



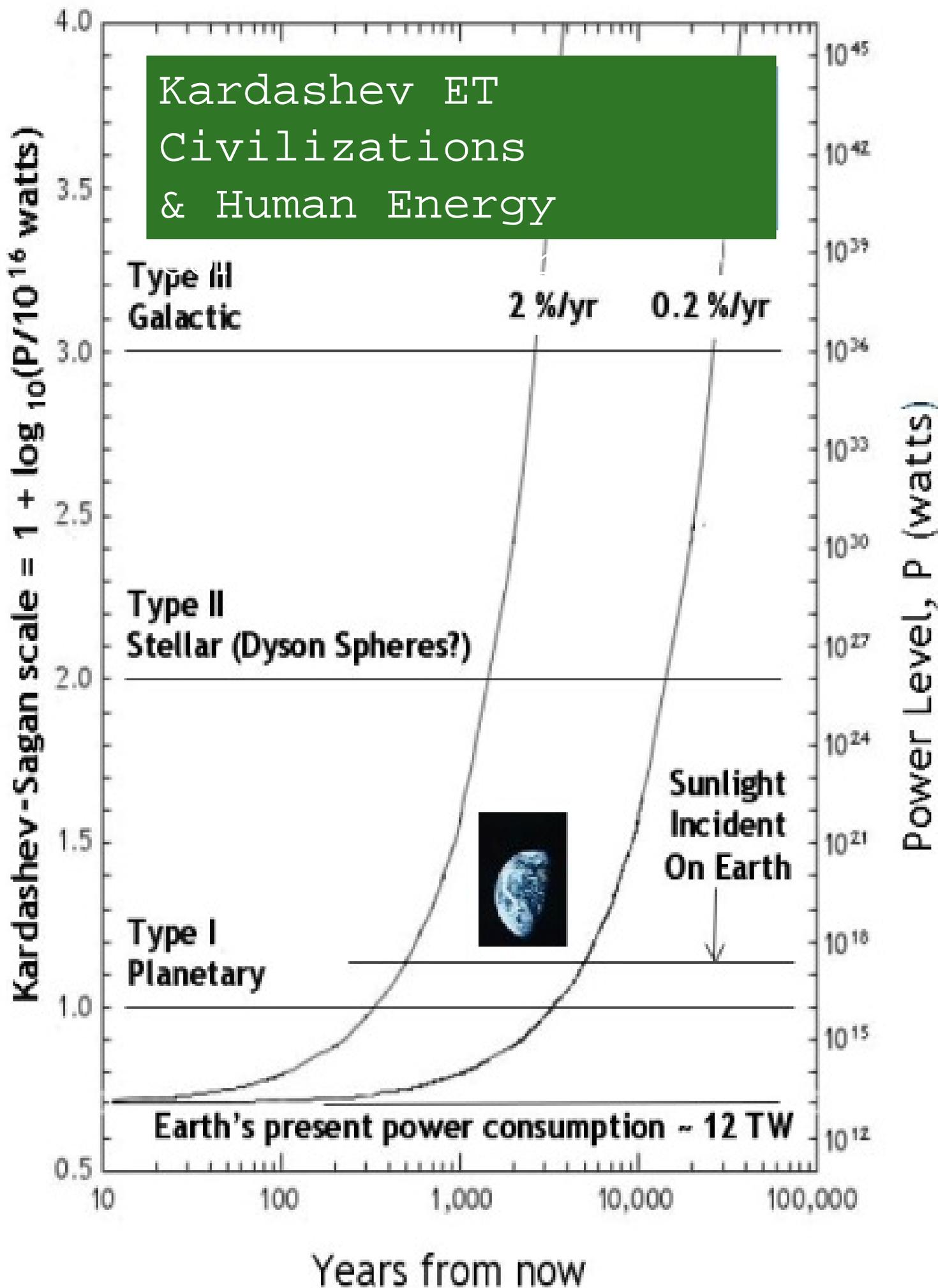
# An Energy Revolution for a Greenhouse Planet

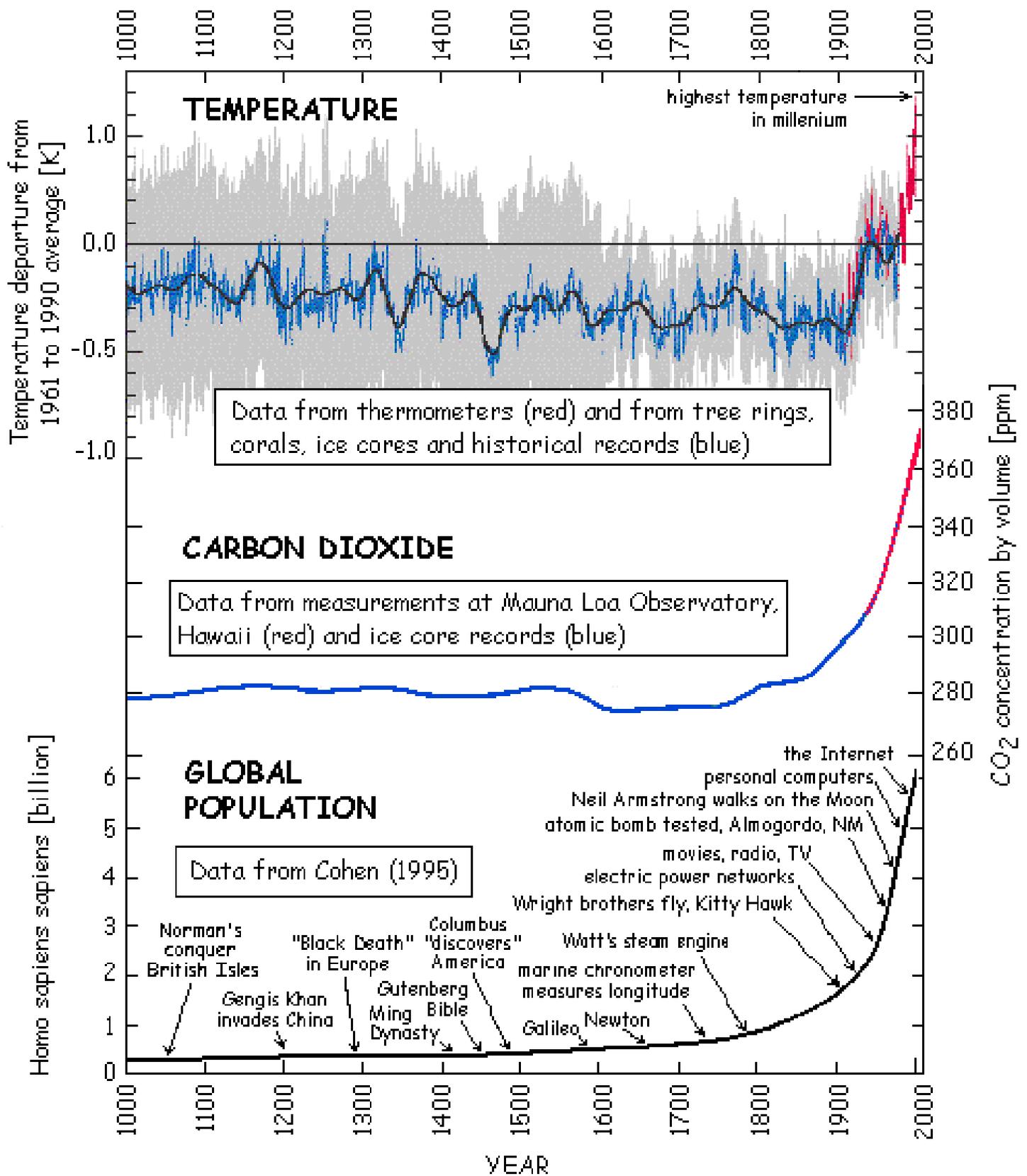
Global Research into Energy  
and Environment at NASA Ames  
Symposium

Oct. 19, 2007, 3:00-4:00 PM,  
Building 201 Auditorium,  
NASA Ames Research Center,  
Moffett Field, CA

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New York, NY 10003

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Crossing the Greenhouse Threshold: Fossil Fuel CO<sub>2</sub> & Human Population Growth Trigger Recent Explosive Emergence of Global Warming

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

Is *Homo sap.* High-Tech  
Civilization Viable on  
Earth Long Term?

- Many Calls for Action
- But What to Do?

## Strange Greenfellows

From longtime global warming warriors to recent converts, the over-50 figures calling for action include an ideologically diverse mix, to say the least.



