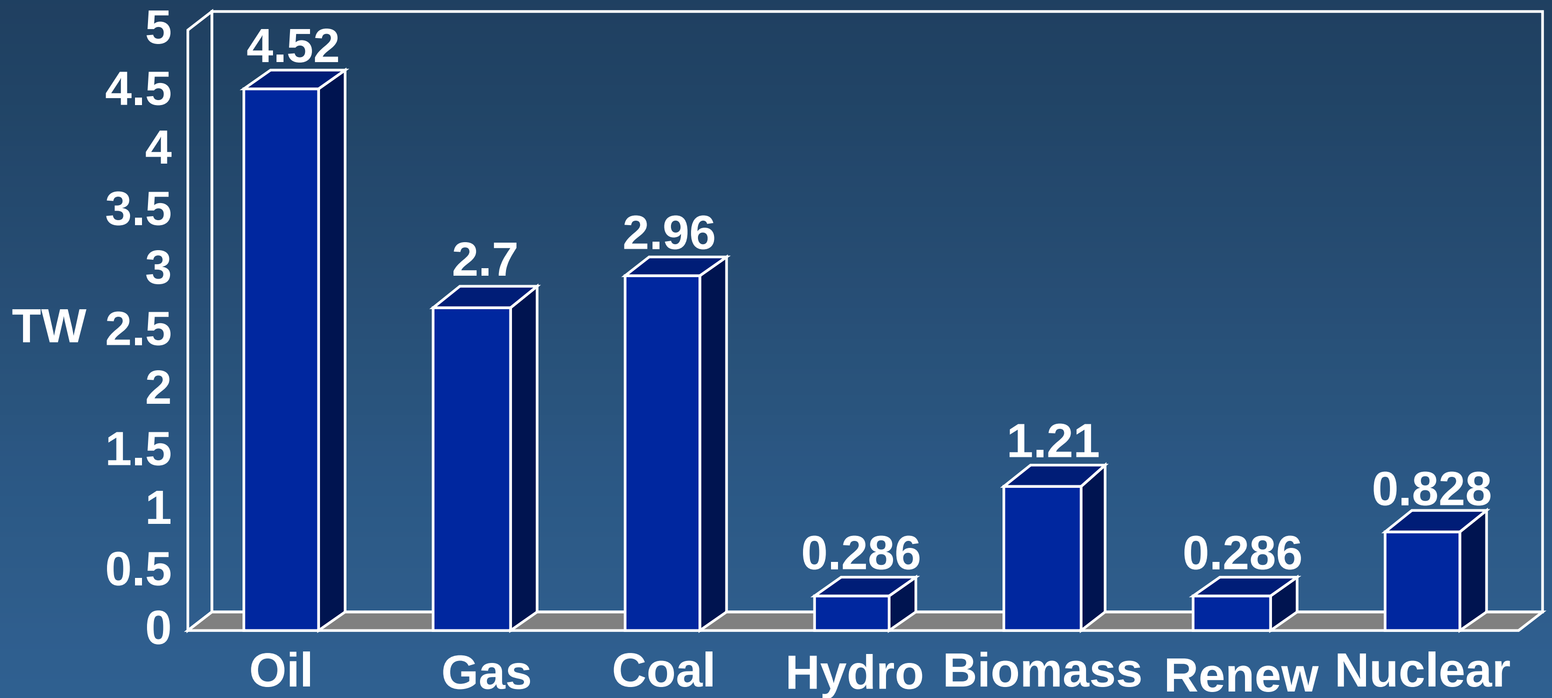
Global Energy Perspective

- Present Primary Power Mix
- Future Constraints Imposed by Sustainability
- Theoretical and Practical Energy Potential of Various Renewables
- Challenges to Exploit Renewables Economically on the Needed Scale

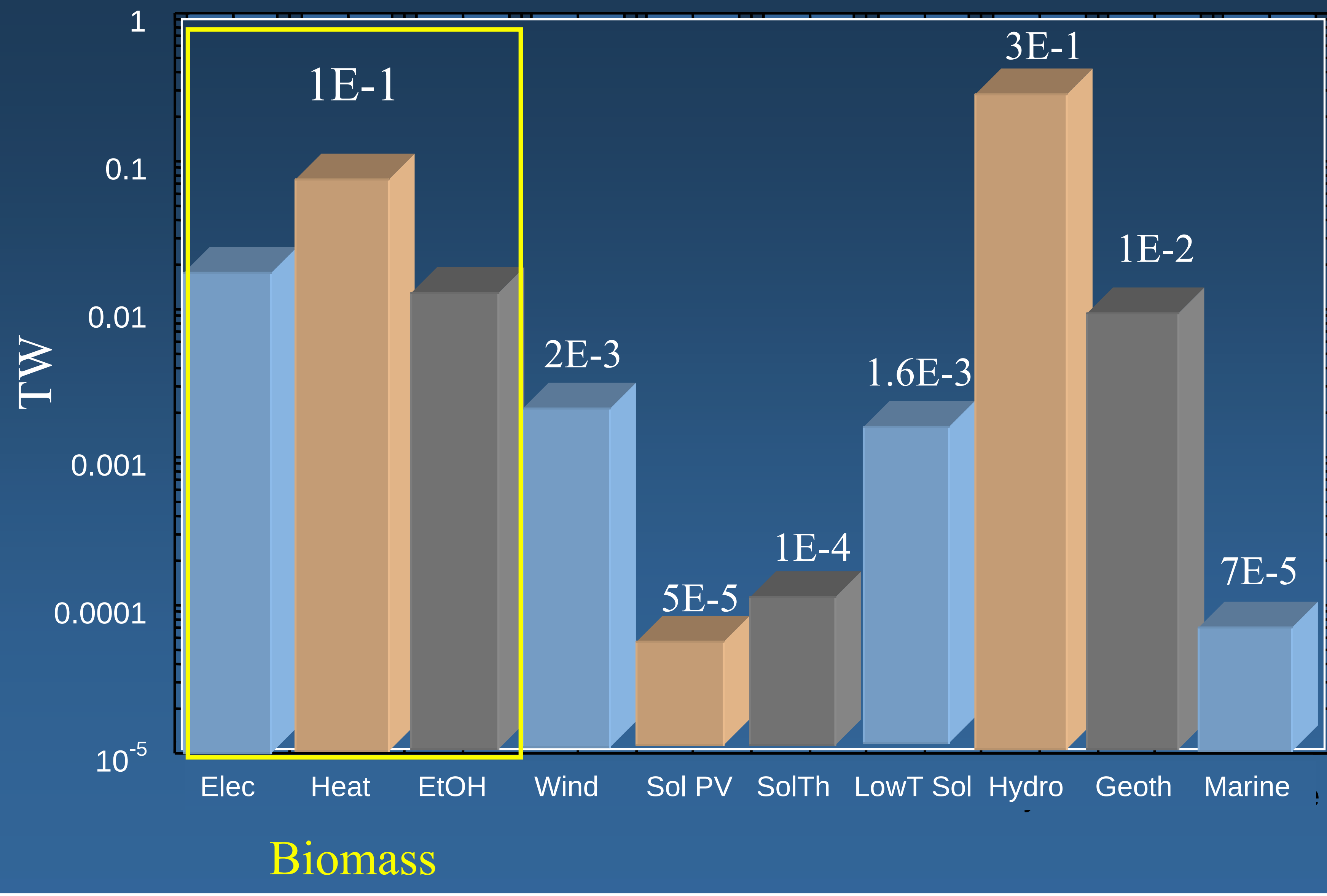
Nathan S. Lewis, California Institute of Technology
Division of Chemistry and Chemical Engineering
Pasadena, CA 91125
http://nsl.caltech.edu

Mean Global Energy Consumption, 1998



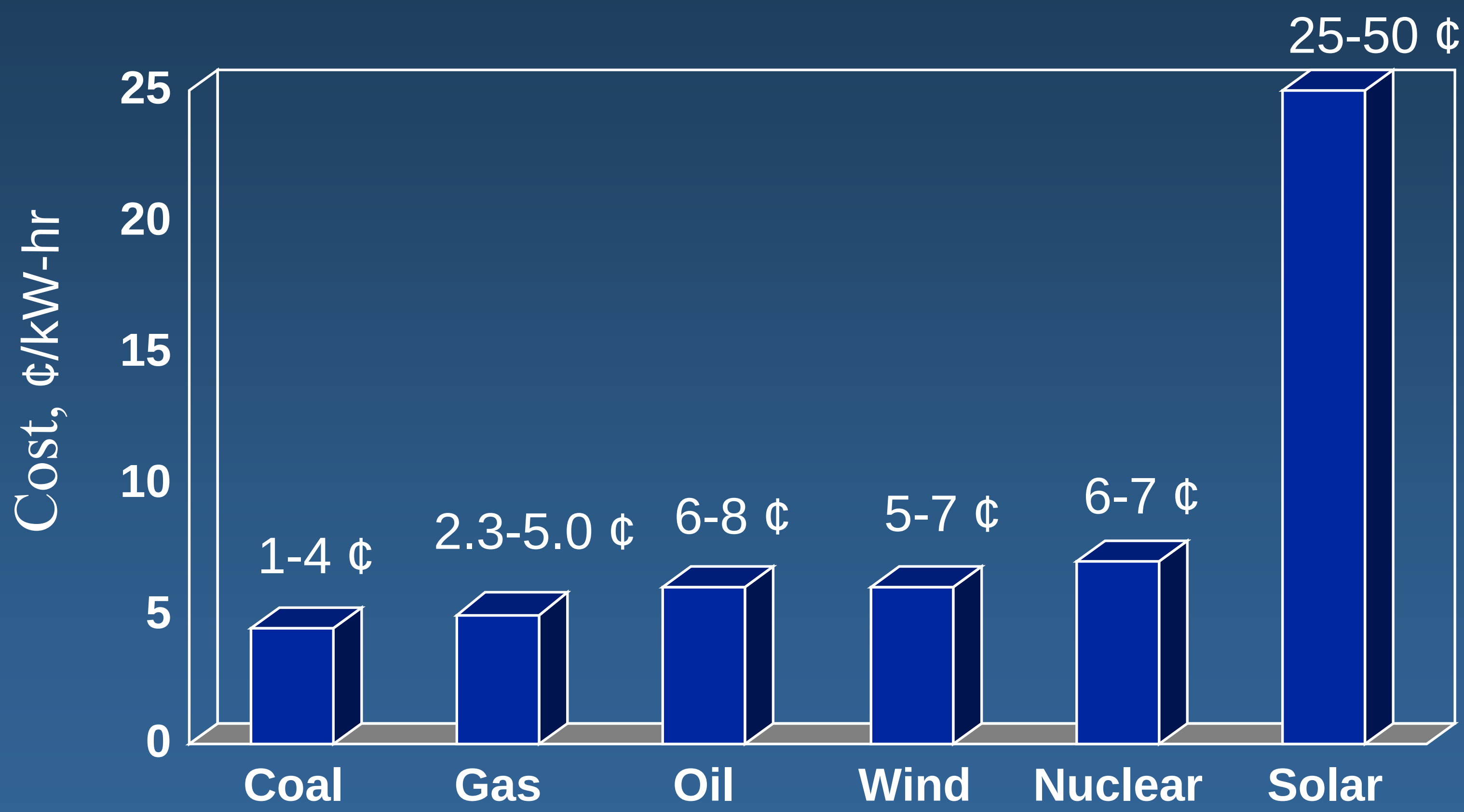
Total: 12.8 TW U.S.: 3.3 TW (99 Quads)

Energy From Renewables, 1998

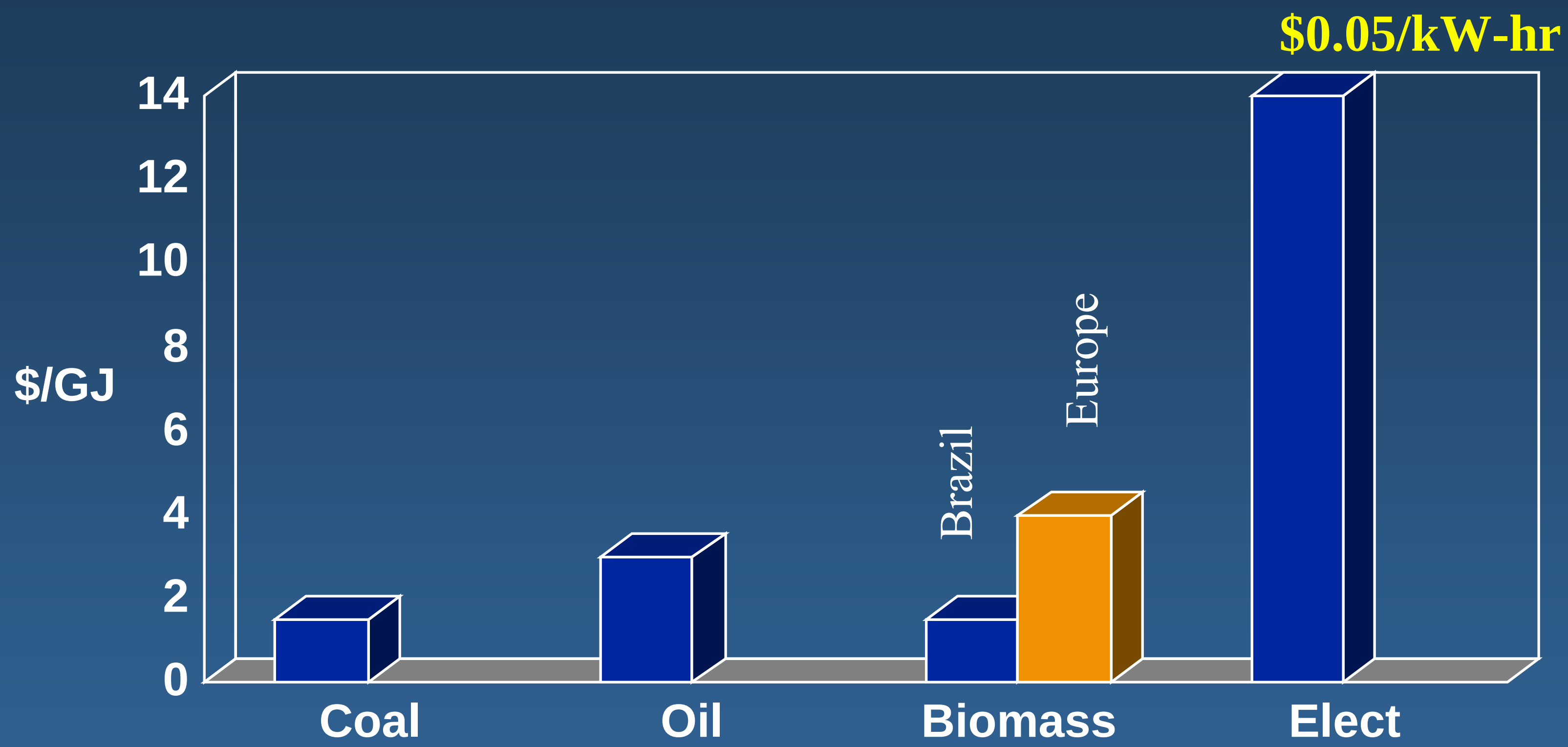


Today: Production Cost of Electricity

(in the U.S. in 2002)

