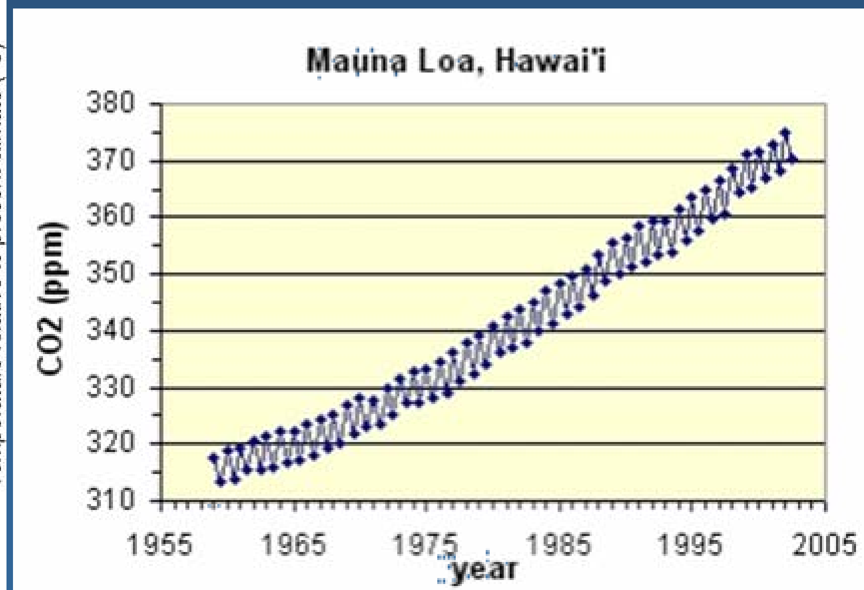


*M. I. Hoffert et. al., Nature, **1998**, 395, 881*

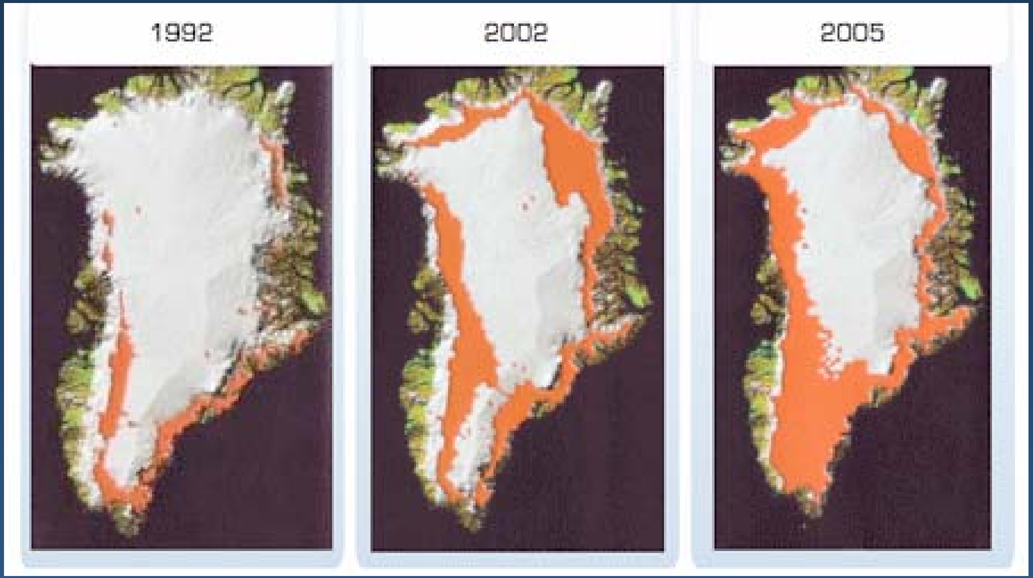
CO_2Emissions for vs CO_2(atm)

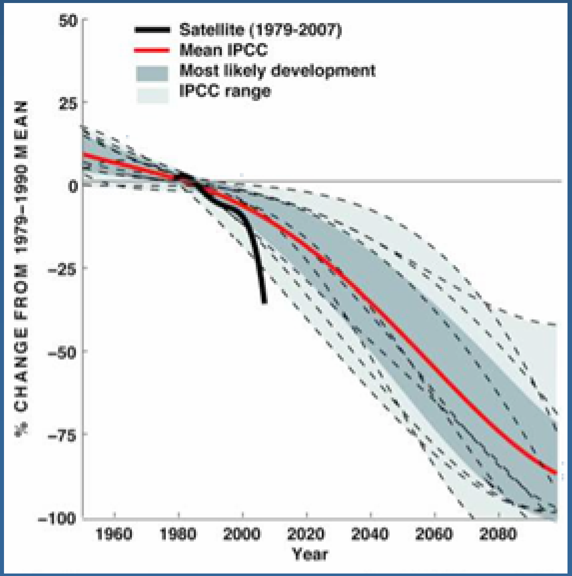






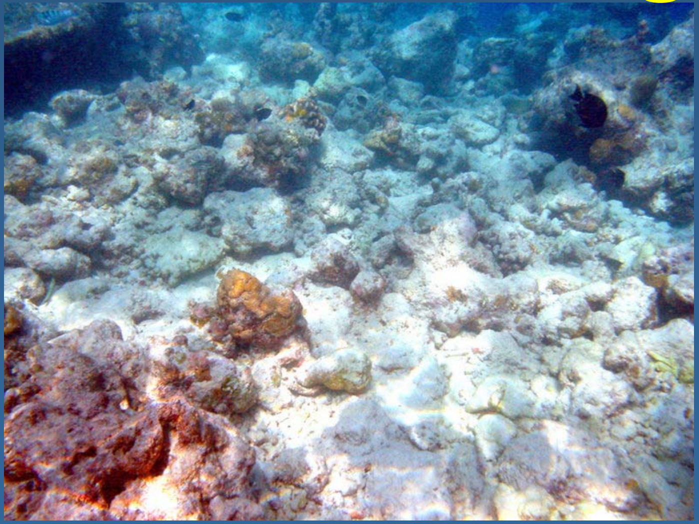
Greenland Ice Sheet



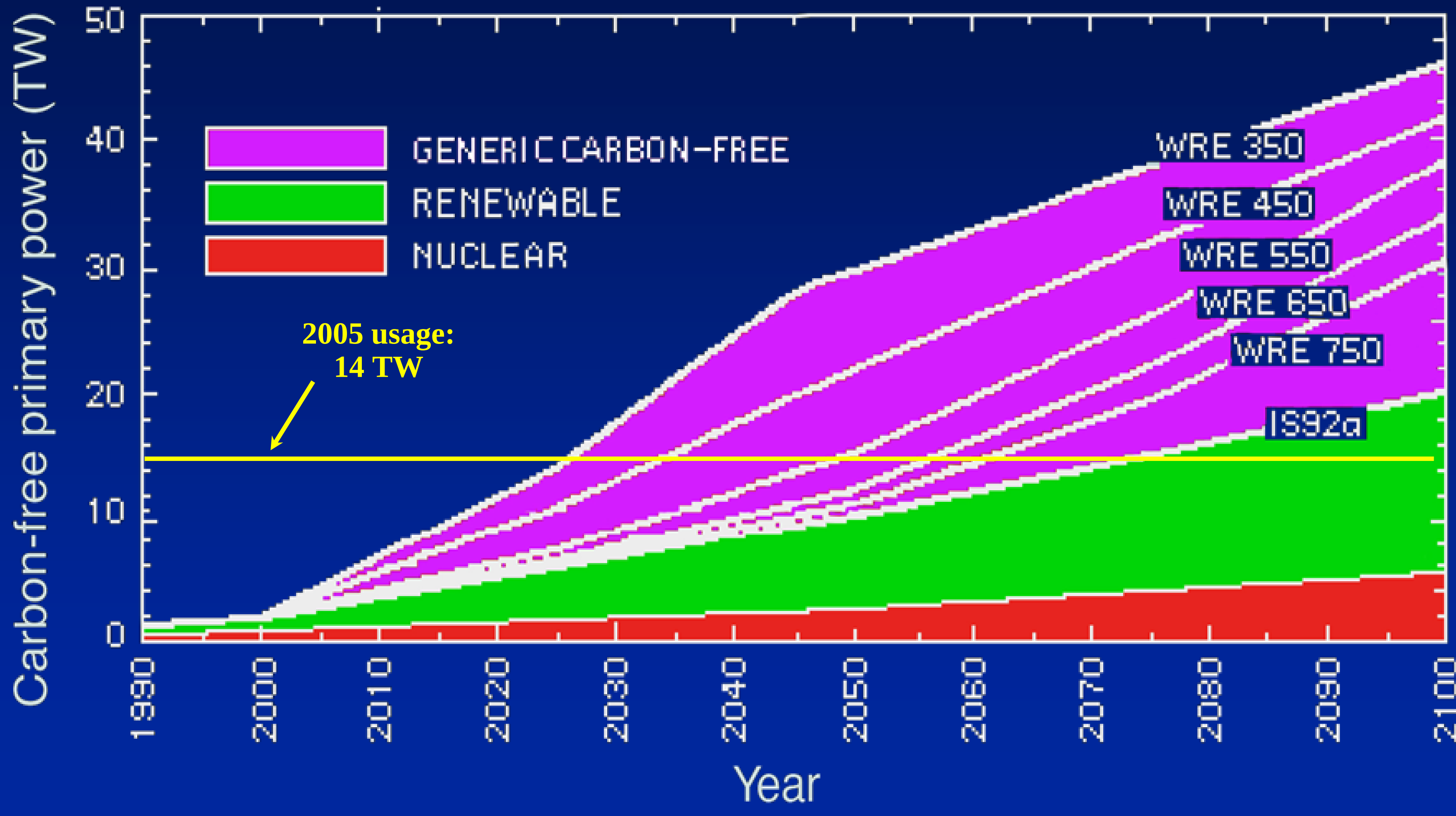


Permafrost

Coral Bleaching



Projected Carbon-Free Primary Power



Hoffert et al.'s Conclusions

- "These results underscore the pitfalls of "wait and see"."
- Without policy incentives to overcome socioeconomic inertia, development of needed technologies will likely not occur soon enough to allow capitalization on a 10-30 TW scale by 2050
- "Researching, developing, and commercializing carbon-free primary power technologies capable of 10-30 TW by the mid-21st century could require efforts, perhaps international, pursued with the urgency of the Manhattan Project or the Apollo Space Program."

Sources of Carbon-Free Power

- Nuclear (fission and fusion)

- Carbon sequestration
- Renewables

Sources of Carbon-Free Power

- Nuclear (fission and fusion)
  - 10 TW = 10,000 new 1 GW reactors
  - i.e., a new reactor every other day for the next 50 years

∏ 2.3 million tonnes proven reserves;
1 TW-hr requires 22 tonnes of U

∏ Hence at 10 TW, terrestrial resource base provides 10 years of energy

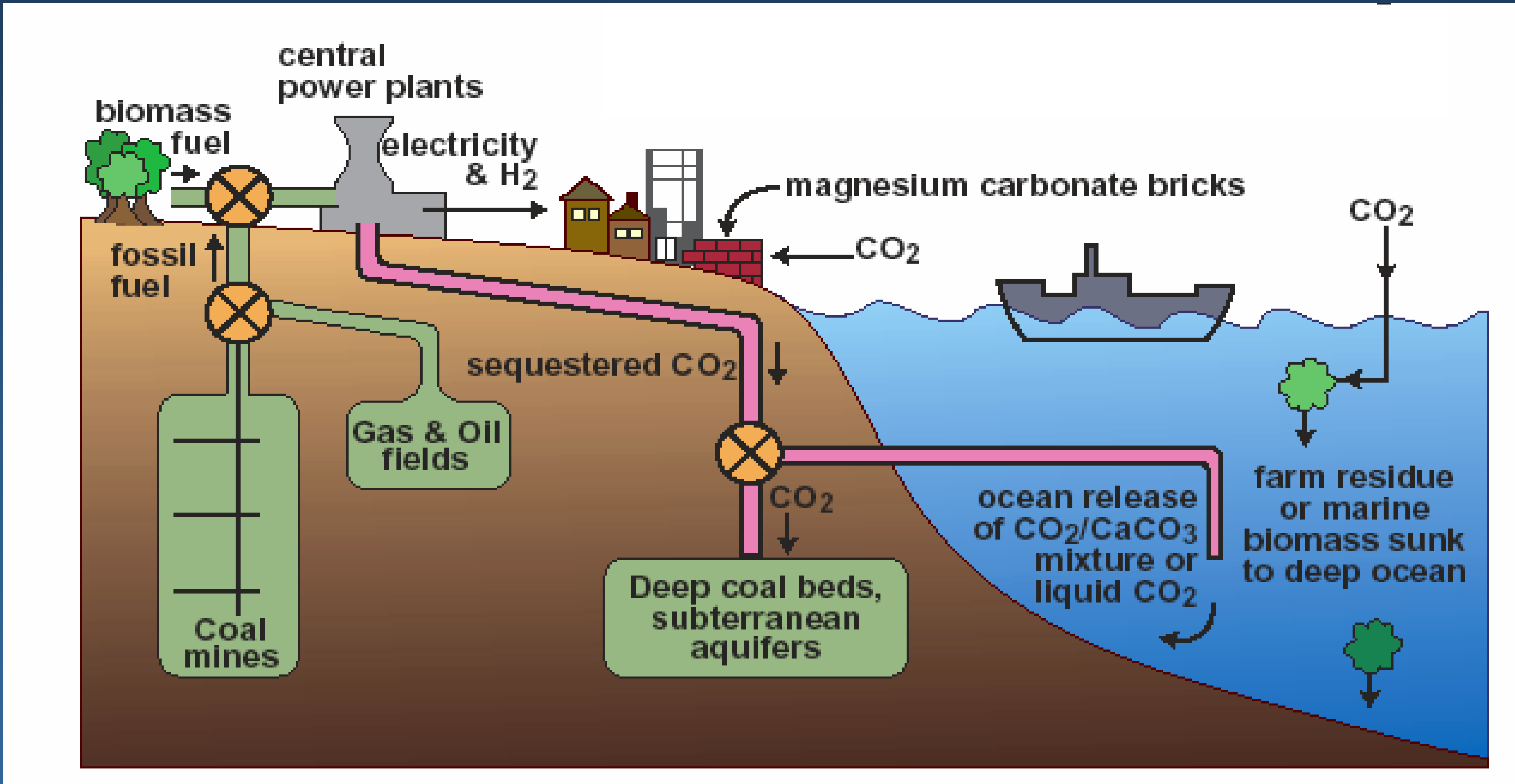
∏ More energy in CH_4 than in ^{235}U

∏ Would need to mine U from seawater (700 x terrestrial resource base; so needs 3000 Niagra Falls or breeders)

∏ At $5/W, requires $50 Trillion (2006 GWP = $65 trillion)

- Carbon sequestration
- Renewables

Carbon Sequestration



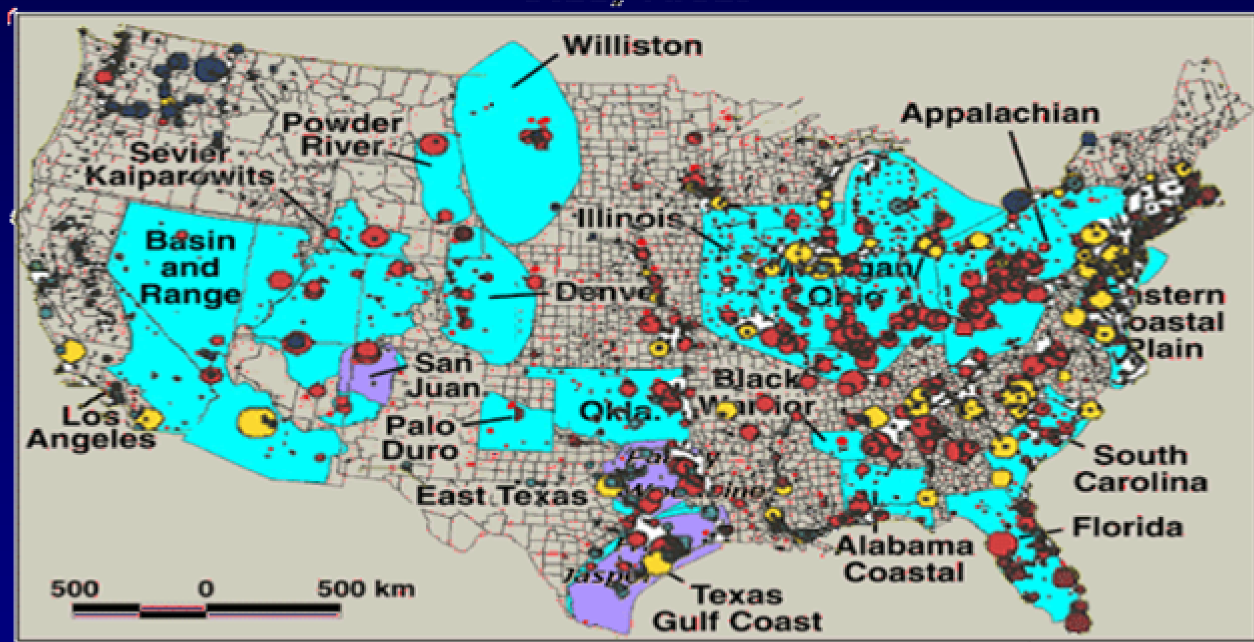
CO_2 Burial: Saline Reservoirs

130 Gt total U.S. sequestration potential

Global emissions 6 Gt/yr in 2002   Test sequestration projects 2002-2004

- **Near sources (power plants, refineries, coal fields)**
- **Distribute only H_2 or electricity**
- **Must not leak**
- **At 2 Gt/yr sequestration rate, surface of U.S. would rise 5 cm by 2100**

Study Areas



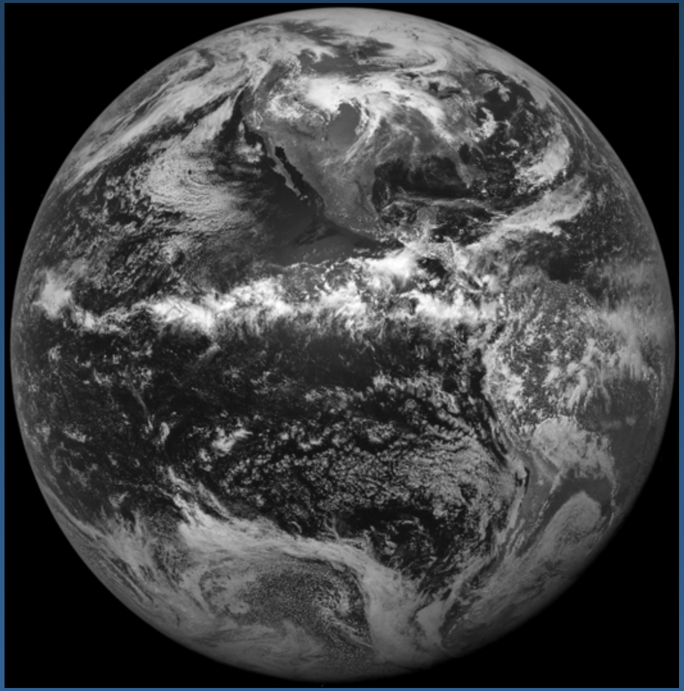
One Formation Studied | Two Formations Studied | Power Plants (dot size proportional to 1996 carbon emissions)