**1.** Senator John McCain (R-AZ) **2.** Ellen Mosley-Thompson, of Ohio State University (OSU), has studied climate change for over 30 years **3.** Bonnie Raitt **4.** Pat Robertson **5.** Warren Washington, head of climate-change

research at the National Center for Atmospheric Research **6.** Governor Arnold Schwarzenegger (R-CA) **7.** Martin I. Hoffert, an NYU professor and energy-research proponent **8.** Senator Barbara Boxer (D-CA) **9.** Senator

Joe Lieberman (ID-CT) **10.** One-time skeptic Rupert Murdoch **11.** Tony Blair **12.** Sheila Watt-Cloutier, an Inuit leader and Nobel Peace Prize nominee **13.** Sir Richard Branson **14.** Lonnie Thompson, a prominent

OSU climate researcher (and Mosley-Thompson's husband; see 2) **15.** Al Gore **16.** Wangari Muta Maathai, Kenyan founder of the Green Belt Movement **17.** Susan Solomon; she pulled together the Intergovernmental Panel

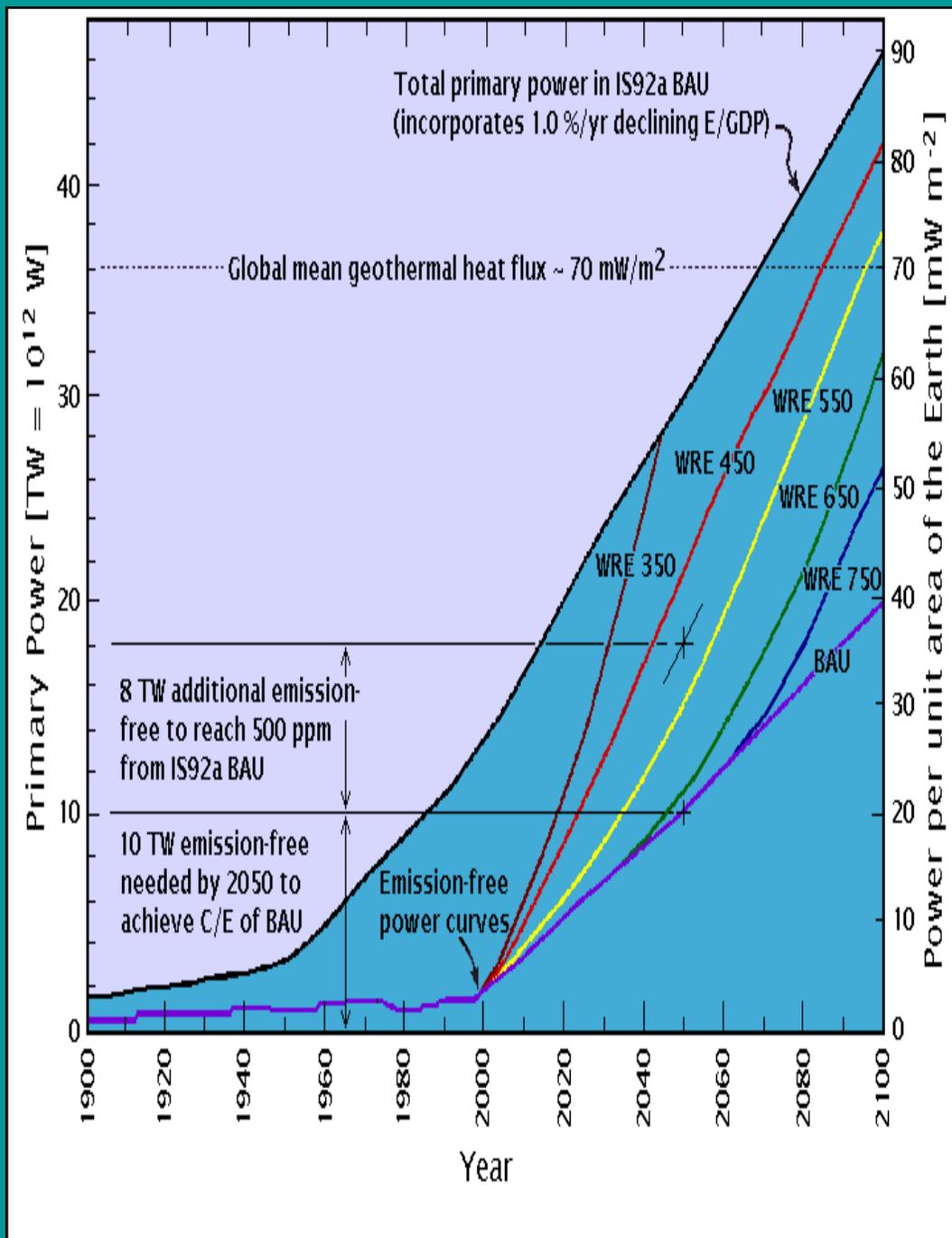
on Climate Change (IPCC) report concluding that humans are the main force behind global warming **18.** Rajendra K. Pachauri, chairman of the IPCC **19.** Newt Gingrich **20.** Robert F. Kennedy Jr. **21.** Ed Begley Jr.

## • Climate Bills in Congress

Provisions	Sponsors				
	Bingaman-Specter	Lieberman-McCain	Sanders-Boxer	Feinstein*	Kerry-Snowe
Emission target by 2050	60% below 2006 levels — provided other countries play ball	60% below 1990 levels	80% below 1990 levels	Cut expected levels for 2020 by 25%; 1.5% annual reductions thereafter	65% of 2000 levels
Carbon allowance	53% to industry; 24% for auction; 9% to states; 14% to others	Allowances distributed across sectors and to a new 'Climate Change Credit Corporation'	Awarded to those most affected by transition to a carbon-free economy	Allowances based on means of electricity generation	To be determined by the president
Technology support	Creates fund for research into low-carbon technologies and vehicles. Supports carbon capture and storage	Climate Technology Finance Board backs public-private research partnerships. Climate Change Credit Corporation supports low-carbon technologies	Grants for carbon capture and storage projects. Recommends boosting R&D for low-carbon technologies by 100% a year for a decade	Climate Action Trust Fund established to commercialize new low-carbon technologies	Recommends boosting R&D by 100% a year for a decade. Creates programme to assist with adaptation to climate variation

\*Applies to electricity sector only  
Source: US Senate

**THE REAL PROBLEM:** To maintain 2-3%/yr GDP growth in this century, some combination of new carbon-emission-free primary power sources (100-300% present fossil fuel ones by 2050) & efficiency-improving technologies will be needed, to also keep global warming < 2 degrees Celsius\* ( $\text{CO}_2 < 500 \text{ ppm}$ ).



\*2 deg C is a nominal global warming target proposed by Tony Blair above which humans "dangerously interfere with climate system" -- interference that the UN Climate Treaty and the Kyoto Protocol process is intended to avoid.

# THE OIL/TRANSPORTATION/"NATIONAL SECURITY" CRISIS: The geochemistry of oil formed over hundreds of millions of years profoundly affects today's geopolitics

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are needed to see this picture.

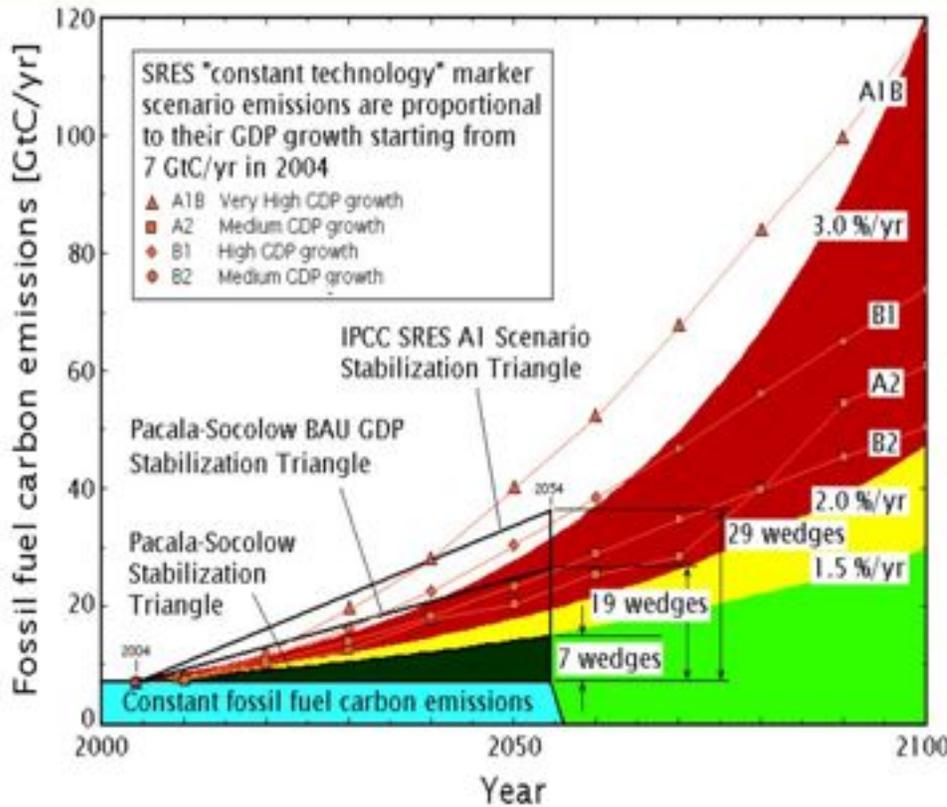
The  
overwhelming  
majority of  
global crude oil  
reserves reside  
in 6 Islamic  
nations of the  
Persian Gulf  
(data from V.  
Smil, *Energies*  
(MIT Press,  
1999), p. 139.

# WHEN, GLOBALLY, WILL WE BE “OUT OF GAS?”

❖ In about 100 years; but Hubbert curves for “cheap oil” production rates estimated by various sources all peak between “now” & mid-century (likewise for cheap natural gas).