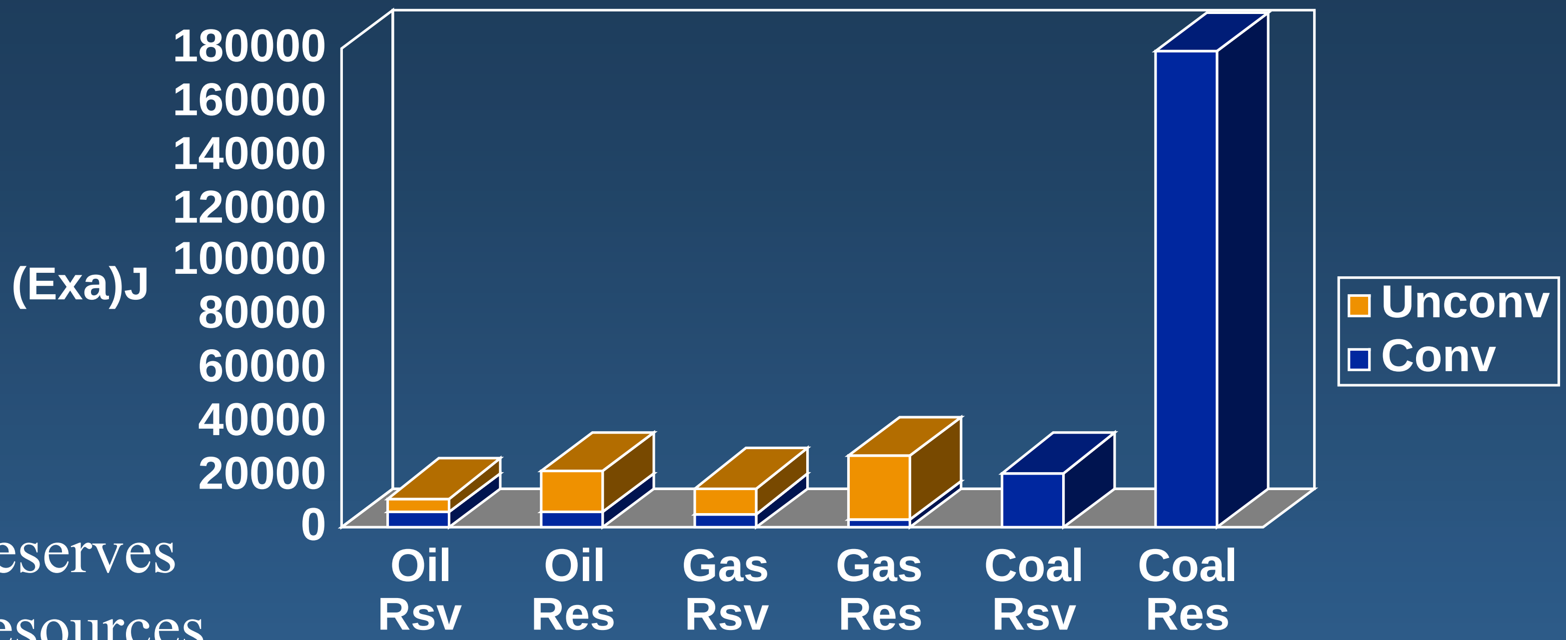


Energy Costs



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

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

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)

Energy and Sustainability

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

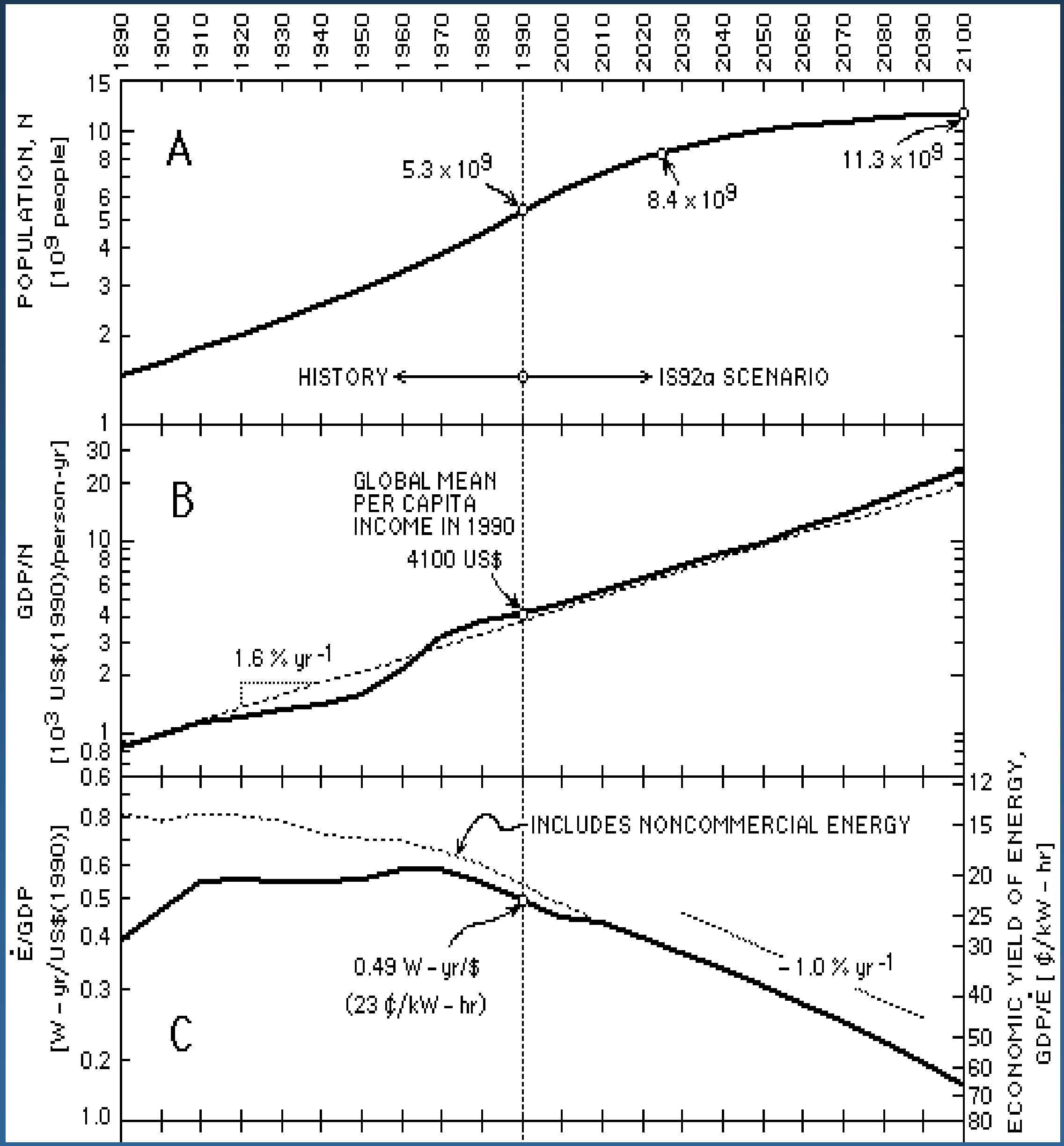
- M. I. Hoffert et. al., *Nature*, **1998**, *395*, 881, "Energy Implications of Future Atmospheric Stabilization of CO_2 Content

  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

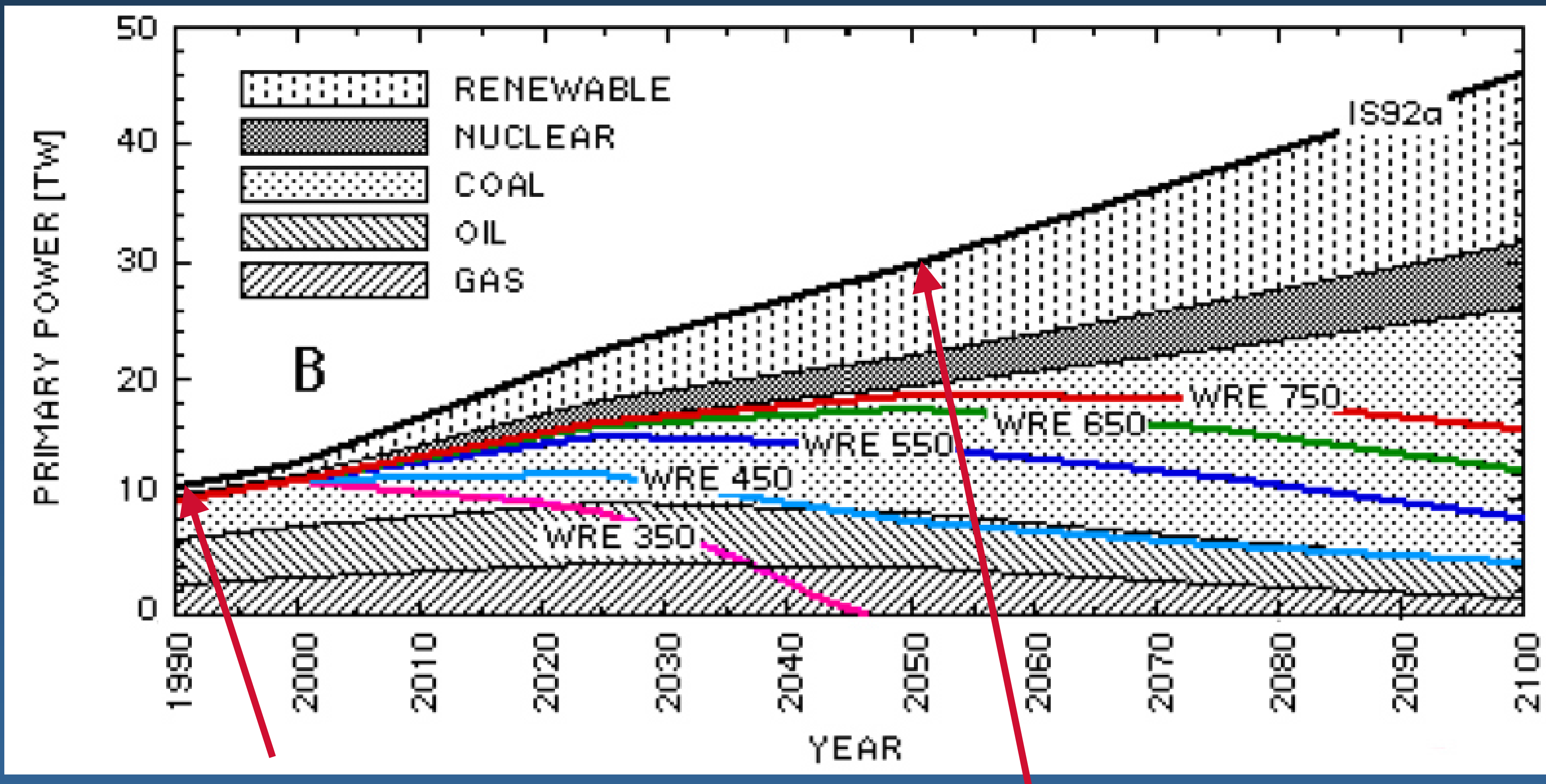
Population Growth to 10 - 11 Billion People in 2050

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

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

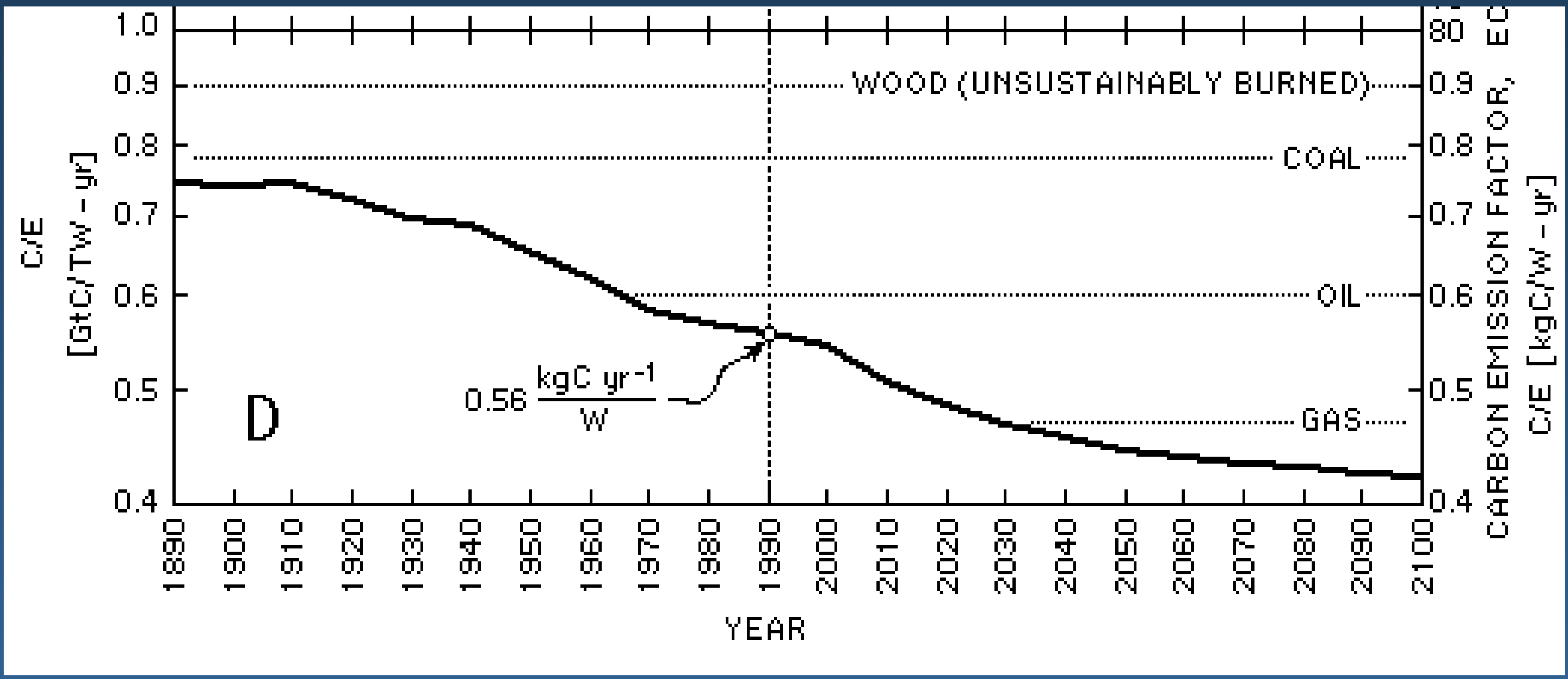


Total Primary Power vs Year



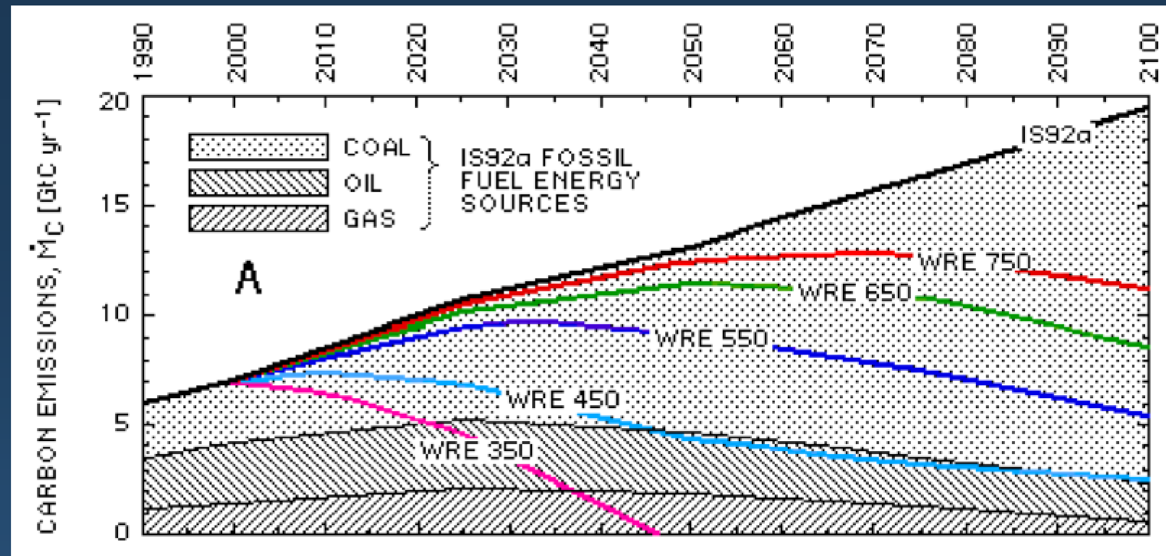
1990: 12 TW 2050: 28 TW

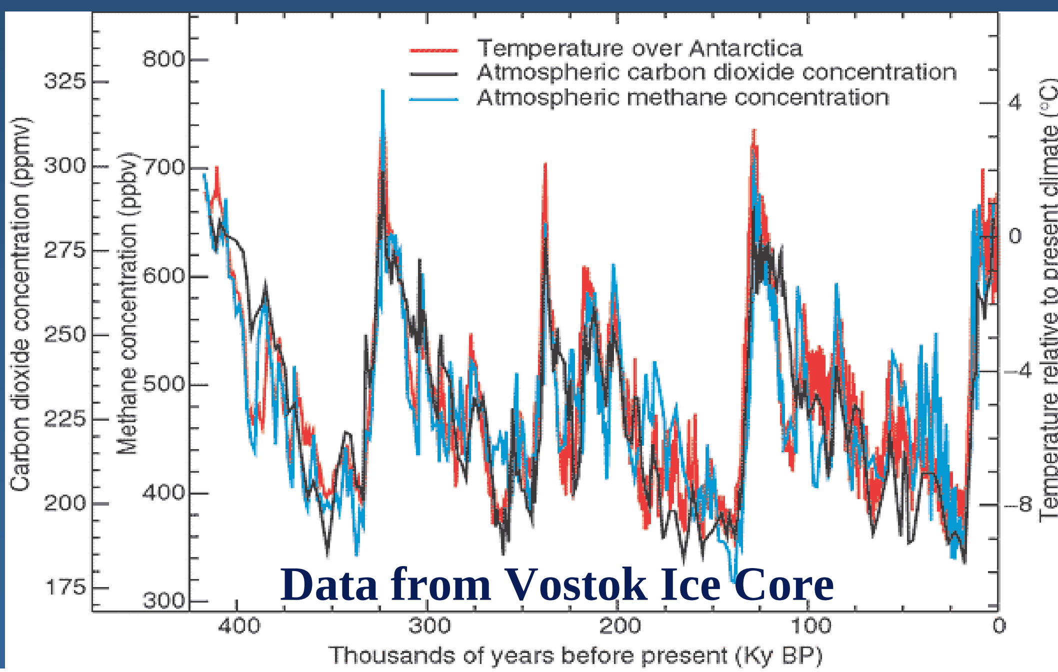
Carbon Intensity of Energy Mix



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

CO_2 Emissions for vs CO_2(atm)