DOE Vision & Goal:
1 Gt storage by 2025, 4 Gt by 2050

Solar

Biomass

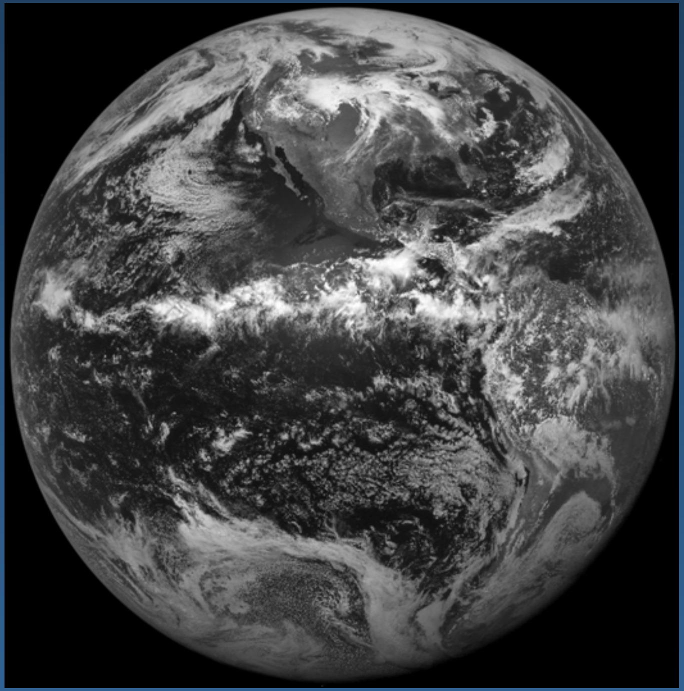
Ocean



Hydroelectric

Wind

Geothermal



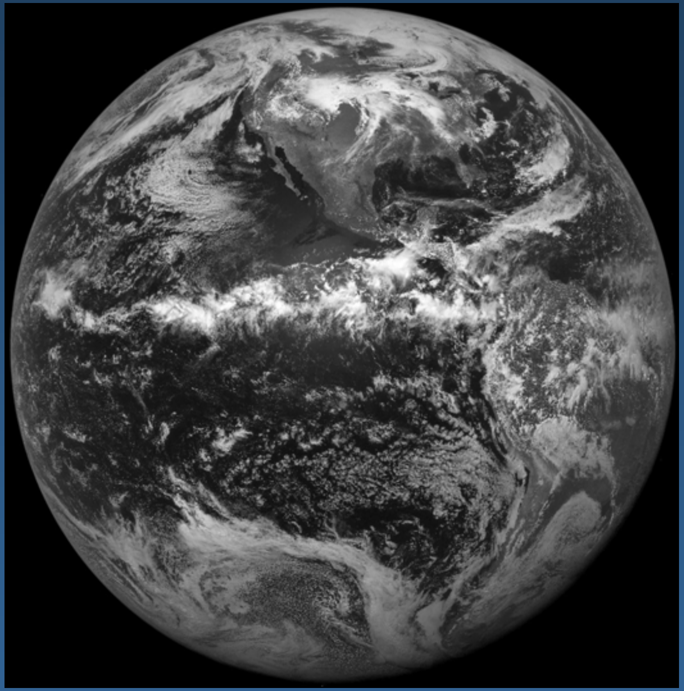
Hydroelectric

Gross: 4.6 TW

Technically Feasible: 1.6 TW

Economic: 0.9 TW

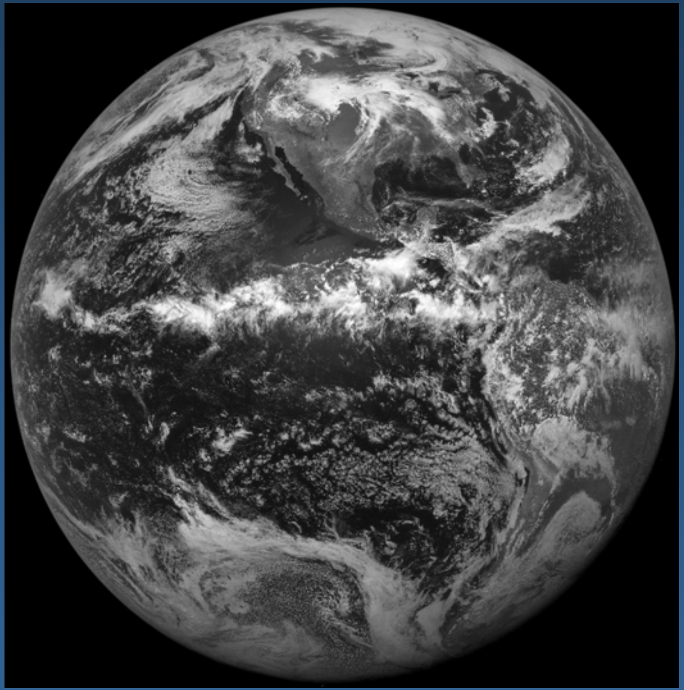
Installed Capacity: 0.6 TW



Geothermal

Mean flux at surface: 0.057 W/m^2

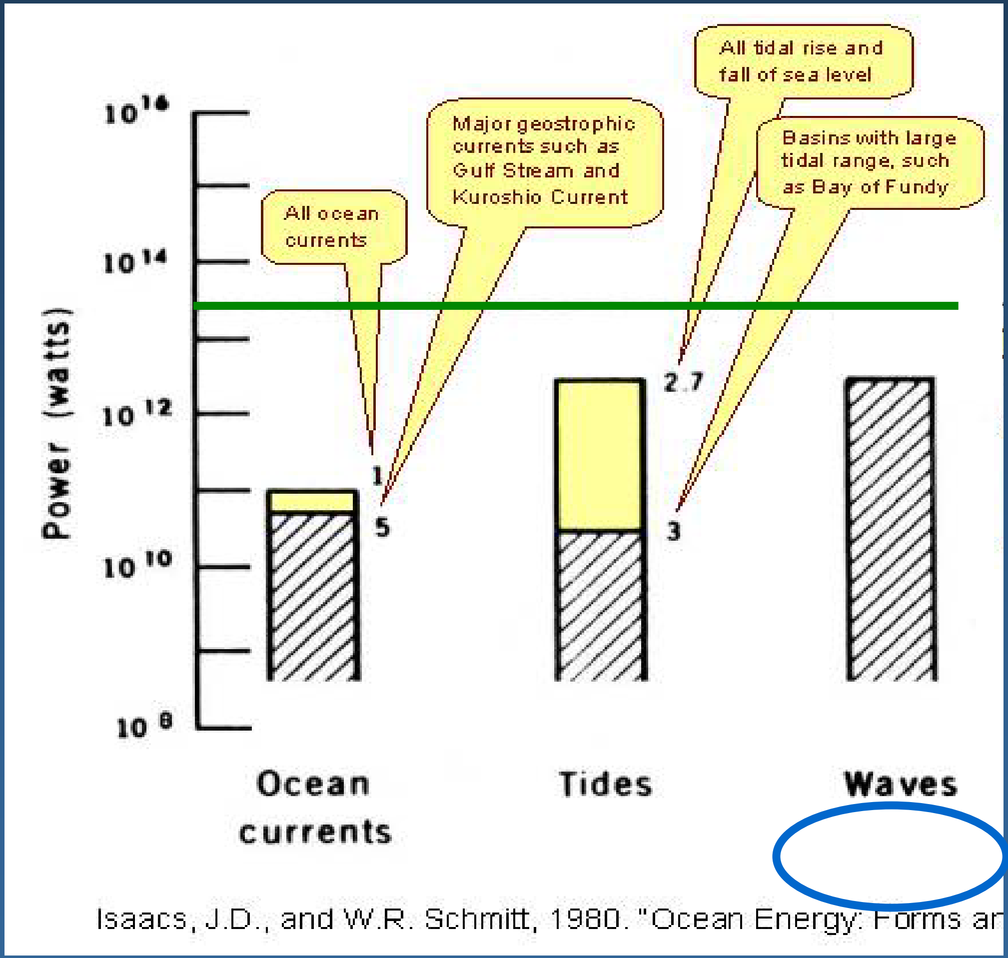
Continental Total Potential: 11.6 TW



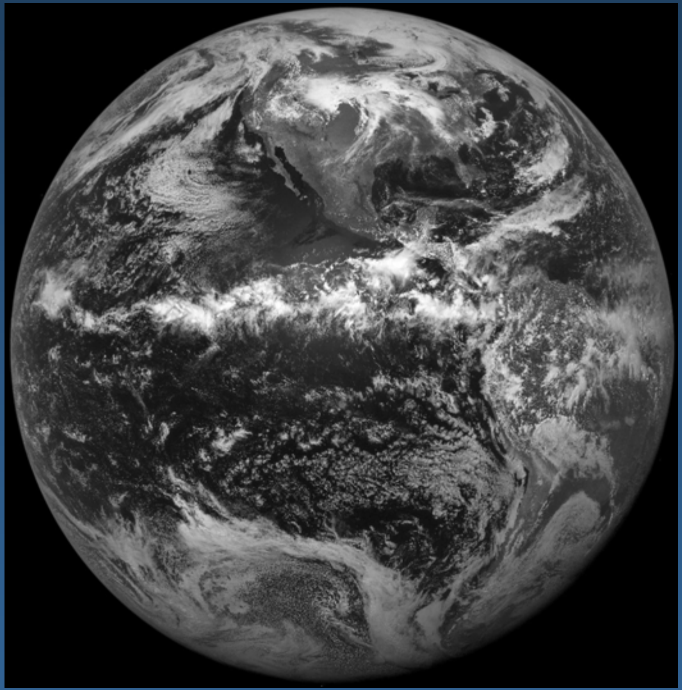
Wind

4% Utilization
Class 3 and
Above
2-3 TW

Ocean Energy Potential



Biomass



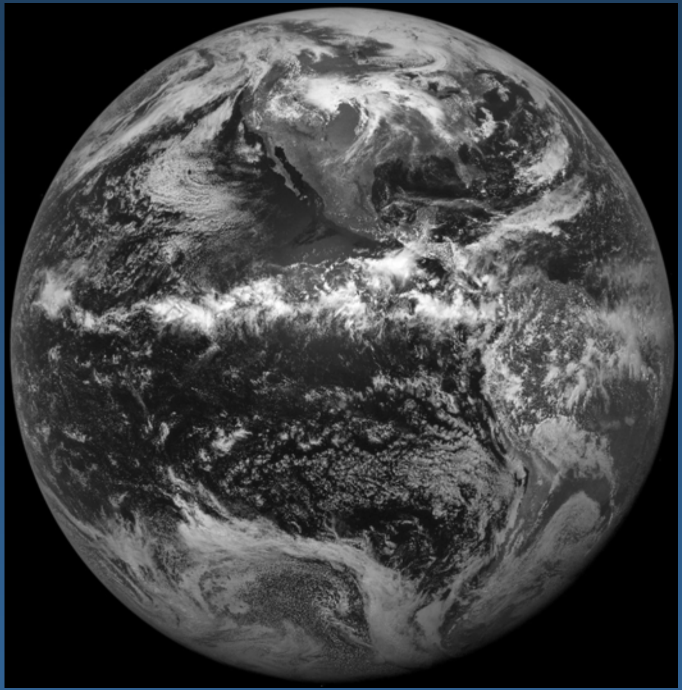
50% of all cultivatable land:
7-10 TW (gross)
1-2 TW (net)

Biomass Energy Potential

Global: Bottom Up

- Land with Crop Production Potential, 1990: 2.45×10^{13} m^2
- Cultivated Land, 1990: 0.897×10^{13} m^2
- Additional Land needed to support 9 billion people in 2050: 0.416×10^{13} m^2
- Remaining land available for biomass energy: 1.28×10^{13} m^2
- At 8.5-15 oven dry tonnes/hectare/year and 20 GJ higher heating value per dry tonne, energy potential is 7-12 TW
- Perhaps 5-7 TW by 2050 through biomass (less CO_2 displaced)
- Possible/likely that this is water resource limited
- 25% of U.S. corn in 2007 provided 2% of transportation fuel

Solar: potential $1.2x10^5$ TW; practical > 600 TW



Solar Energy Potential

- Theoretical: 1.2x10^5 TW solar energy potential

  (1.76 x10^5 TW striking Earth; 0.30 Global mean albedo)

  - Energy in 1 hr of sunlight $\leftrightarrow$ 14 TW for a year

- Practical: > 600 TW solar energy potential

  (50 TW - 1500 TW depending on land fraction etc.; WEA 2000)

  Onshore electricity generation potential of ≈60 TW (10% conversion efficiency):

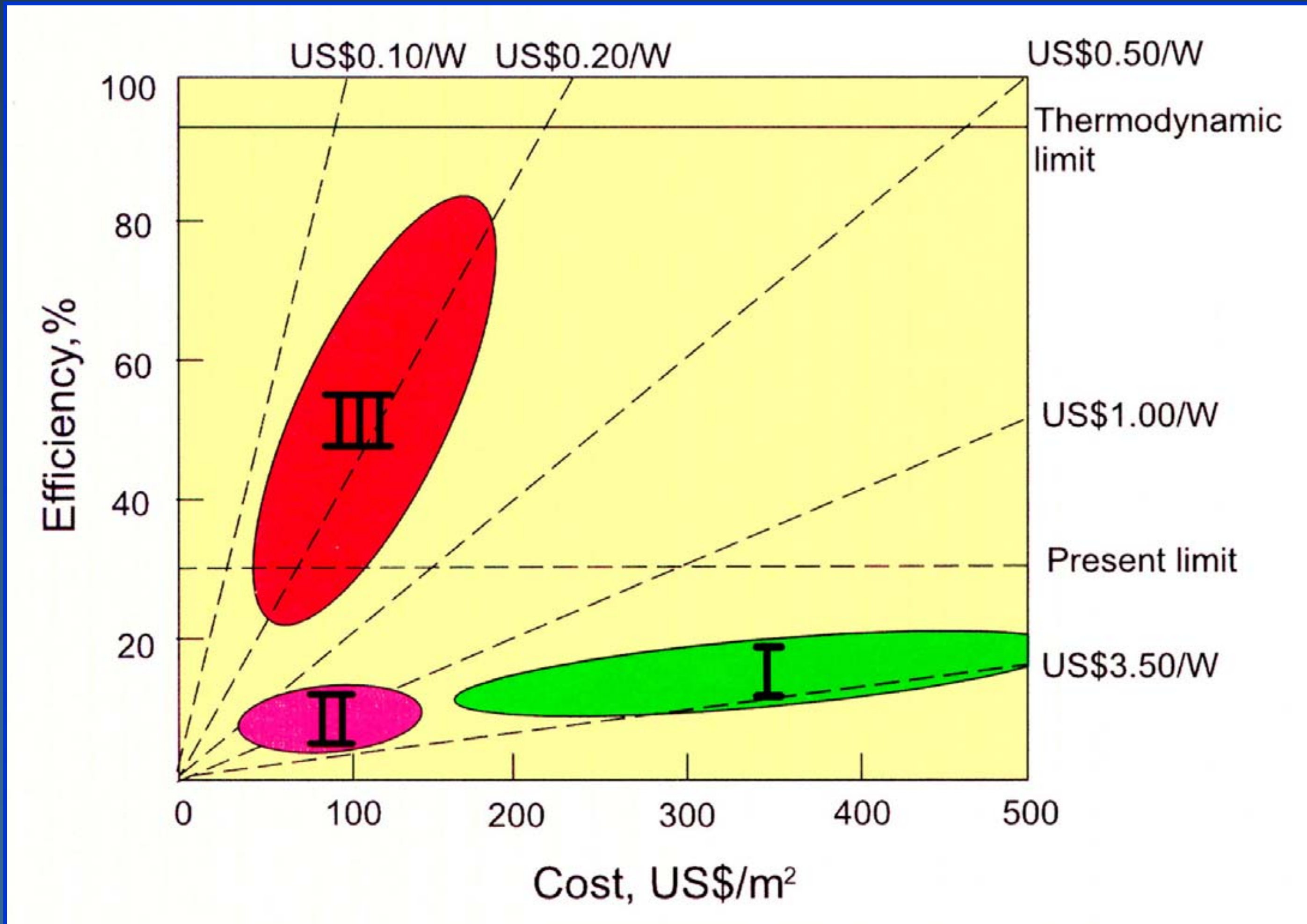
- *Photosynthesis*: 90 TW

Solar Land Area Requirements

Solar Land Area Requirements

6 Boxes at 3.3 TW Each

Cost/Efficiency of Photovoltaic Technology



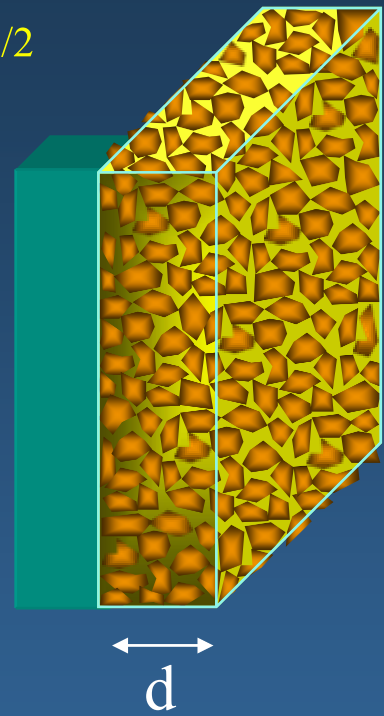
Costs are modules per peak W; installed is \$5-10/W; \$0.35-\$1.5/kW-hr

Cost vs. Efficiency Tradeoff

Efficiency $\propto \tau^{1/2}$

Large Grain
Single
Crystals

Long d
High τ
High Cost

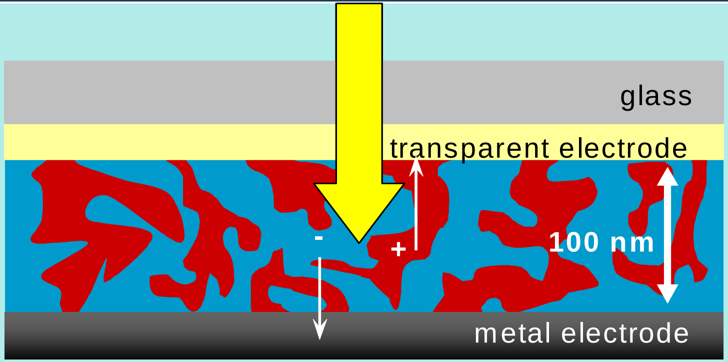


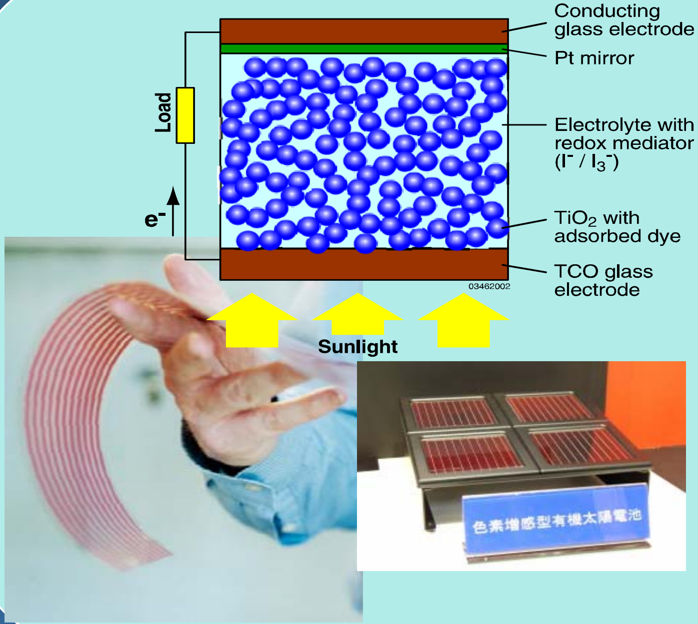
Small Grain
And/or
Polycrystalline
Solids

