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Energy – the U.S. and World – and **Carbon**…

Henry W. Brandhorst, Jr.

June 25, 2007

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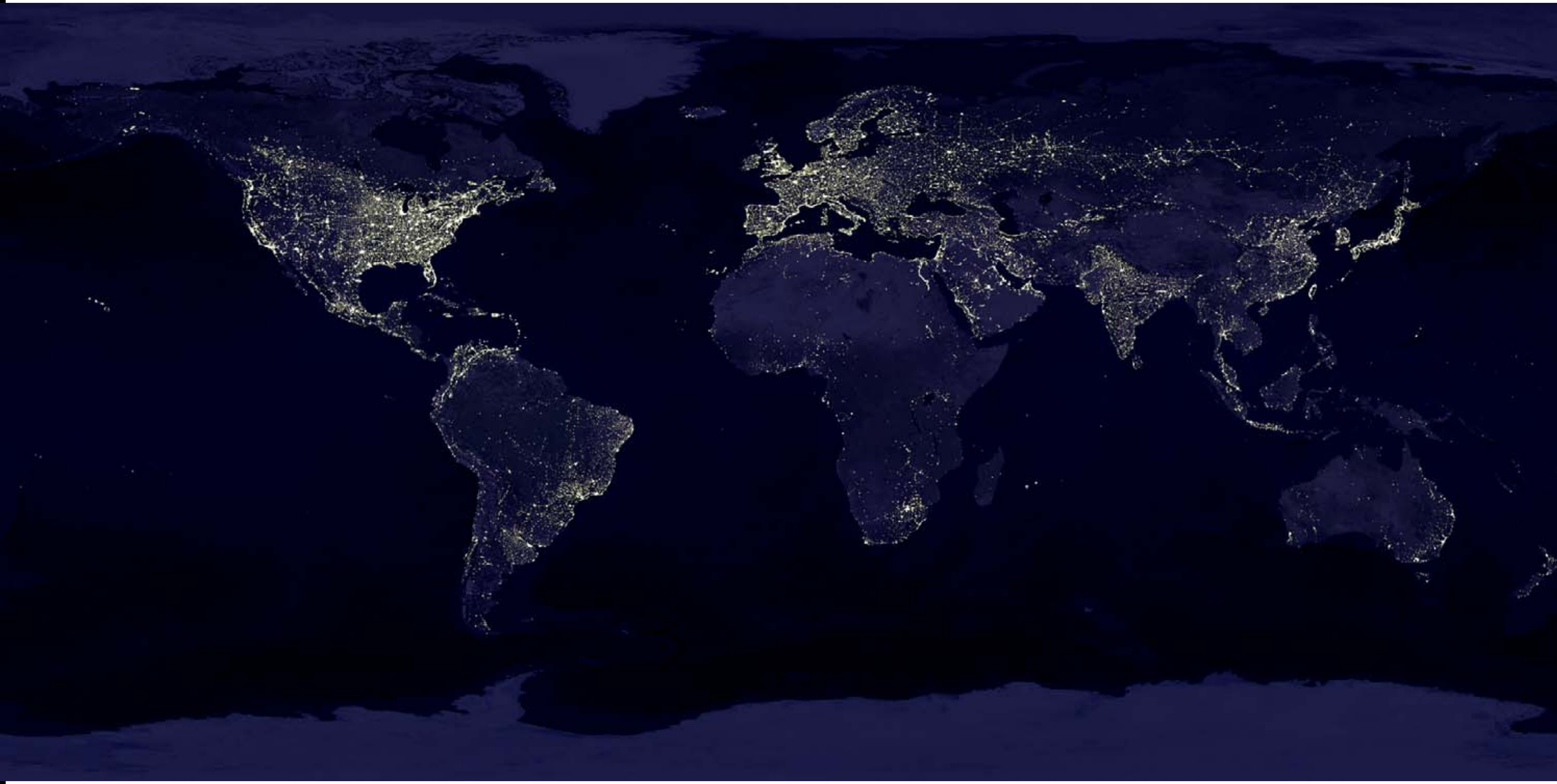
The World at Night



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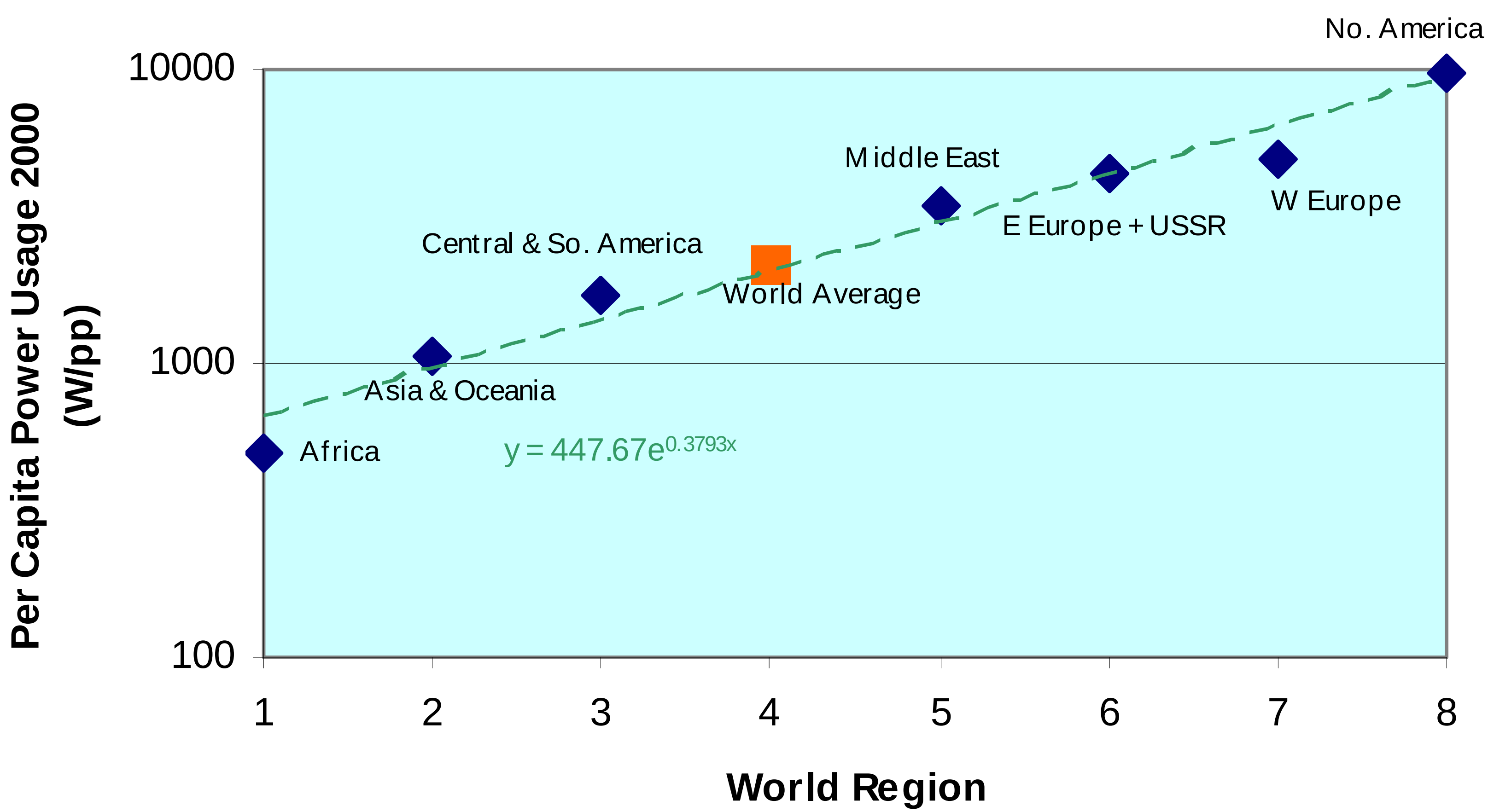
The Terrestrial Energy Situation



Source: EIA/DOE; 2000 data

Energy is the key to economic development

Global Energy Consumption

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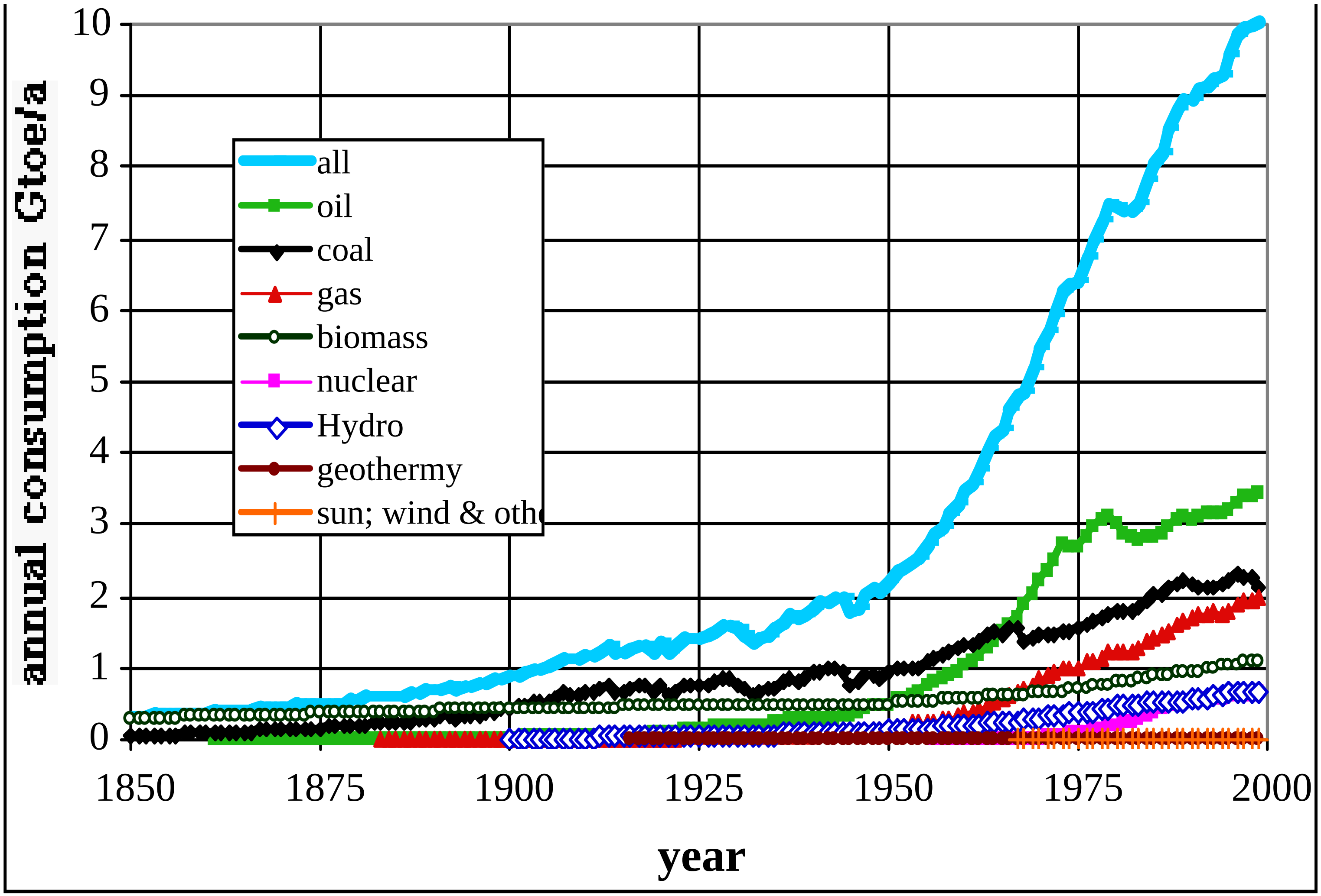