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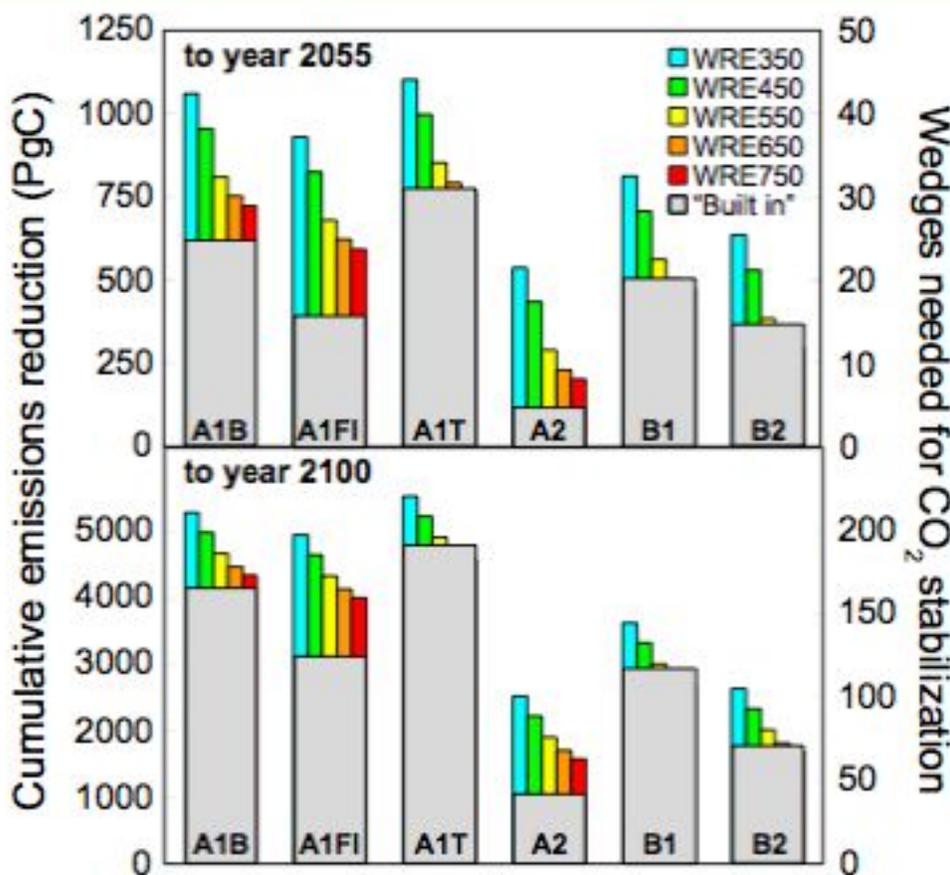
# How Many Wedges?



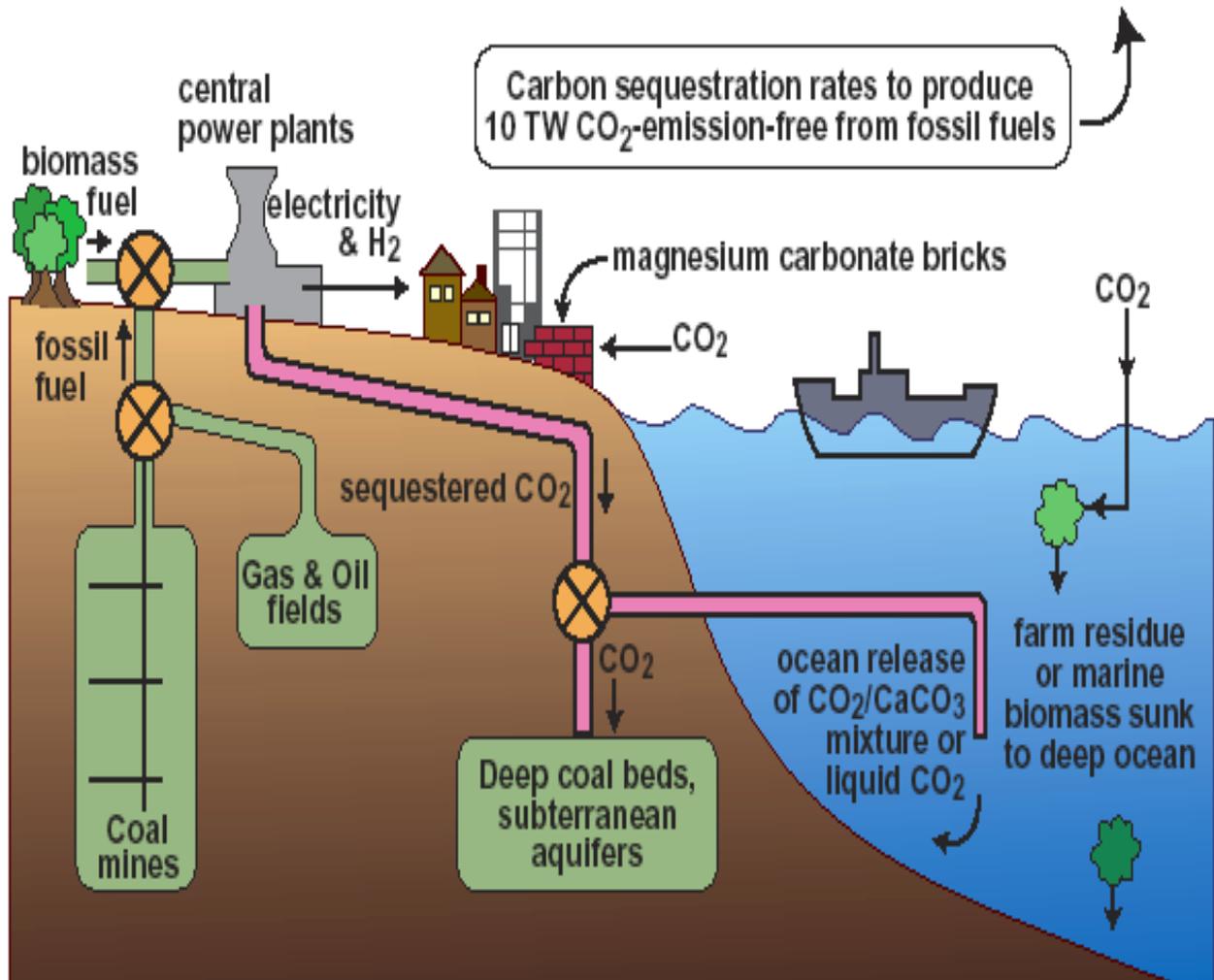
**If:** 1 "wedge" = 25 billion tonnes less carbon emitted over 50 years from carbon-neutral or energy efficient technology,

**Then:** 19 wedges are needed for Pacala-Socolow Scenario: 12 "virtual" wedges to get from 3%/yr GDP growth to 1.5%/yr emission growth + 7 to get from 1.5%/yr to zero emission growth for 50 yr.

**Even More Important:** The wedge count becomes huge in the 2nd half of the 21st century. We need to target this now. (Tom Wigley calculation)