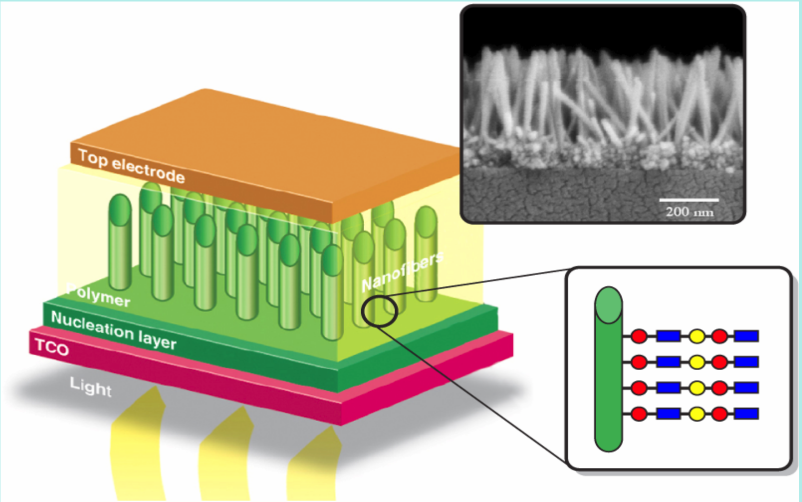
Long d
Low τ
Lower Cost

τ decreases as grain size (and cost) decreases

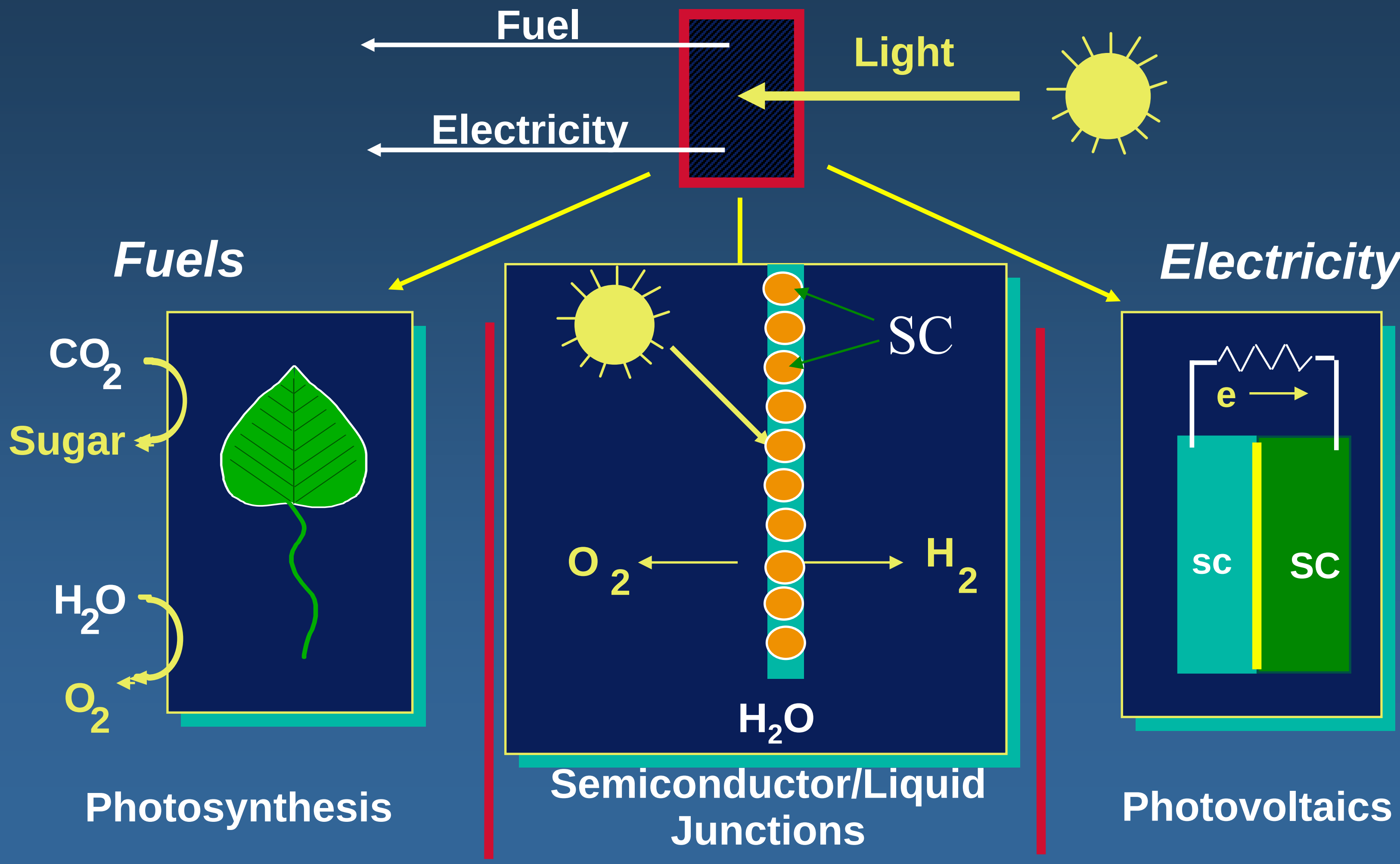
Interpenetrating Nanostructured Networks





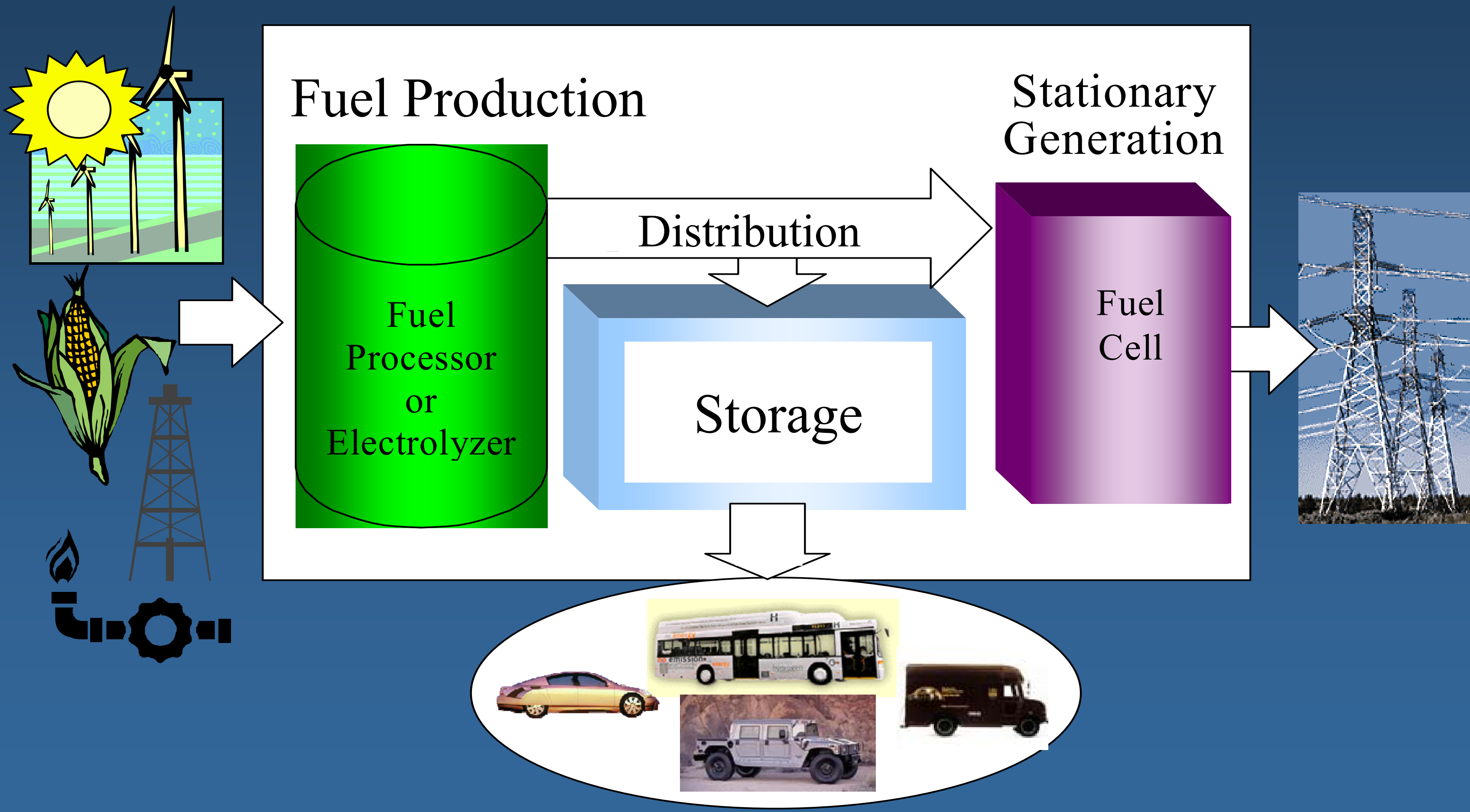


Energy Conversion Strategies

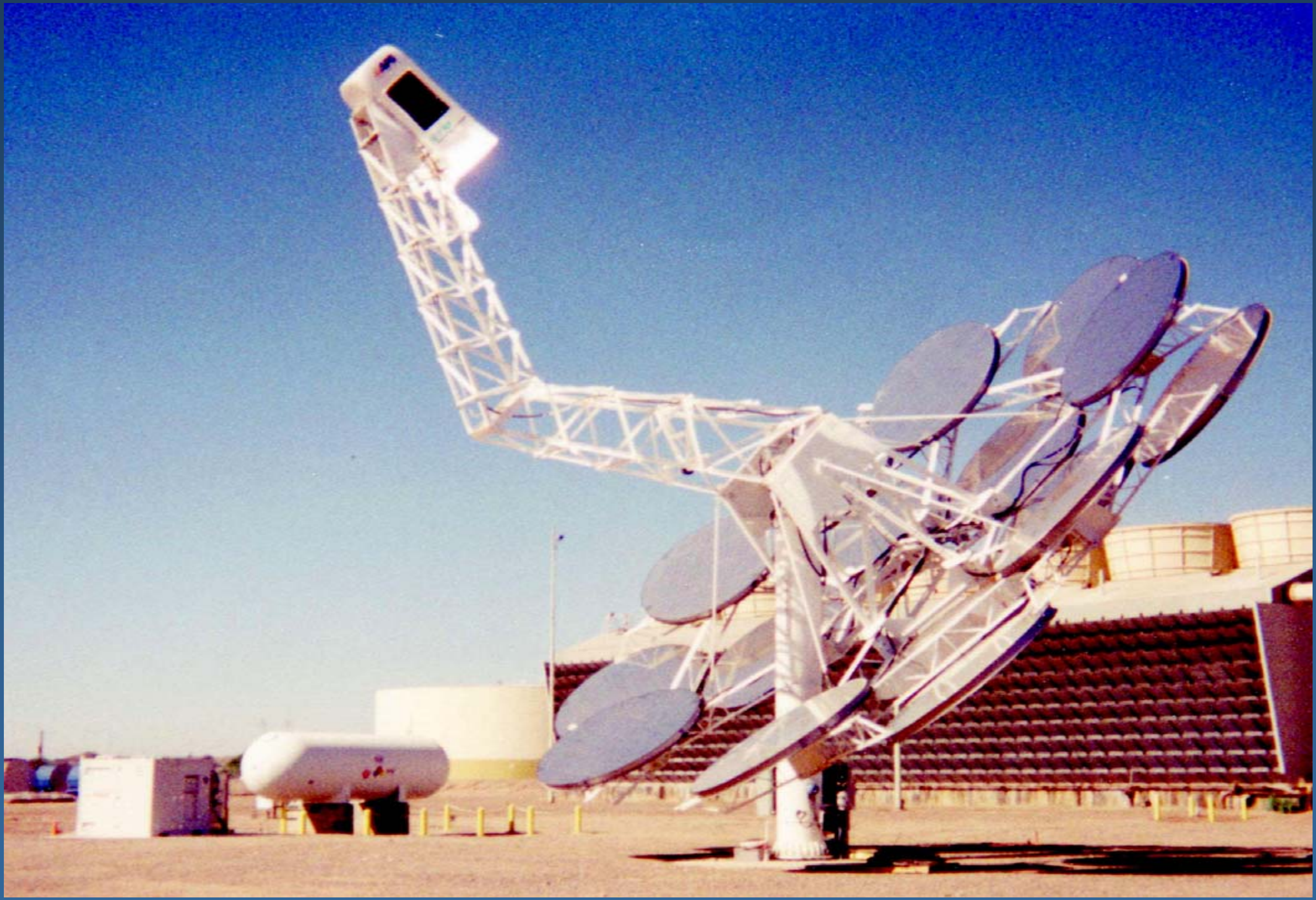


The Need to Produce Fuel

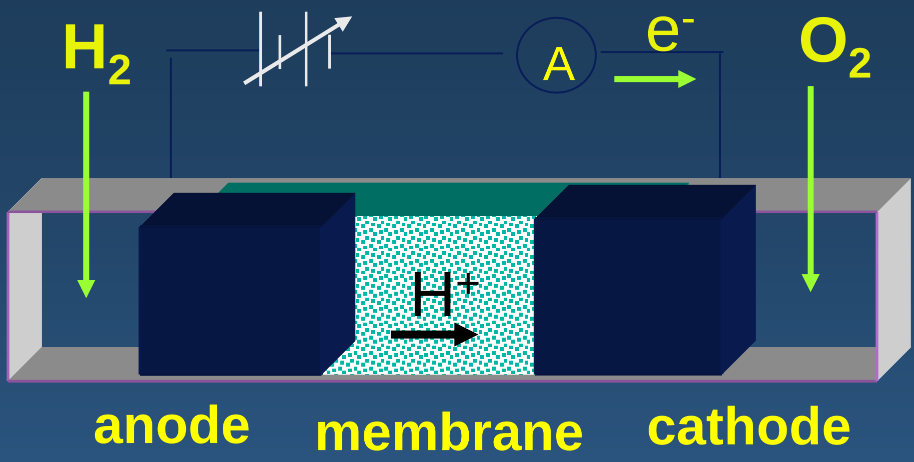
"Power Park Concept"



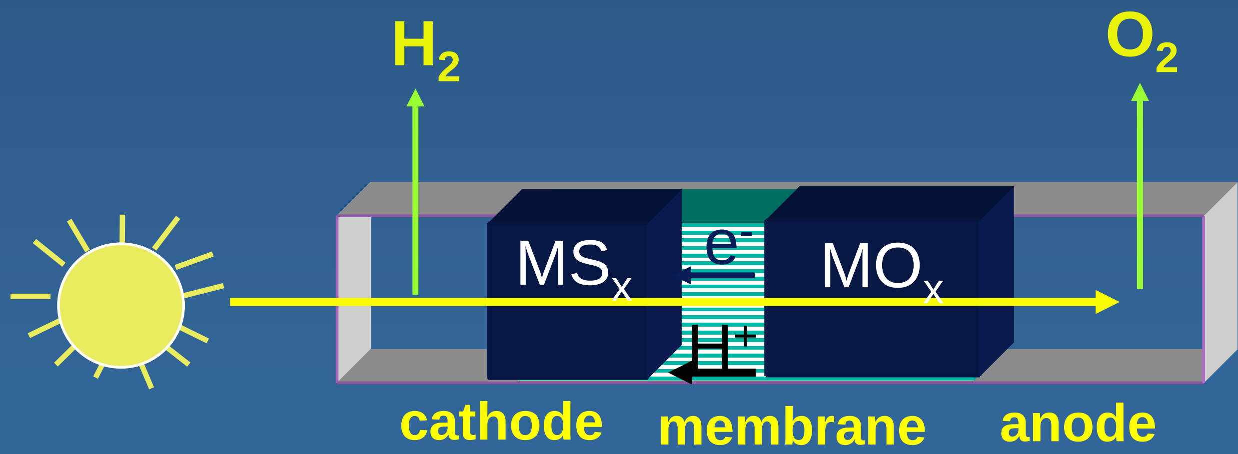
Photovoltaic + Electrolyzer System



Fuel Cell vs Photoelectrolysis Cell

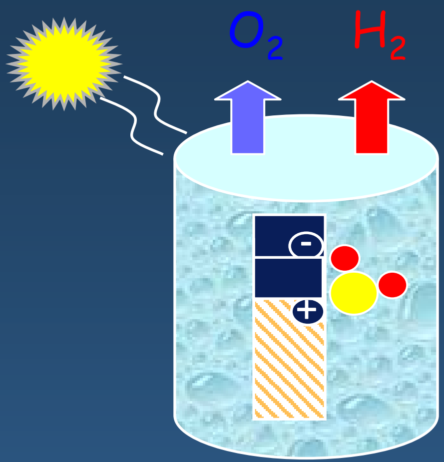


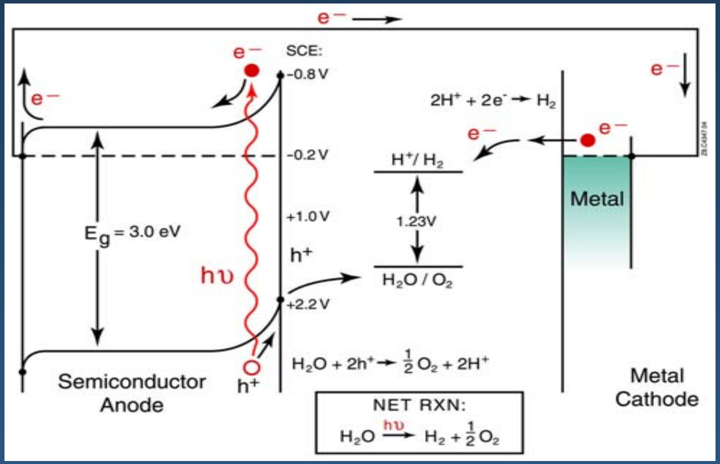
Fuel Cell
MEA



Photoelectrolysis
Cell MEA

Efficient Solar Water Splitting



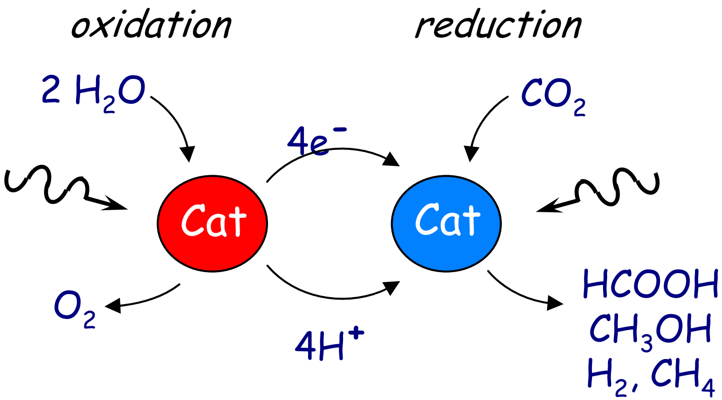


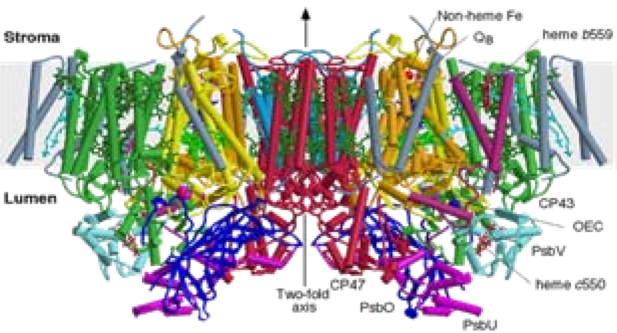
demonstrated efficiencies 10-18% in laboratory

Scientific Challenges

- cheap materials that are robust in water
- catalysts for the redox reactions at each electrode
- nanoscale architecture for electron excitation ⇒ transfer ⇒ reaction