Mean Global Energy Consumption
(1998)

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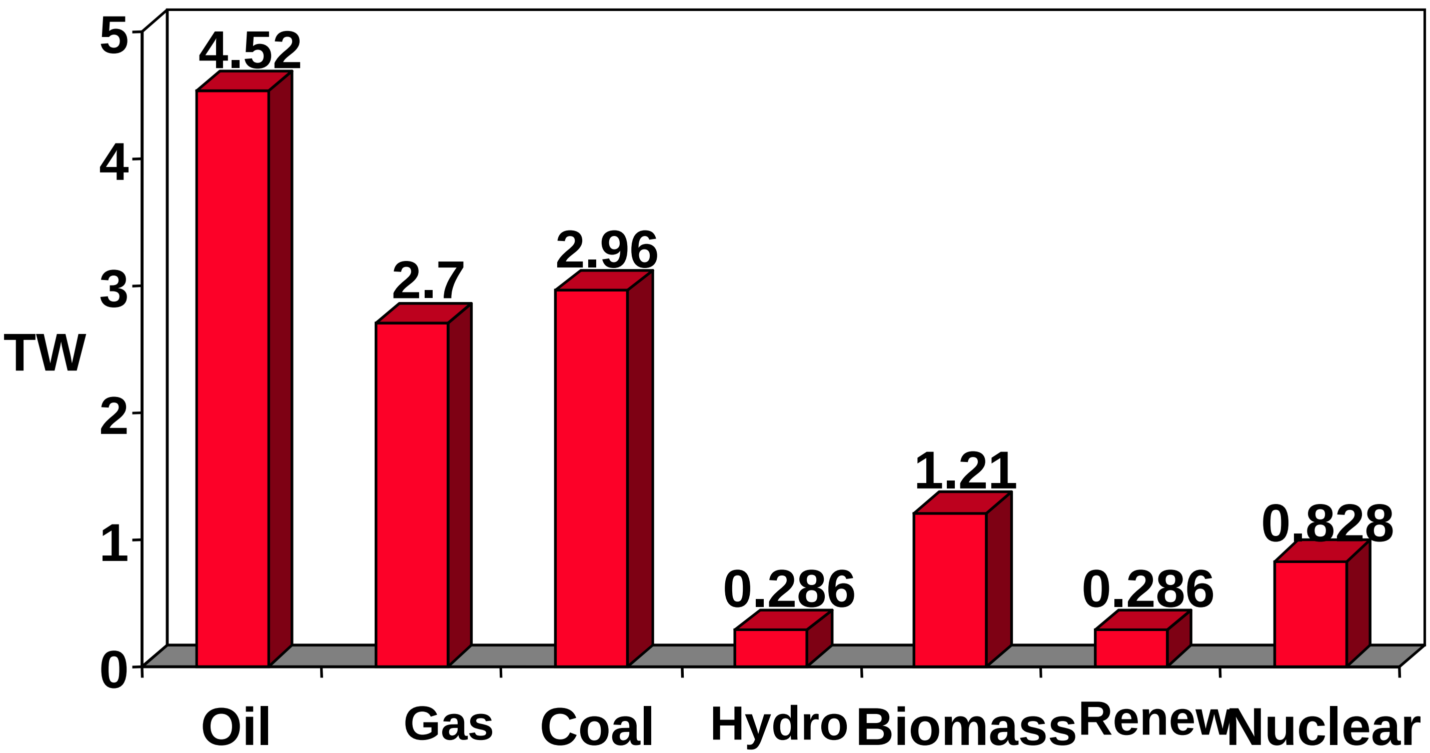

Total: 12.8 TW U.S.: 3.3 TW (99 Quads)

Ref: Nate Lewis, 2005

Production Cost of Electricity
(in the U.S., 2002)

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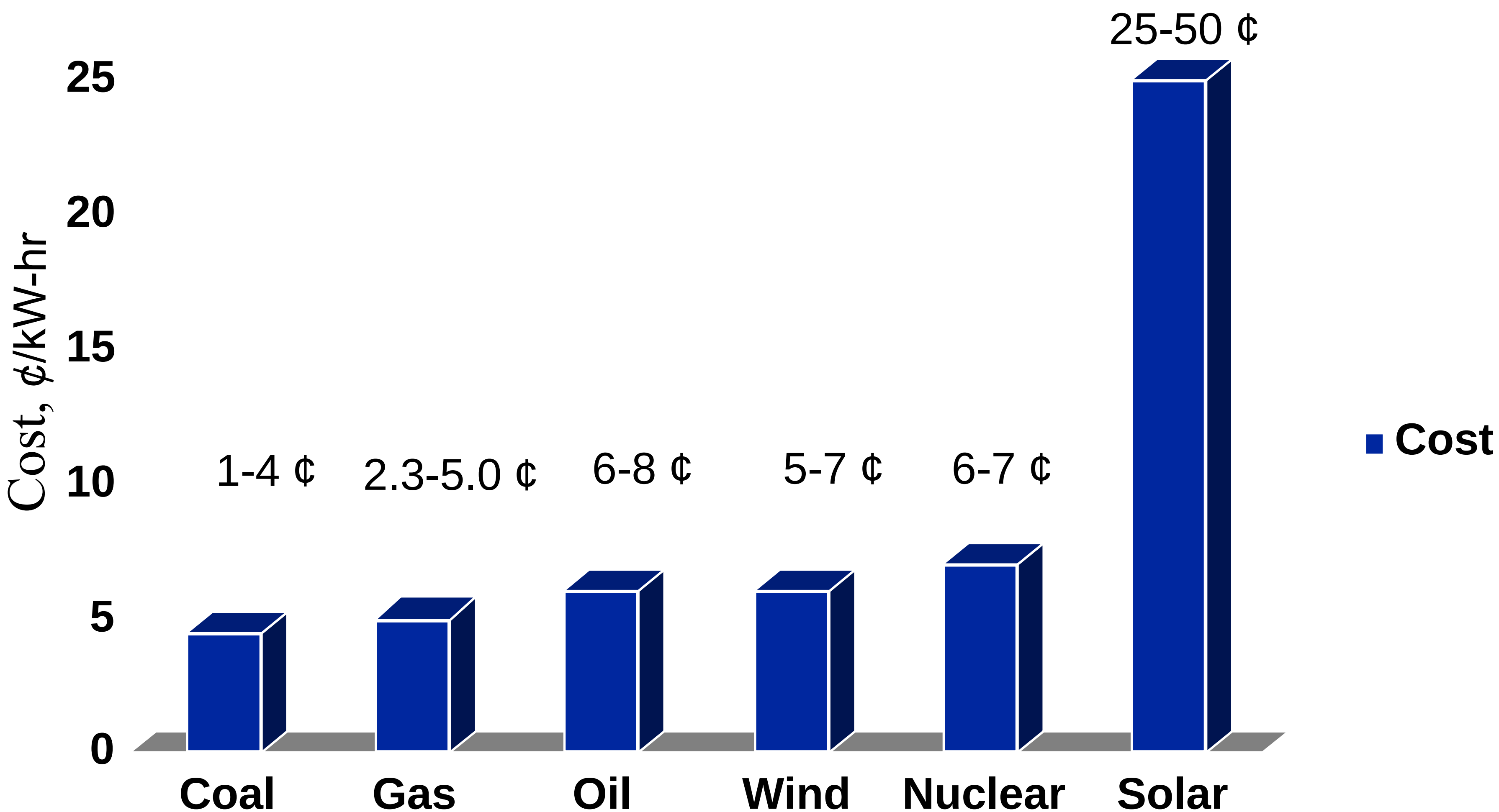

Ref: Nate Lewis, 2005

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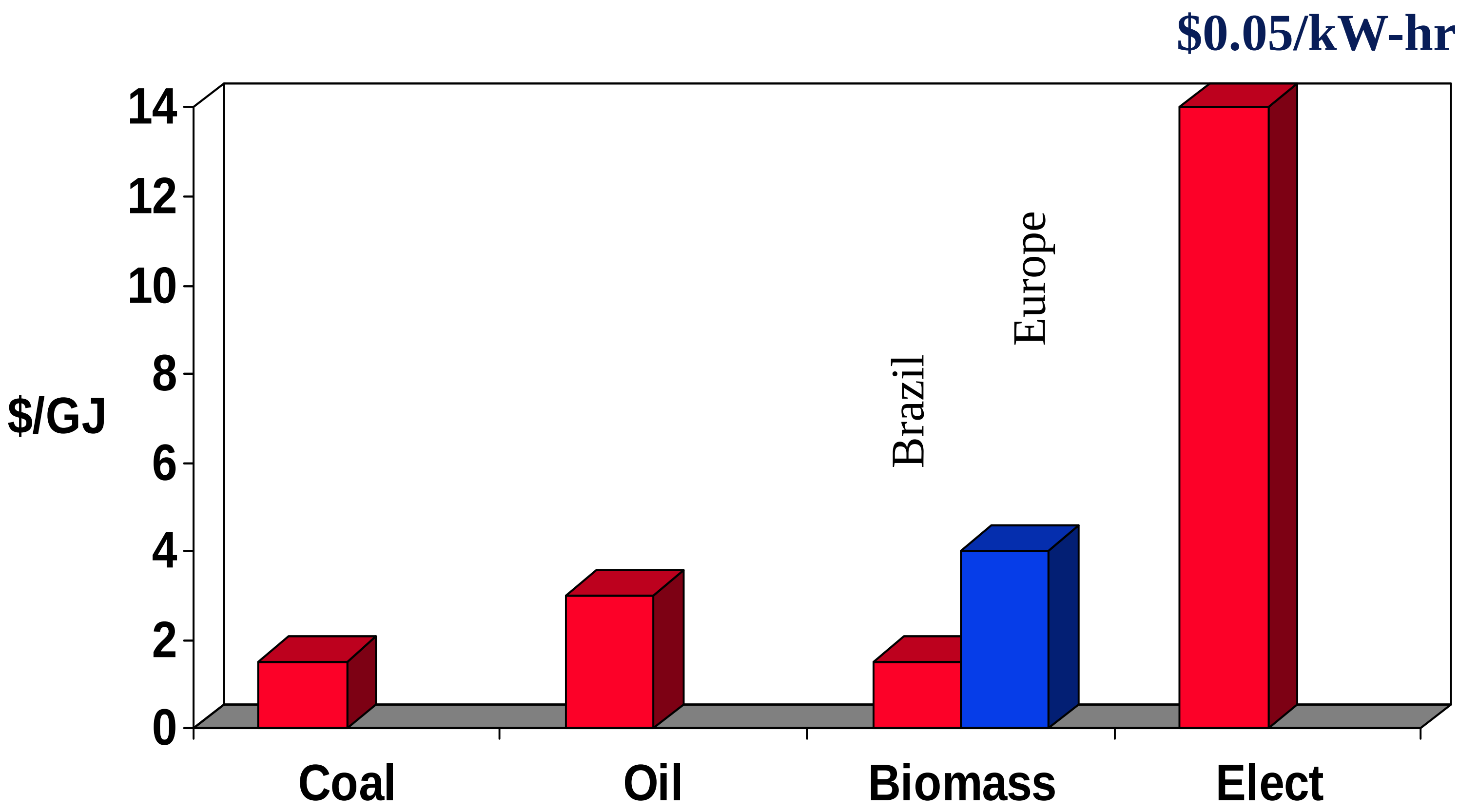
Energy Costs