Data from Vostok Ice Core

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

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

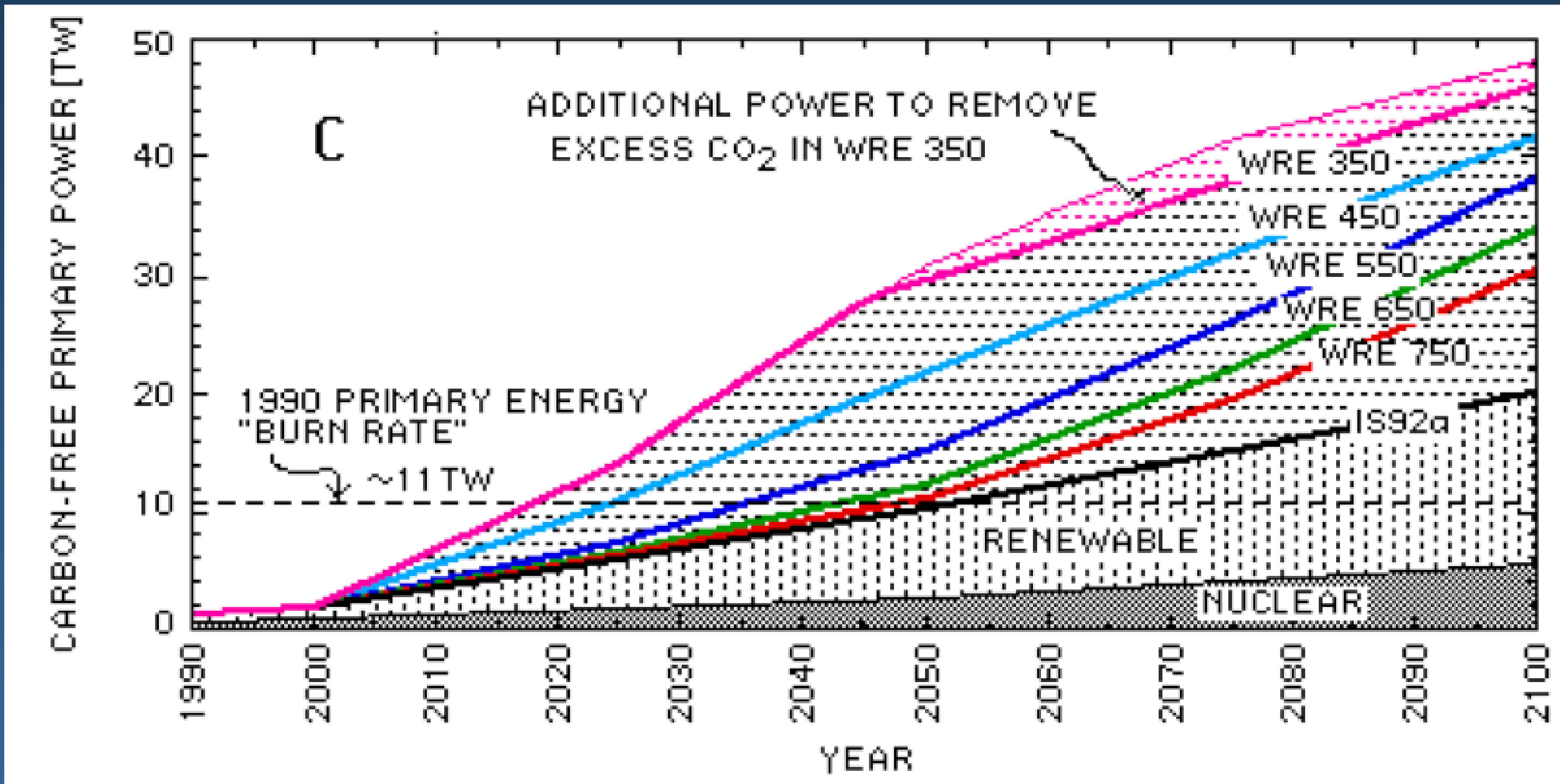
Grinell Glacier and Grinnell Lake, Glacier National Park, 1910-1997

Greenland Ice Sheet

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

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."

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

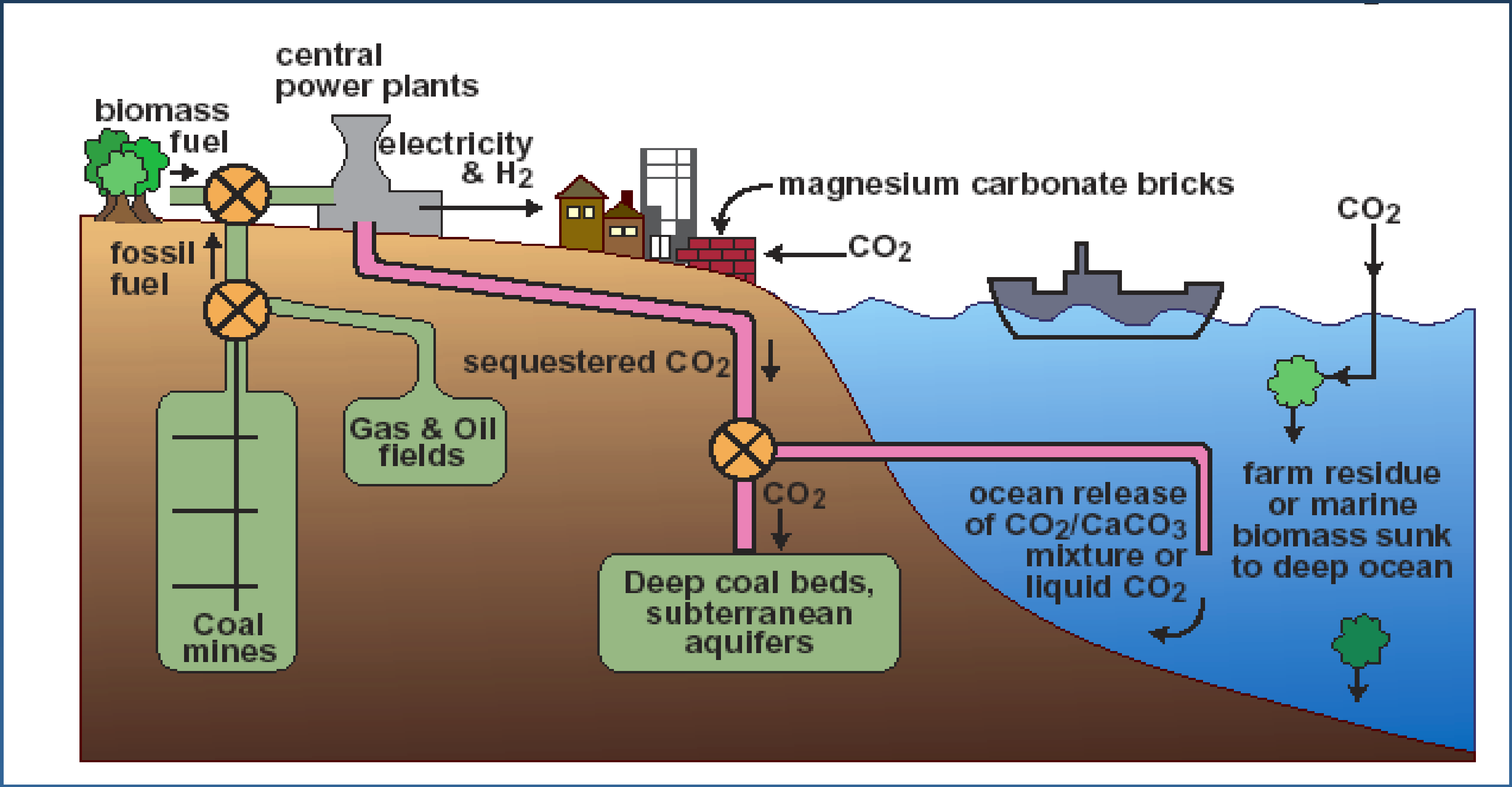
Sources of Carbon-Free Power

- Nuclear (fission and fusion)

- Carbon sequestration

- Renewables

Carbon Sequestration



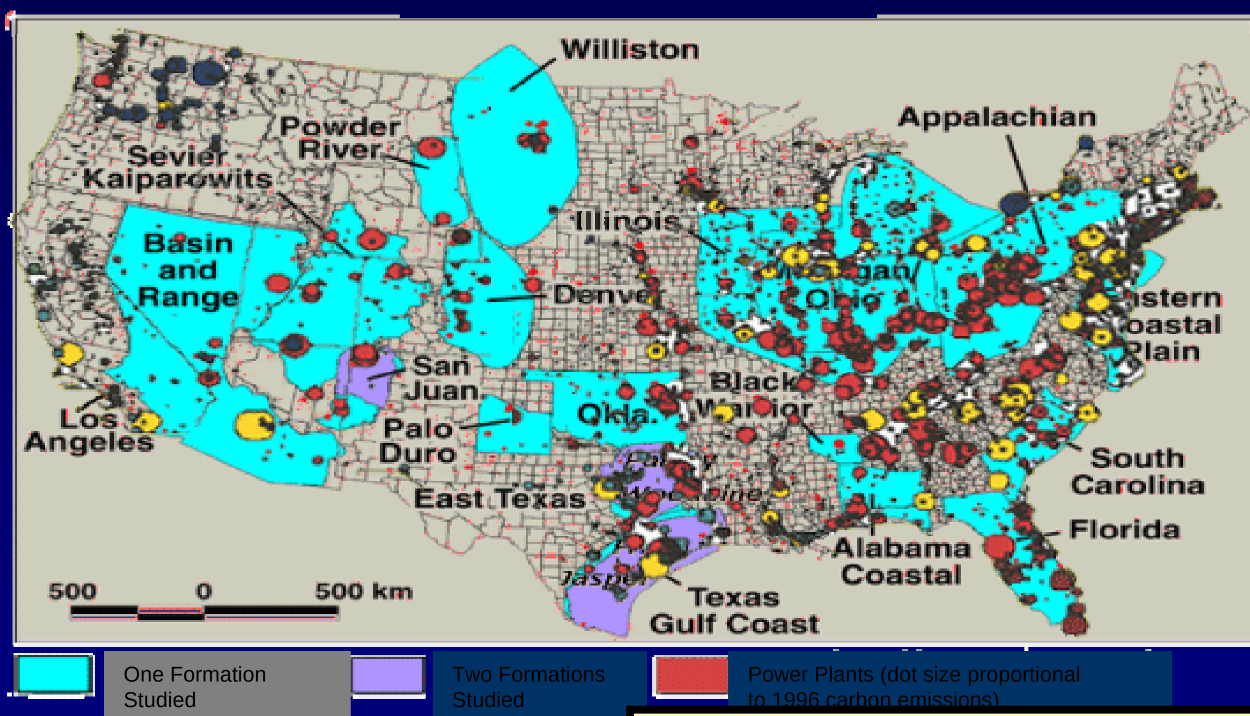
CO_2 Burial: Saline Reservoirs

130 Gt total U.S. sequestration potential

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

Study Areas

- **Near sources (power plants, refineries, coal fields)**
- **Distribute only H_2 or electricity**
- **Must not leak**



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

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

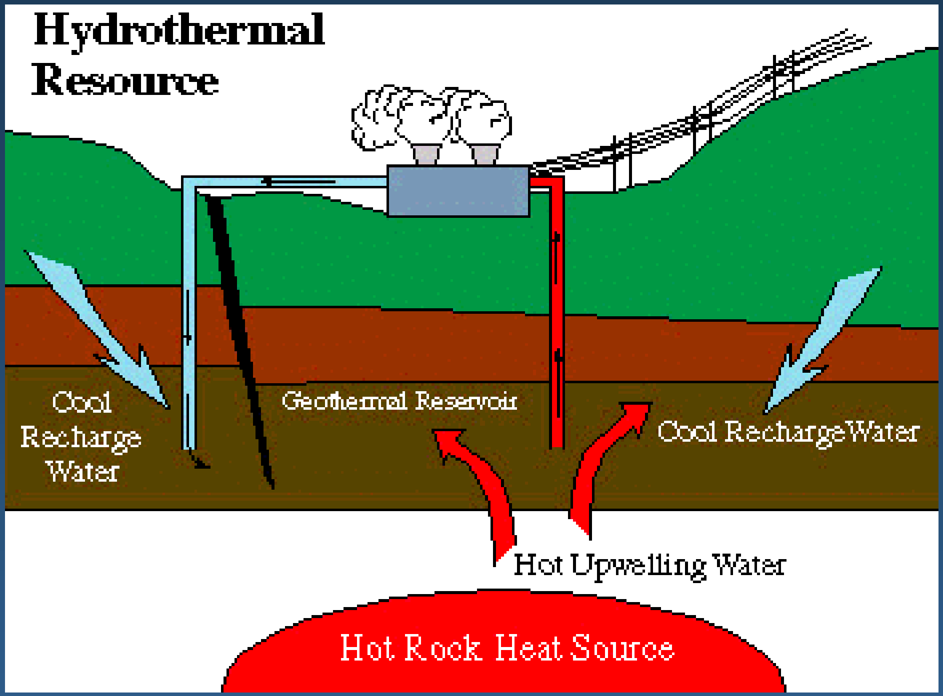
□(can get to 80% capacity in some cases)