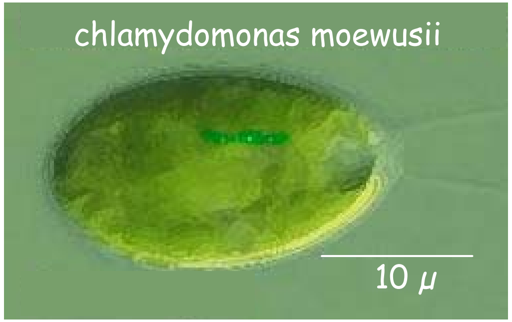
Solar-Powered Catalysts for Fuel Formation

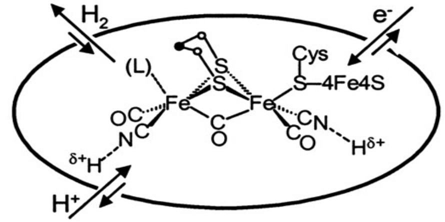




photosystem II

$2\ H_2O \Leftrightarrow O_2 + 4\ e^- + 4H^+$

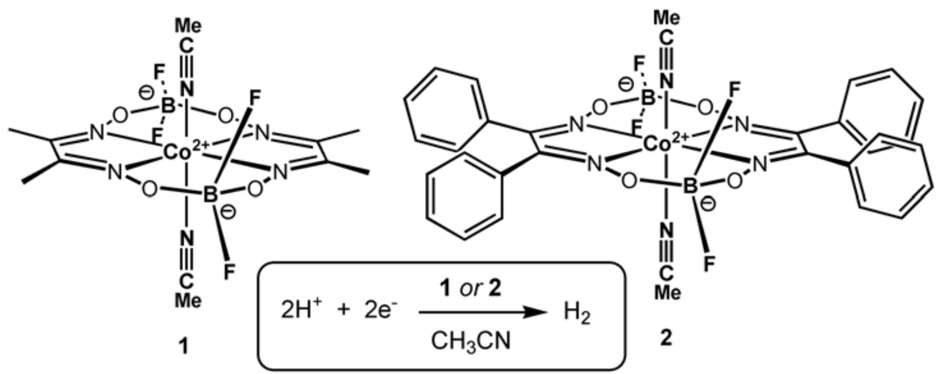




Active site of Fe-H$_2$ase

hydrogenase

$2H^+ + 2e^- \Leftrightarrow H_2$



Summary

- Need for Additional Primary Energy is Apparent
- Case for Significant (Daunting?) Carbon-Free Energy Seems Plausible (Imperative?):
  CO_2 emissions growth: 1990-1999: 1.1%/yr; 2000-2006: 3.1%/yr

Scientific/Technological Challenges

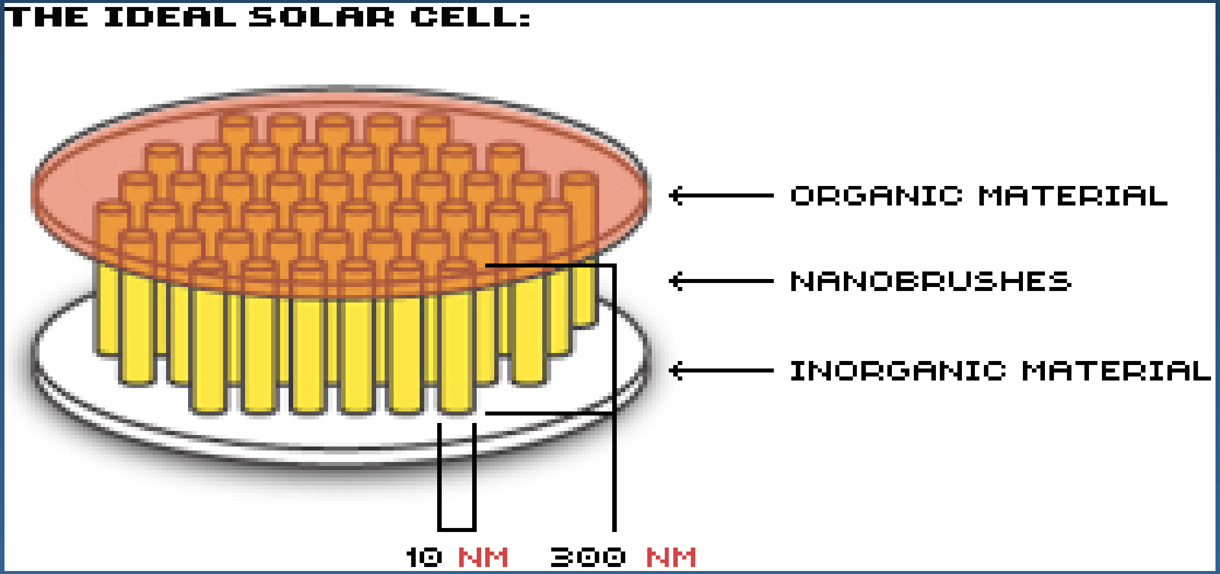
- Energy efficiency: energy security and environmental security
- Coal/sequestration; nuclear/breeders; **Cheap Solar Fuel**

Inexpensive conversion systems, effective storage systems

Policy Challenges

- Is Failure an Option?
- Will there be the needed commitment? In the remaining time?

Nanotechnology Solar Cell Design



Conclusion

- Solar is a critical piece of any long-term energy strategy
- PV is a significant, and growing, market
- Sustained, targeted, long-term investment is needed to enable the technology breakthroughs that will unlock the ultimate potential of Solar Energy

Biomass Energy Potential

Carbon Debts and Land Use Changes

- Land with Crop Production Potential, 1990: 2.45×10^{13} m^2
- Cultivated Land, 1990: 0.897×10^{13} m^2
- Additional Land needed to support 9 billion people in 2050: 0.416×10^{13} m^2
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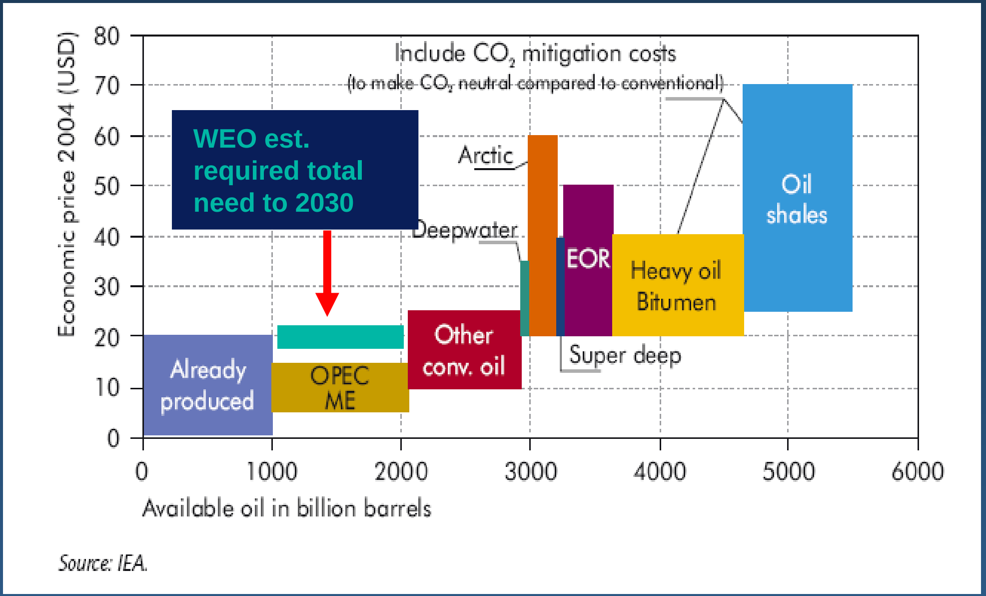
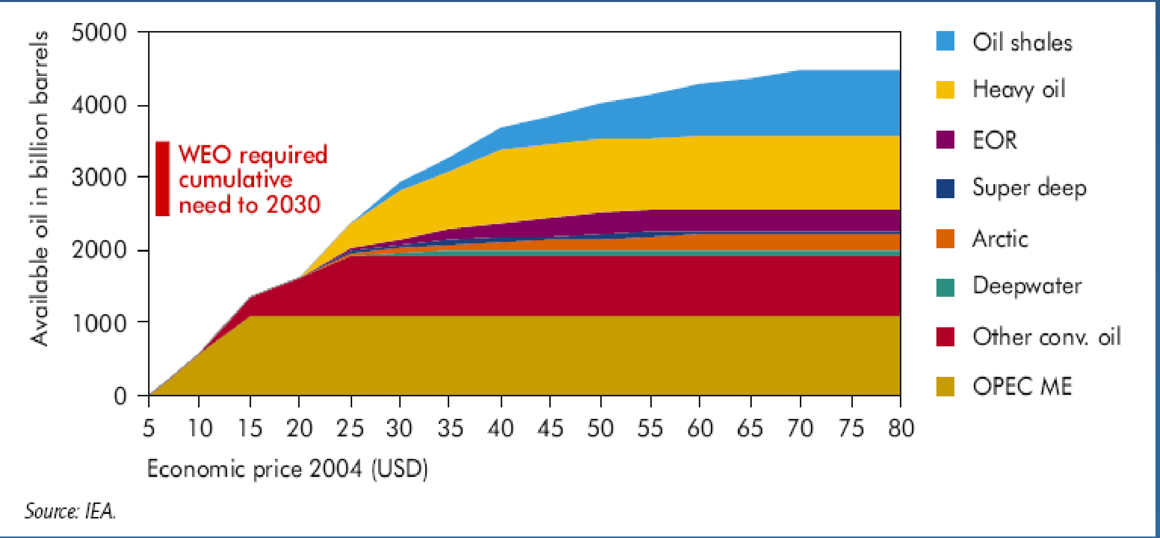
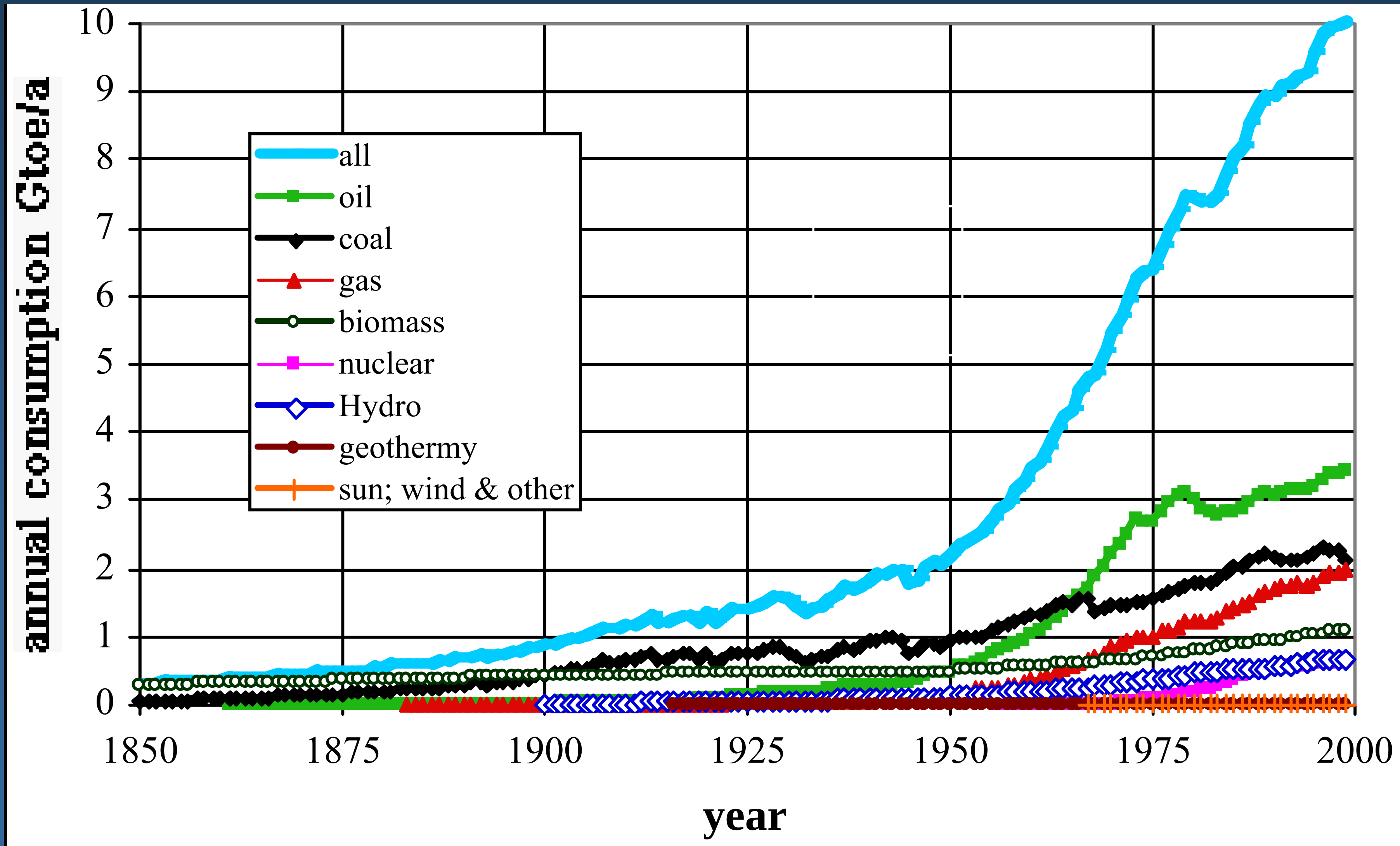
- 25% of U.S. corn in 2007 provided 2% of transportation fuel

Oil Supply Curves





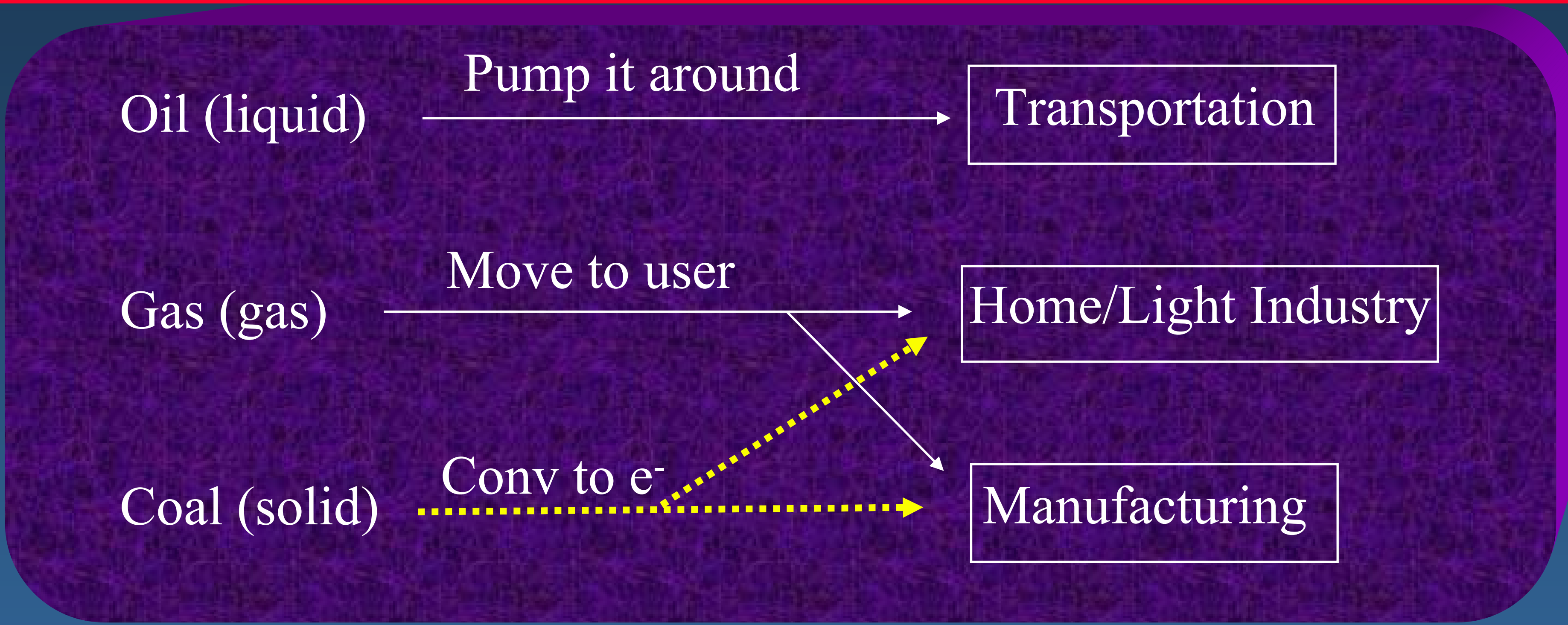
Global Energy Consumption



Solar Land Area Requirements

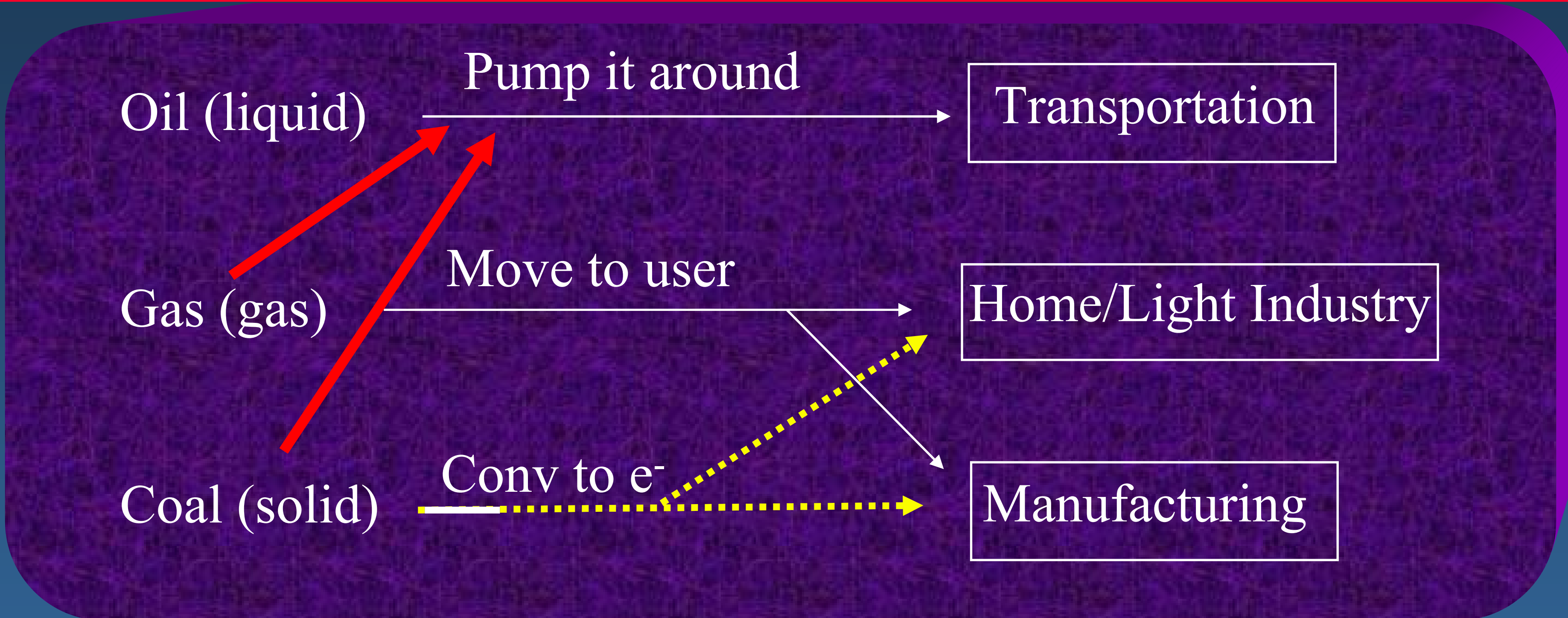
- 1.2×10^5 TW of solar energy potential globally
- Generating 2×10^1 TW with 10% efficient solar farms requires $2 \times 10^2 / 1.2 \times 10^5 = 0.16\%$ of Globe $= 8 \times 10^{11}\ m^2$ (i.e., 8.8 % of U.S.A)
- Generating 1.2×10^1 TW (1998 Global Primary Power) requires $1.2 \times 10^2 / 1.2 \times 10^5 = 0.10\%$ of Globe $= 5 \times 10^{11}\ m^2$ (i.e., 5.5% of U.S.A.)