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

Ref: Nate Lewis, 2005

Space Research Institute

Energy Reserves and Resources

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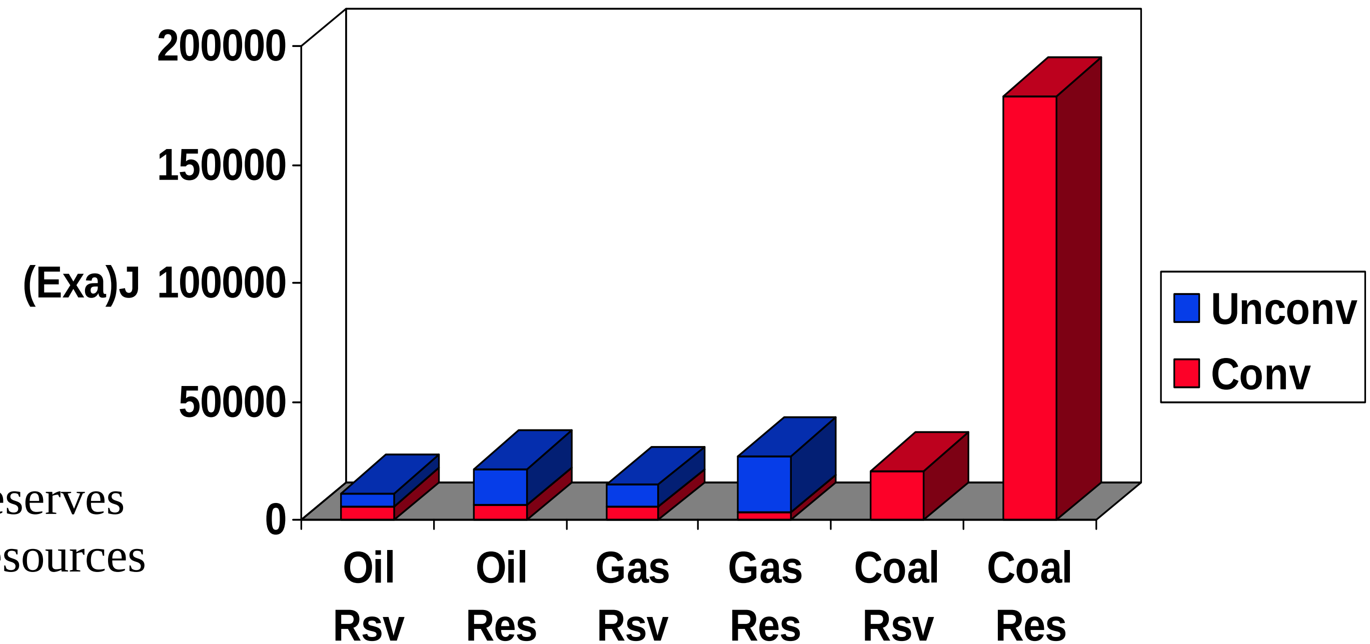


Rsv=Reserves
Res=Resources

Reserves/(1998 Consumption/yr)

Oil	40-78
Gas	68-176
Coal	224

Resource Base/(1998 Consumption/yr)

51-151
207-590
2160

Ref: Nate Lewis, 2005

Conclusions (1)

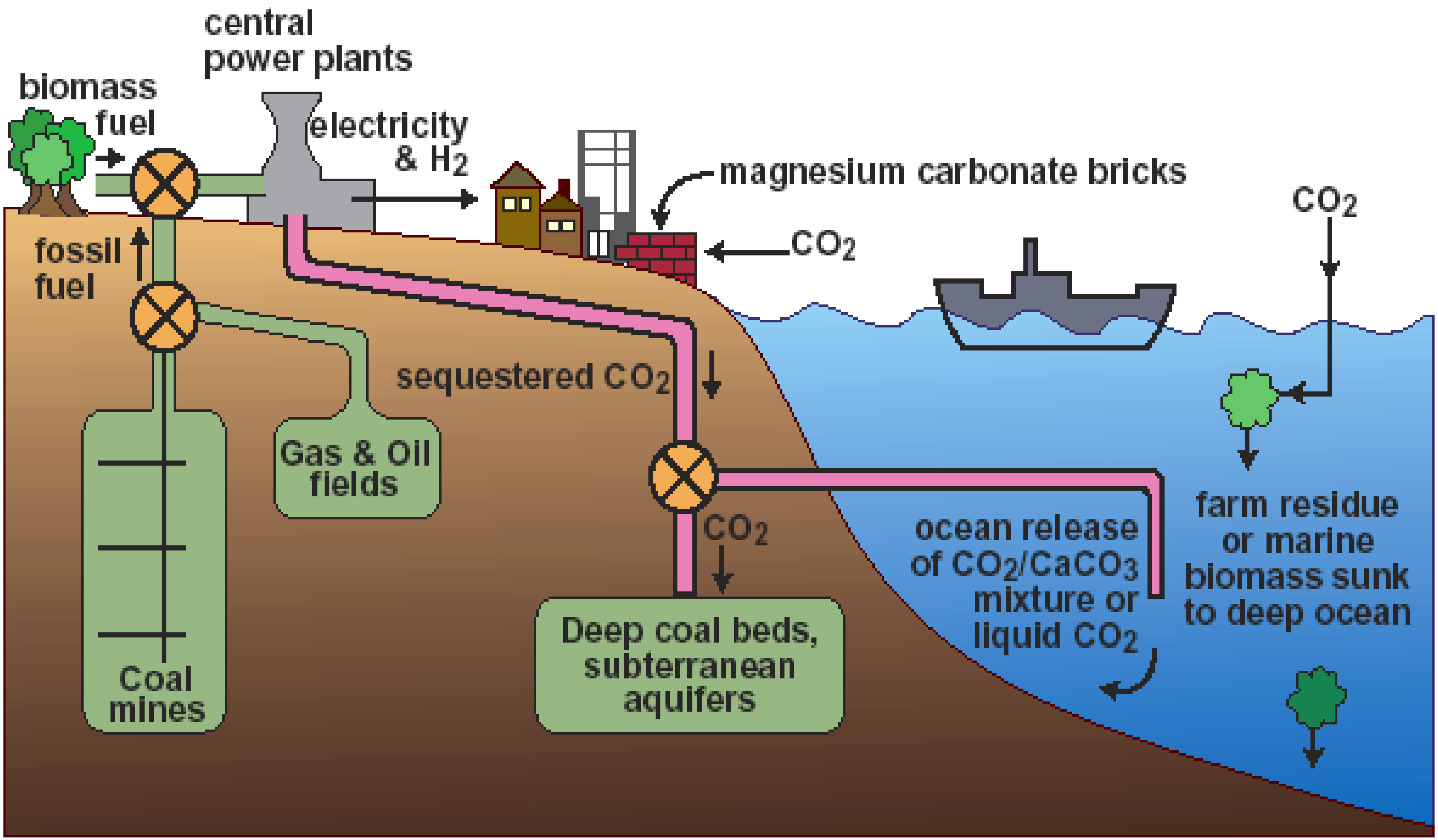
- Abundant, inexpensive resource base of fossil fuels exists
- Renewables will not play a large role in primary power generation unless/until:
  - Technological/cost breakthroughs are achieved, or
  - Unpriced externalities are introduced (e.g. environmentally-driven carbon taxes

Ref: Nate Lewis, 2005

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 10 TW provides 1 year of energy
    - Terrestrial resource base provides 10 years of energy
  - Would need to mine U from seawater
    - ~700x terrestrial resource base
- Carbon sequestration
- Renewables