Source: WEA 2000

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

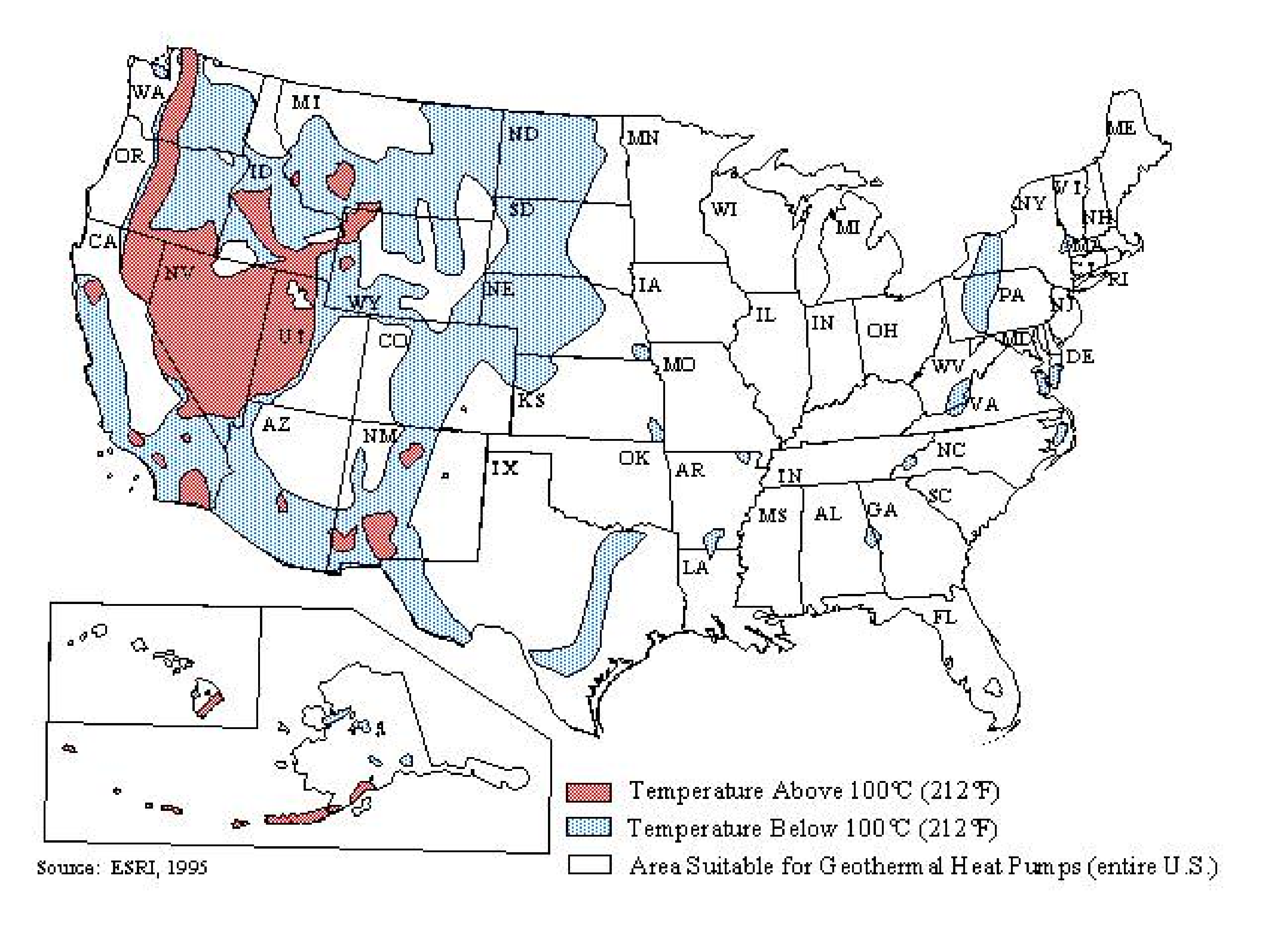
Geothermal Energy

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

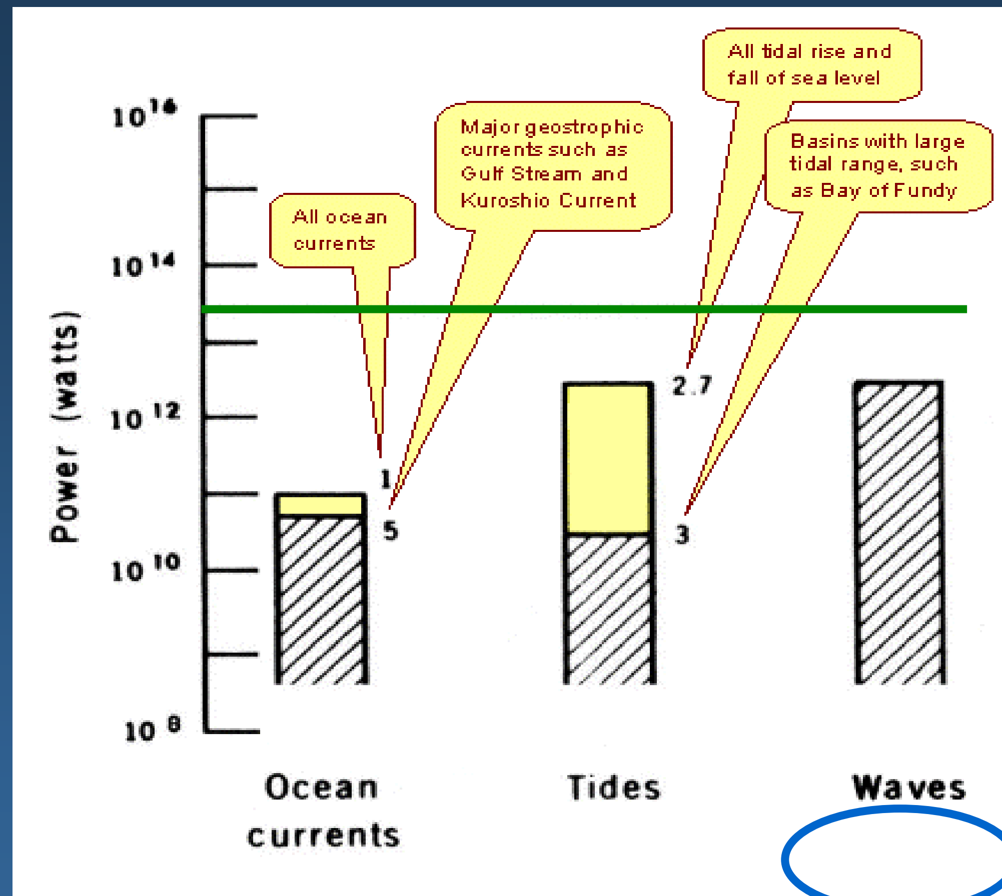
• Mean terrestrial geothermal flux at earth's surface	0.057 W/m^2
• Total continental geothermal energy potential	11.6 TW
• Oceanic geothermal energy potential	30 TW

• 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

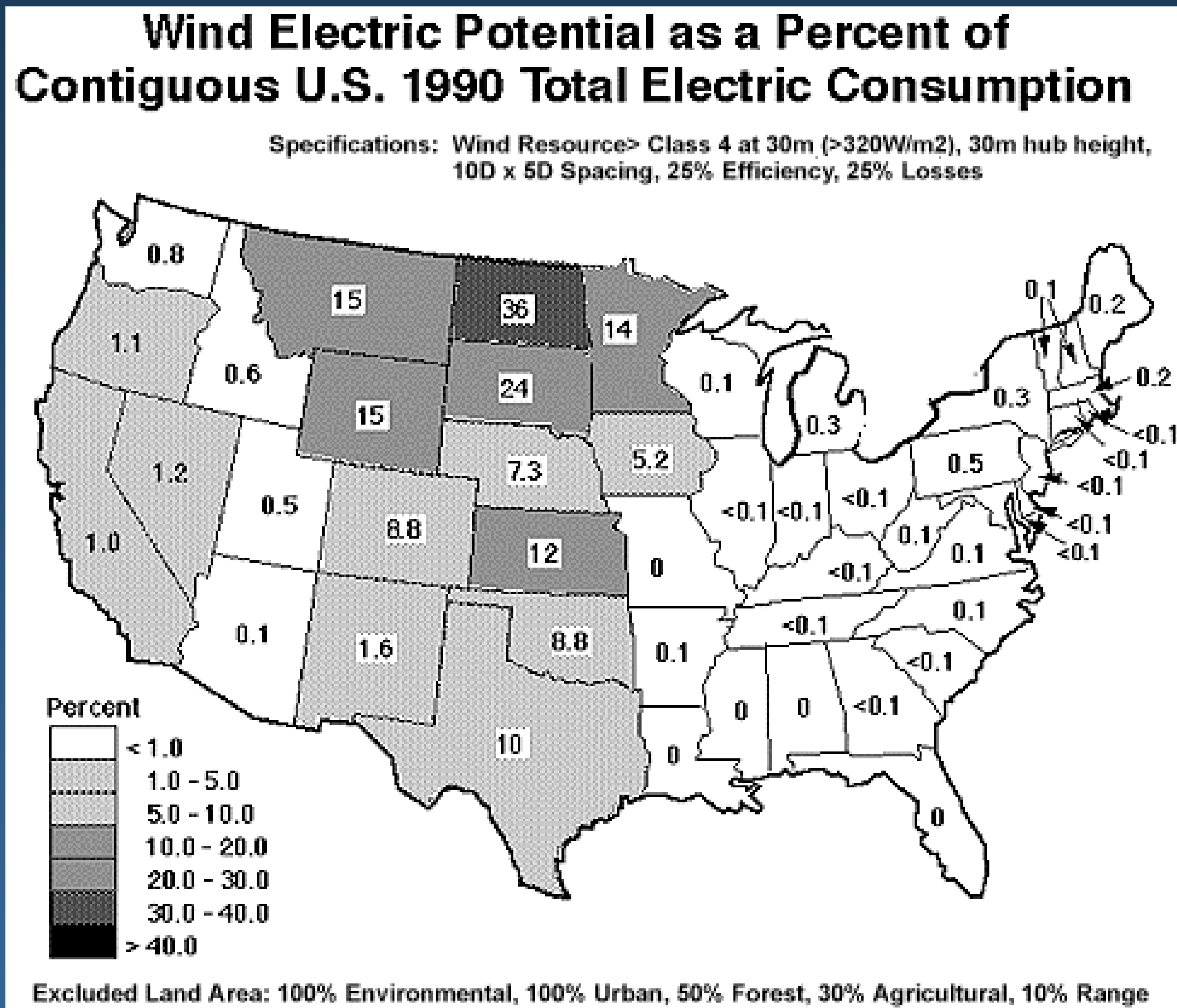
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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



Isaacs, J.D., and W.R. Schmitt, 1980. "Ocean Energy: Forms ar

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

Electric Potential of Wind

- Significant potential in US Great Plains, inner Mongolia and northwest China

- U.S.:
  Use 6% of land suitable for wind energy development; practical electrical generation potential of ≈0.5 TW

- Globally:
  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)

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

Electric Potential of Wind

- Relatively mature technology, not much impacted by chemical sciences
- Intermittent source; storage system could assist in converting to baseload power
- Distribution system not now suitable for balancing sources vs end use demand sites
- Inherently produces electricity, not heat; perhaps cheapest stored using compressed air ($0.01 kW-hr)

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

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

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

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 (recall: $1.5-4/GJ)
- Possible/likely that this is water resource limited
- Challenges for chemists: cellulose to ethanol; ethanol fuel cells

Solar Energy Potential

- Theoretical: 1.2×10^5 TW solar energy potential

  (1.76×10^5 TW striking Earth; 0.30 Global mean albedo)

  - Energy in 1 hr of sunlight ↔ 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 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

- $1.2x10^5$ TW of solar energy potential globally
- Generating $2x10^1$ TW with 10% efficient solar farms requires $2x10^2/1.2x10^5$ = 0.16% of Globe = $8x10^{11}$ m^2 (i.e., 8.8 % of U.S.A)
- Generating $1.2x10^1$ TW (1998 Global Primary Power) requires $1.2x10^2/1.2x10^5$= 0.10% of Globe = $5x10^{11}$ m^2 (i.e., 5.5% of U.S.A.)

Solar Land Area Requirements

Solar Land Area Requirements

6 Boxes at 3.3 TW Each

Solar Land Area Requirements

- U.S. Land Area: $9.1x10^{12}$ 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:

  $3.3x10^{12}$ W/($2x10^2$ W/m^2 x 10% Efficiency) = $1.6x10^{11}$ m^2

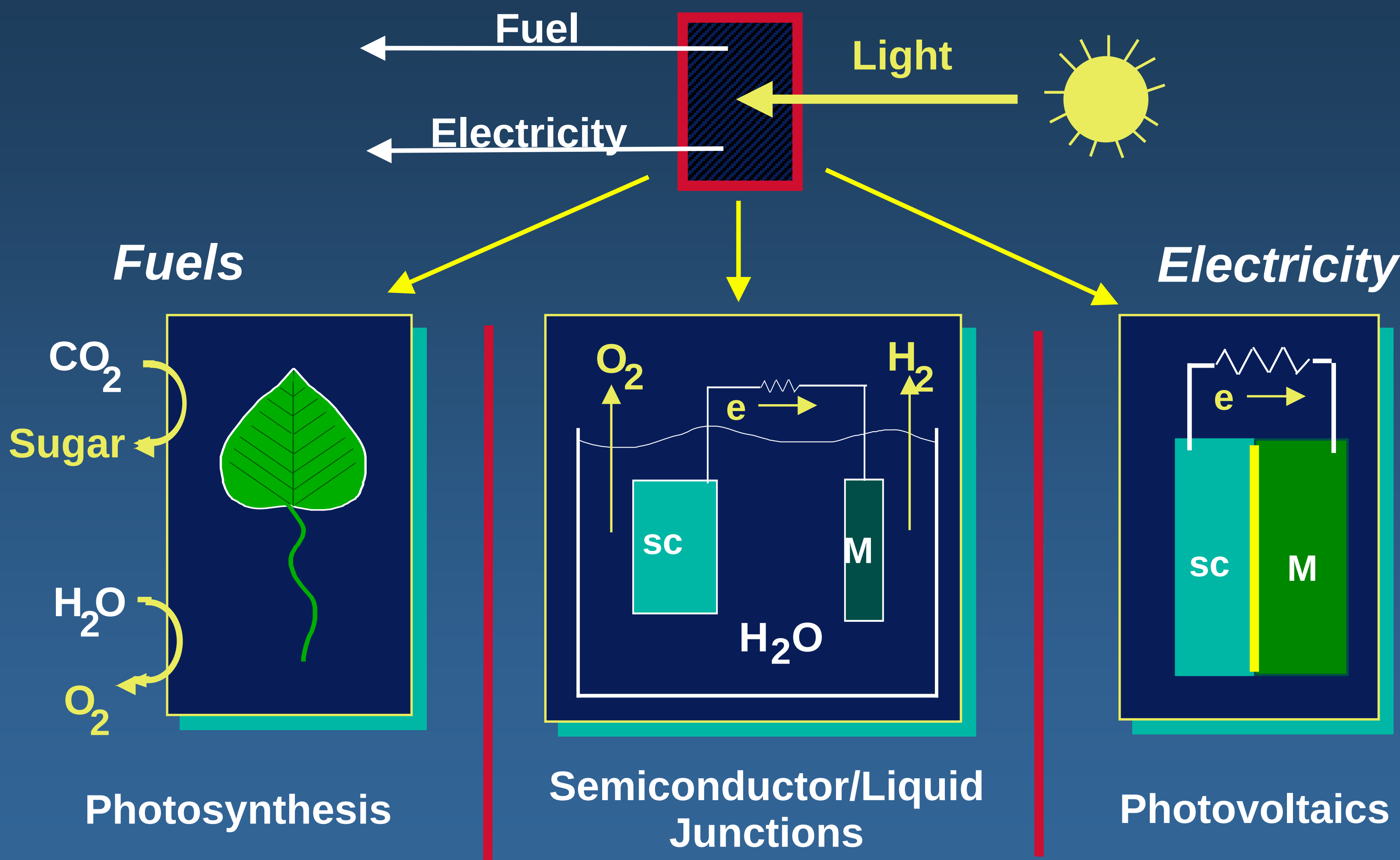
  Requires $1.6x10^{11}$ m^2/ $9.1x10^{12}$ m^2 = 1.7% of Land