Matching Supply and Demand



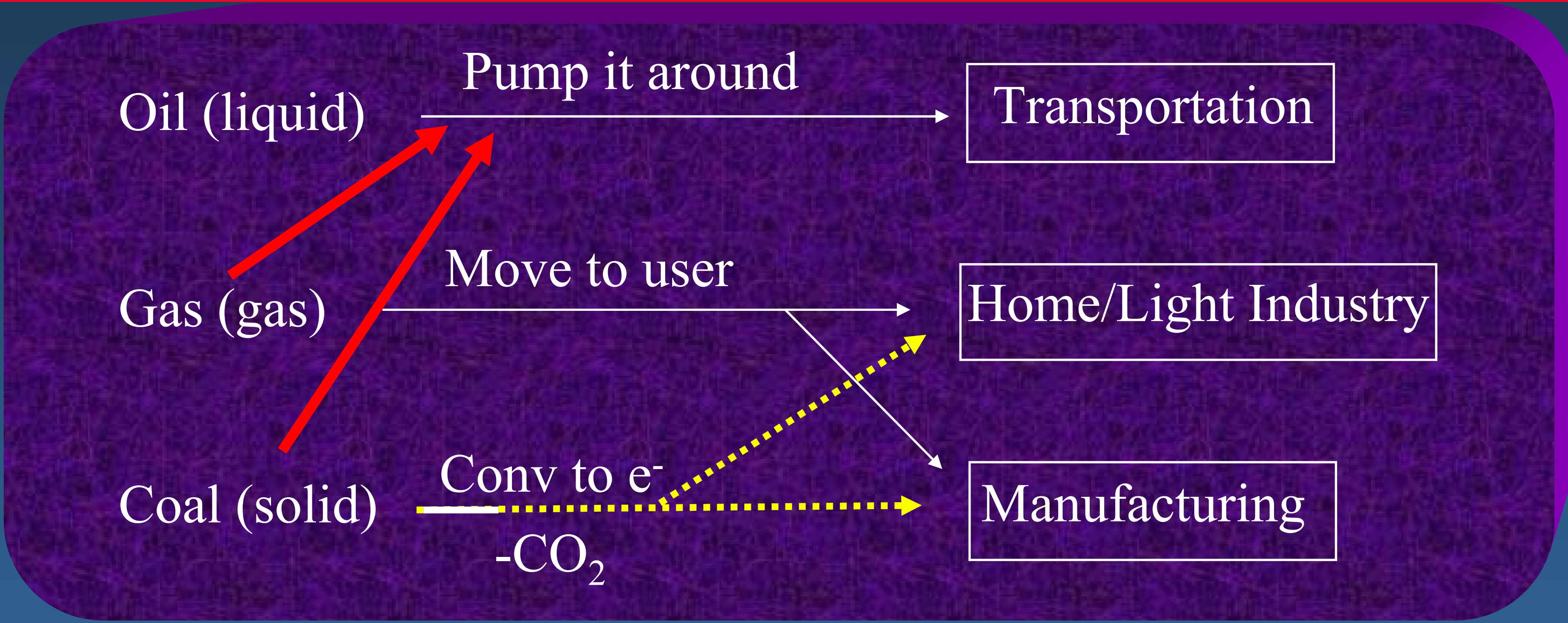
Currently end use well-matched to physical properties of resources

Matching Supply and Demand



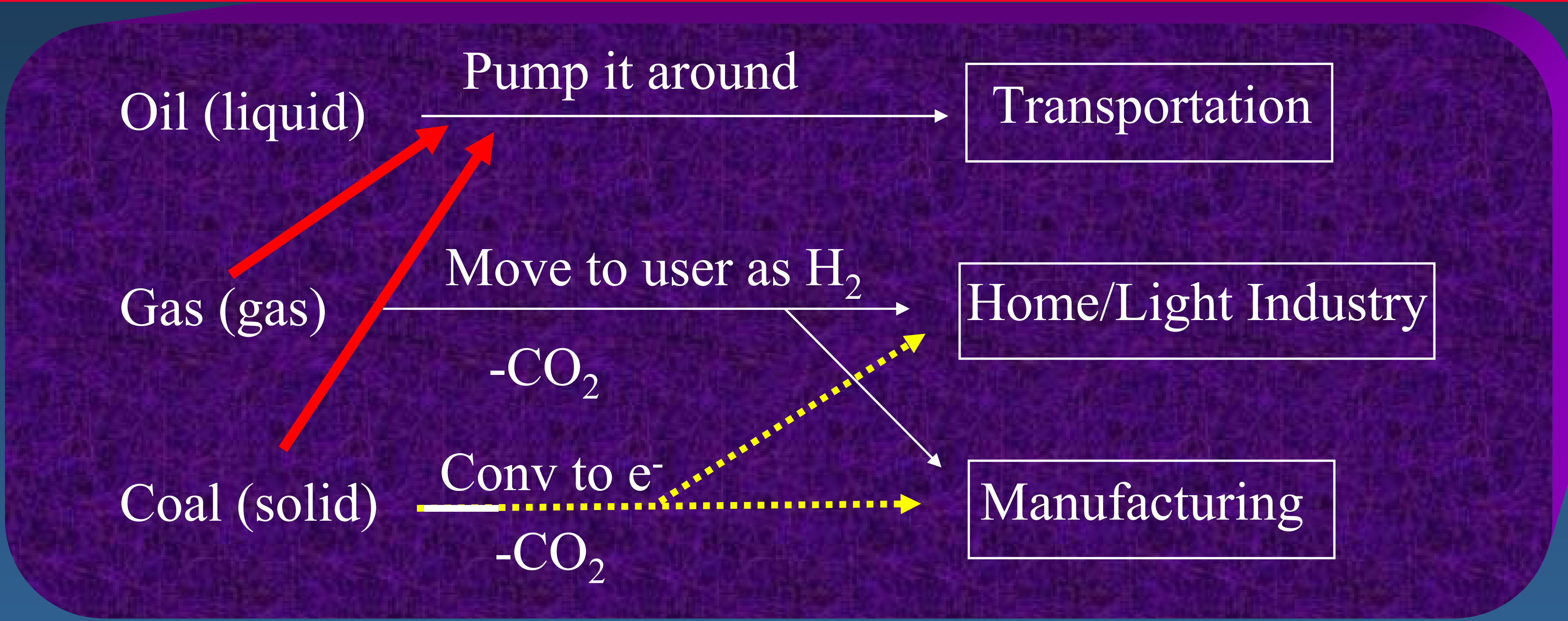
If deplete oil (or national security issue for oil), then liquify gas,coal

Matching Supply and Demand



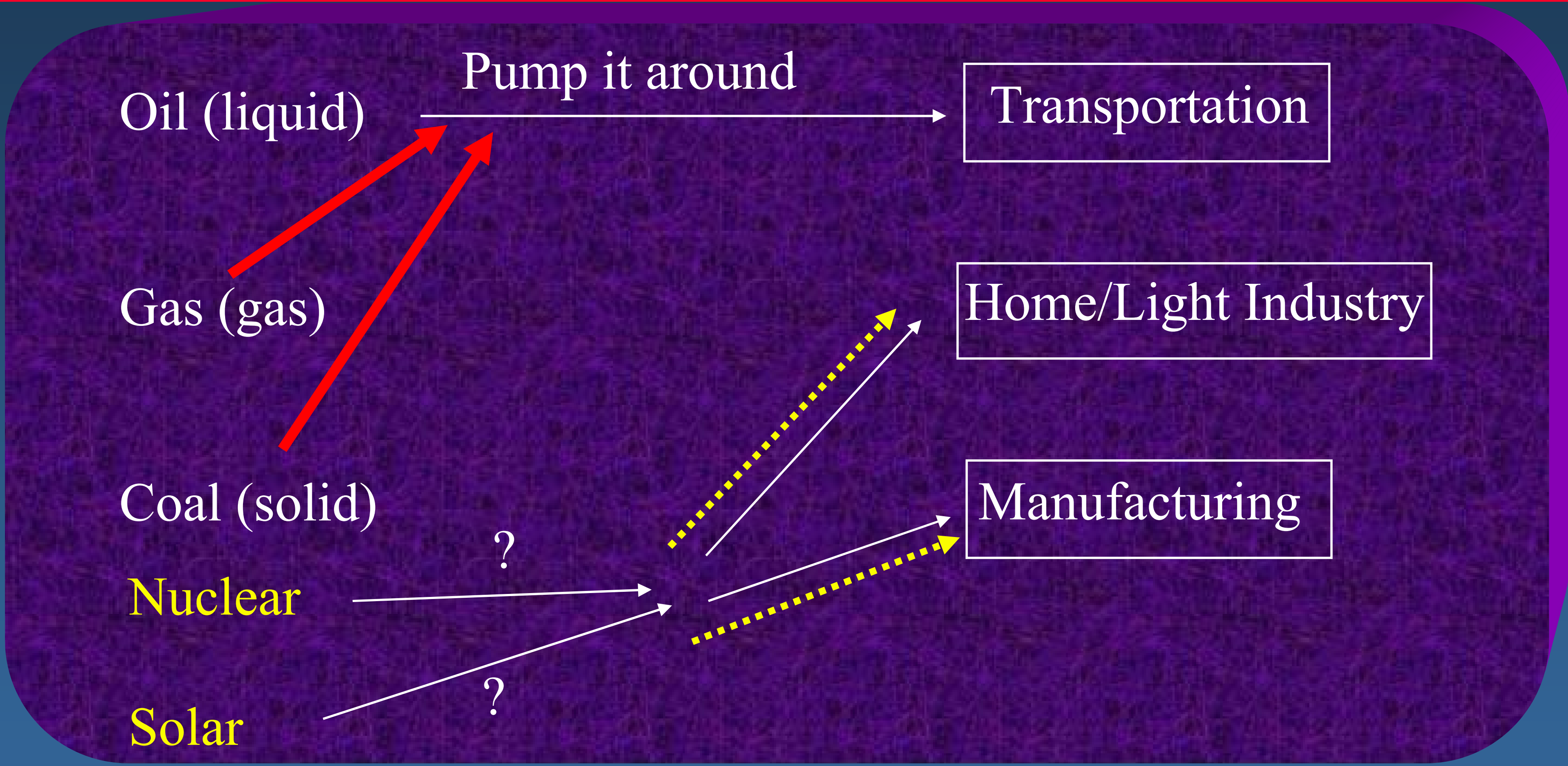
If carbon constraint to 550 ppm *and* sequestration works

Matching Supply and Demand



If carbon constraint to <550 ppm *and* sequestration works

Matching Supply and Demand

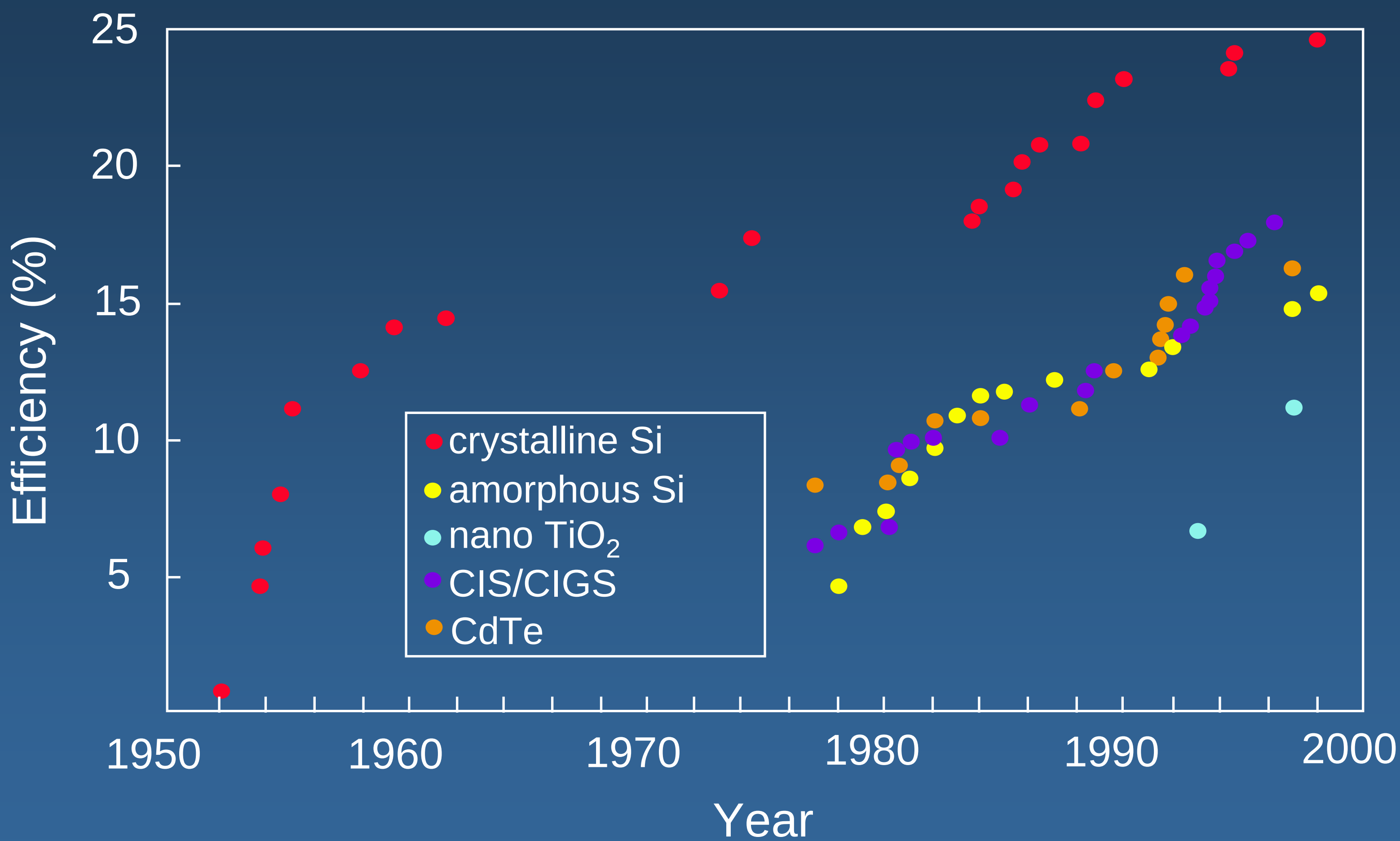


If carbon constraint to 550 ppm *and* sequestration does *not* work

Solar Electricity, 2001

- Production is Currently Capacity Limited (100 MW mean power output manufactured in 2001)
  - *but*, subsidized industry (Japan biggest market)
- High Growth
  - *but*, off of a small base (0.01% of 1%)
- Cost-favorable/competitive in off-grid installations
  - *but*, cost structures up-front vs amortization of grid-lines disfavorable
- Demands a systems solution: Electricity, heat, storage

Efficiency of Photovoltaic Devices



Quotes from PCAST, DOE, NAS

The principles are known, but the technology is not

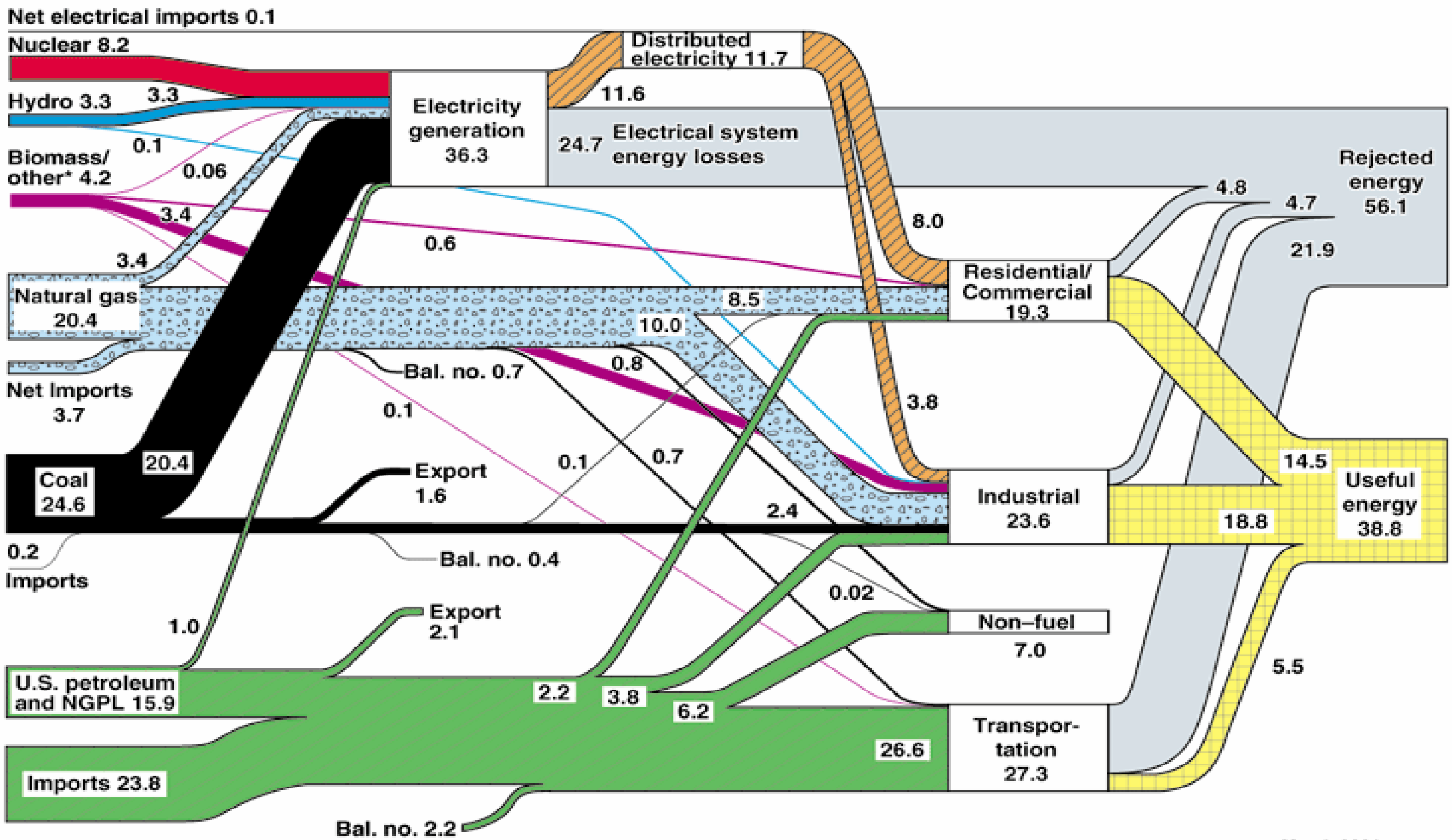
Will our efforts be too little, too late?

- Solar in 1 hour > Fossil in one year
- 1 hour $$$ gasoline > solar R&D in 6 years

Will we show the commitment to do this?

Is failure an option?