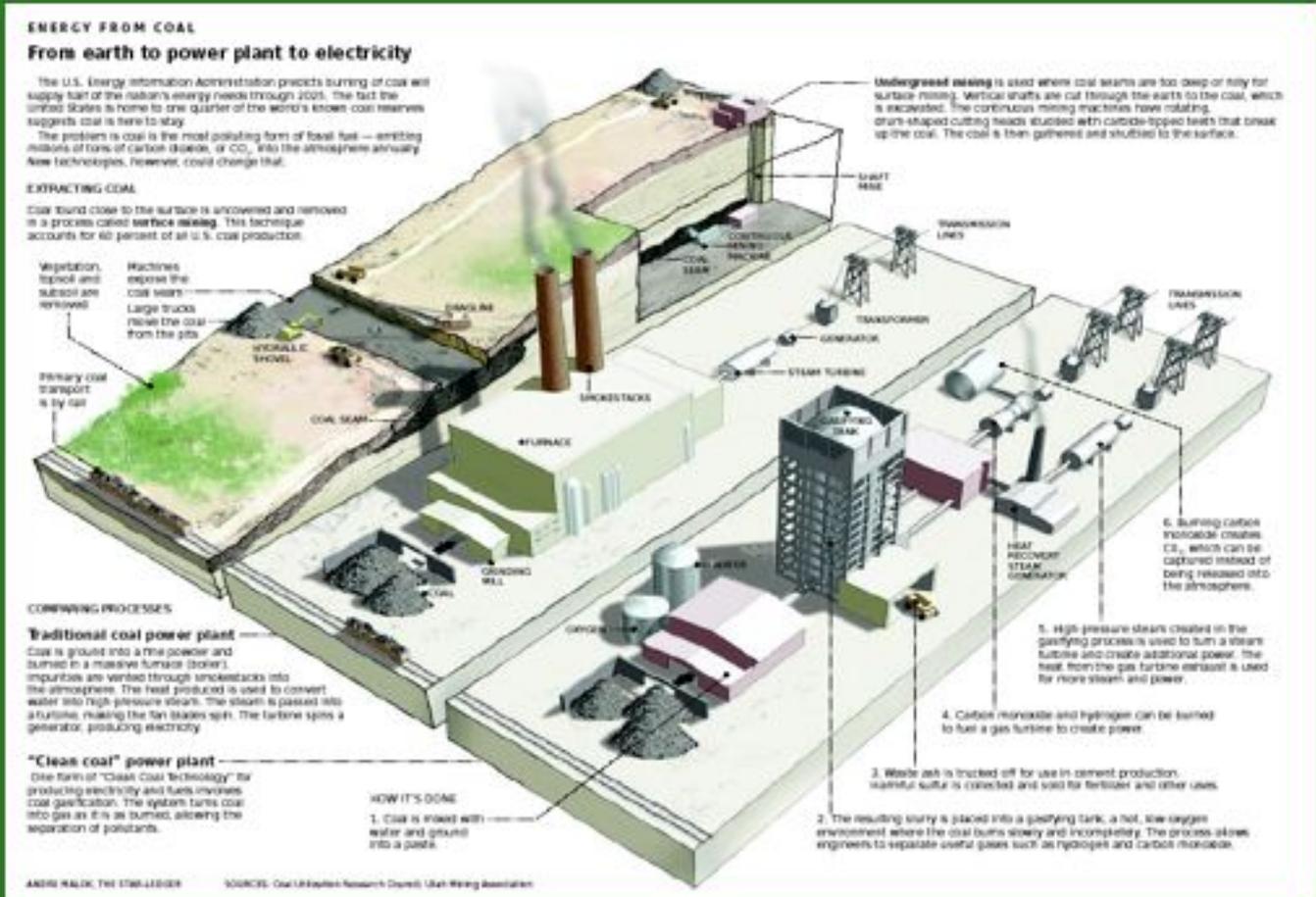


Fossil fuel	Energy content [TW-yr]	Carbon content [GtC]	$(E_{fuel}/C)$ [TW-yr/GtC]	$(E/C)$ [TW-yr/GtC]	Sequestration rate [GtC/yr]
Gas	1200	570	2.1	1.9 - 1.6	5 - 6
Oil	1200	750	1.6	1.4 - 1.2	7 - 8
Coal	4800	3690	1.3	1.2 - 1.0	9 - 10

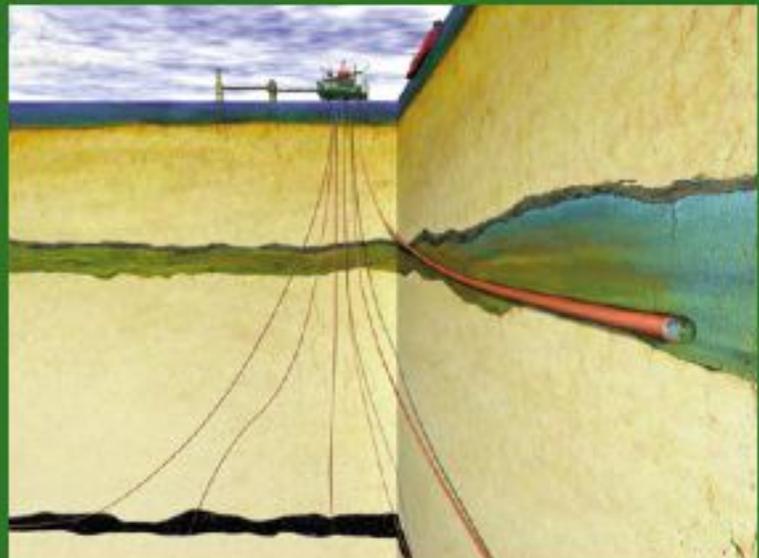


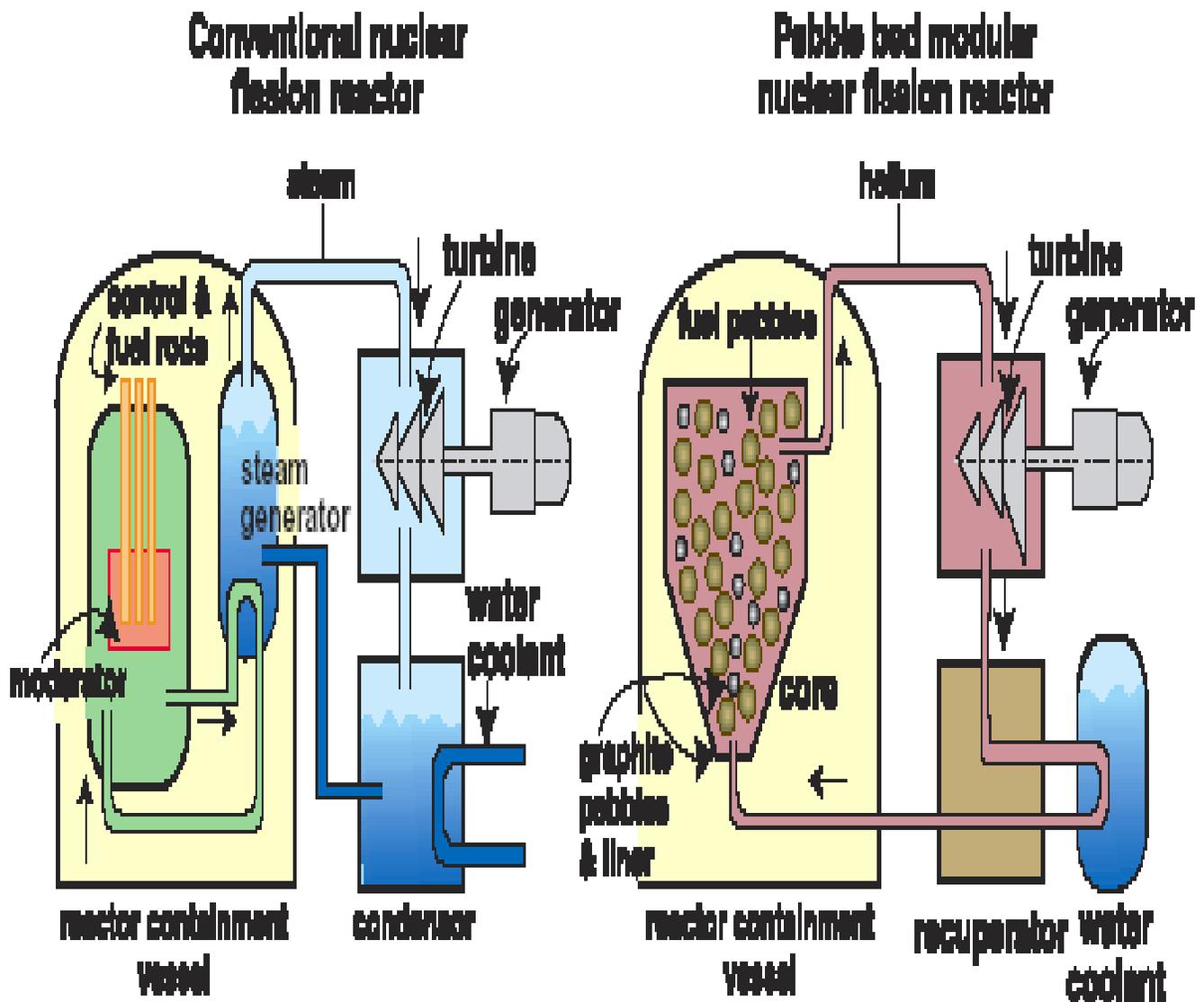
Fossil fuel CO<sub>2</sub> sequestration concepts & burial rates needed, to generate 10 TW carbon-emission-free

- "FutureGen" coal-gasifier driving combined cycle (steam & gas turbines) for electricity generation and fuel cell grade H<sub>2</sub> with carbon capture & storage



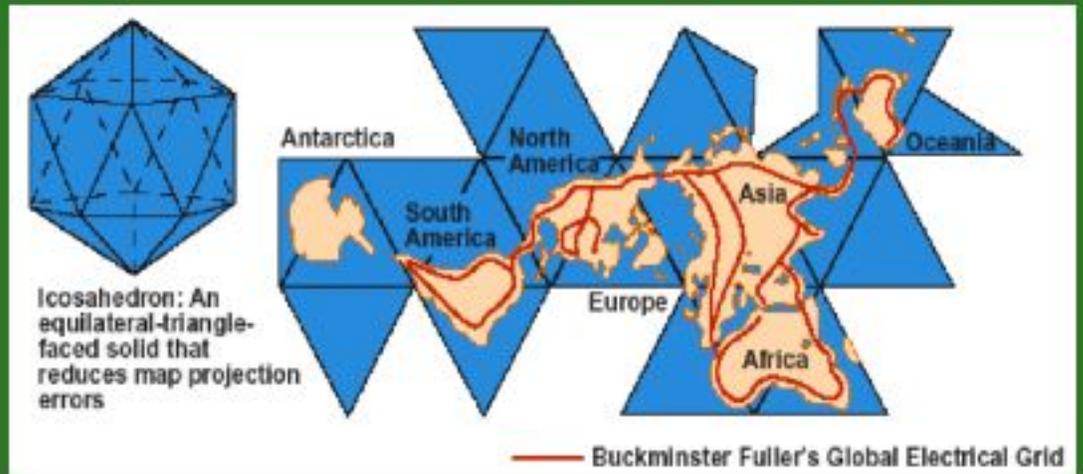
- CO<sub>2</sub> storage demo under Norwegian Statoil's Sleipner North Sea field





(LEFT) The conventional light water reactor (LWR) employs water as both coolant and working fluid. (RIGHT) The helium-cooled, graphite-moderated, pebble bed, modular nuclear fission reactor is theoretically immune to loss of coolant (TMI) and criticality (Chernobyl) accidents.