Carbon Sequestration



CO_2 Burial: Saline Reservoirs

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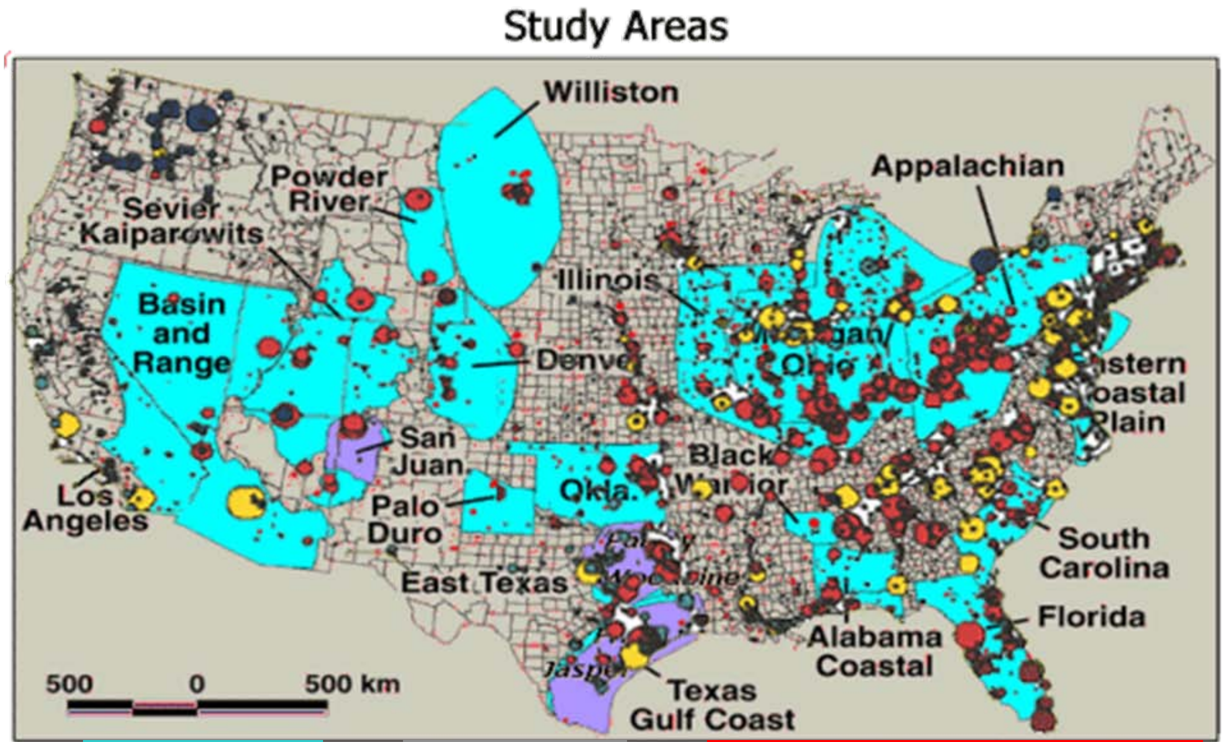
130 Gt total U.S. sequestration potential
Global emissions 6 Gt/yr in 2002
Test sequestration projects 2002-2004



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

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

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Globally

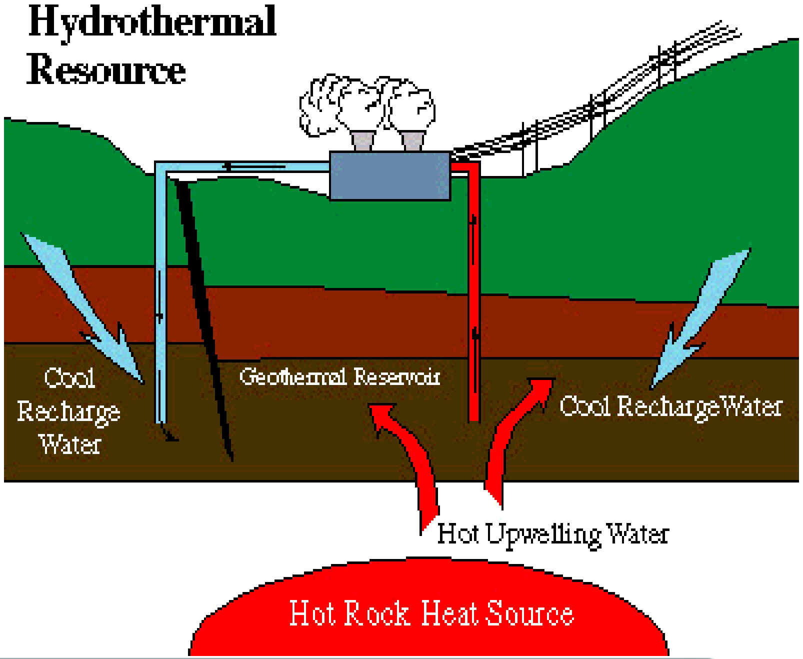
- Gross theoretical potential 4.6 TW
- Technically feasible potential 1.5 TW
- Economically feasible potential 0.9 TW
- Installed capacity in 1997 0.6 TW
- Production in 1997 0.3 TW

  □(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 ºC at 10 km depth)

Geothermal Energy Potential

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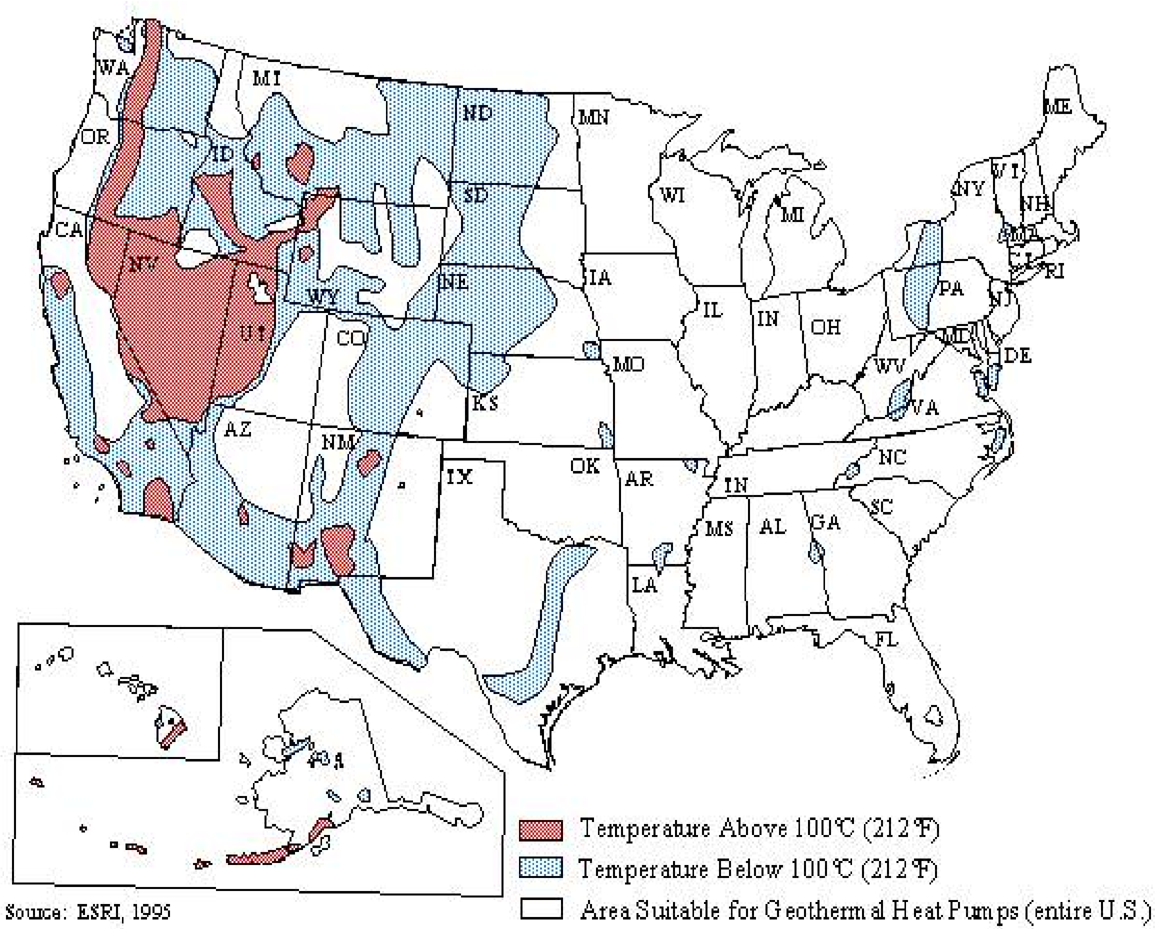

Ocean Energy Potential

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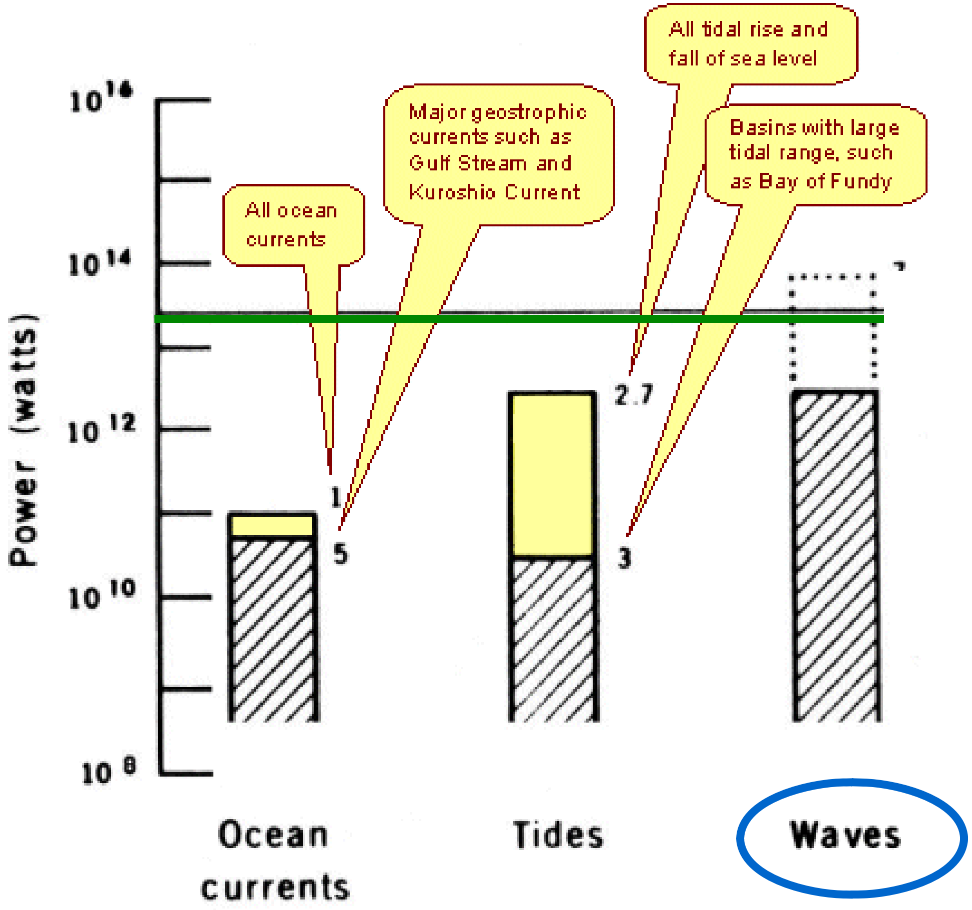