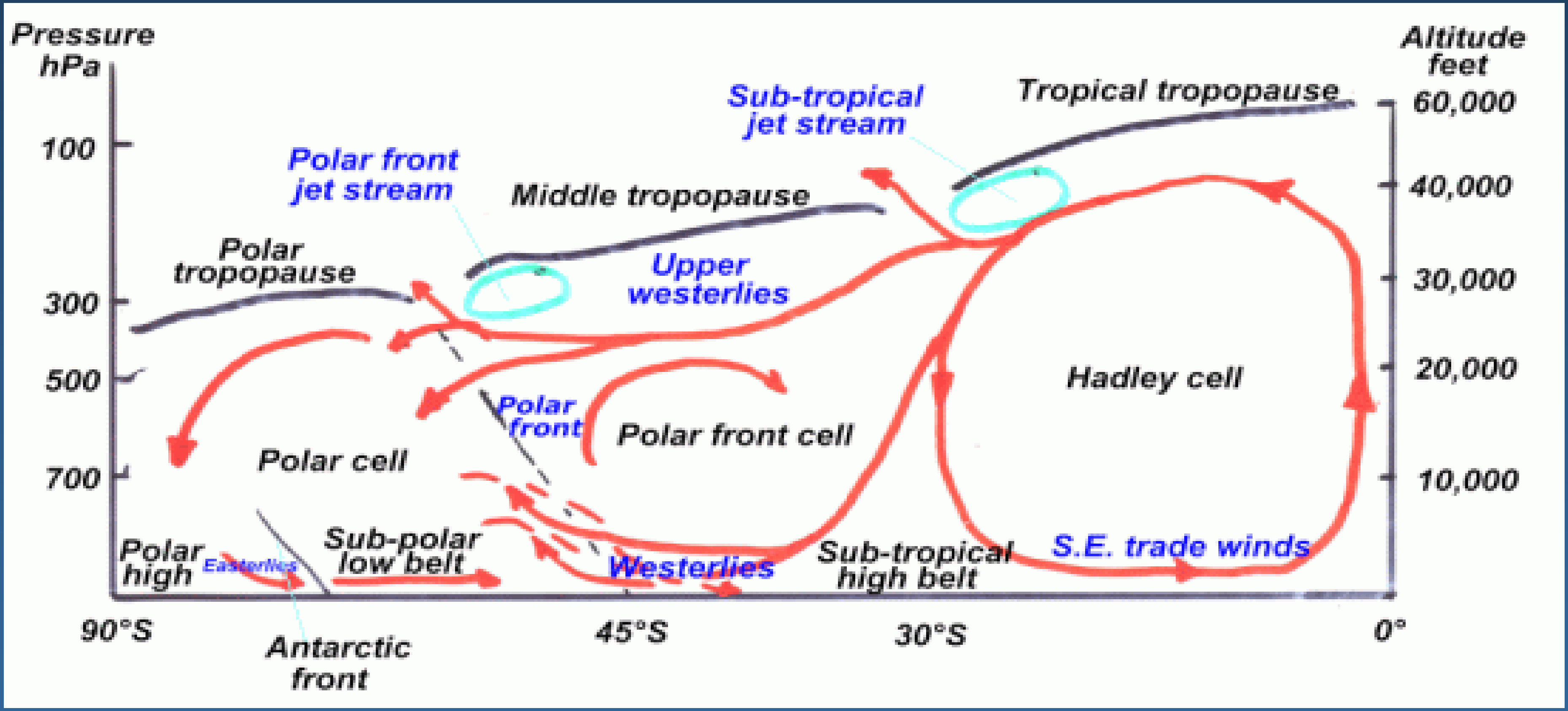
US Energy Flow -1999
Net Primary Resource Consumption 102 Exajoules



Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 1999*
*Biomass/other includes wood and waste, geothermal, solar, and wind.

March 2001
Lawrence Livermore National Laboratory

Tropospheric Circulation Cross Section



Primary vs. Secondary Power

Transportation Power

- Hybrid Gasoline/Electric
- Hybrid Direct Methanol Fuel Cell/Electric
- Hydrogen Fuel Cell/Electric?

Primary Power

- Wind, Solar, Nuclear; Bio.
- CH_4 to CH_3OH
- "Disruptive" Solar
- $CO_2 \longrightarrow CH_3OH + (1/2)\ O_2$
- $H_2O \longrightarrow H_2 + (1/2)\ O_2$

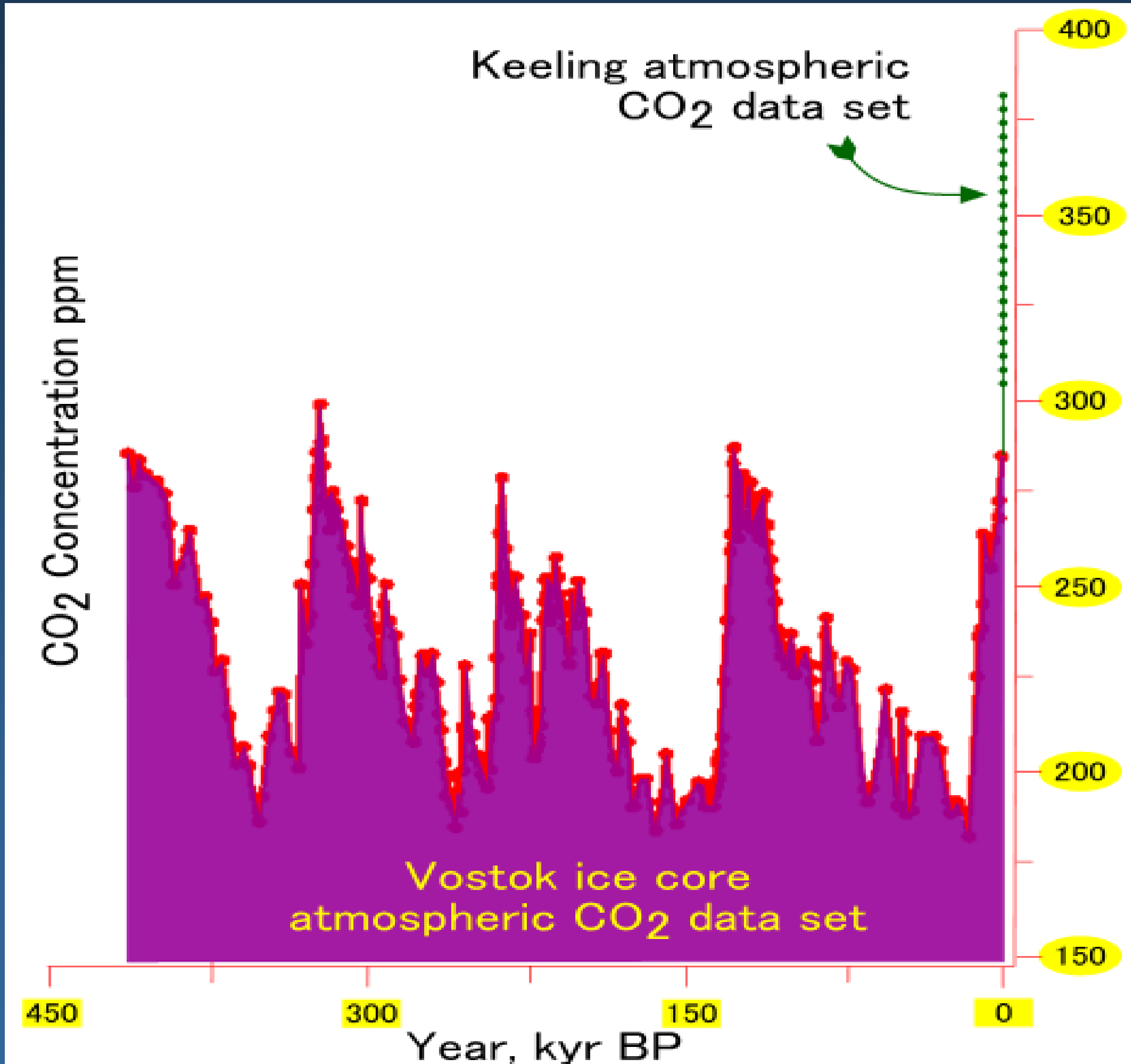
Challenges for the Chemical Sciences

CHEMICAL TRANSFORMATIONS

- Methane Activation to Methanol: $CH_4 + (1/2)O_2 = CH_3OH$
- Direct Methanol Fuel Cell: $CH_3OH + H_2O = CO_2 + 6H^+ + 6e^-$
- CO_2 (Photo)reduction to Methanol: $CO_2 + 6H^+ + 6e^- = CH_3OH$

- H_2/O_2 Fuel Cell: $H_2 = 2H^+ + 2e^-$; $O_2 + 4\ H^+ + 4e- = 2H_2O$
- (Photo)chemical Water Splitting:
  $2H^+ + 2e^- = H_2$; $2H_2O = O_2 + 4H^+ + 4e^-$

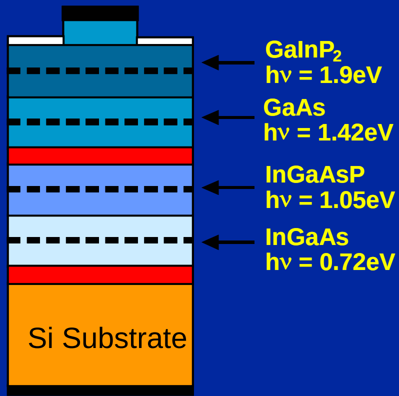
- Improved Oxygen Cathode; $O_2 + 4H^+ + 4e^- = 2H_2O$



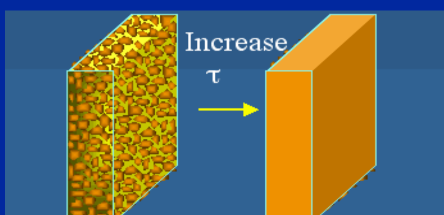
Keeling atmospheric
CO_2 data set
400
350
300
250
200
150
CO_2 Concentration ppm
Vostok ice core
atmospheric CO_2 data set
450
300
150
0
Year, kyr BP

Powering the Planet

Solar → Electric

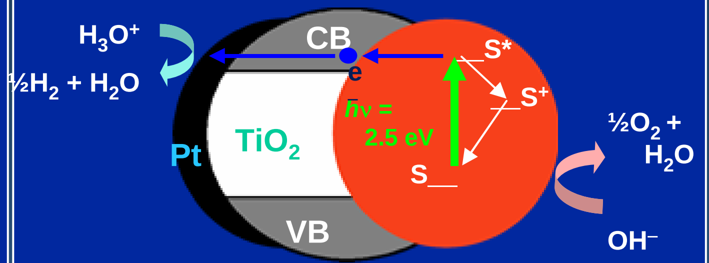


Extreme efficiency
at moderate cost

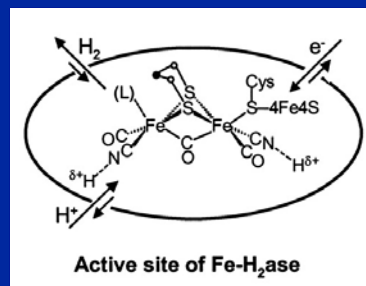


Solar paint: grain
boundary passivation

Solar → Chemical

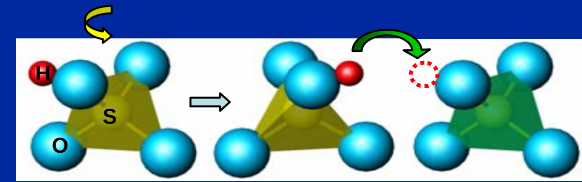


Photoelectrolysis: integrated
energy conversion and fuel
generation

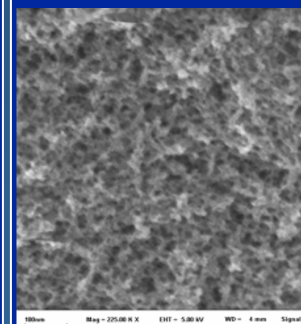


Bio-inspired
fuel generation

Chemical → Electric



Inorganic electrolytes:
bare proton transport



100 nm

Catalysis:
ultra high
surface area,
nanoporous
materials

Synergies: Catalysis, materials
discovery, materials processing

Hydrogen vs Hydrocarbons

- By essentially all measures, H_2 is an inferior transportation fuel relative to liquid hydrocarbons

- So, why?

- Local air quality: 90% of the benefits can be obtained from clean diesel without a gross change in distribution and end-use infrastructure; no compelling need for H_2

- Large scale CO_2 sequestration: Must distribute either electrons or protons; compels H_2 be the distributed fuel-based energy carrier

- Renewable (sustainable) power: no compelling need for H_2 to end user, e.g.: $CO_2 + H_2 \rightarrow CH_3OH \rightarrow DME \rightarrow$ other liquids

Observations of Climate Change

Evaporation & rainfall are increasing;

- More of the rainfall is occurring in downpours
- Corals are bleaching
- Glaciers are retreating
- Sea ice is shrinking
- Sea level is rising
- Wildfires are increasing
- Storm & flood damages are much larger

Solar Thermal, 2001

- Roughly equal global energy use in each major sector: transportation, residential, transformation, industrial
- World market: 1.6 TW space heating; 0.3 TW hot water; 1.3 TW process heat (solar crop drying: ≈ 0.05 TW)
- Temporal mismatch between source and demand requires storage
- (ΔS) yields high heat production costs: ($0.03-$0.20)/kW-hr
- High-T solar thermal: currently lowest cost solar electric source ($0.12-0.18/kW-hr); potential to be competitive with fossil energy in long term, but needs large areas in sunbelt
- Solar-to-electric efficiency 18-20% (research in thermochemical fuels: hydrogen, syn gas, metals)

Solar Land Area Requirements

- U.S. Land Area: 9.1×10^{12} m^2 (incl. Alaska)

- Average Insolation: 200 W/m^2

- 2000 U.S. Primary Power Consumption: 99 Quads=3.3 TW
- 1999 U.S. Electricity Consumption = 0.4 TW

- Hence:

  3.3×10^{12} W/(2×10^{2} W/m^2 x 10% Efficiency) = 1.6×10^{11} m^2

  Requires 1.6×10^{11} m^2/ 9.1×10^{12} m^2 = 1.7% of Land

U.S. Single Family Housing Roof Area

- 7×10^7 detached single family homes in U.S.
  ≈2000 sq ft/roof = 44ft x 44 ft = 13 m x 13 m = 180 m^2/home
  = 1.2×10^{10} m^2 total roof area

- Hence can (only) supply 0.25 TW, or ≈1/10th of 2000 U.S. Primary Energy Consumption

Cost vs. Efficiency Tradeoff

Efficiency $\propto \tau^{1/2}$

Ordered
Crystalline
Solids

d

Long d
High τ
High Cost

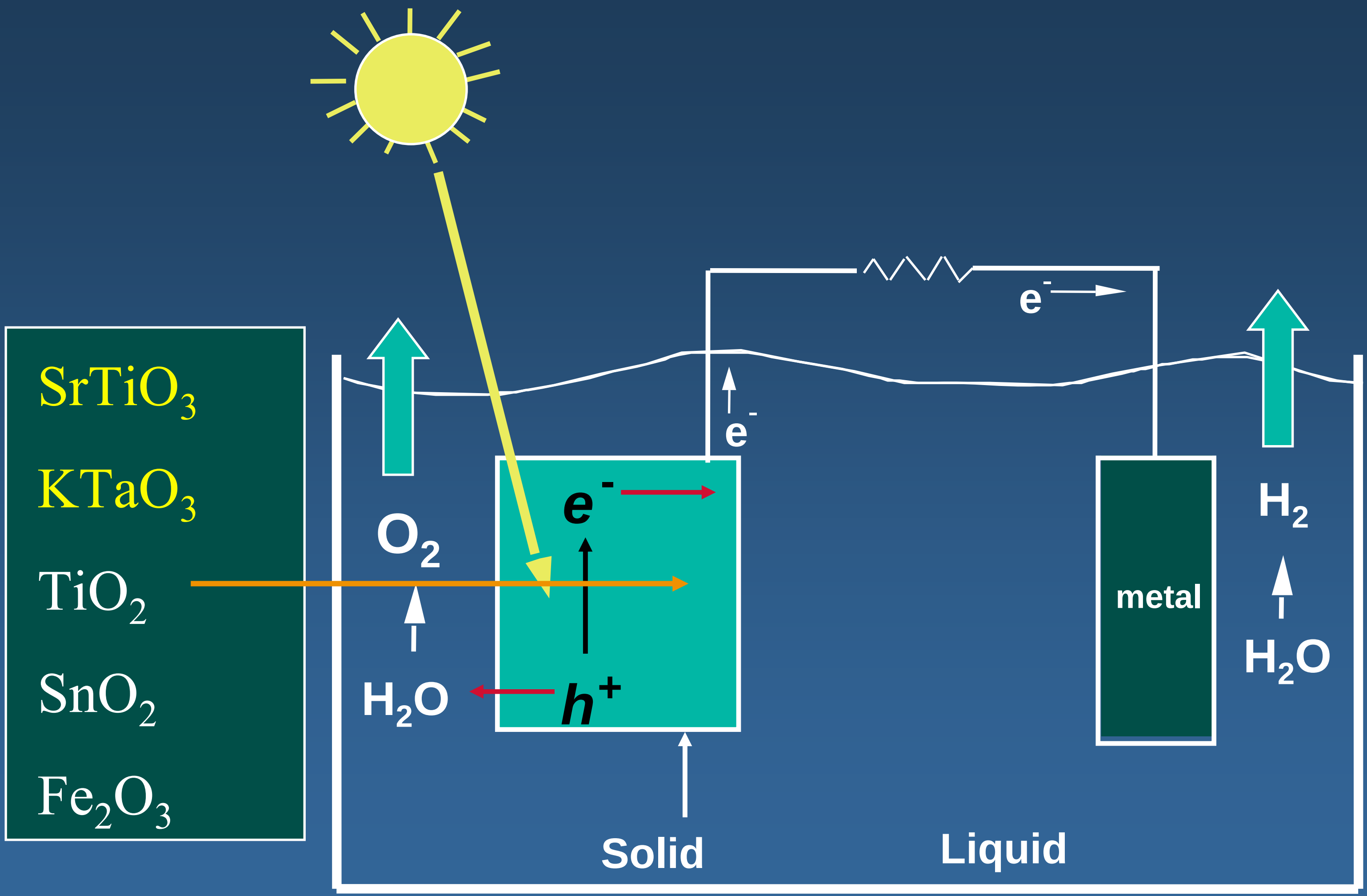
d

Long d
Low τ
Lower Cost

Disordered
Organic
Films

τ decreases as material (and cost) decreases

Photoelectrochemical Cell



Light is Converted to Electrical+Chemical Energy

Potential of Renewable Energy

- Hydroelectric
- Geothermal
- Ocean/Tides
- Wind
- Biomass
- Solar

Hydroelectric Energy Potential

Globally

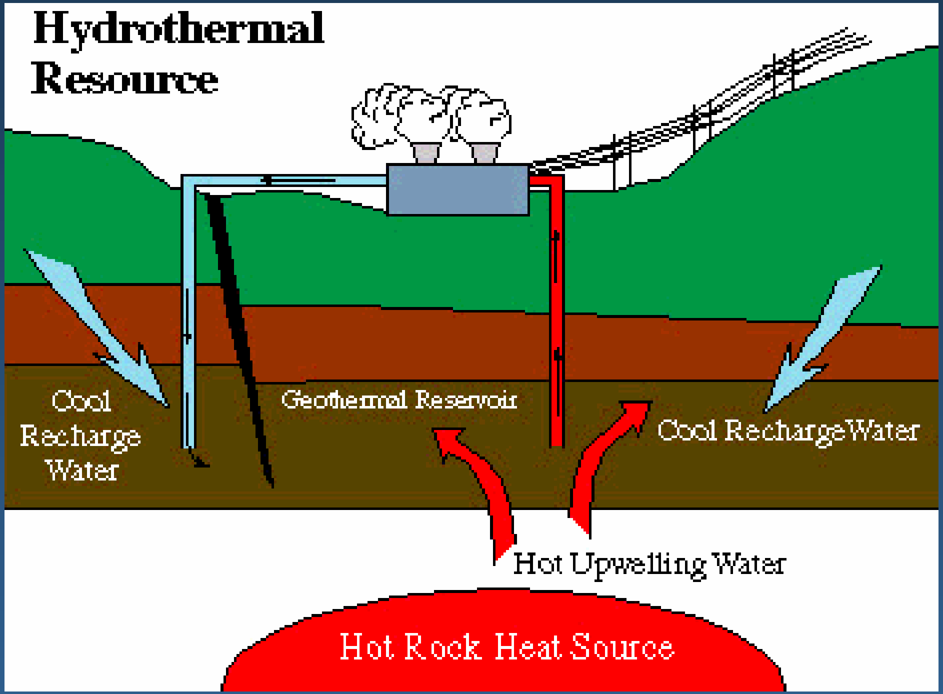
• Gross theoretical potential	4.6 TW
• Technically feasible potential	1.5 TW
• Economically feasible potential	0.9 TW
• Installed capacity in 1997	0.6 TW
• Production in 1997	0.3 TW