# • Global Superconducting electric power grid



Features of MHR: Ceramic TRISO fuel, Solid Graphite Moderator, Neutron-Transparent Helium Coolant

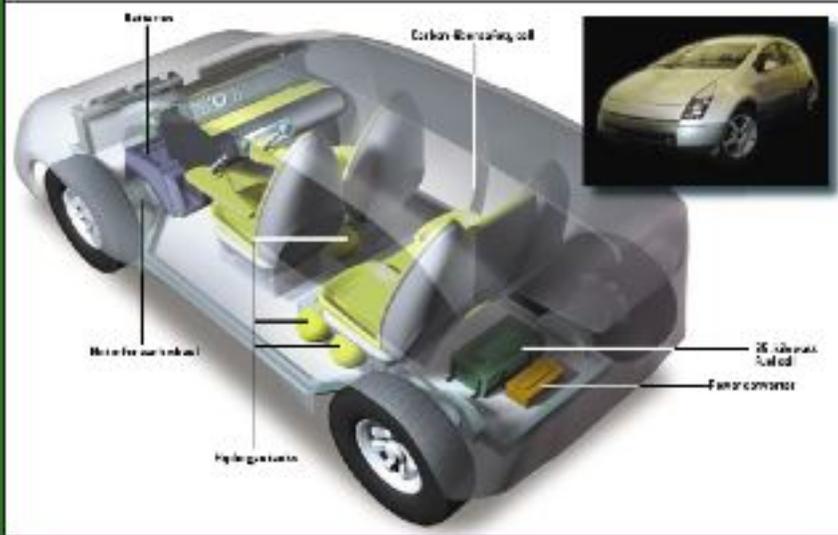


## • Safer, gas-cooled, graphite-moderated reactors making electricity & hydrogen could burn U-233 bred from thorium

## • Ultralight, low-drag plug-in hybrid cars & trucks rechargeable with wind and solar electricity

### ALEAN, MEAN DRIVING MAC INC

Ultralight cars can be fast, strong, safe and efficient. A concept five-seater midsize SUV called the Revolution, designed to weigh only 1000 kilograms—less than half the weight of conventional SUVs—gets its carbon-fiber body and fuel cell from a plug-in hybrid from England and will be on the road in five vehicles. A 2.0-liter fuel cell car will be used for 500 kilometers a day and will be recharged in 15 minutes. And the Revolution could be used for up to 100 kilometers per hour in E.U. roads.

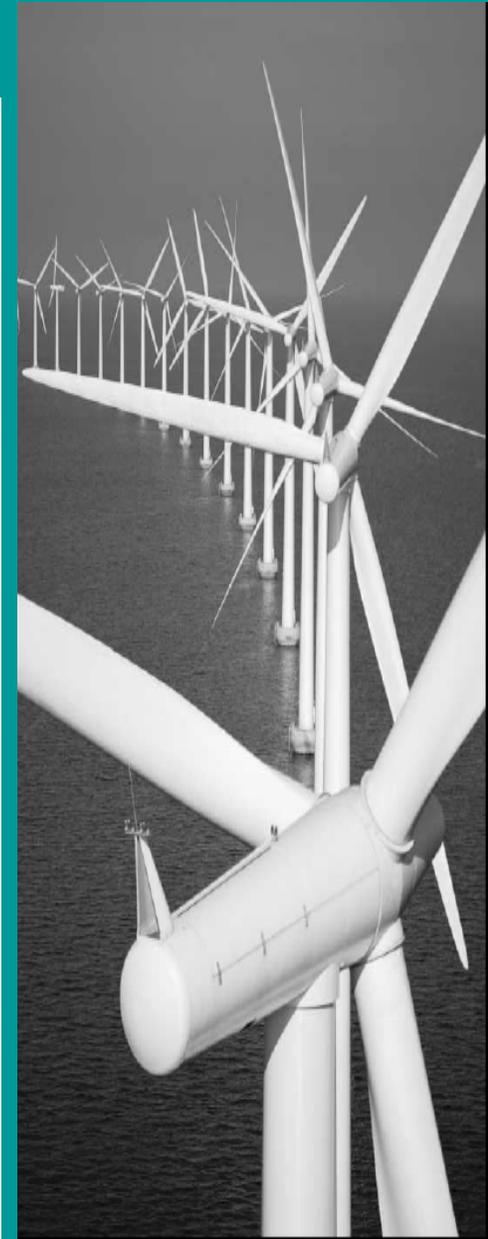
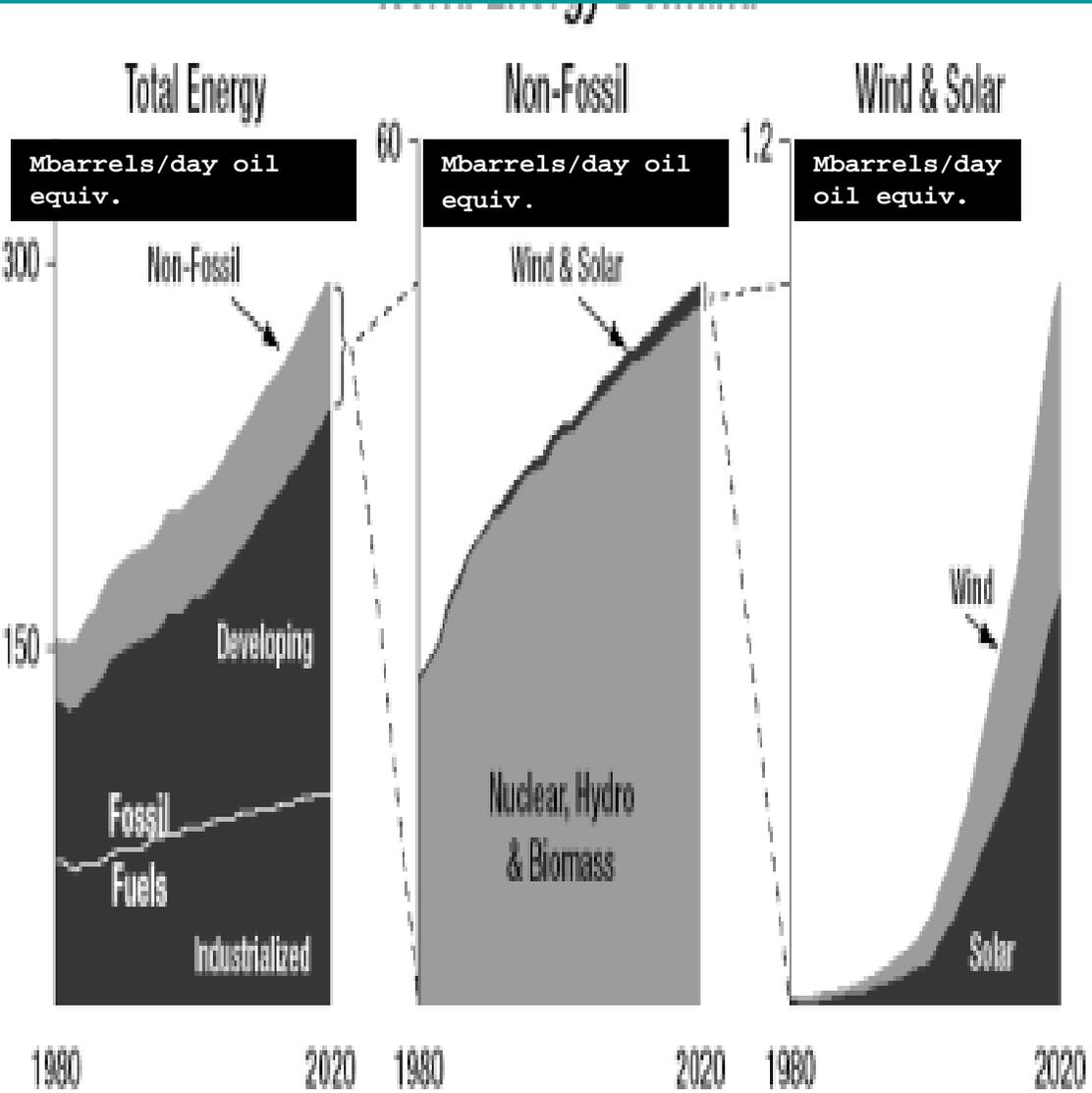