Isaacs, J.D., and W.R. Schmitt, 1980. "Ocean Energy: Forms ar

Electric Potential of Wind

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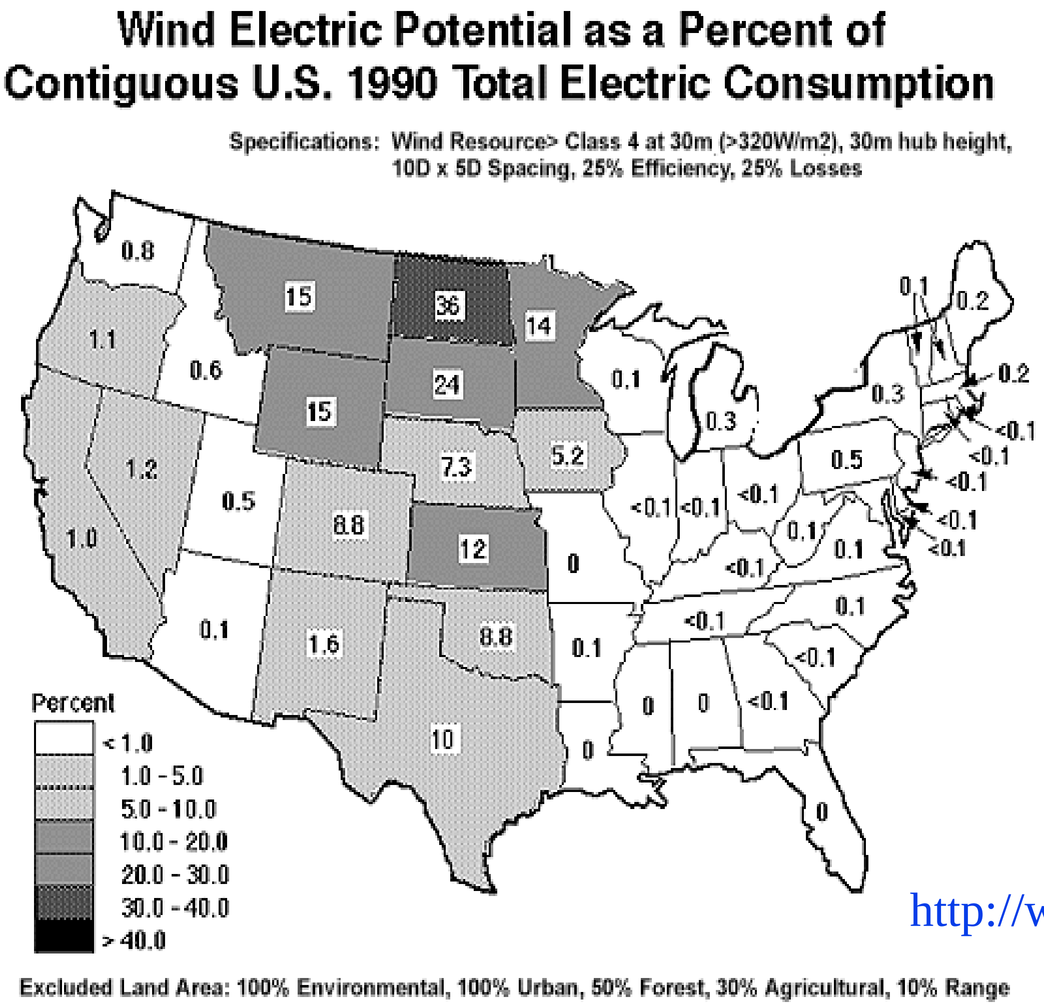

In 1999, U.S consumed 3.45 trillion kW-hr of Electricity = 0.39 TW

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

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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)

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Electric Potential of Wind

- Relatively mature technology, not much impacted by chemical sciences
- Intermittent source; storage system could assist in converting to base load 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 = 6×10^{12} m^2
- 20 TW requires ≈ 4×10^{13} m^2
- Total land area of earth: 1.3×10^{14} m^2
- Hence requires 4/13 = 31% of total land area

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

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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


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Solar Thermal

- 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 >20% (research in thermochemical fuels: hydrogen, NH_3, syn gas, metals)

Solar Land Area Requirements


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

Solar Land Area Requirements

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Solar Land Area Requirements

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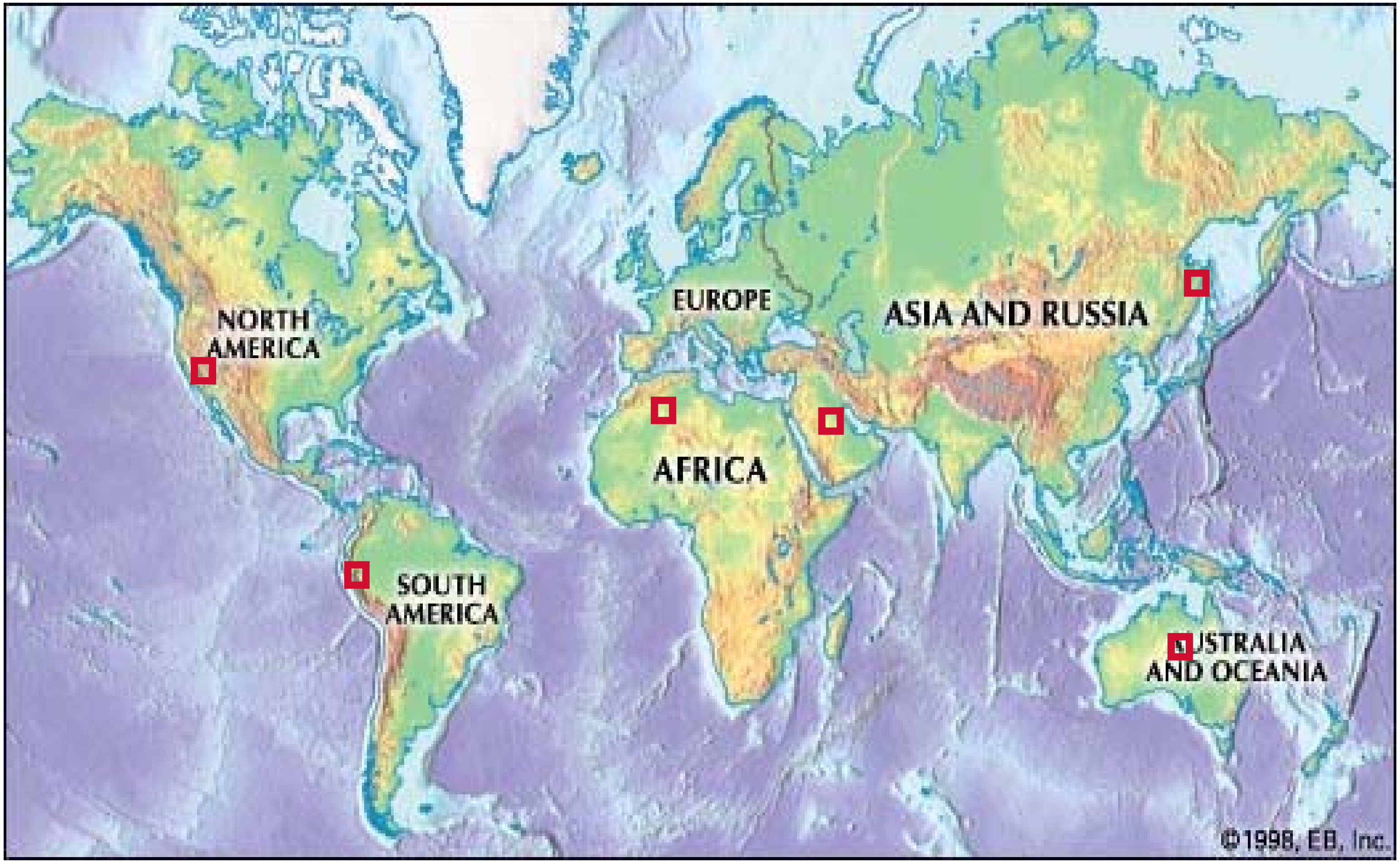

6 Boxes at 3.3 TW Each

Solar Land Area Requirements


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- U.S. Land Area: $9.1\text{x}10^{12}$ 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:
  $3.3\text{x}10^{12}$ W/($2\text{x}10^2$ W/m^2 x 10% Efficiency) = $1.6\text{x}10^{11}$ m^2
  Requires $1.6\text{x}10^{11}$ m^2/ $9.1\text{x}10^{12}$ m^2 = 1.7% of Land

Solar Electricity

- 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

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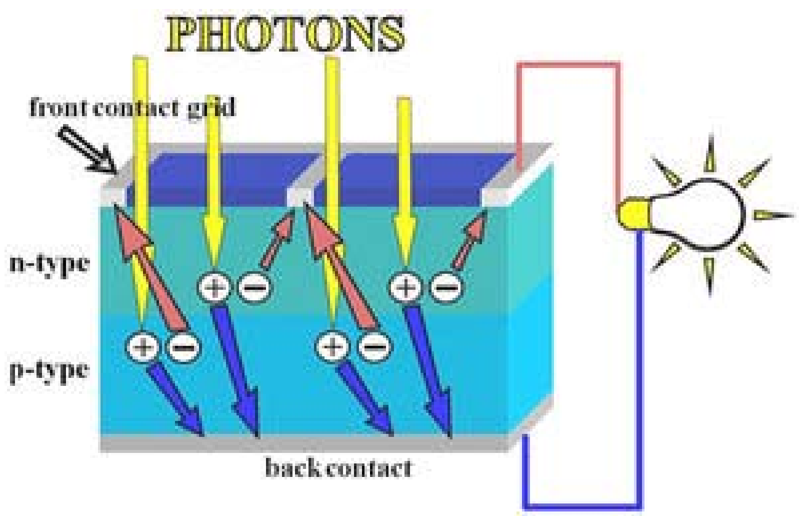
Converting the Sun’s Radiation into Electricity – Two Main Pathways

Photovoltaics

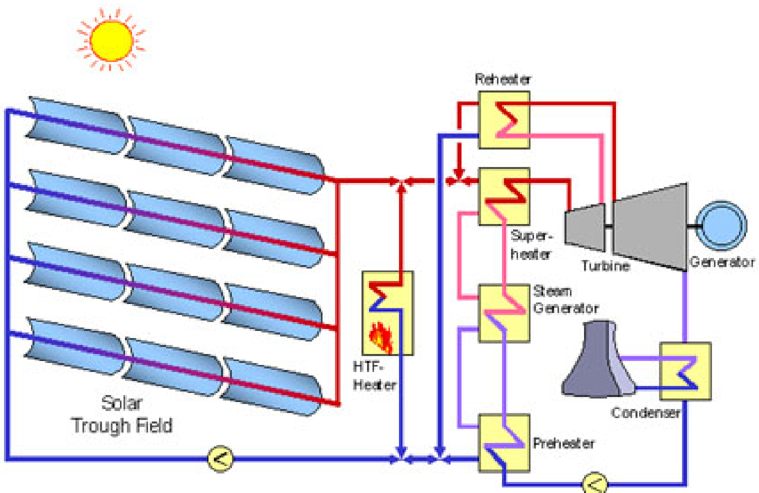
Cells of semi-conductors absorb photons and directly convert them into electrical current.



Can be used anywhere in the U.S.

Concentrating Solar Power

Mirrors focus solar radiation to heat fluids that are used to drive electric generators.