□(can get to 80% capacity in some cases)

Source: WEA 2000

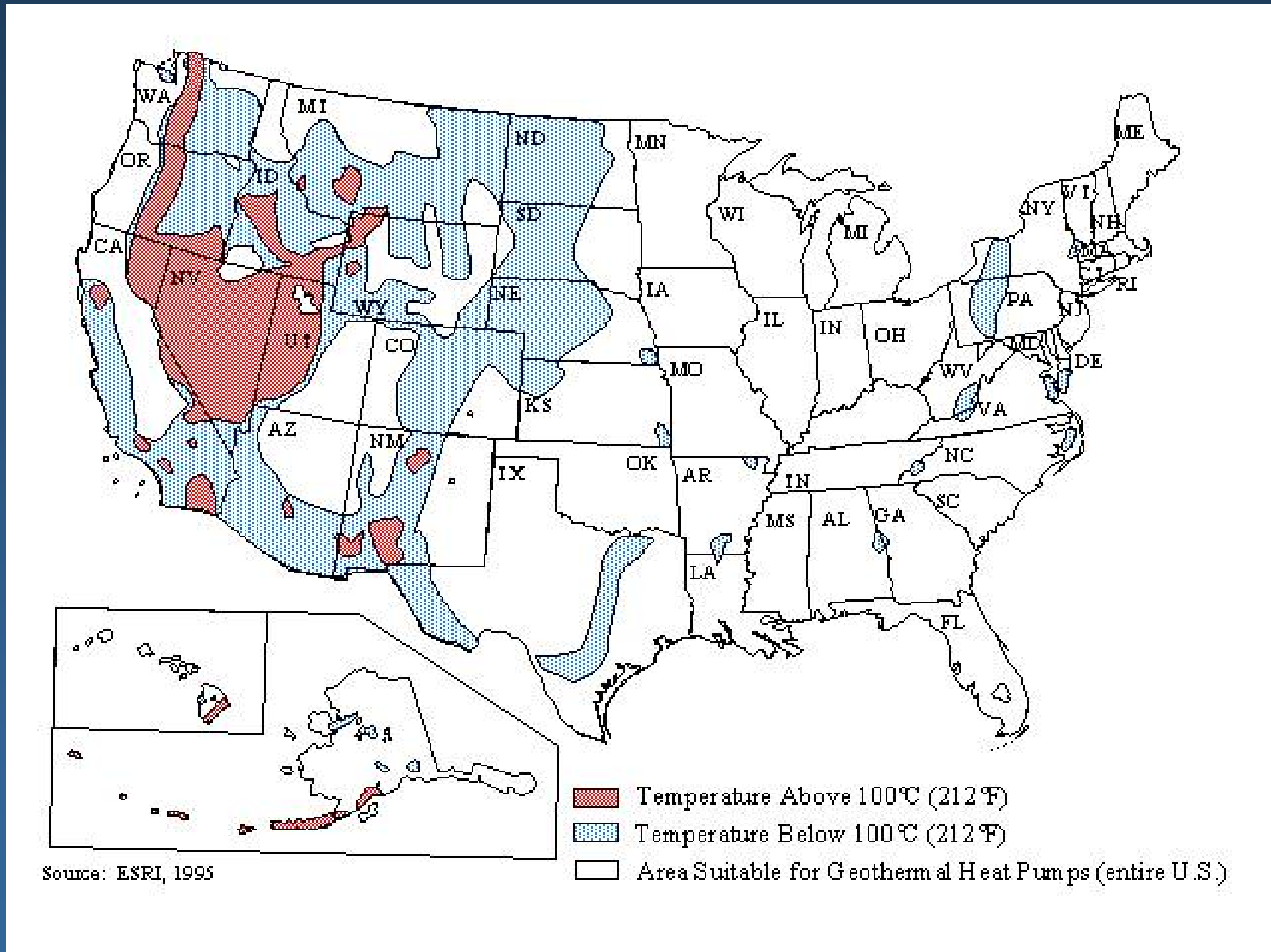
Geothermal Energy

1.3 GW capacity in 1985



Hydrothermal systems
Hot dry rock (igneous systems)
Normal geothermal heat (200 C at 10 km depth)

Geothermal Energy Potential



Geothermal Energy Potential

- Mean terrestrial geothermal flux at earth's surface 0.057 W/m^2
- Total continental geothermal energy potential 11.6 TW
- Oceanic geothermal energy potential 30 TW

- Wells "run out of steam" in 5 years
- Power from a good geothermal well (pair) 5 MW
- Power from typical Saudi oil well 500 MW
- Needs drilling technology breakthrough (from exponential $/m to linear $/m) to become economical)

Ocean Energy Potential

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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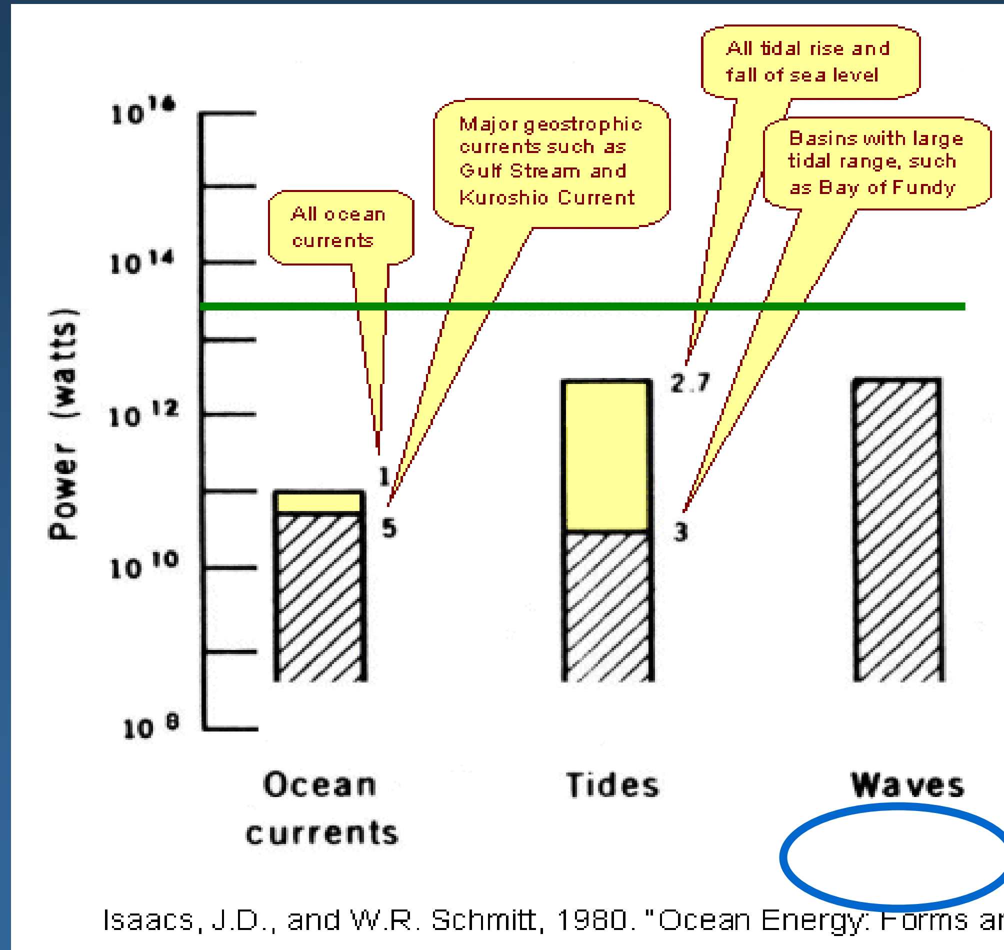
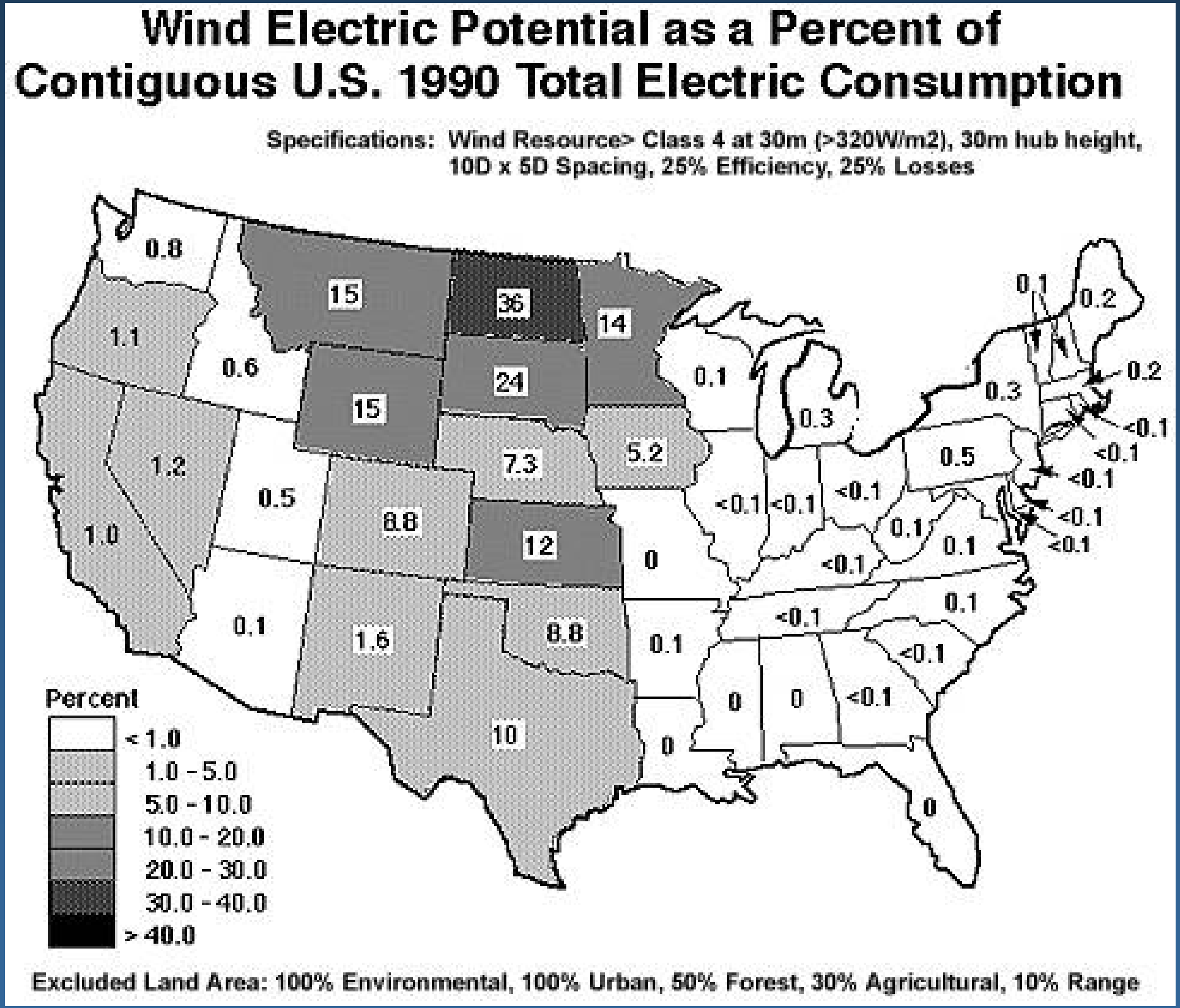


Electric Potential of Wind



In 1999, U.S consumed 3.45 trillion kW-hr of Electricity = 0.39 TW

http://www.nrel.gov/wind/potential.html

Global Potential of Terrestrial Wind

- **Top-down**:
  Downward kinetic energy flux: 2 W/m^2
  Total land area: $1.5x10^{14}$ m^2
  Hence total available energy = 300 TW
  Extract <10%, 30% of land, 30% generation efficiency:
  2-4 TW electrical generation potential

- **Bottom-Up**:
  Theoretical: 27% of earth's land surface is class 3 (250-300 W/m^2 at 50 m) or greater
  If use entire area, electricity generation potential of 50 TW
  Practical: 2 TW electrical generation potential (4% utilization of ≥class 3 land area, IPCC 2001)

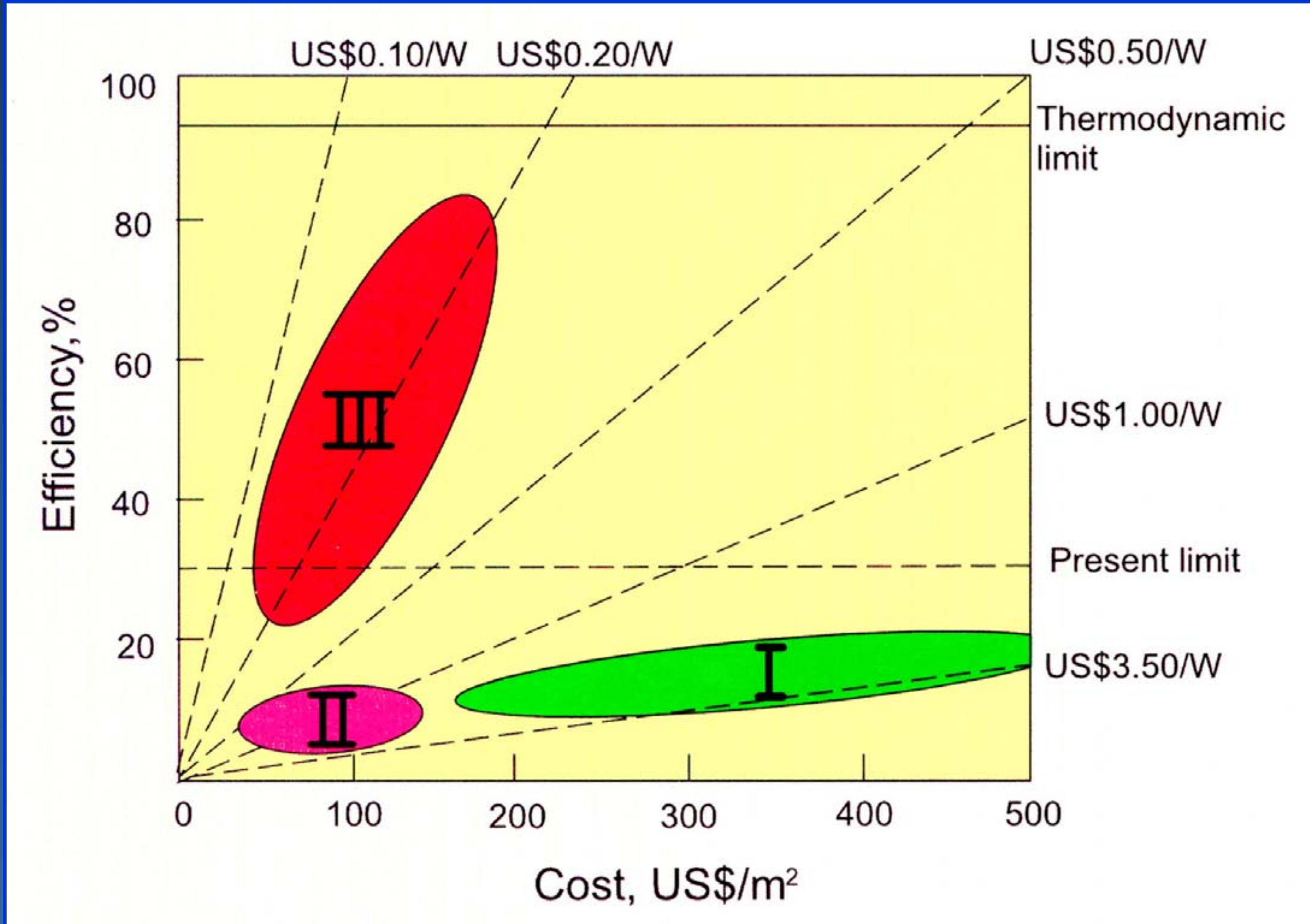
  Off-shore potential is larger but must be close to grid to be interesting; (no installation > 20 km offshore now)

Biomass Energy Potential

Global: Top Down

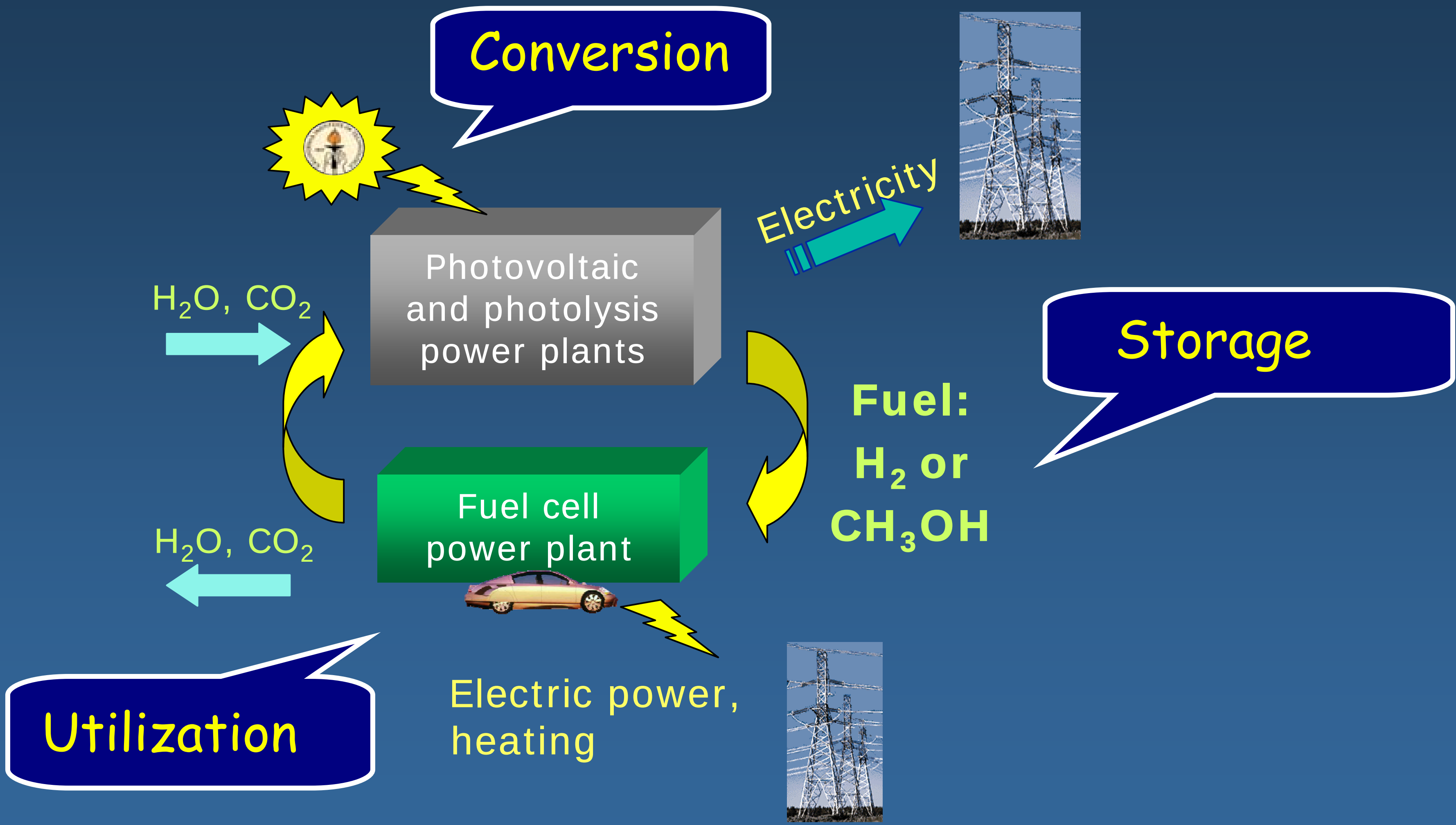
- Requires Large Areas Because Inefficient (0.3%)
- 3 TW requires ≈ 600 million hectares = $6x10^{12}$ m^2
- 20 TW requires ≈ $4x10^{13}$ m^2
- Total land area of earth: $1.3x10^{14}$ m^2
- Hence requires 4/13 = 31% of total land area