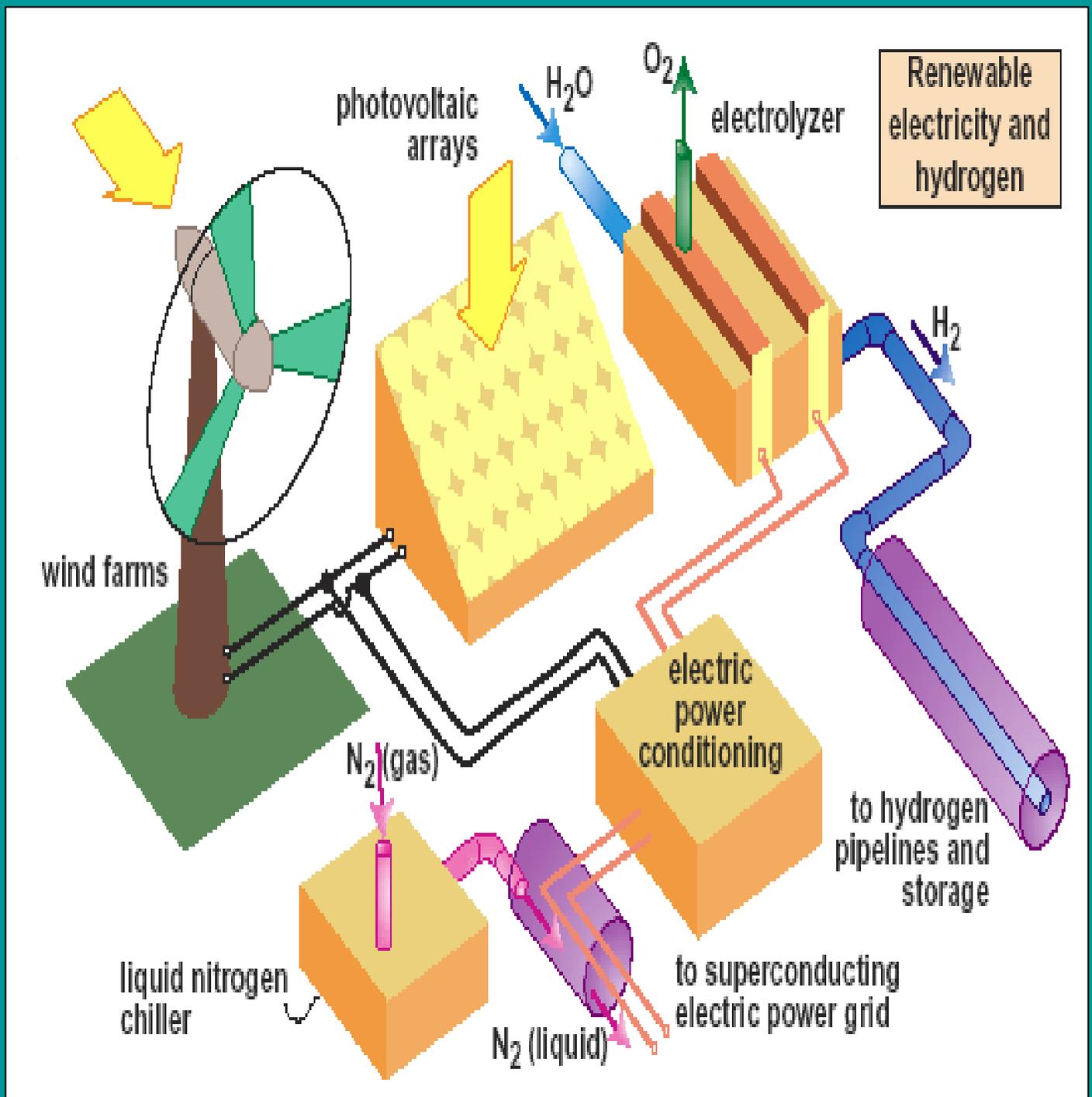
# POLICY IMPLICATION FOR RENEWABLE ENERGY:

Some critics claim we will never power civilization with renewable energy.

Fact: Wind & solar are fastest-growing primary power sources, but are unlikely to grow from present ~ 1% of supply to 10% by 2025 and >30% by 2050 without major incentives, R & D and demonstration of enabling technologies. There are no known show-stoppers

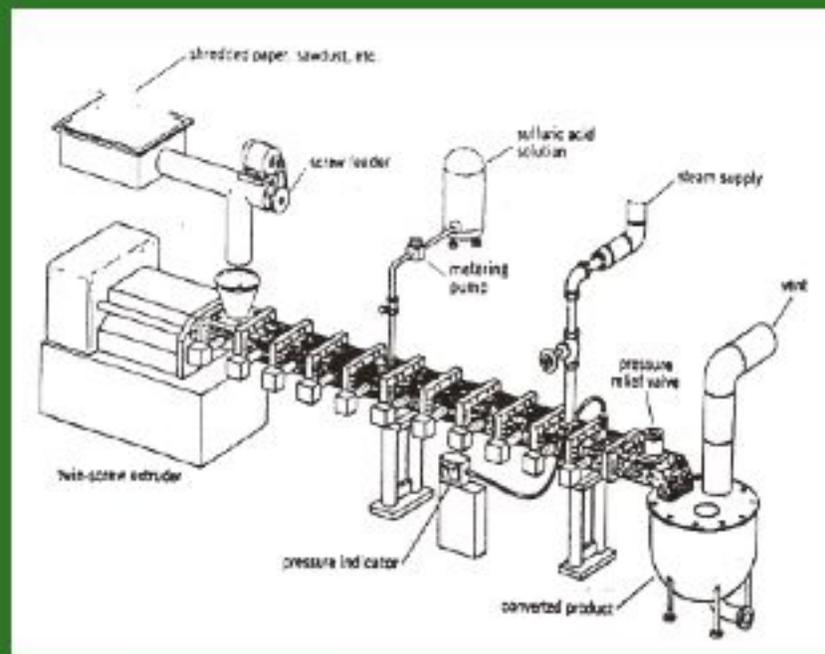
## Energy Demand 1980-2020 (BAU)





Mass-produced widely distributed PV arrays and wind turbines may eventually generate 10-30 TW emission-free

- Biofuels need large areas, energy inputs & cellulose converters for large-scale use. NYU acid hydrolysis technology (cellulose -> sugar -> ethanol) of '70s is shown



- Original Daniel Libeskind Freedom Tower design for WTC site shown had wind turbines inside open upper story tensioned lattices to provide 20% of the building's electricity

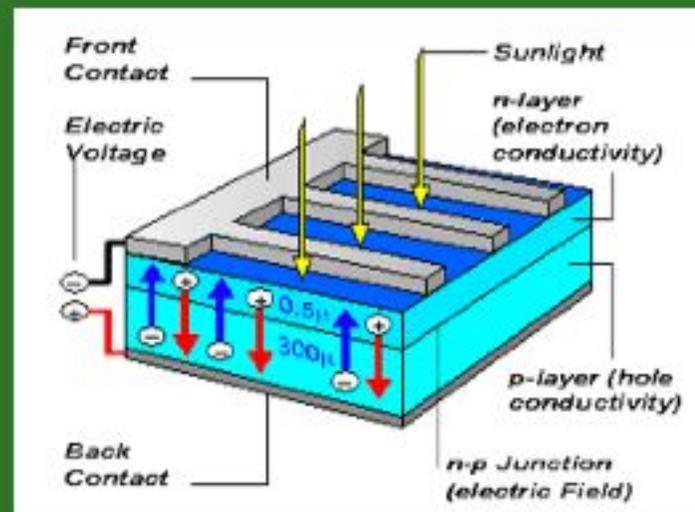
- Solar Hydrogen Home on LI by NY Institute of Technology & USMMA with PV electrolysis, H2 storage & fuel cell



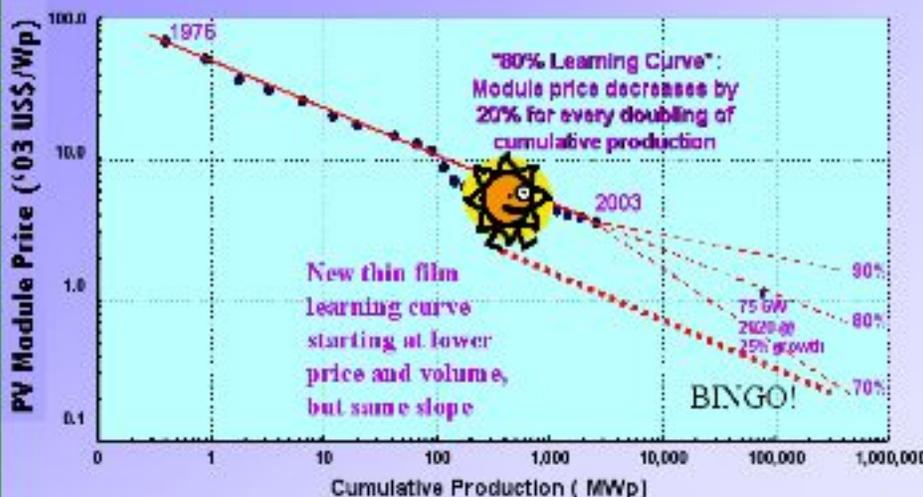


- High-altitude tethered autogiros could tap high kinetic energy in jet streams

- Photovoltaic (PV) cells convert photons more energetic than semiconductor band gaps to DC electricity. Dominant technology today is crystalline Si modules