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

Energy Conversion Strategies



Solar Electricity, 2001

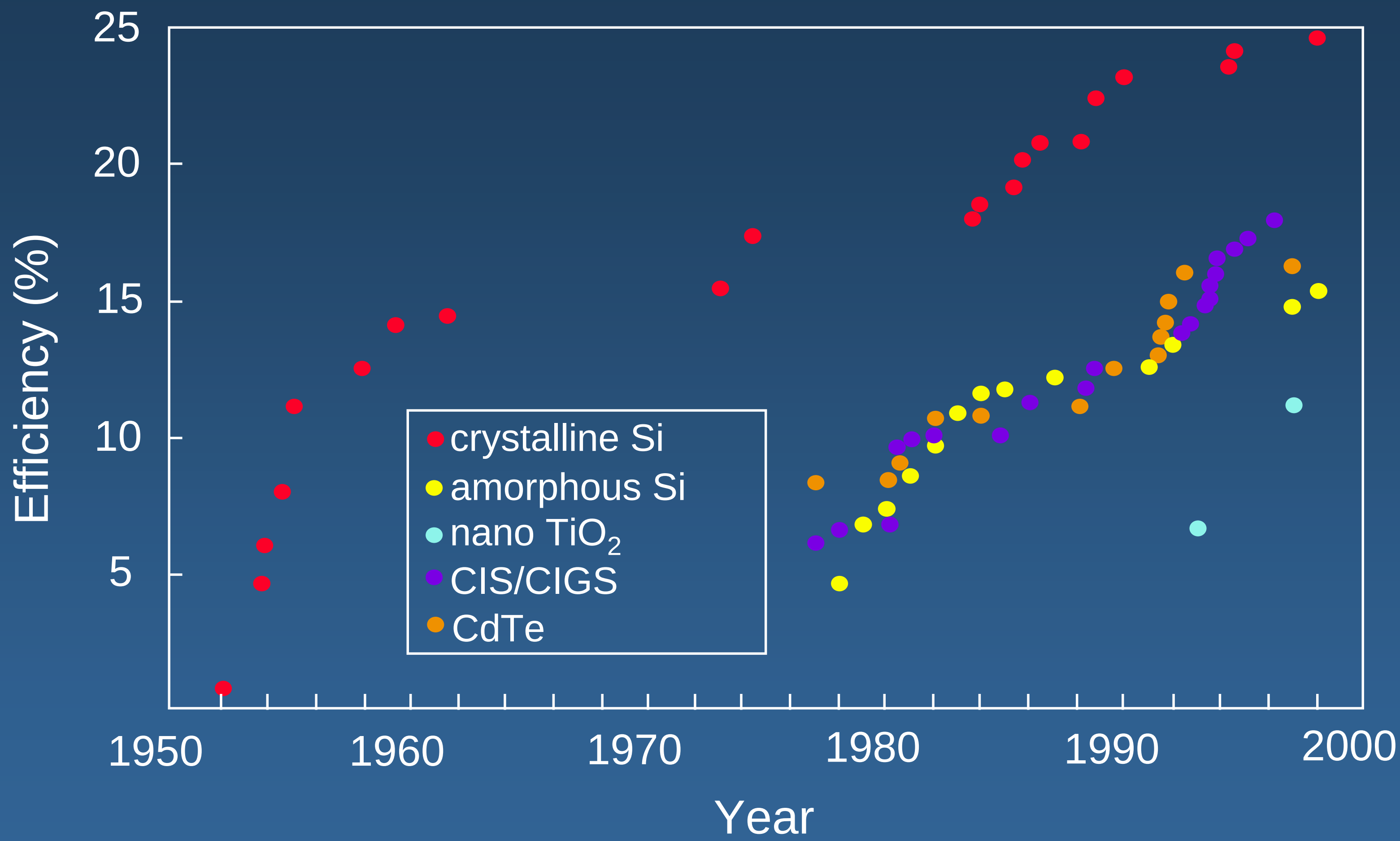
- Production is Currently Capacity Limited (100 MW mean power output manufactured in 2001)
  - *but*, subsidized industry (Japan biggest market)

- High Growth
  - *but*, off of a small base (0.01% of 1%)

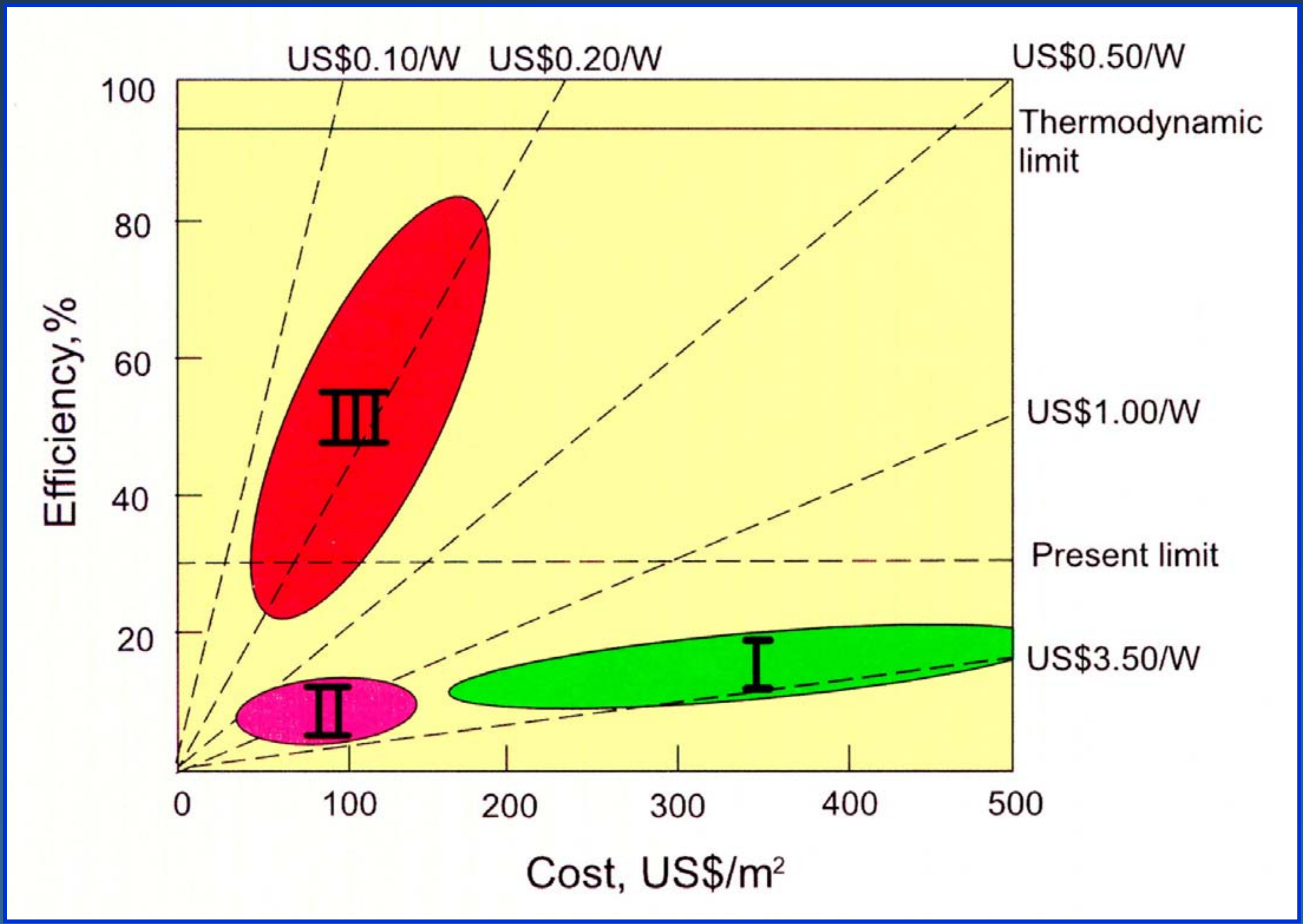
- Cost-favorable/competitive in off-grid installations
  - *but*, cost structures up-front vs amortization of grid-lines disfavorable

- Demands a systems solution: Electricity, heat, storage

Efficiency of Photovoltaic Devices



Cost/Efficiency of Photovoltaic Technology

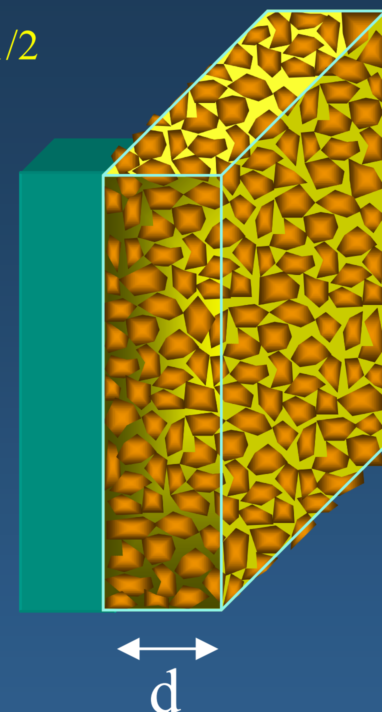


Costs are modules per peak W; installed is \$5-10/W; \$0.35-\$1.5/kW-hr

Cost vs. Efficiency Tradeoff

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

Large Grain
Single
Crystals



Small Grain
And/or
Polycrystalline
Solids

Long d
High τ
High Cost

Long d
Low τ
Lower Cost

τ decreases as grain size (and cost) decreases

Cost vs. Efficiency Tradeoff

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

Ordered
Crystalline
Solids

Long d
High τ
High Cost

Disordered
Organic
Films

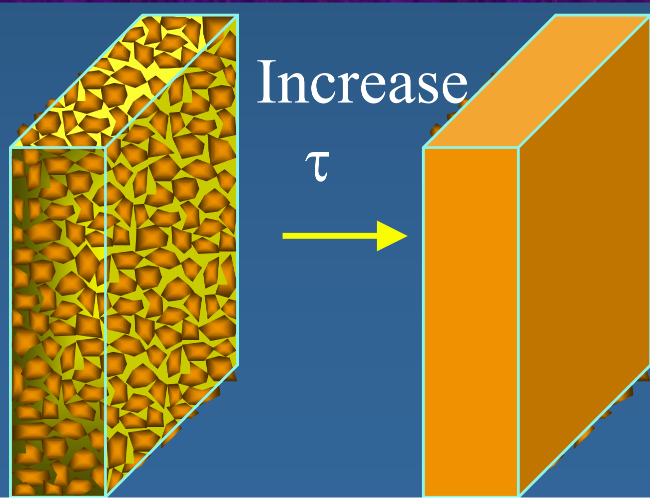
Long d
Low τ
Lower Cost

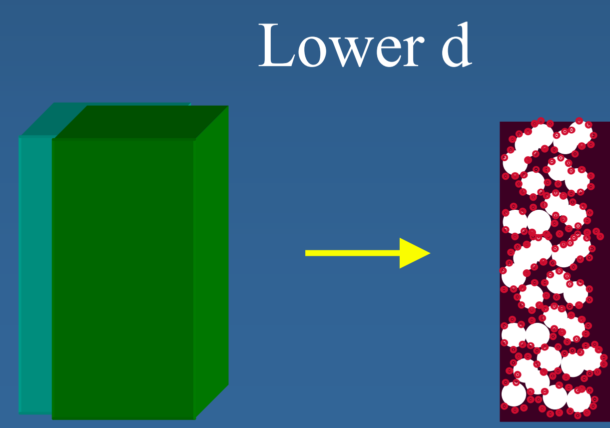
τ decreases as material (and cost) decreases

Challenges for the Chemical Sciences

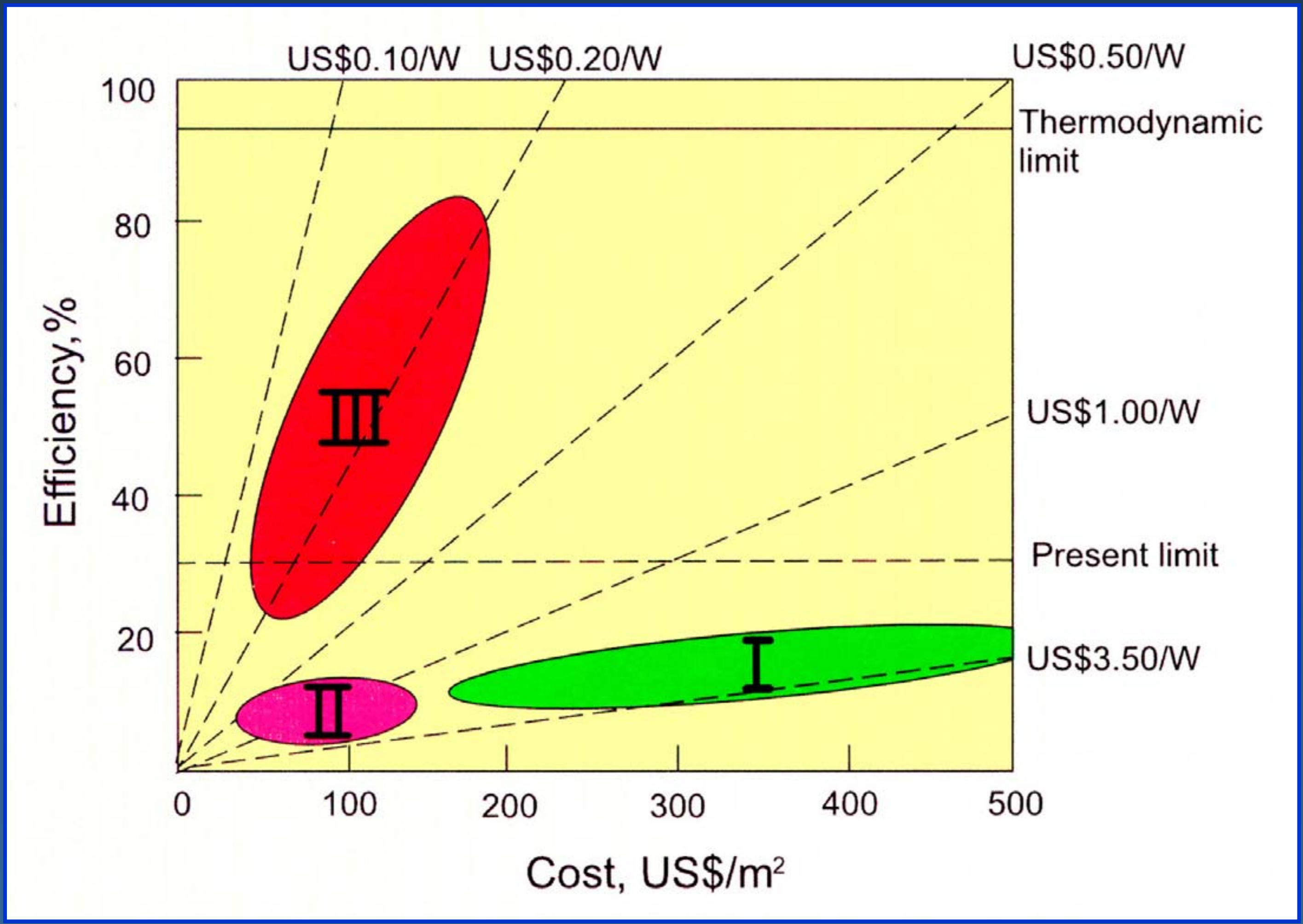
SOLAR ELECTRICITY GENERATION

- Develop Disruptive Solar Technology: "Solar Paint"
- Grain Boundary Passivation
- Interpenetrating Networks while Minimizing Recombination Losses





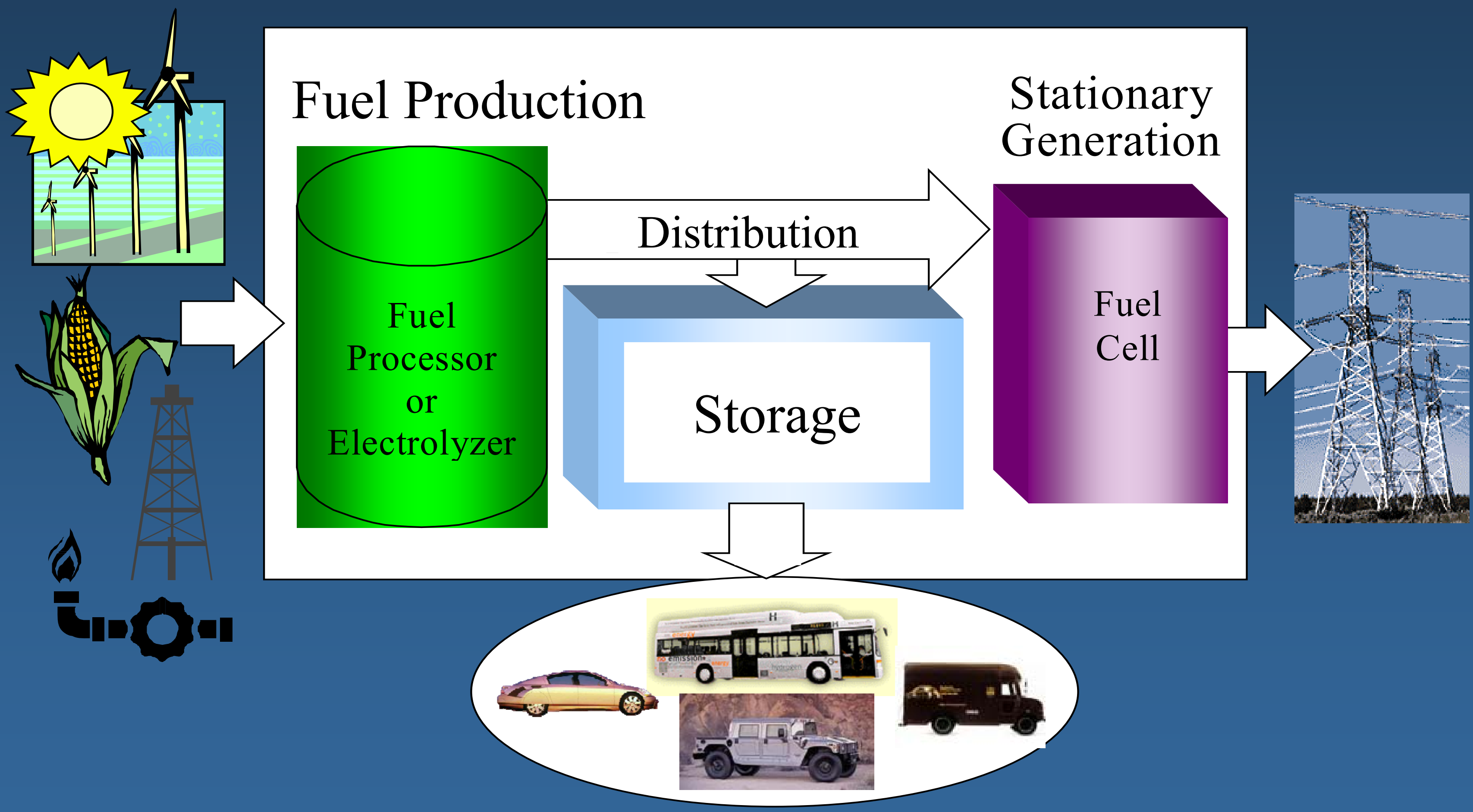
Cost/Efficiency of Photovoltaic Technology