Predominantly in the Southwest U.S. (requires direct sunlight)

U.S. Solar Resources Significantly Outweigh Energy Use

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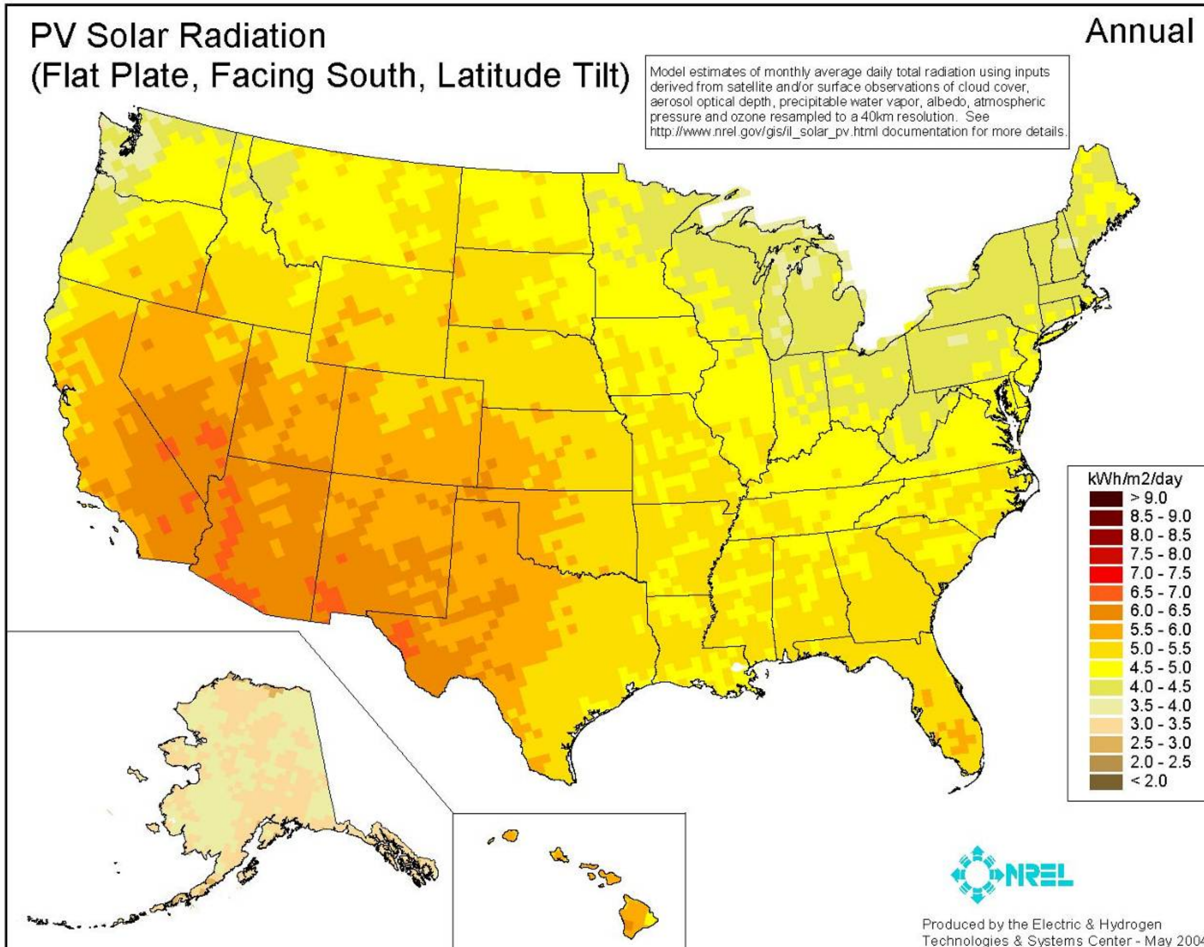
- Currently, solar provides less than 0.1% of the electricity used in the U.S.
- For the U.S., a 100-mi by 100-mi area in the Southwest could provide all of our electricity
- Covering less than 0.2% of the land on the earth with 10%-efficient solar cells would provide twice the power used by the world.



Photovoltaic (PV) technologies

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Commercial

Residential

- A Growing Source for Distributed & Centralized Electricity Generation

Utility-scale

Dramatic Reduction in Cost and Increase in Efficiency of PV Over Past 25 Years

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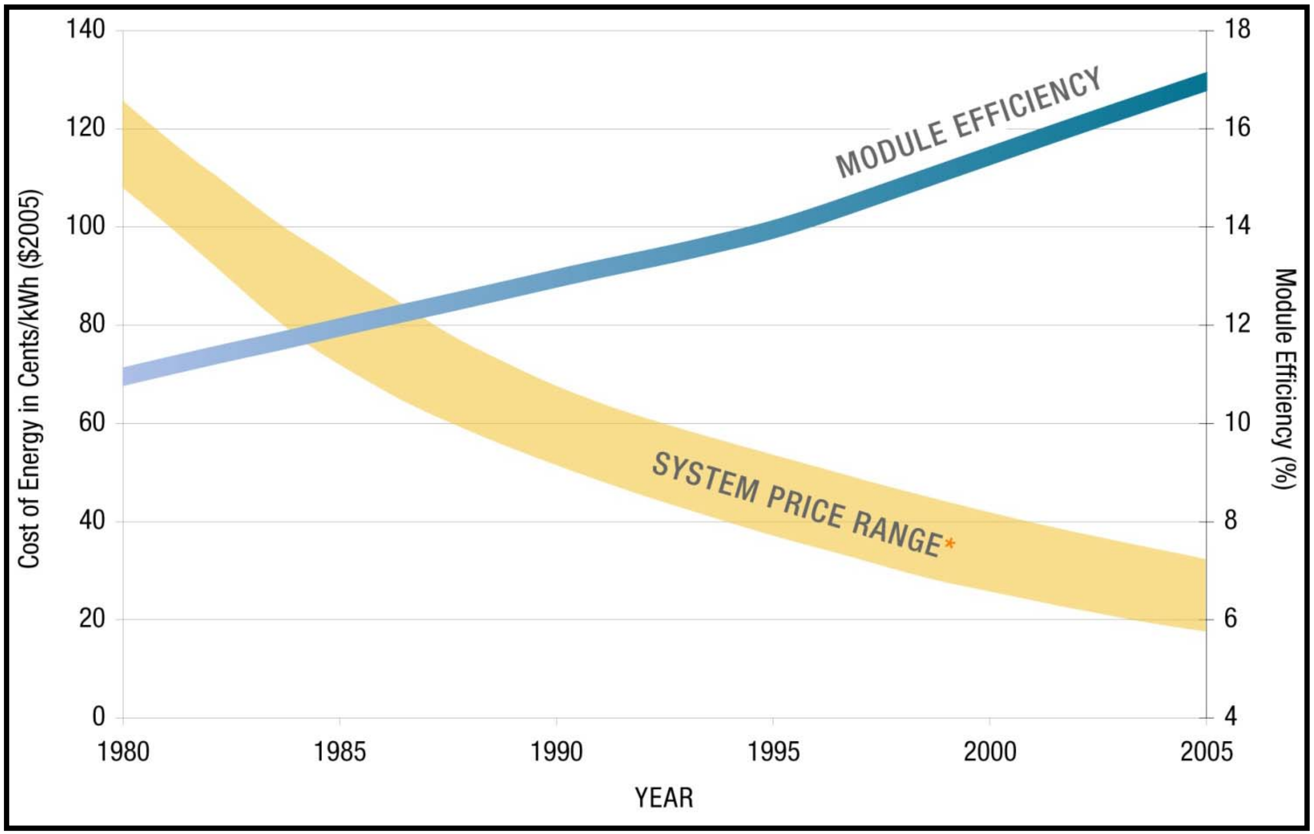
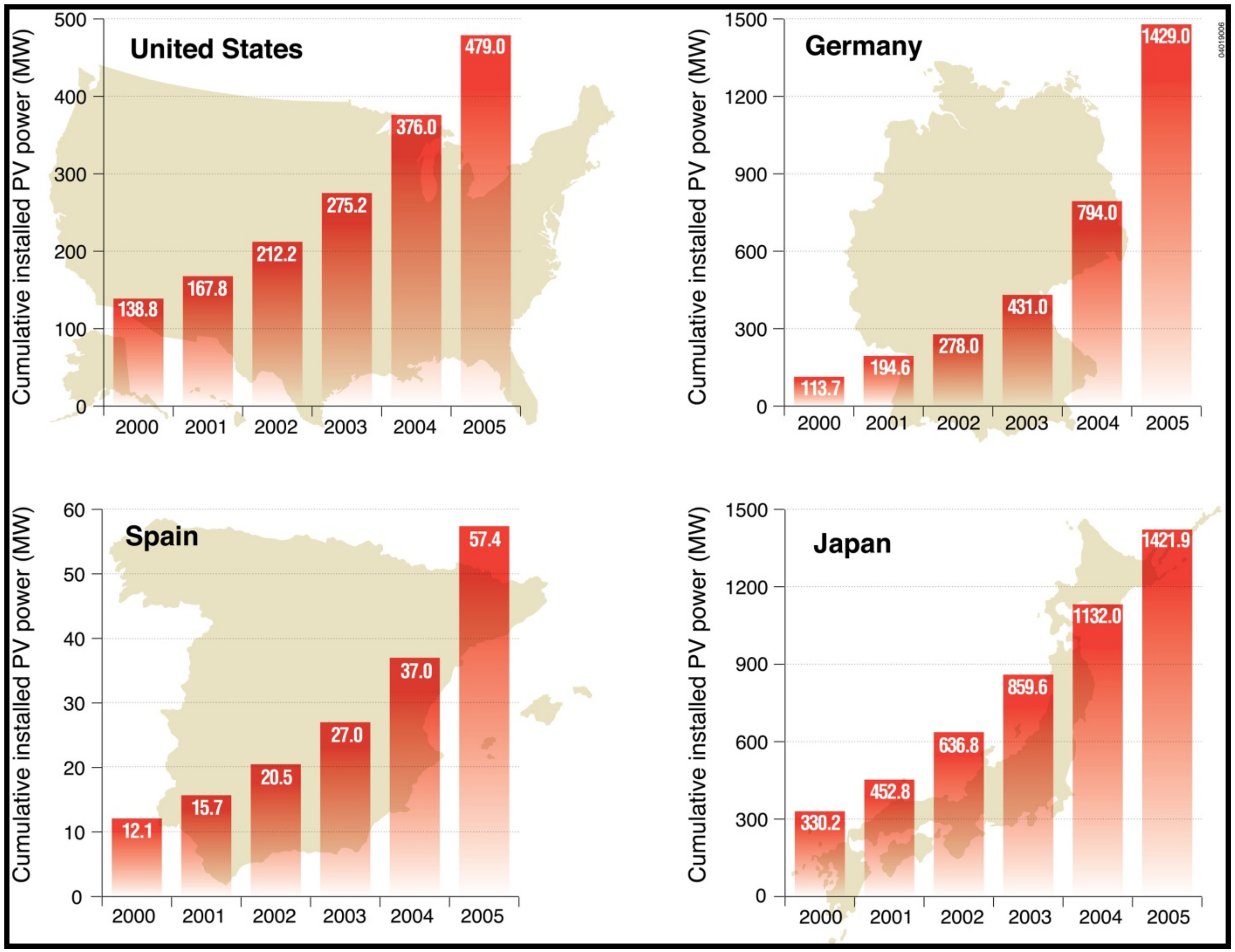
Historical PV Cost Curve (Silicon-based Technologies)



