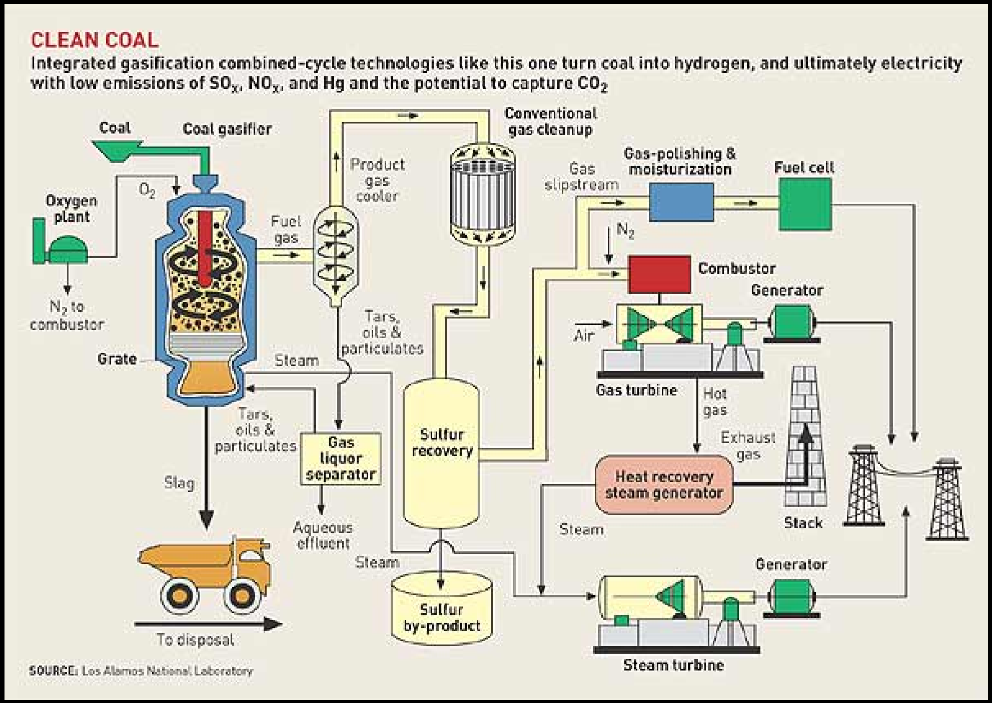
Integrated Gasification Combined Cycle (IGCC) Power Generation



Most pollutants are removed before combustion and are not created when fuel is burned. Sulfur is collected in a form that can be used. The CO_2 concentration will be 90% of the flue gases, thus making it easy to capture.

IGCC Gasifier: Carbon based raw material reacts with steam and oxygen at high temperature and pressure (chemically broken apart). Mostly hydrogen is produced in the gasifier, along with carbon monoxide, methane and carbon dioxide. The gasifier's high temperature vitrifies inorganic materials into a course, sand like material or slag.

The synthetic fuel (syngas) leaves the gasifier and is further cleaned of impurities. It is used in the system to run primary and secondary gas and steam turbines, similar to a natural gas combined cycle (NGCC) power generating system.