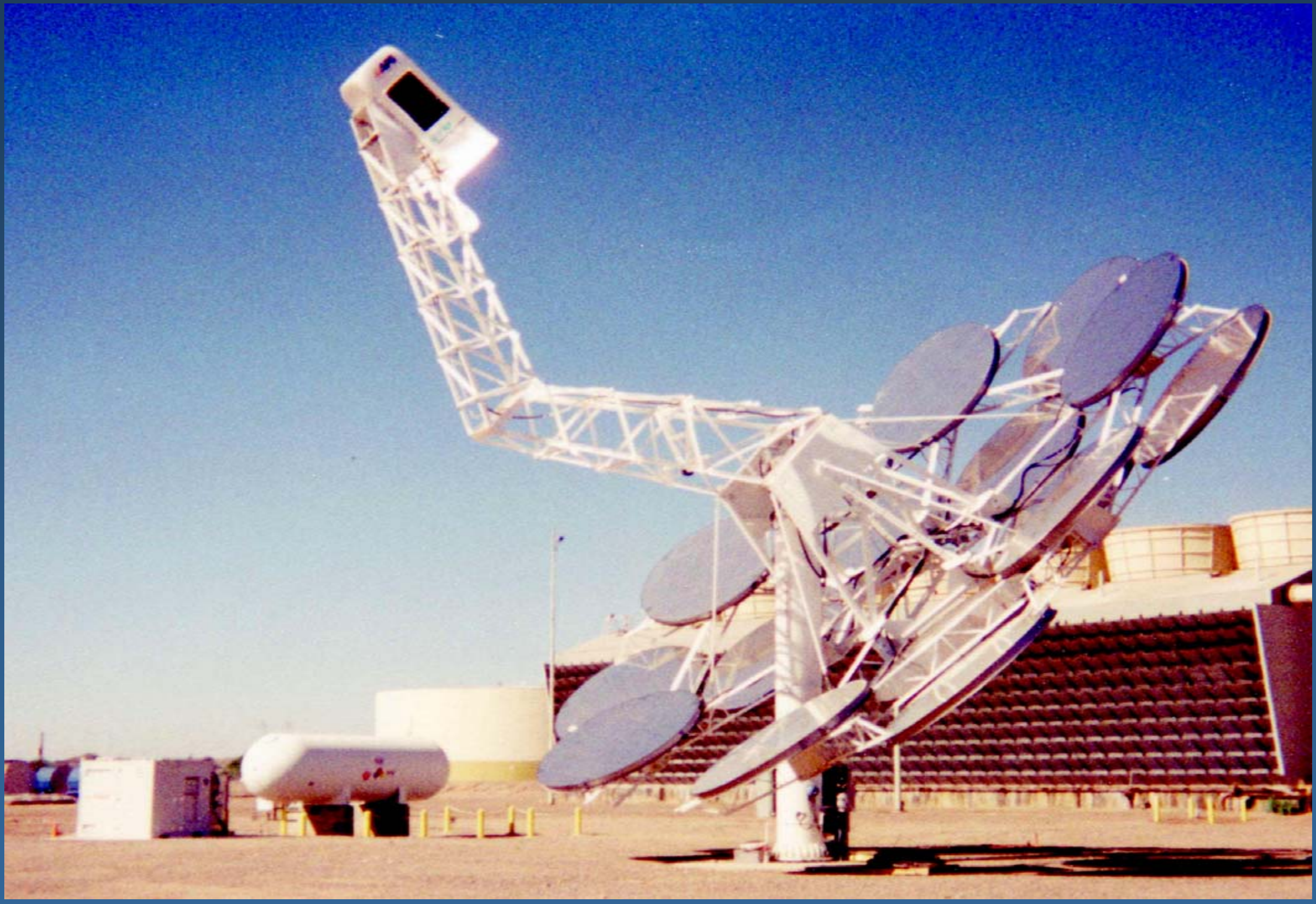
Costs are modules per peak W; installed is $5-10/W; $0.35-$1.5/kW-hr

The Need to Produce Fuel

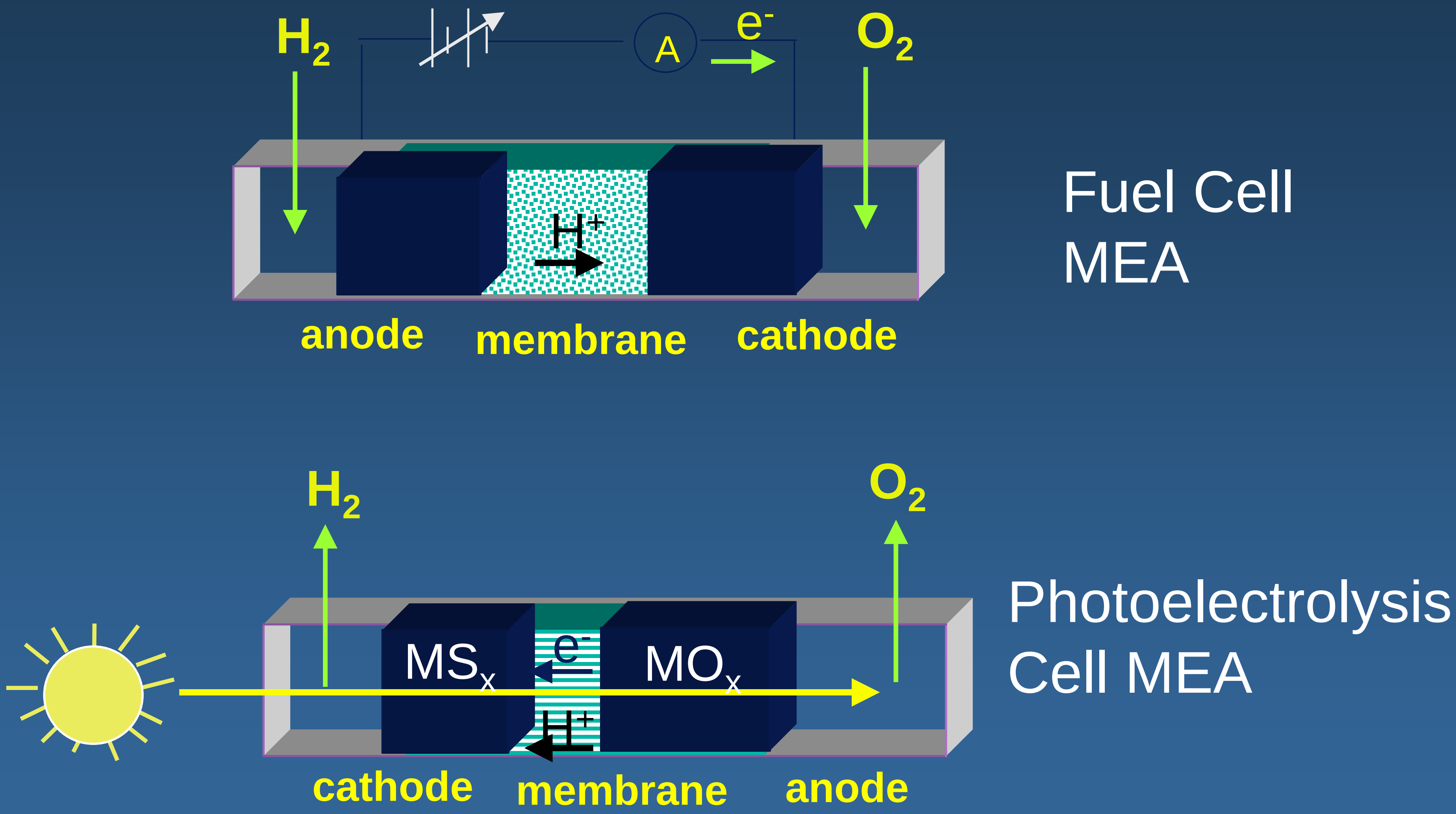
"Power Park Concept"



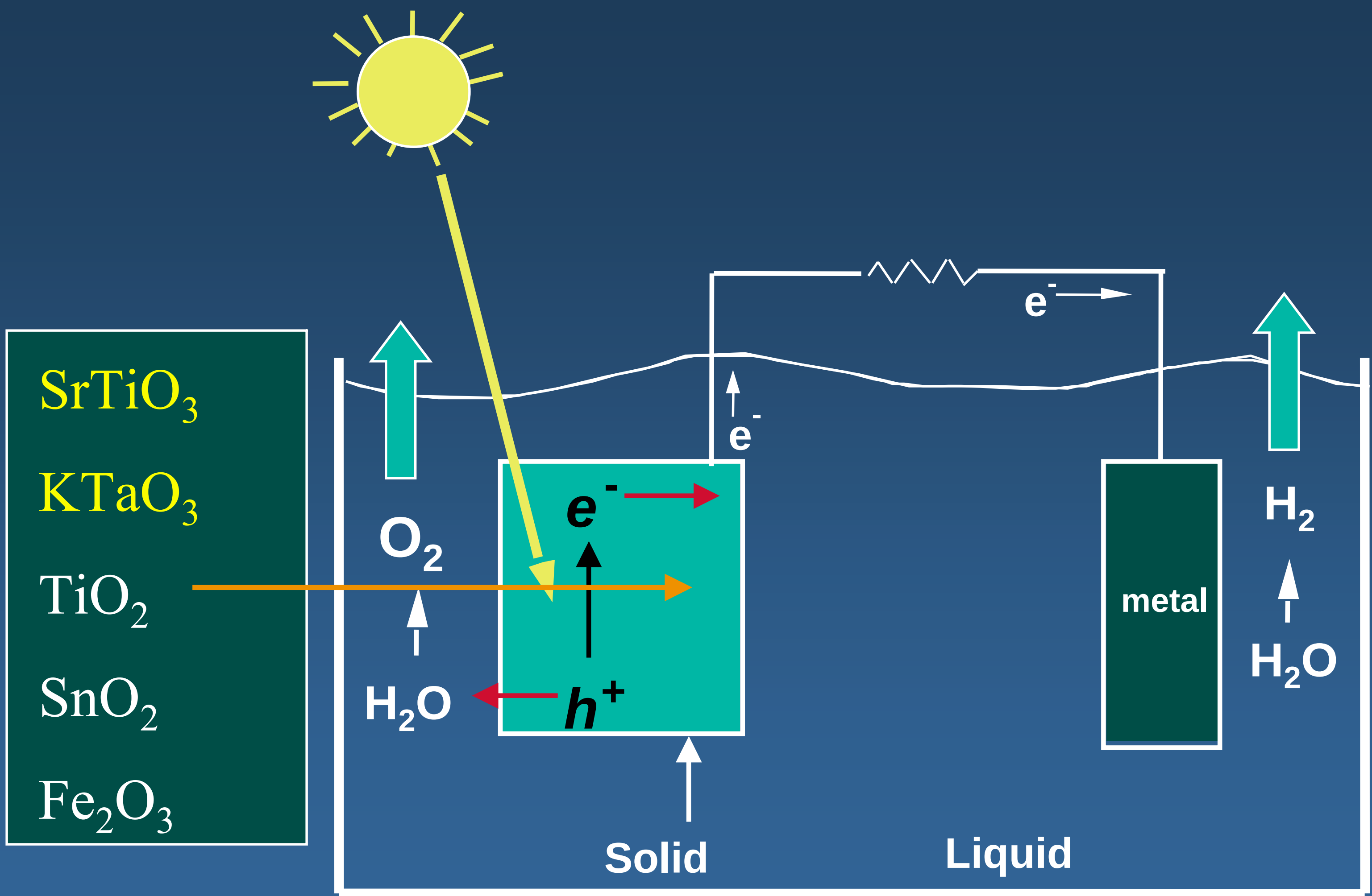
Photovoltaic + Electrolyzer System



Fuel Cell vs Photoelectrolysis Cell



Photoelectrochemical Cell



Light is Converted to Electrical+Chemical Energy

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

Summary

- Need for Additional Primary Energy is Apparent
- Case for Significant (Daunting?) Carbon-Free Energy Seems Plausible