Cost/Efficiency of "Solar Farms"

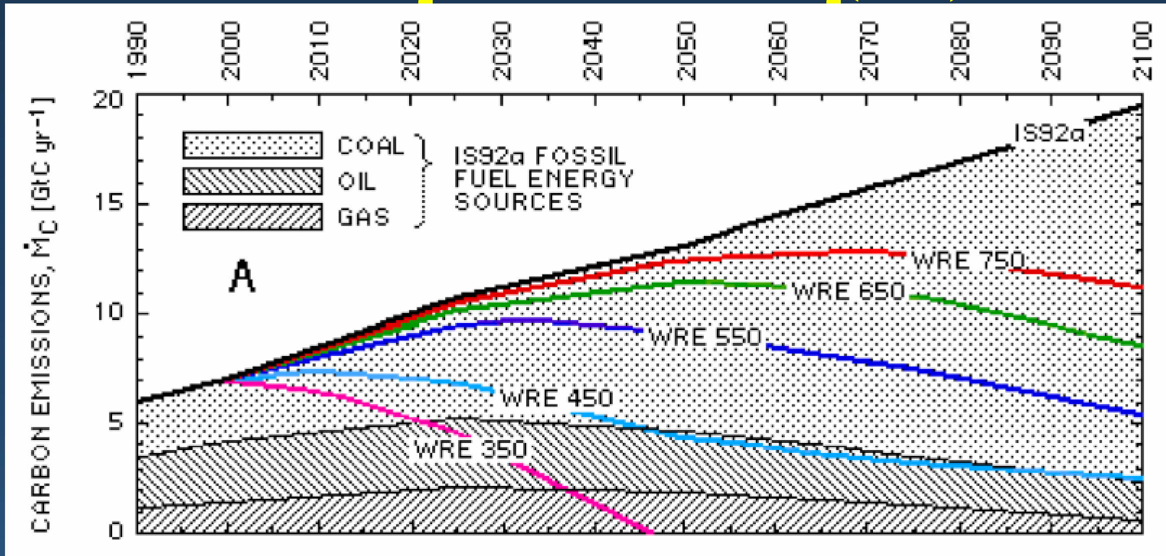


Costs are modules per peak W; installed is \$5-10/W; \$0.35-\$1.5/kW-hr

The Vision


Conversion
Photovoltaic and photolysis power plants
Electricity
Storage
Fuel: H_2 or CH_3OH
H_2O, CO_2
H_2O, CO_2
Fuel cell power plant
Electric power, heating
Utilization

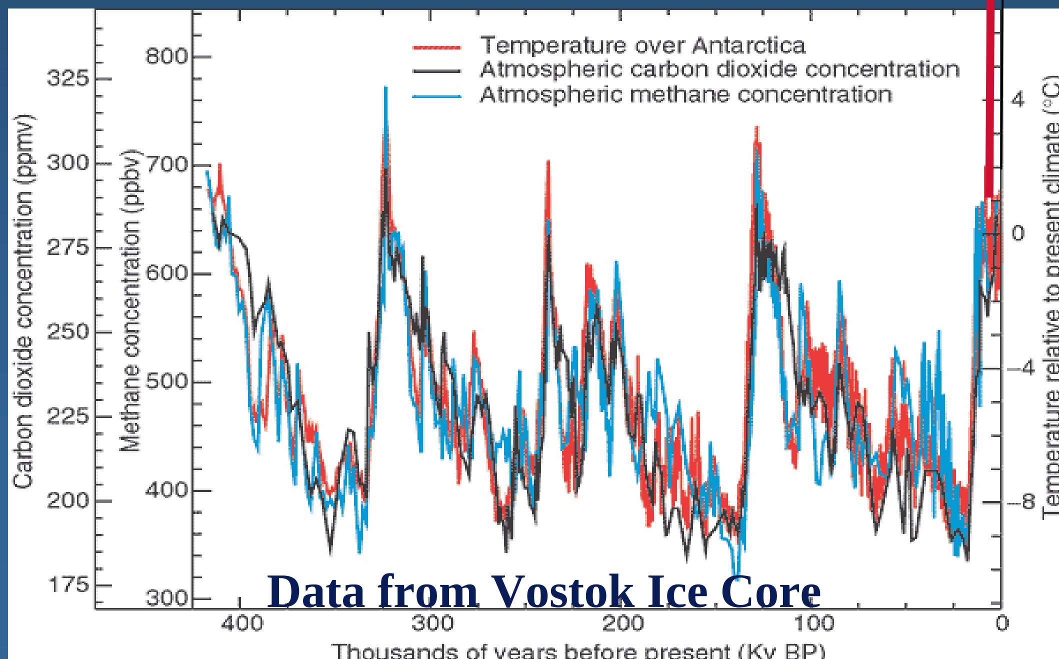
CO_2 Emissions vs CO_2(atm)



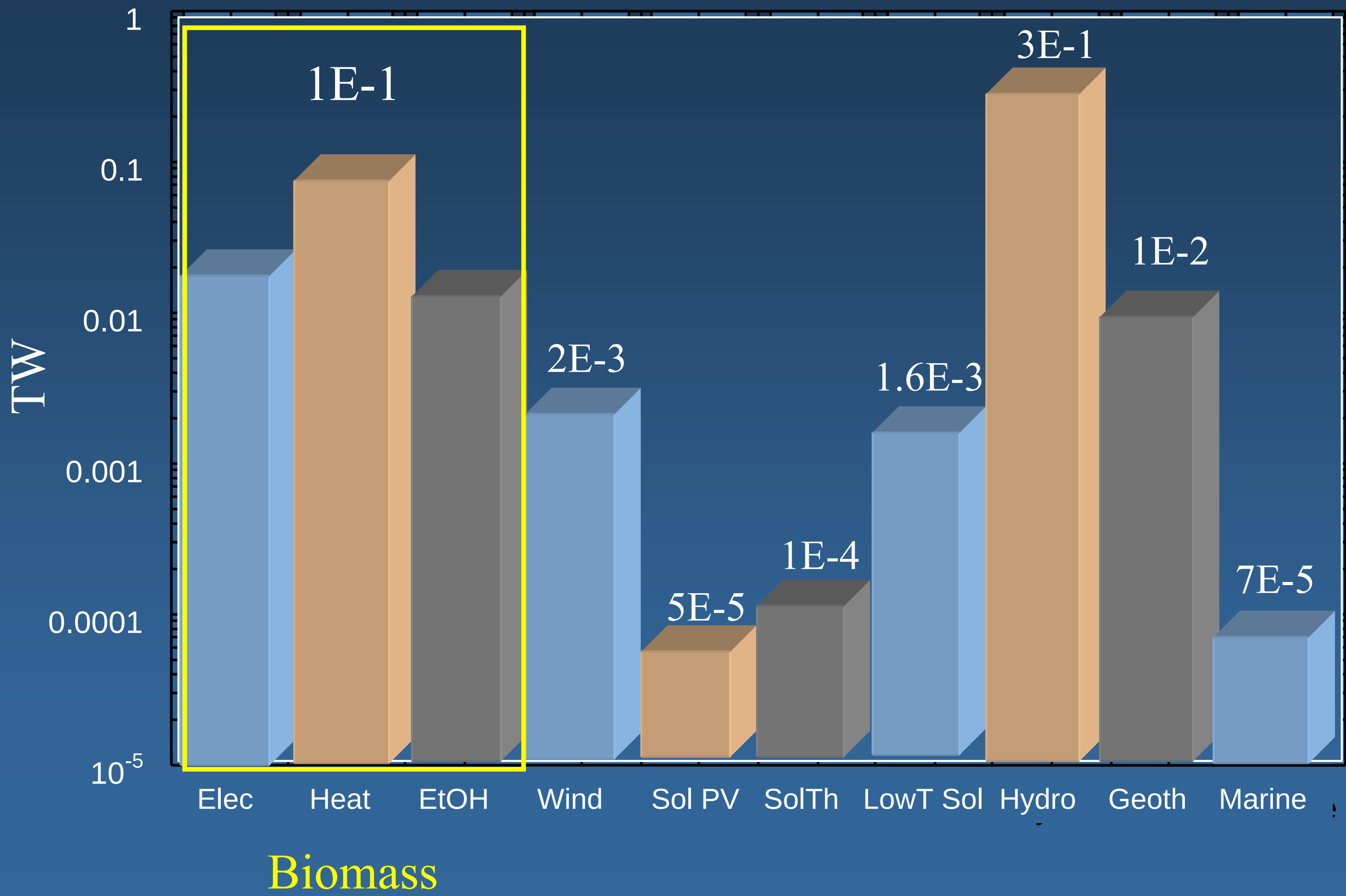
500 ppmv

400 ppmv

382 ppmv

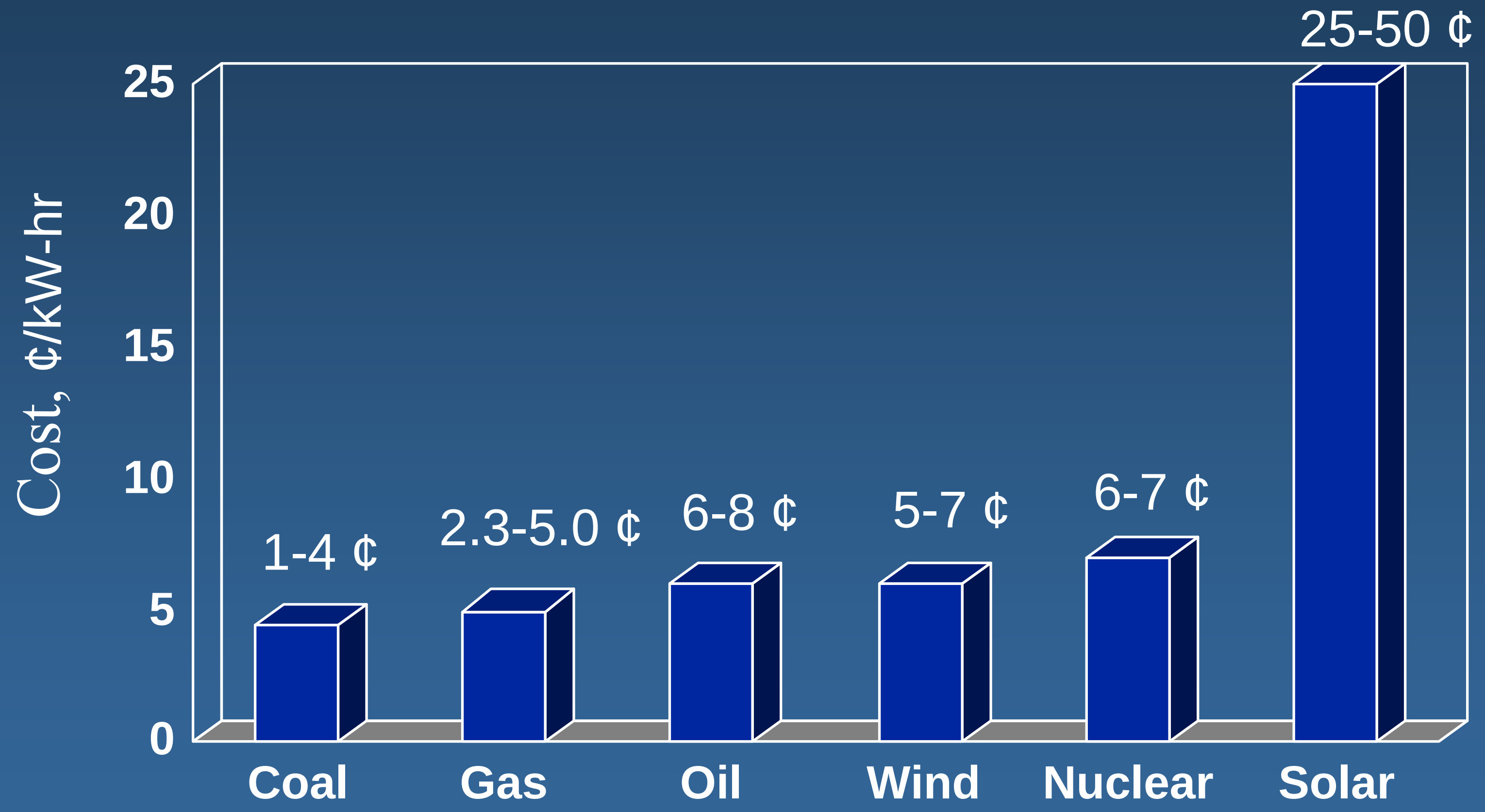


Energy From Renewables, 1998

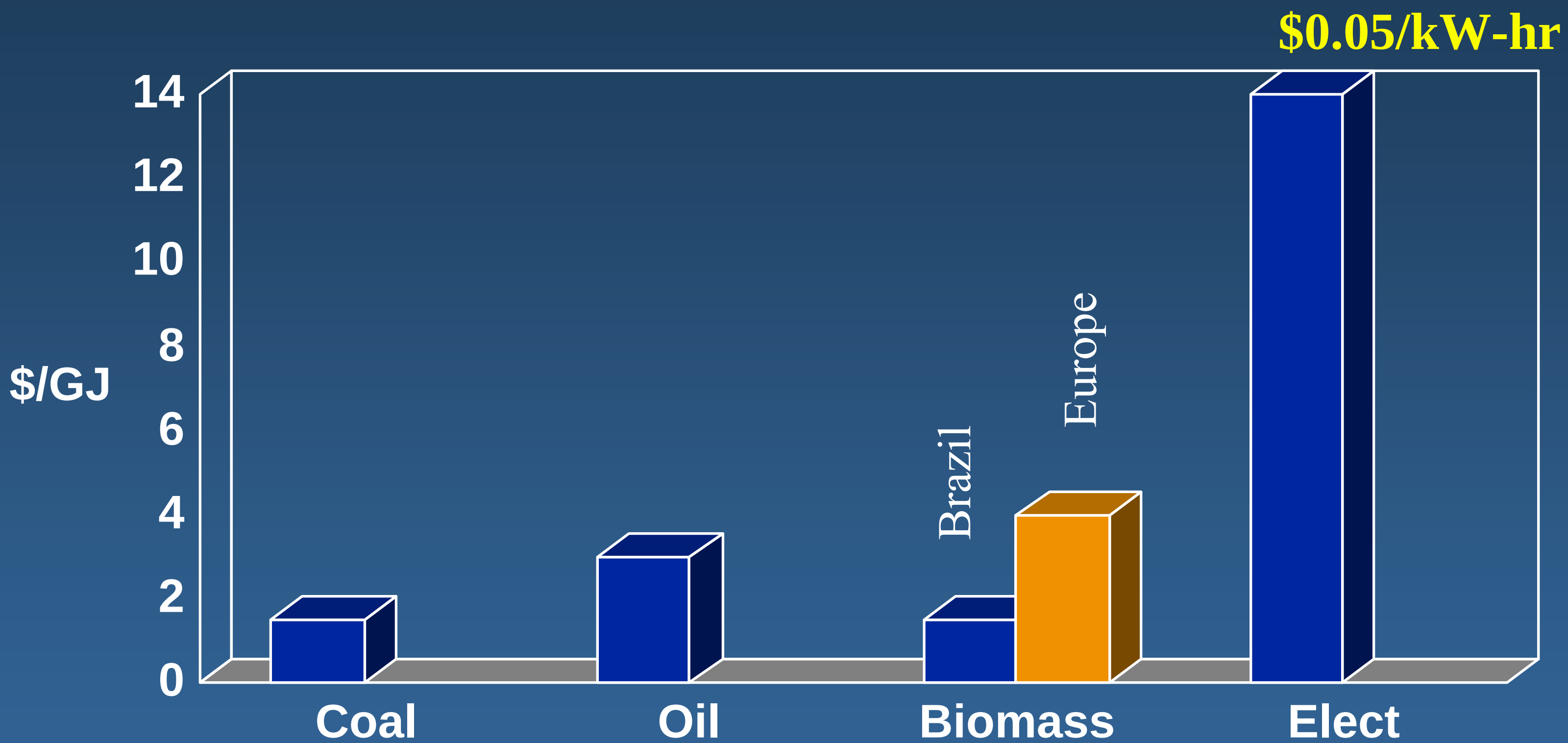


Today: Production Cost of Electricity

(in the U.S. in 2002)



Energy Costs

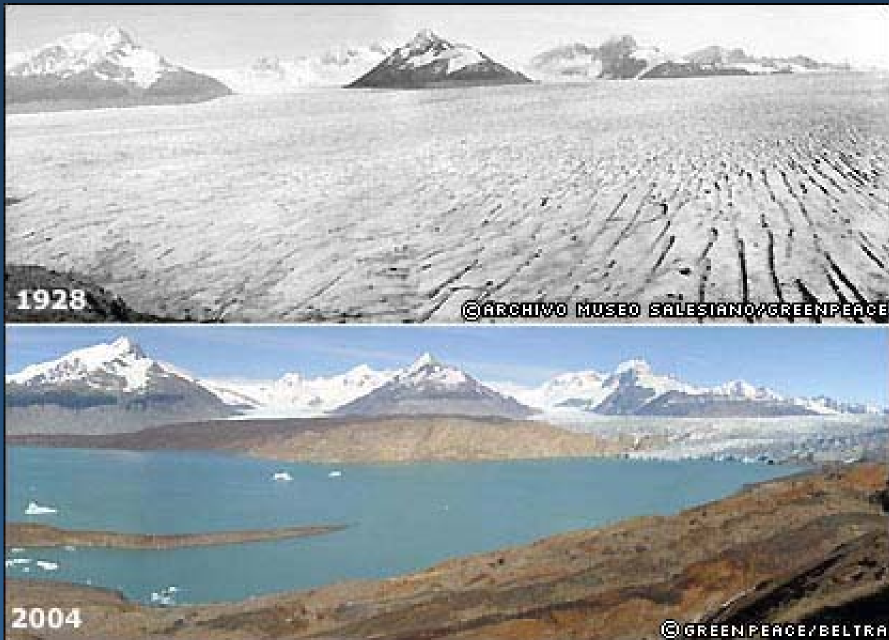


www.undp.org/seed/eap/activities/wea

Conclusions

- Abundant, Inexpensive Resource Base of Fossil Fuels
- Renewables will not play a large role in primary power generation unless/until:
  - –technological/cost breakthroughs are achieved, or
  - –unpriced externalities are introduced (e.g., environmentally -driven carbon taxes)

Argentina



Upsala Glacier

You can observe a lot
by watching…

Portage Lake/Glacier

Lewis' Conclusions

- If we need such large amounts of carbon-free power, then:
  - current pricing is not the driver for year 2050 primary energy supply
- Hence,
  - Examine energy potential of various forms of renewable energy
  - Examine technologies and costs of various renewables
  - Examine impact on secondary power infrastructure and energy utilization

Oil Supply Curves