IGCC COSTS

Cost and Performance for 500 MW Power Plants

Pittsburgh #8 Bituminous Coal –for National Coal Council Report

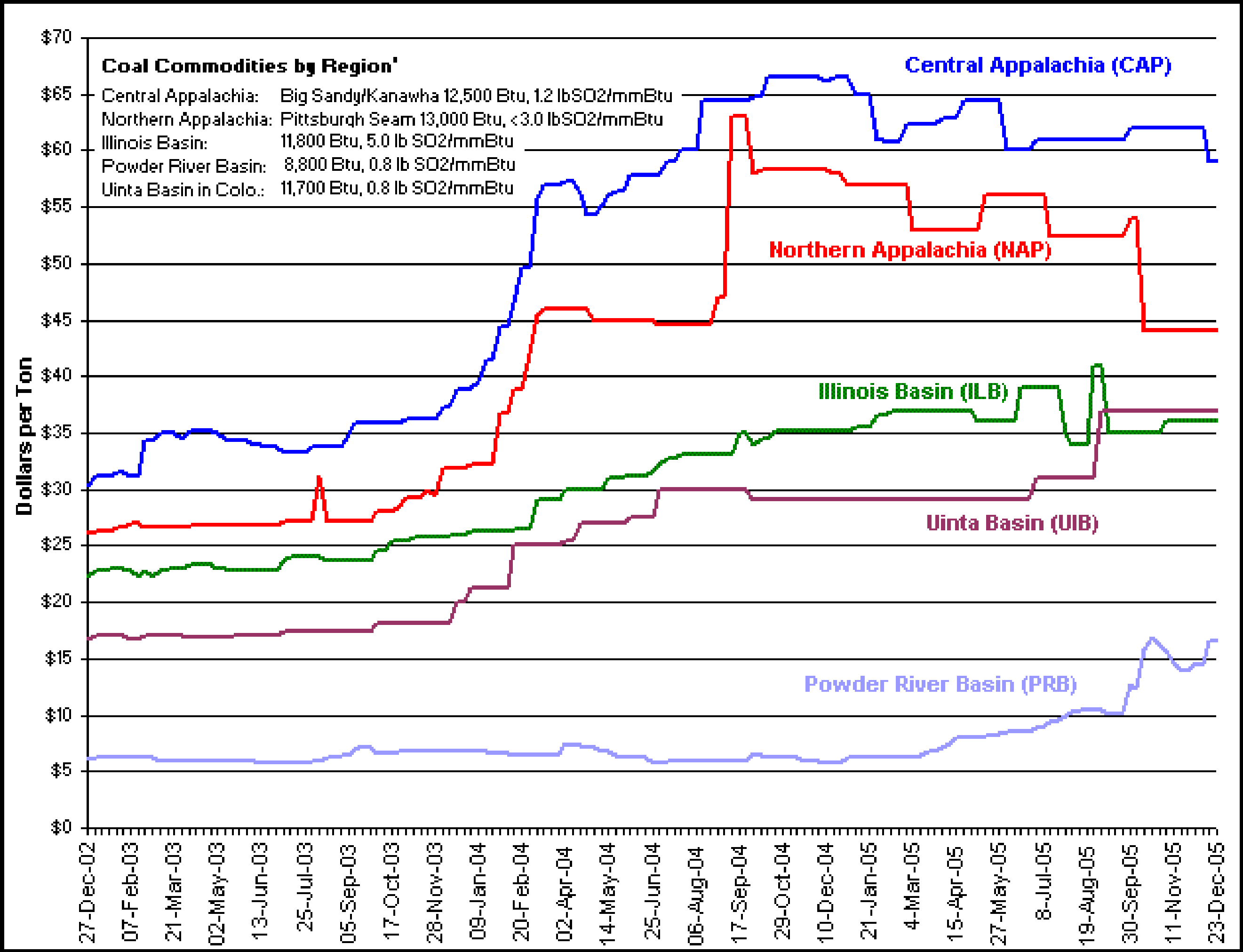
	PC Subcritical	PC Supercritical	IGCC (E-Gas) Spare/No Spare	NGCC
Total Plant Cost, $/kW	1,230	1,290	1,350/1,250	440
Total Capital Requirement, $/kW	1,430	1,490	1,610/1,490	475
Fixed O&M, $/kW-yr	40.5	41.1	56.1/52.0	5.1
Variable O&M, $/MWh	1.7	1.6	0.9	2.1
Ave. Heat Rate, Btu/kWh (HHV)	9,300	8,690	8,630	7,200
Capacity Factor, %	80	80	80	80/40
Levelized Fuel Cost, $/MBtu	1.50	1.50	1.50	5.00
Levelized COE, $/MWh (2003$)	46.5	46.6	49.9/47.2	47.3/56.5