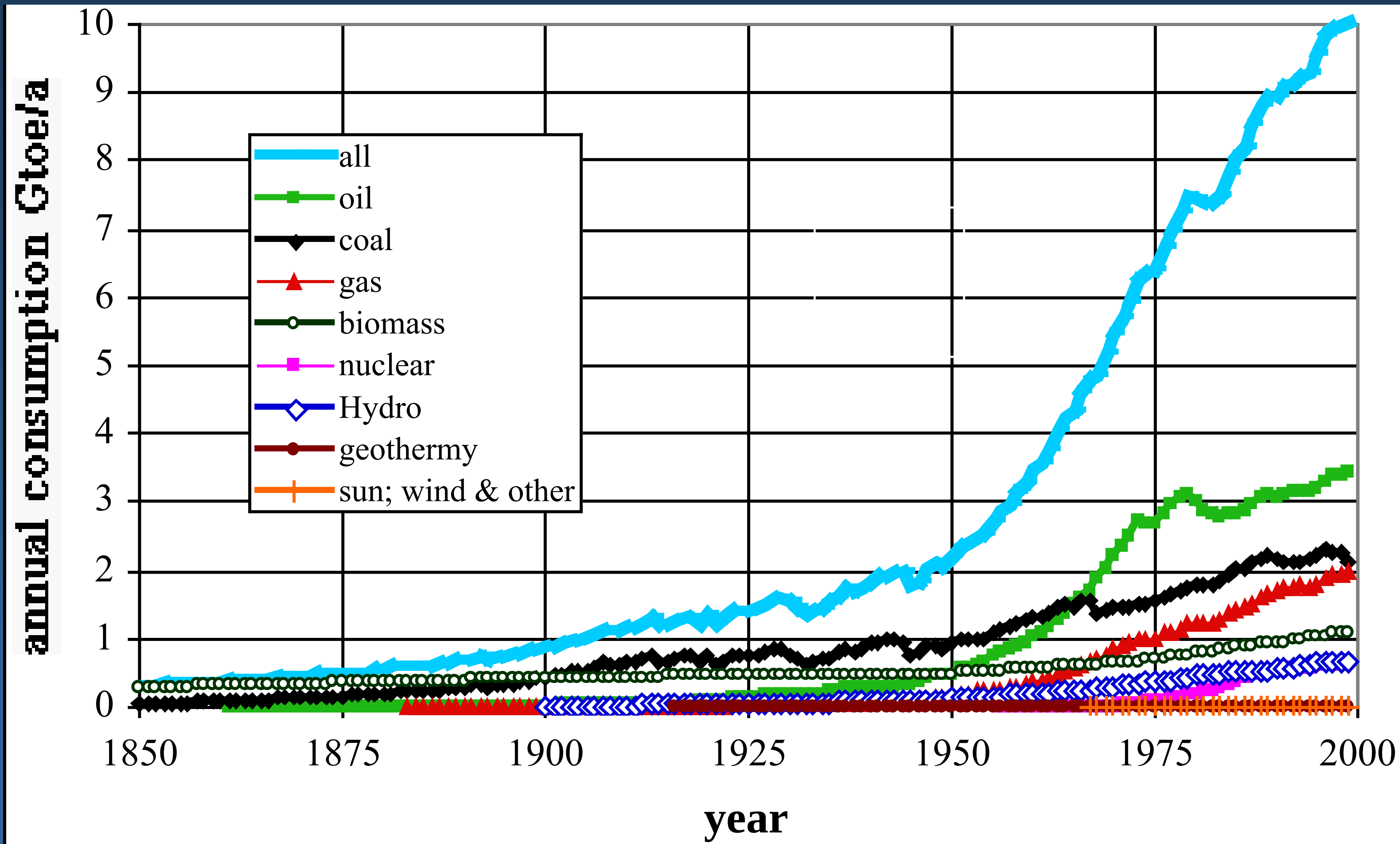
Scientific/Technological Challenges

- Provide Disruptive Solar Technology: **Cheap Solar Fuel**

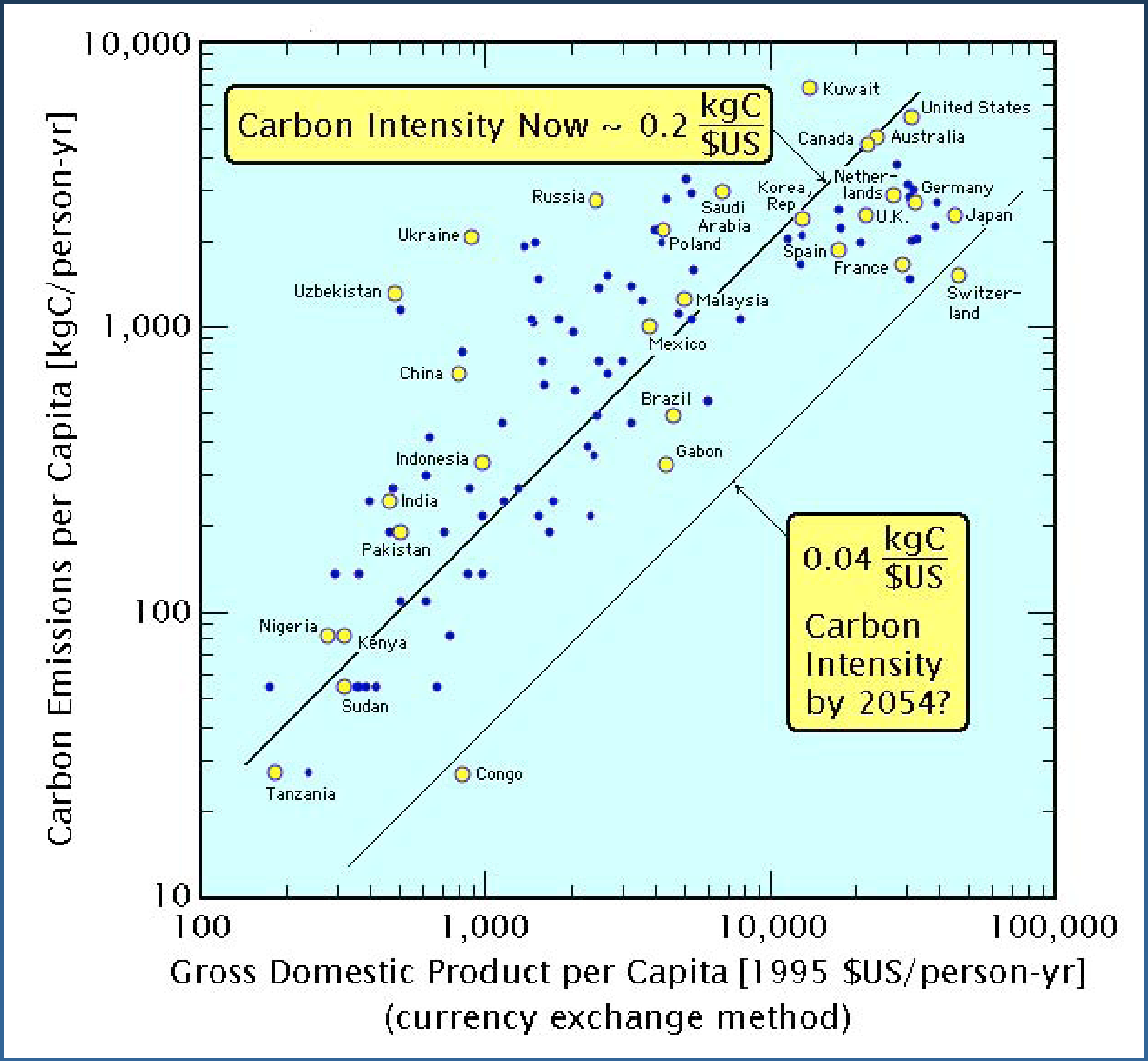
Inexpensive conversion systems, effective storage systems

- Provide the New Chemistry to Support an Evolving Mix in Fuels for Primary and Secondary Energy
- **Policy Challenges**
- Will there be the needed commitment? Is Failure an Option?

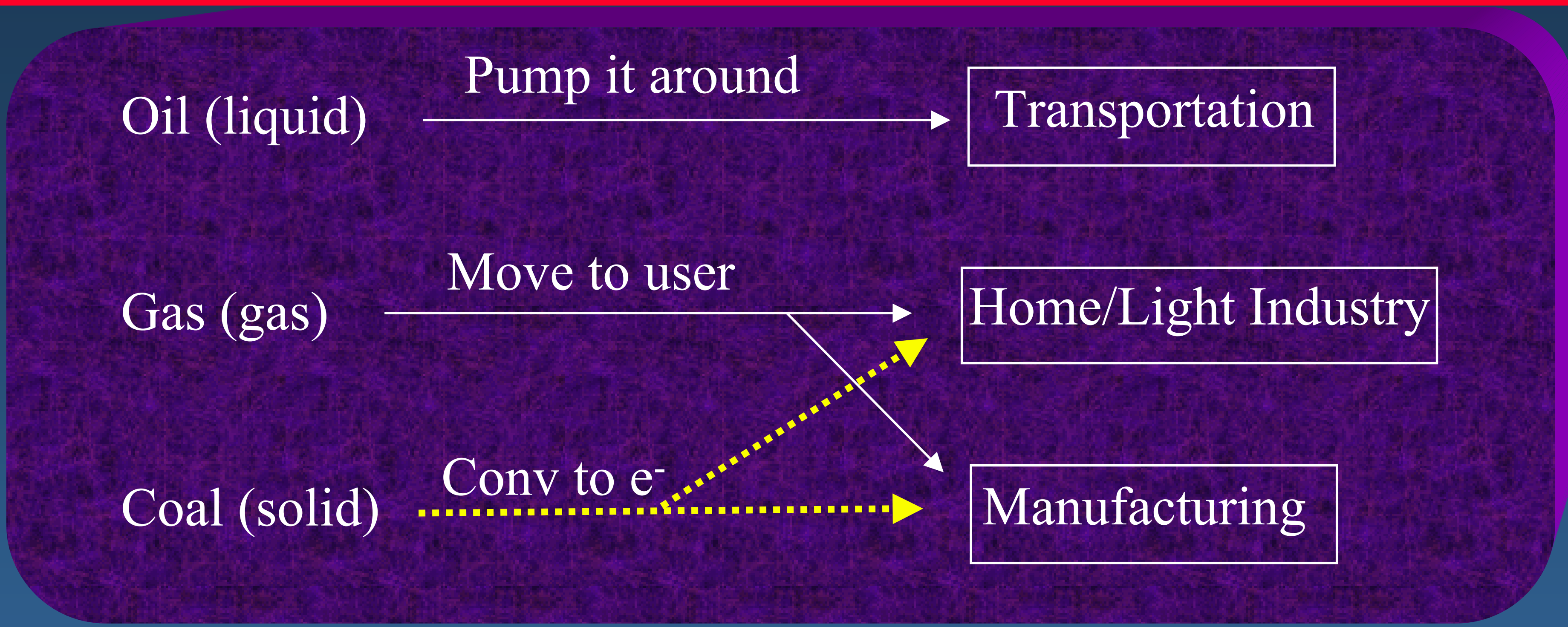
Global Energy Consumption



Carbon Intensity vs GDP

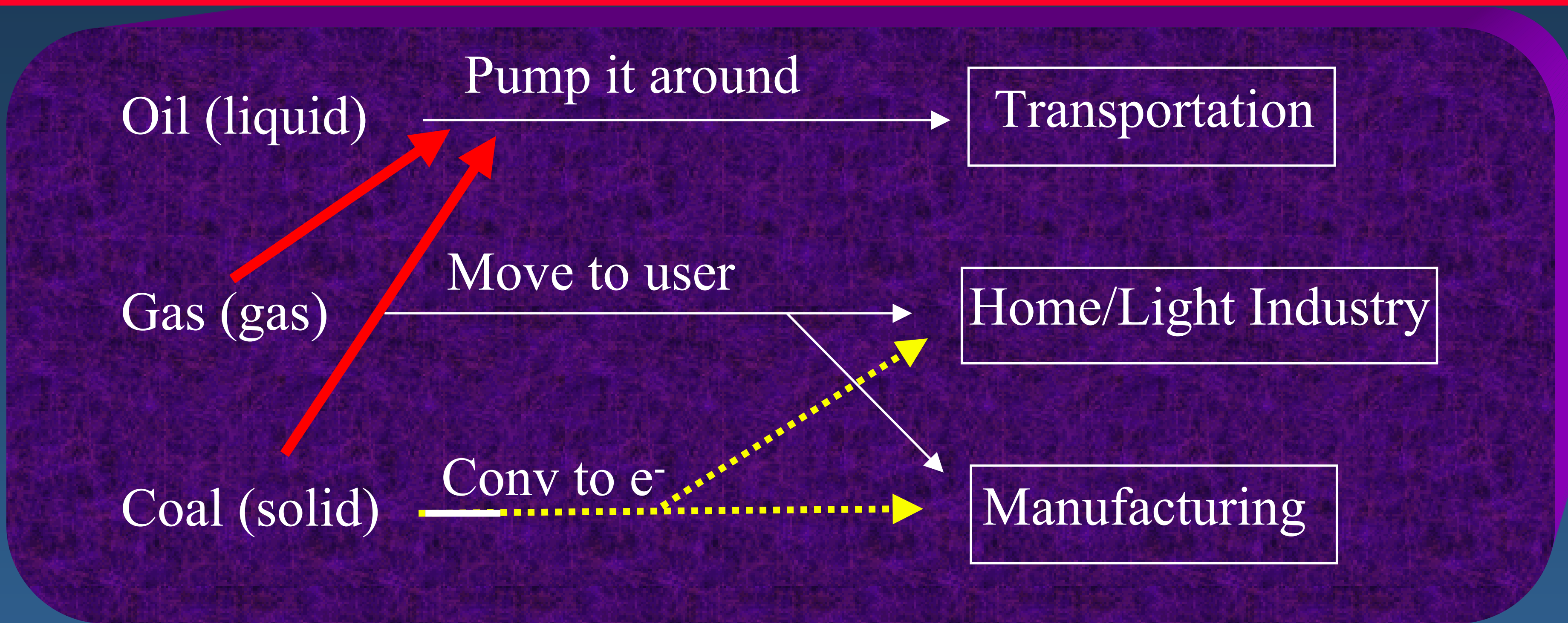


Matching Supply and Demand



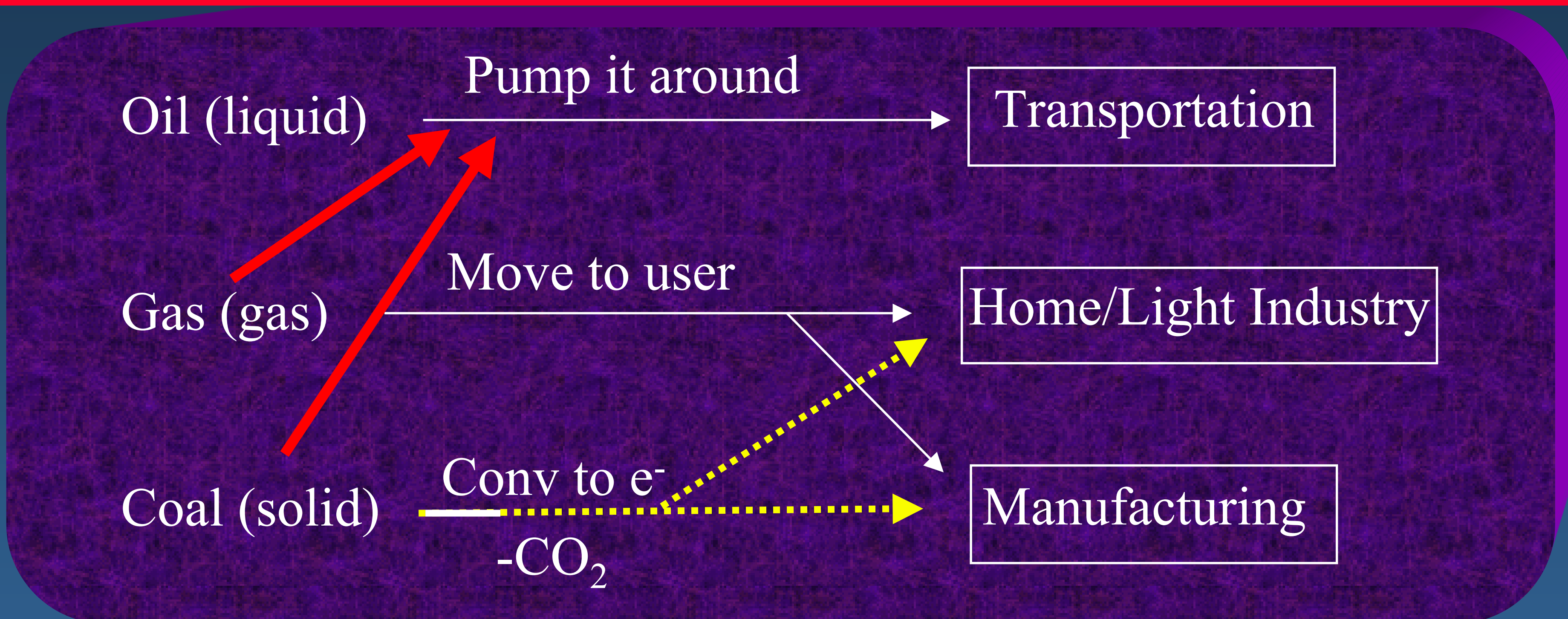
Currently end use well-matched to physical properties of resources

Matching Supply and Demand



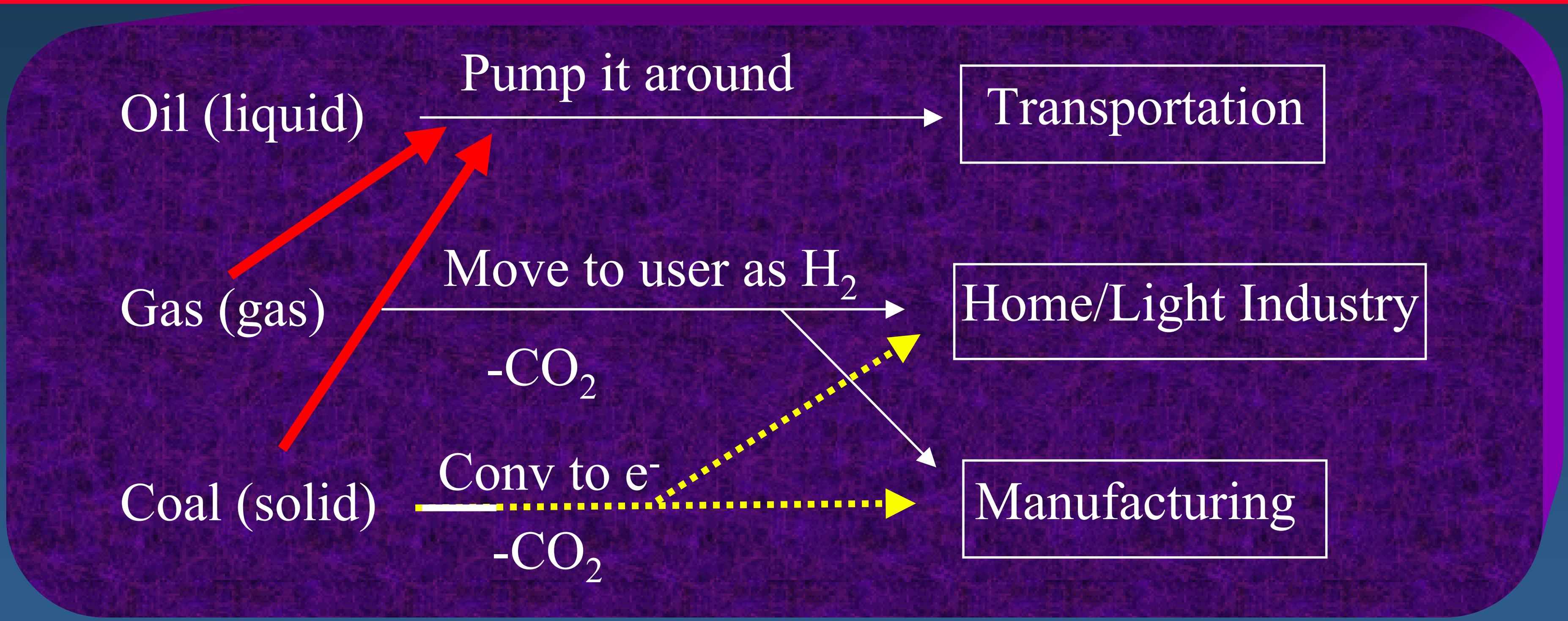
If deplete oil (or national security issue for oil), then liquify gas,coal