- ✶ Government investment in solar R&D has had a significant impact
- ✶ System prices must come down another 50-70% to achieve grid-parity nationwide

*** System price is dependent upon location, application and variable financing options (Source: NREL)**

PV Growing Rapidly in Key Countries



- Grid-connected PV is fastest growing market
- Incentives have driven steep growth in installations
- Average annual global growth rate has been 40+% for the past 5 years
- PV could capture > 30% of market share for new capacity additions within next 5-10 years

Source: International Energy Agency (2006)

Carbon Intensity vs GDP

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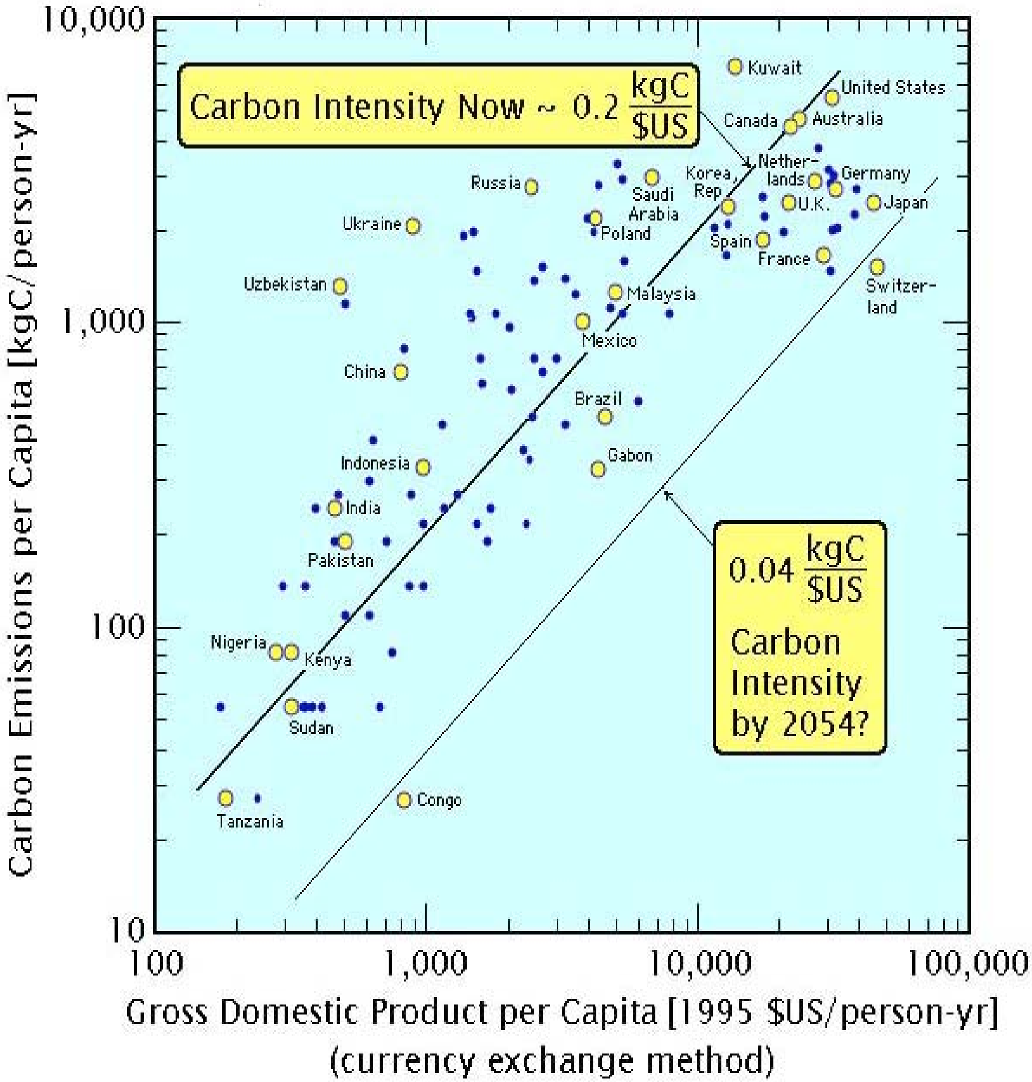

Energy is the most critical issue for the nation (and world) today

Ref: Nate Lewis, 2005

US Energy Flow -1999

Net Primary Resource Consumption, 102 Exajoules

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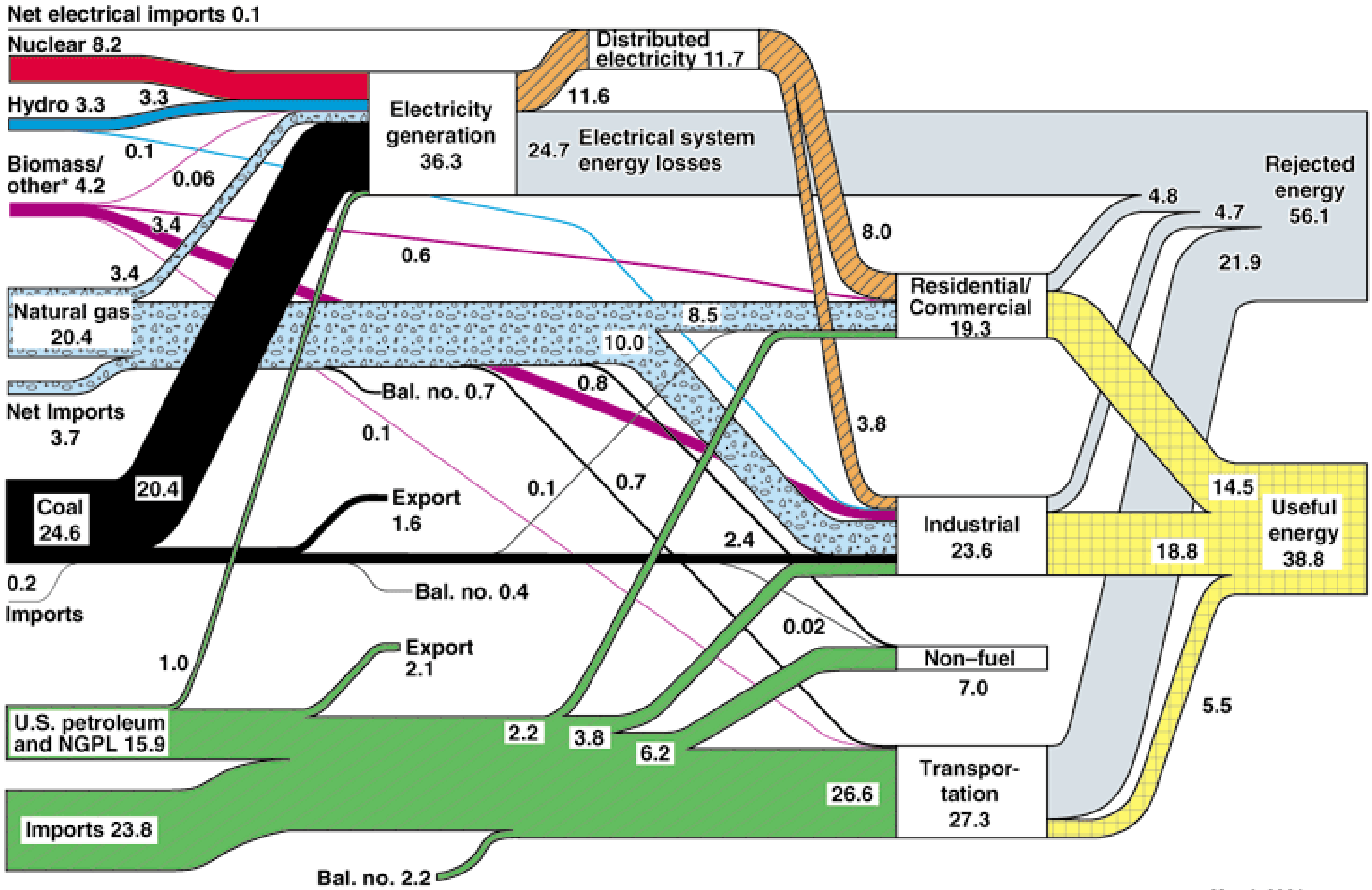

Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 1999*
*Biomass/other includes wood and waste, geothermal, solar, and wind.