PV Module Cost Versus Cumulative Production in peak megawatts: History & projected "Learning by Doing" & by accelerated R & D curve for thin films (from Ken Zweibel, NREL)



- Exotic thin films (GaAs, CuInSe<sub>2</sub>, CdTe, amorphous-Si) promise cost breakthroughs. An alternate approach is solar concentrators focused on small PV spots

# Power audits & carbon footprints

- Average amt. emitted per kilowatt-hr of electricity consumed in the US in the year 2000

= 1.340 lb CO<sub>2</sub>/kWe-hr

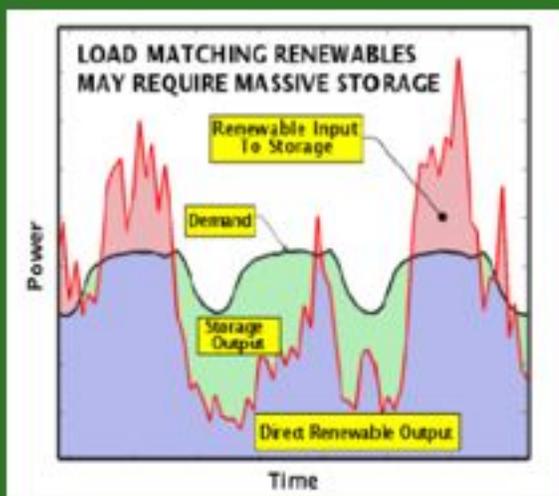
= 0.365 lb C/kWe-hr

= 0.166 kg C/kWe-hr



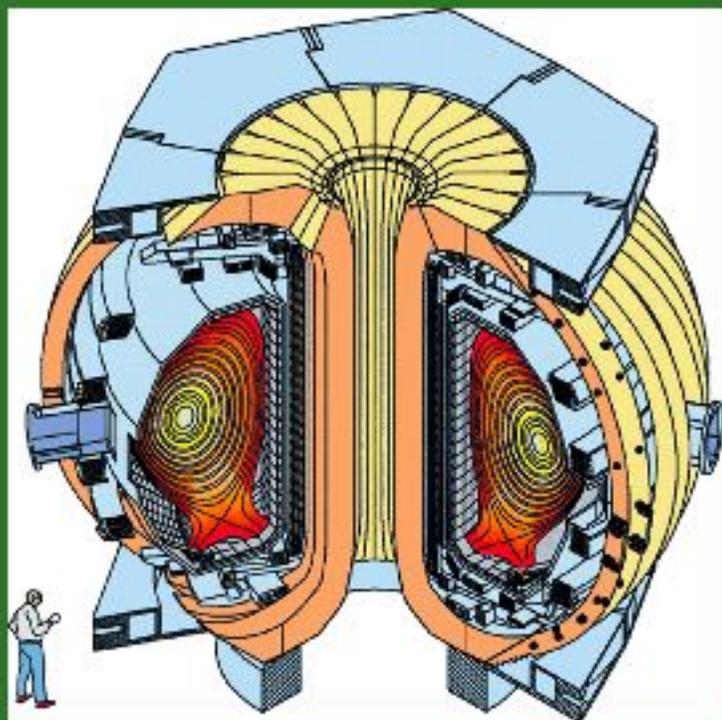
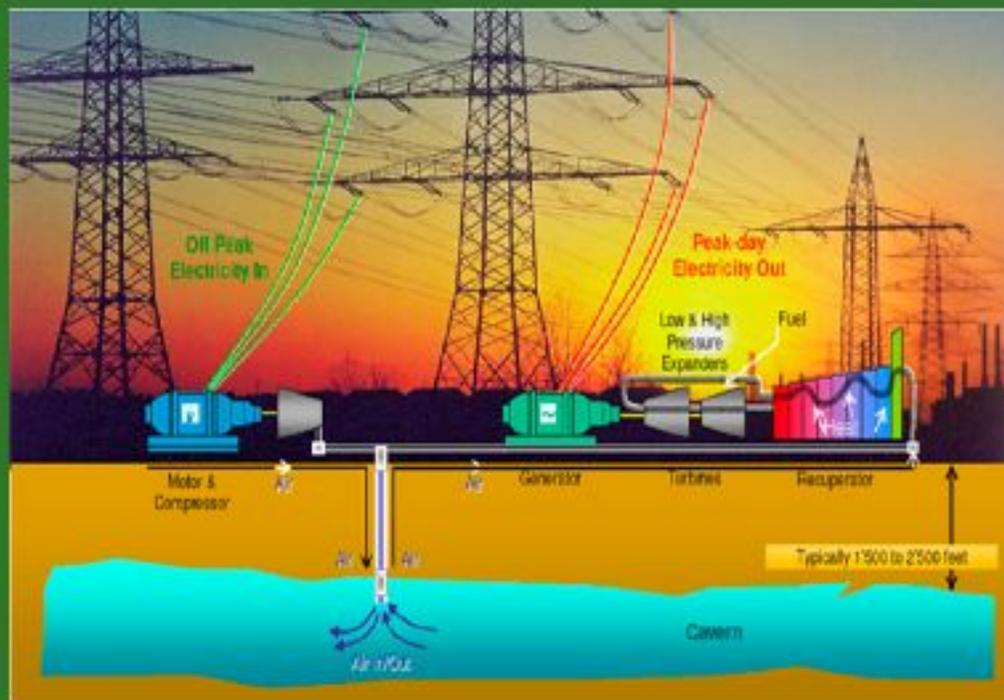
- Therefore, even a home with 0.8 kWe mean solar power input (at least 20 square meters of solar panels) using electricity at a mean rate of 7.8 kWe as in the example above would cause CO<sub>2</sub> to be emitted at the power plant at the rate 7.8 kWe x 0.166 kg C/kWe-hr = 1.3 kg/hr

- In one year (8760 hr) the carbon emitted would be 11,400 kg C, or 11.4 metric tonnes.



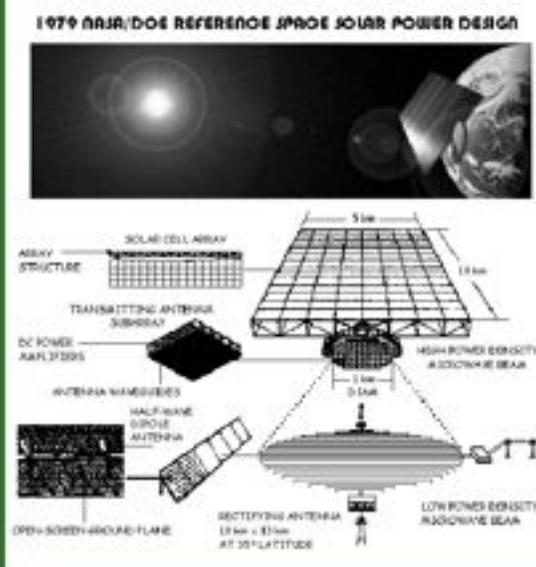
- Large-scale solar and wind will need energy storage, transmission and power management technologies to match supply & demand

- Compressed air energy storage (CAES) is one promising approach for the US where pumped hydro is limited



- Pure fusion is the Holy Grail (the ITER tokamak is shown). But early implementation of fusion neutrons to breed fissionable U-233 from thorium in burner-breeders should perhaps come first

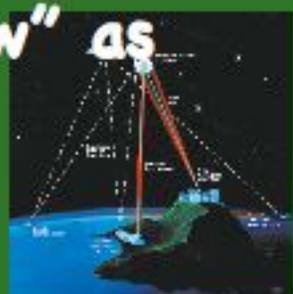
• Space solar power (SSP) Solar power continuously available in GEO 5-10 times surface intensity is beamed to Earth for base load. The NASA-DoE design of the 70s employing microwave beamers is shown



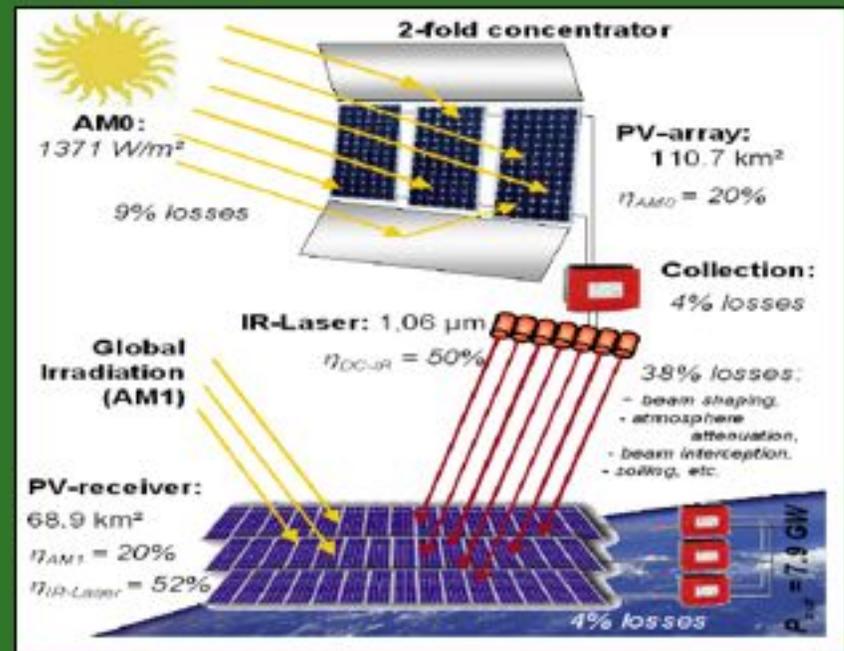
LAUNCH COST EVOLUTION: \$20,000/kg -> \$2/kg  
 (adapted from I. Bekey, *Advanced Space System Concepts and Technologies 2010-2030*, Aerospace Press, El Segundo, CA, 2004, p. 54)