Matching Supply and Demand



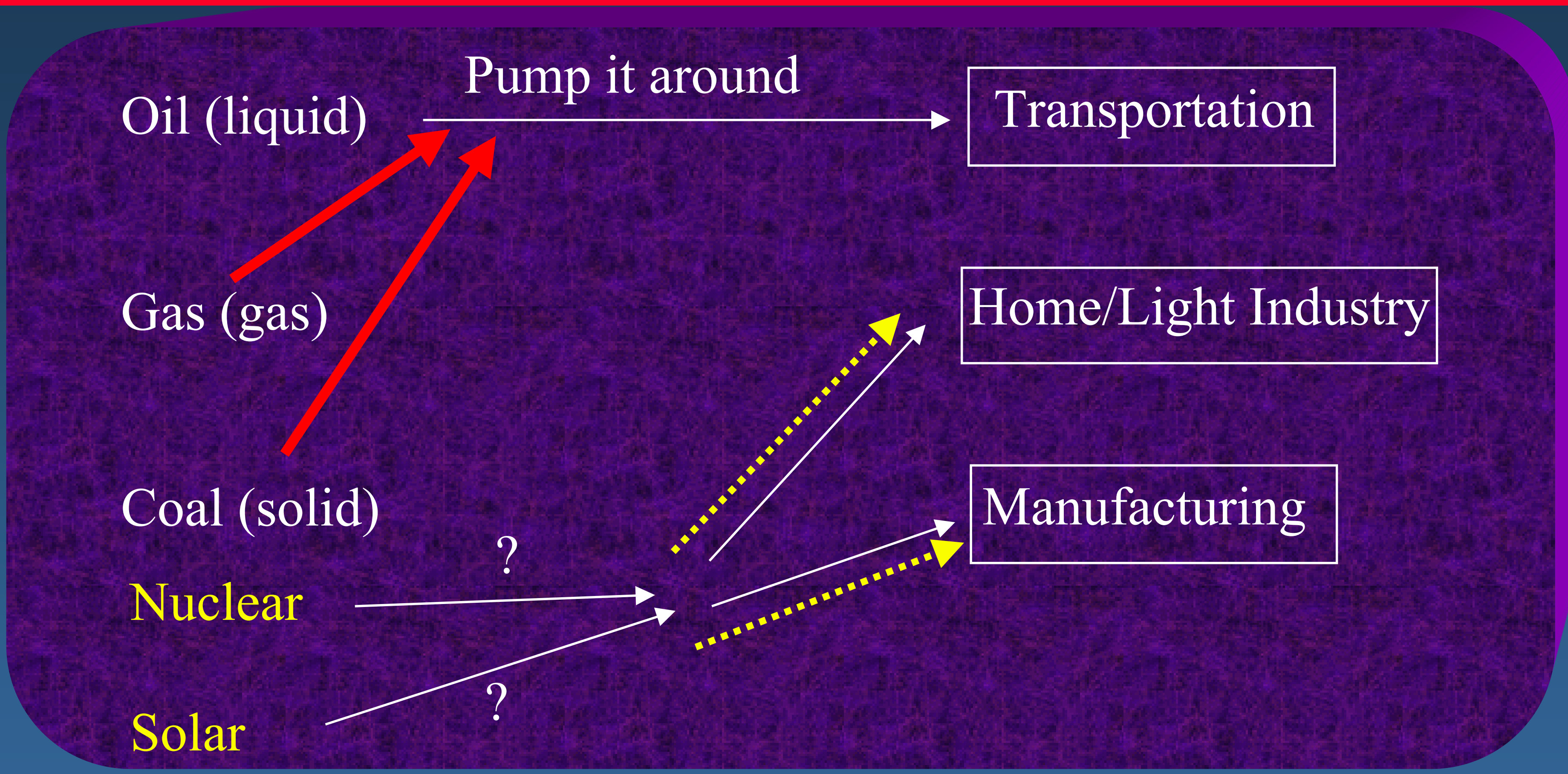
If carbon constraint to 550 ppm *and* sequestration works

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

Quotes from PCAST, DOE, NAS

The principles are known, but the technology is not

Will our efforts be too little, too late?

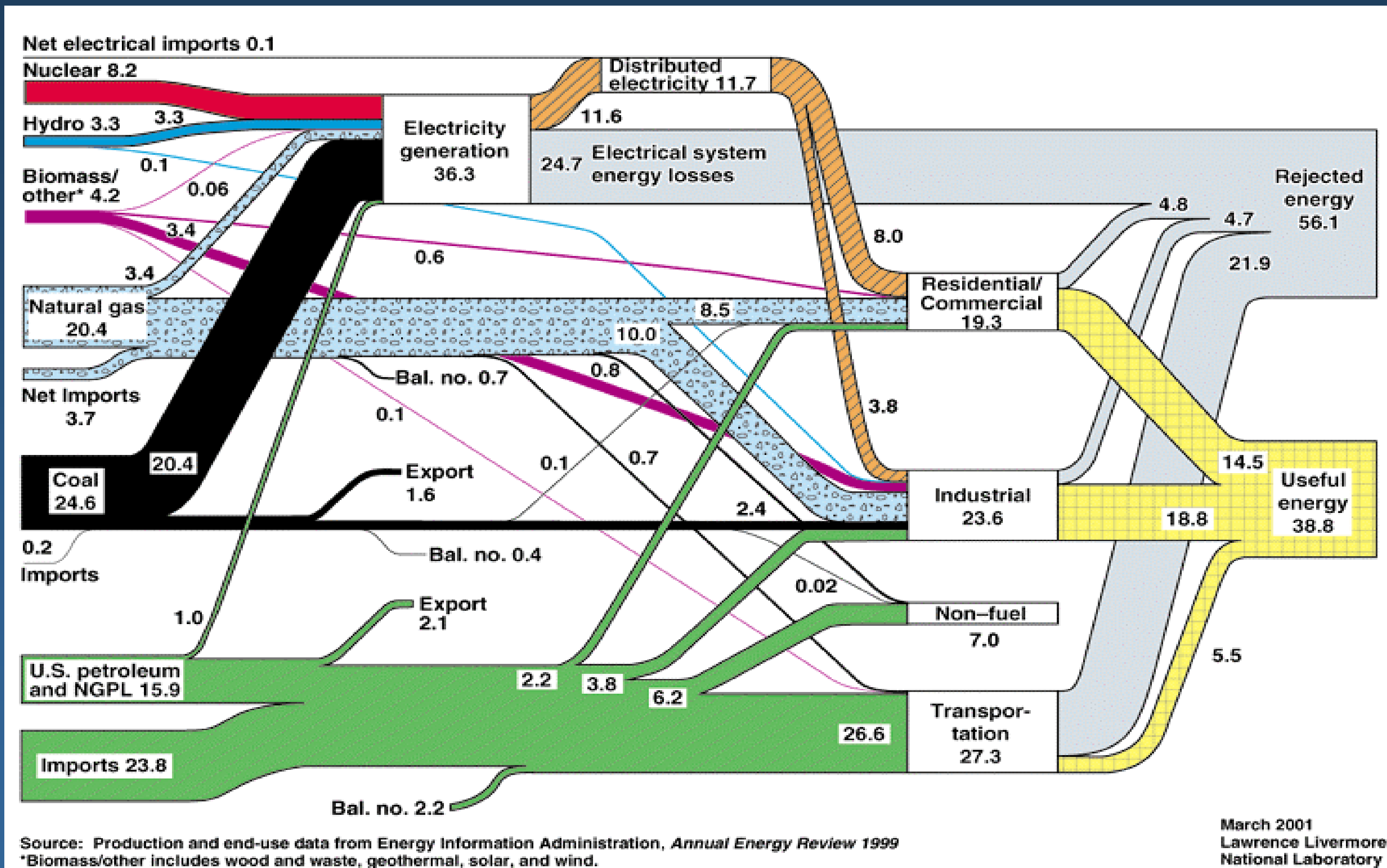
Solar in 1 hour > Fossil in one year

1 hour $$$ gasoline > solar R&D in 6 years

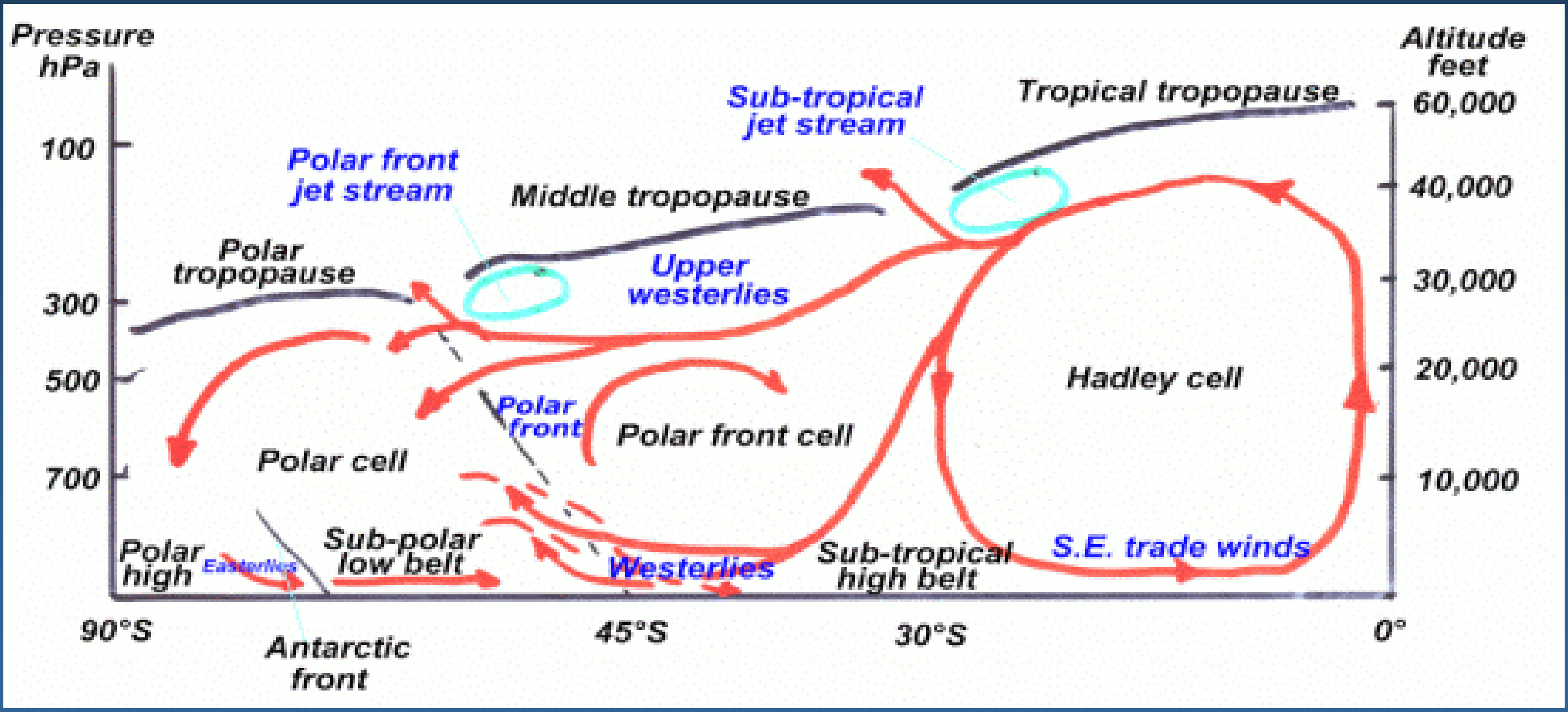
Will we show the commitment to do this?

Is failure an option?

US Energy Flow -1999
Net Primary Resource Consumption 102 Exajoules



Tropospheric Circulation Cross Section



Primary vs. Secondary Power

Transportation Power

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

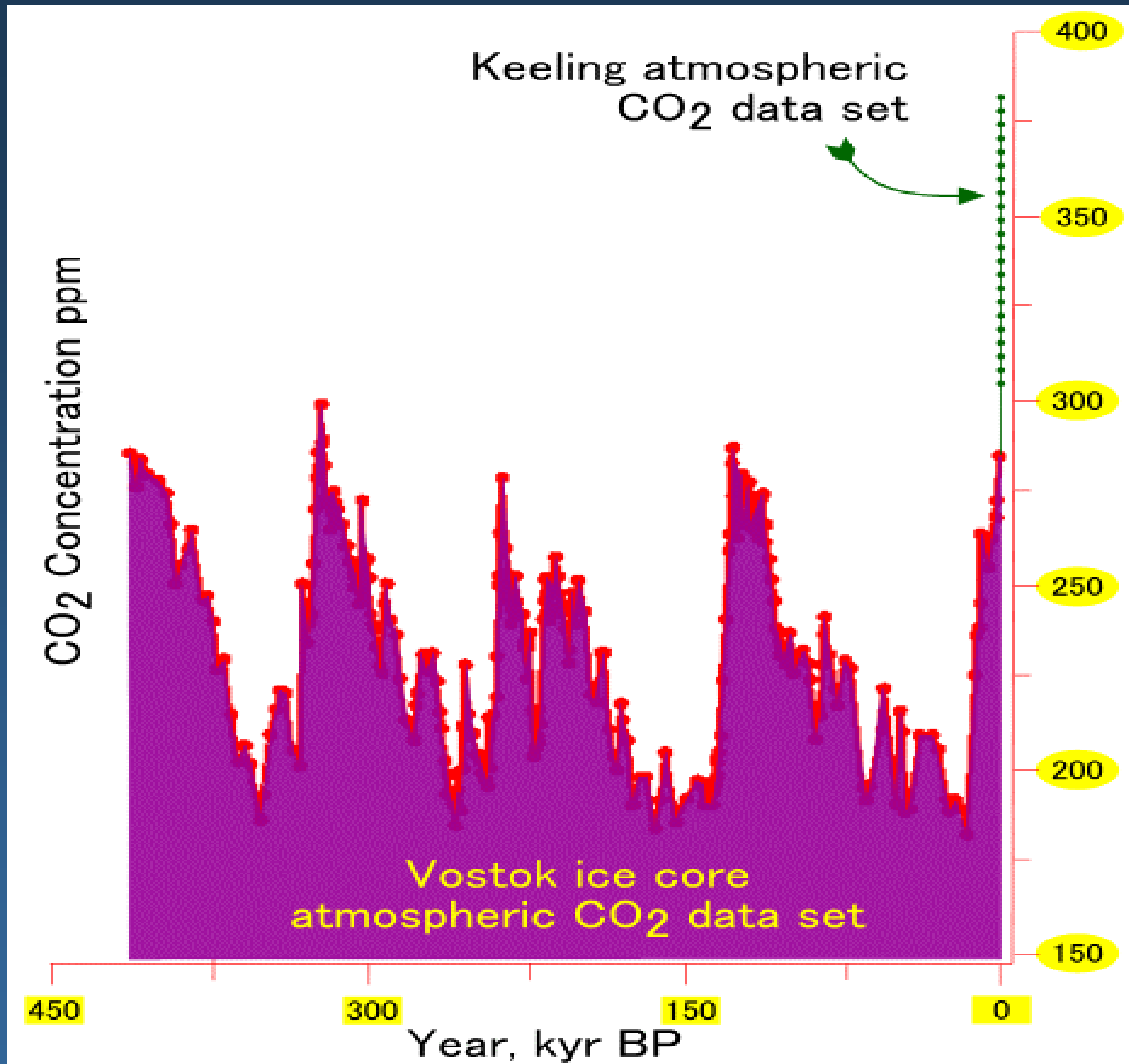
Primary Power

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