March 2001
Lawrence Livermore
National Laboratory

Ref: Nate Lewis, 2005

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Matching Supply and Demand

Oil (liquid) — Pump it around → Transportation

Gas (gas) — Move to user → Home/Light Industry; → Manufacturing

Coal (solid) — Conv. to e^- → Home/Light Industry; → Manufacturing

Currently end use well-matched to physical properties of resources

Ref: Nate Lewis, 2005

Matching Supply and Demand

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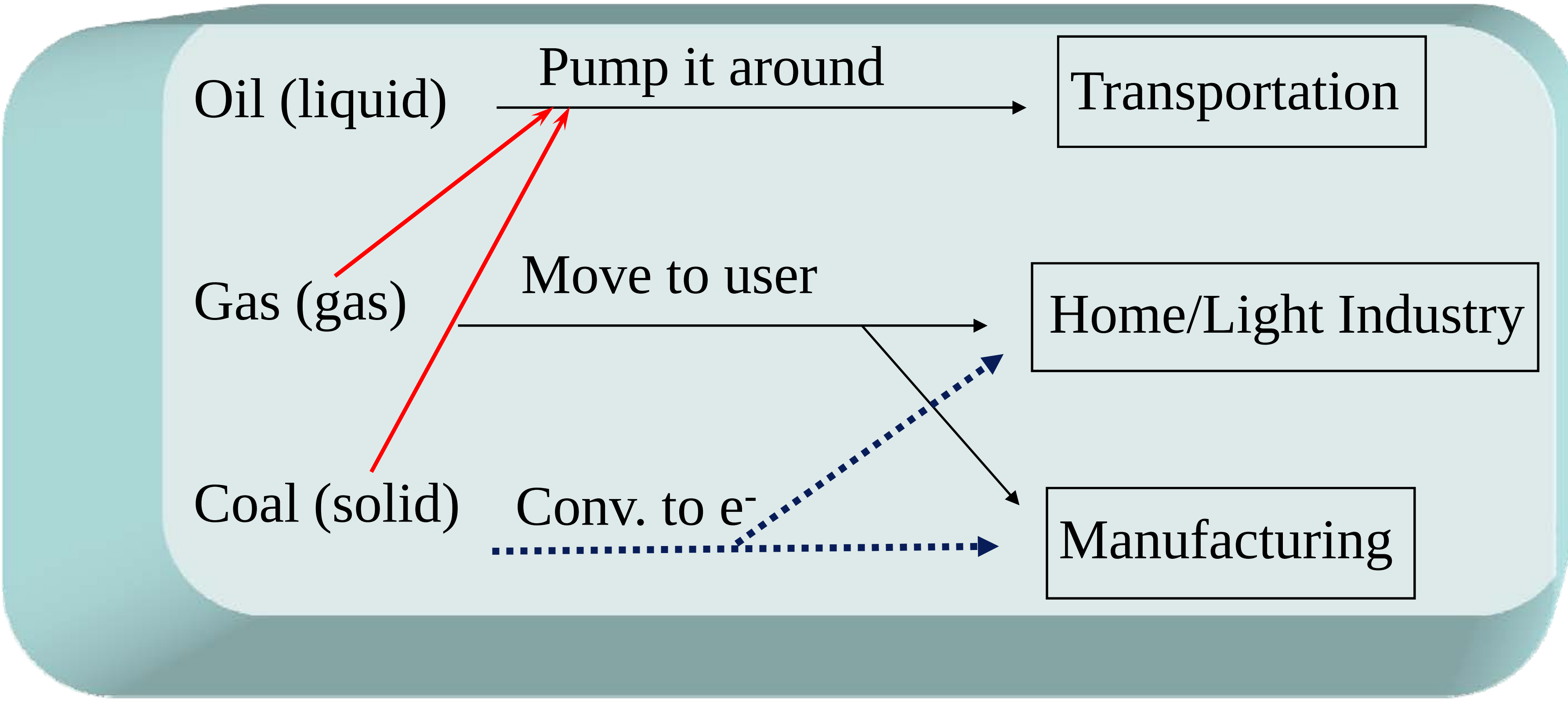

If deplete oil (or national security issue for oil), then liquefy gas,coal

Ref: Nate Lewis, 2005

Matching Supply and Demand

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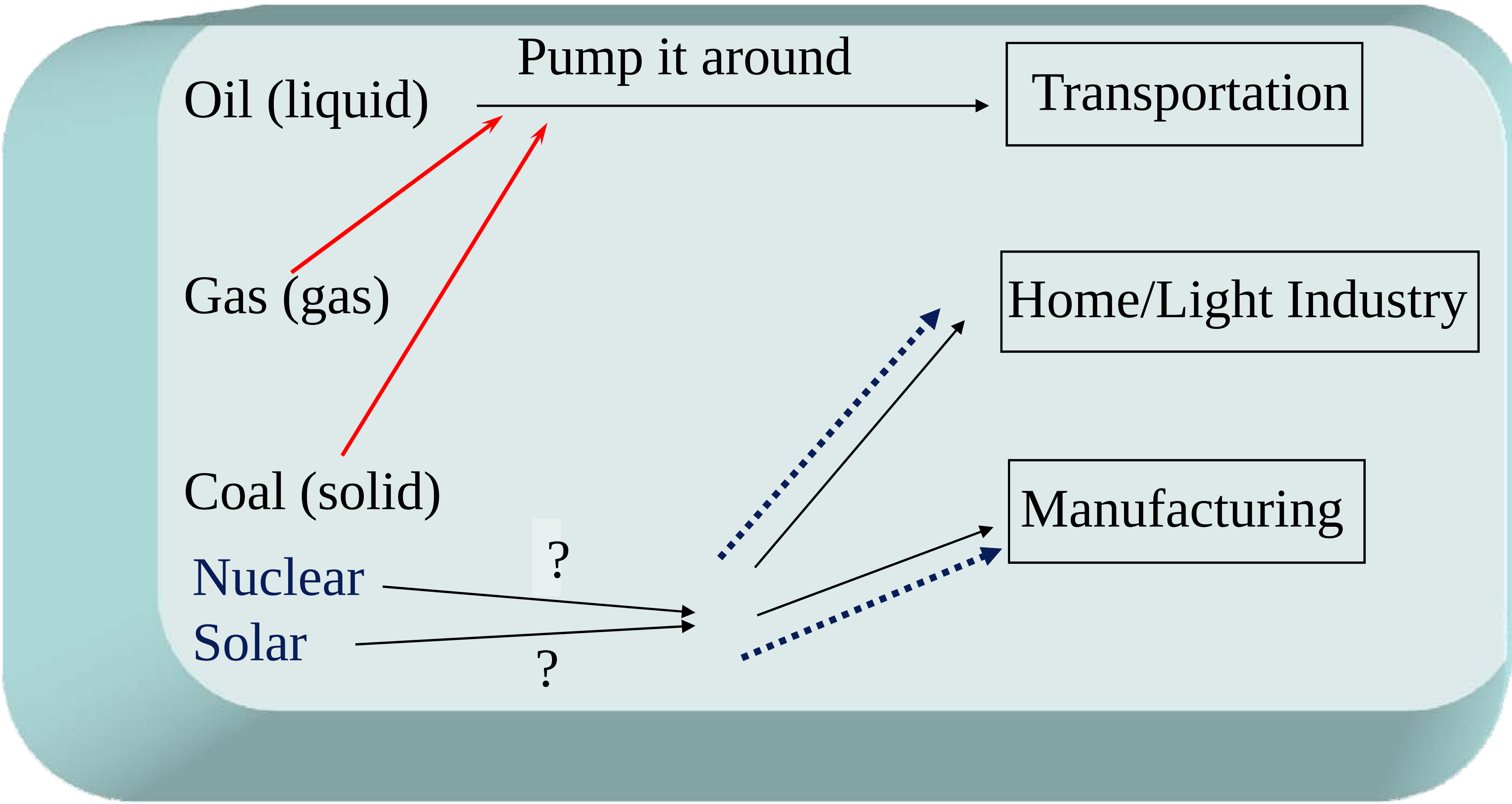

If carbon constraint to 550 ppm *and* sequestration does *not* work

Ref: Nate Lewis, 2005

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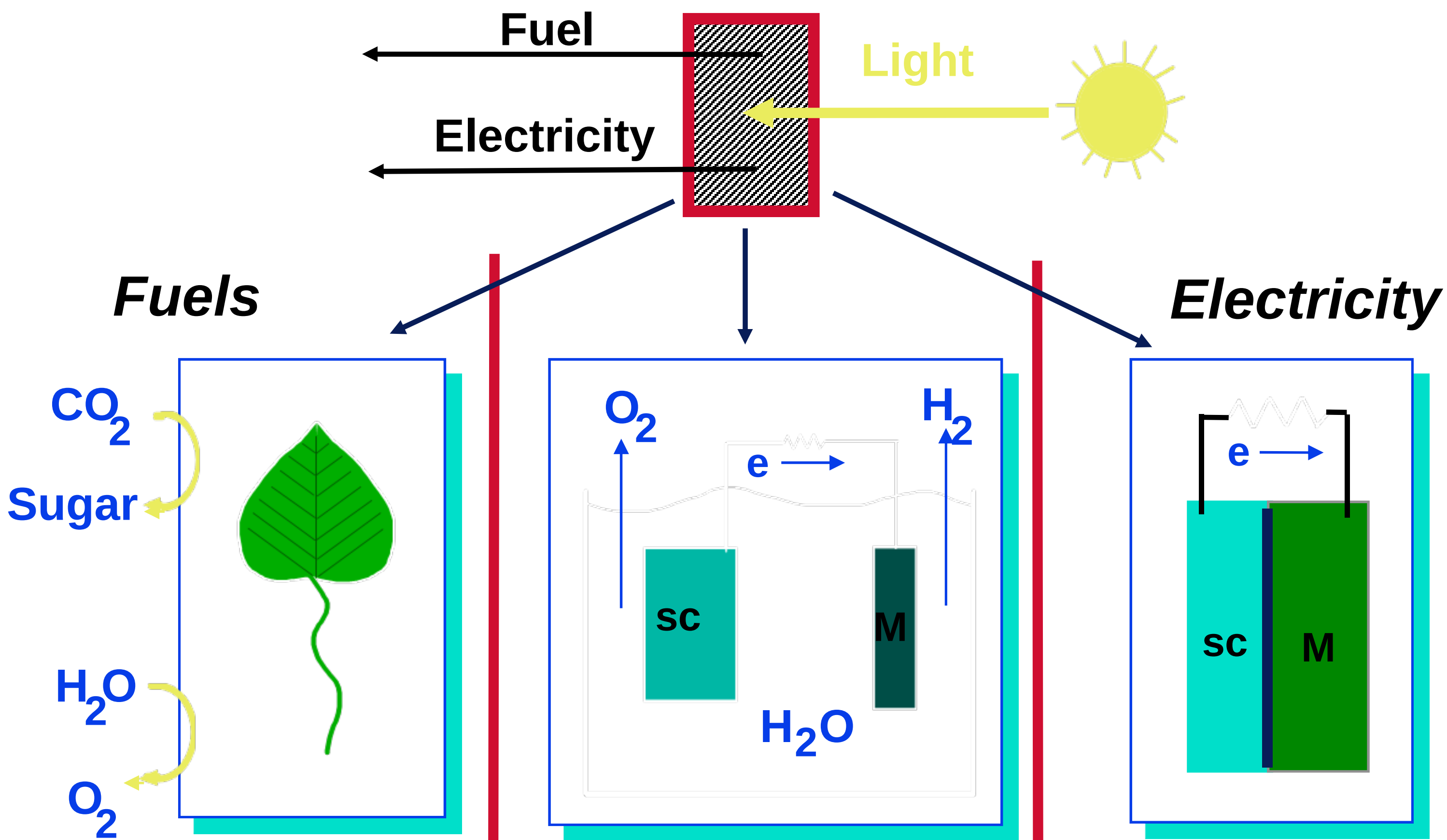
Energy Conversion Strategies



Photosynthesis

Semiconductor/Liquid Junctions

Photovoltaics

Integrated Carbon-Free System

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- Planar/Concentrator PV
- Solar Dynamic (Stirling)
- Wind
- Hydro
- Nuclear

Plus water for electrolysis

- Electrolyzer
- H_2 for chem.

- H_2 Storage (?)
- Hydrides,
- Chemical,
- Cryogenic
- NH_3
- Other…

- Conversion:
- Fuel cell
- Catalytic reforming for:
- Combustion
- (IC and EC engines)

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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?