Impractical and not fully reusable	Not reusable	Partly reusable	Fully reusable off-board energy	Fully reusable energy reusable
Rocket	Rocket	Rocket	jet + rocket	space structure
Cost: \$20,000/kg	Cost: 40,000/kg	Cost: \$200/kg	Cost: \$20/kg	Cost: \$2/kg
10-20 yrs	20-30 yrs	20-40 yrs	40-50 yrs	

• Launch costs could potentially drop from the present Shuttle \$20,000/kg to \$2/kg, comparable to "Moore's Law" as shown



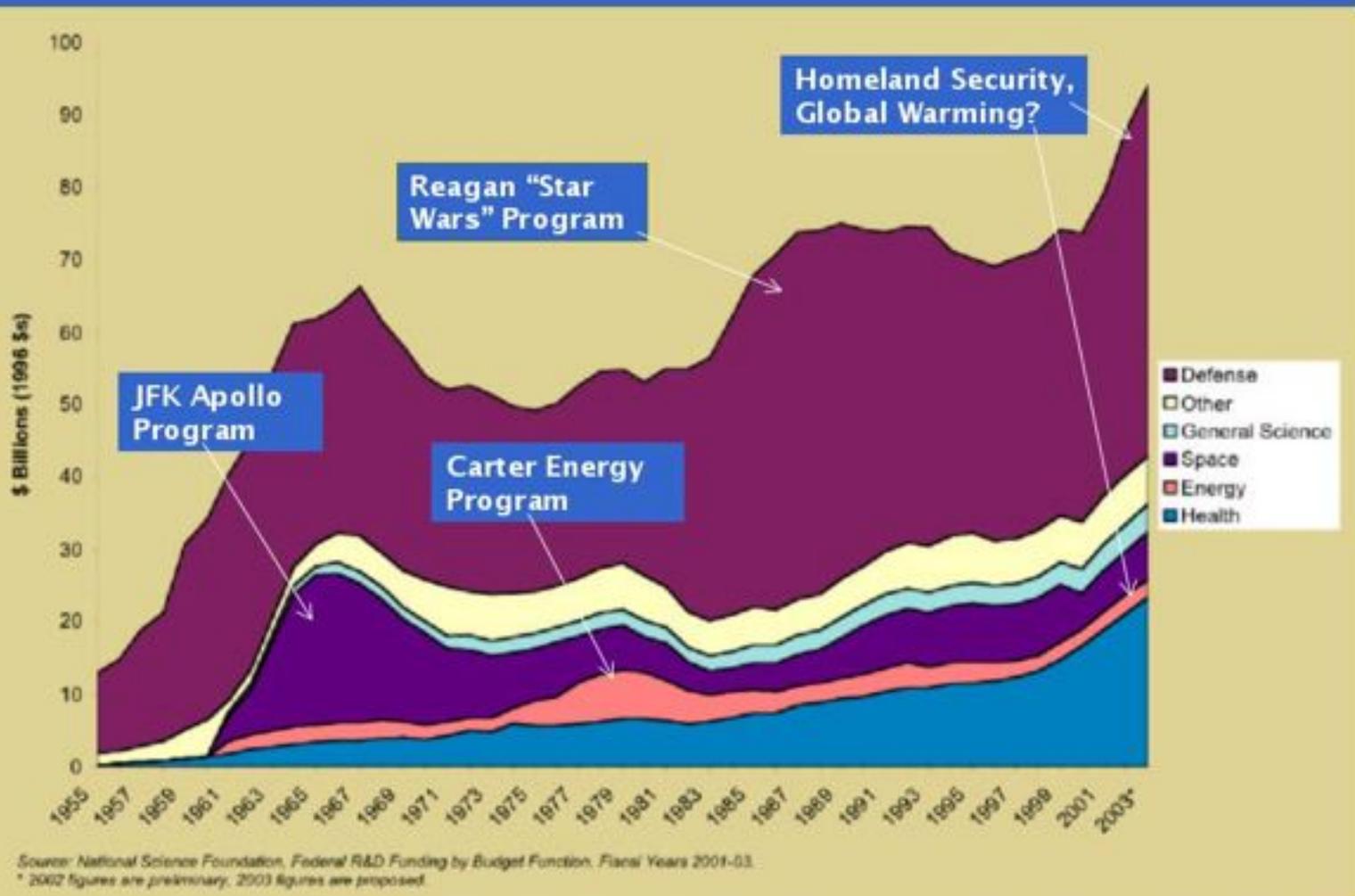
• Relay mirror laser demo of '90s ---->



• Laser diode SSP beaming to PV modules in Sahara could supply load curve of Europe according to recent study

- Is solving the climate/energy problem limited by money?
- Or by failure of imagination?

## HISTORY OF US FEDERAL GOVERNMENT R & D

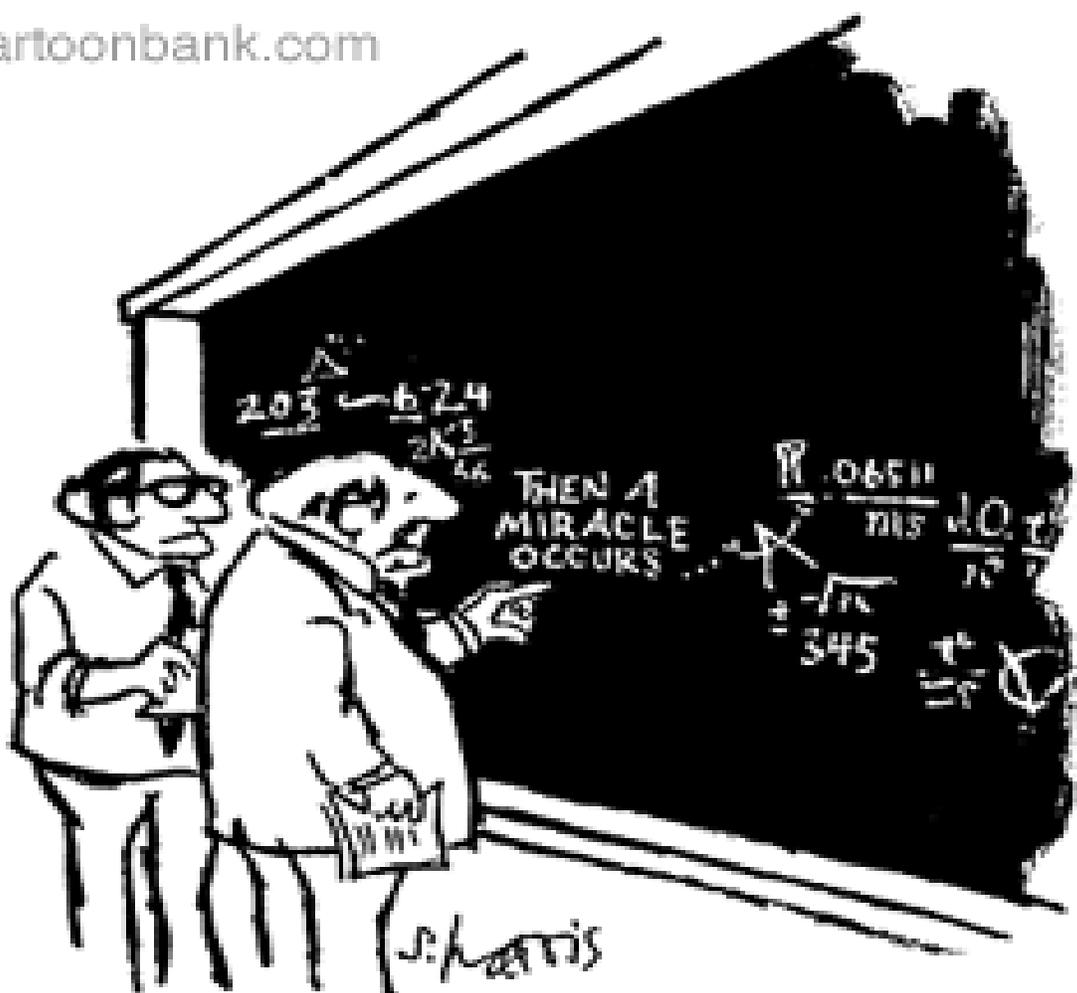


- We can well afford "Apollo Programs" in sustainable alternative energy research, development, demonstration & global deployment
- What we can't afford is collapse of our high-tech civilization built on cheap energy

# Does Economics Trump Technology?

Or: Does Technology Create  
New Economic Realities?

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**"I think you should be more  
explicit here in step two."**