EPRI

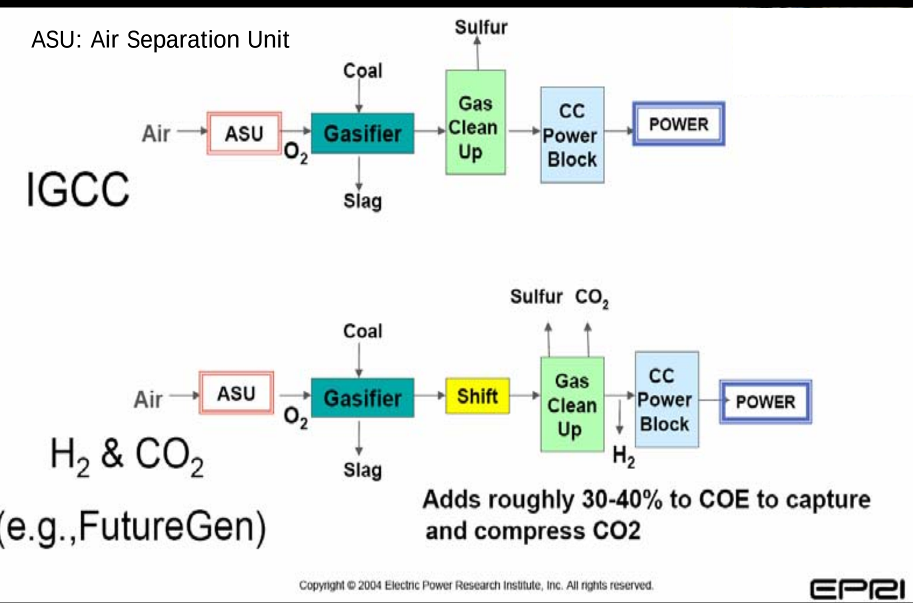
~ $10-
January
2006

Source: Stu Dalton, EPRI, 2004

Coal Price


Coal Commodities by Region'
Central Appalachia: Big Sandy/Kanawha 12,500 Btu, 1.2 lbSO2/mmBtu
Northern Appalachia: Pittsburgh Seam 13,000 Btu, <3.0 lbSO2/mmBtu
Illinois Basin: 11,800 Btu, 5.0 lb SO2/mmBtu
Powder River Basin: 8,800 Btu, 0.8 lb SO2/mmBtu
Uinta Basin in Colo.: 11,700 Btu, 0.8 lb SO2/mmBtu
Central Appalachia (CAP)
Northern Appalachia (NAP)
Illinois Basin (ILB)
Uinta Basin (UIB)
Powder River Basin (PRB)
Dollars per Ton
$70
$65
$60
$55
$50
$45
$40
$35
$30
$25
$20
$15
$10
$5
$0
27-Dec-02
07-Feb-03
21-Mar-03
02-May-03
13-Jun-03
25-Jul-03
05-Sep-03
17-Oct-03
28-Nov-03
09-Jan-04
20-Feb-04
02-Apr-04
14-May-04
25-Jun-04
06-Aug-04
17-Sep-04
29-Oct-04
10-Dec-04
21-Jan-05
4-Mar-05
15-Apr-05
27-May-05
8-Jul-05
19-Aug-05
30-Sep-05
11-Nov-05
23-Dec-05

Future Gen Plant: CO_2 Capture and Storage



Fuel Cost $/MBtu	Technology	COE $/MWh without Capture	COE $/MWh with Capture	COE $MWH with Capture and Sequestration	Avoided Cost $/Metric Ton of Carbon
3.50 NG	NGCC F 525 MW	36.5	59.0	61.1	267
5.00NG	NGCC 525 MW	47.3	72.8	74.9	300
1.50 Pitts #8	Texaco Quench IGCC F 520 MW	48.6	61.0	65.3	88
1.50 Pitts #8	USC PC 600 MW	45.0	75.4	79.8	174

Notes: Pittsburg #8 coal at $1.50MBtu delivered
Natural Gas at $3.50 and $5.00MBtu
Cost of CO_2 Transportation and Sequestration $5/metric ton of CO_2
Plant Size with CO_2 removal ~ 450MW
Capacity Factor 80% for all technologies

8 cents/kWh

Source: Stu Dalton, EPRI, 2004

IGCC Advantages

- IGCC may become the coal technology of choice with carbon constraints
  - Low emissions
  - High efficiency
  - CO_2 capture on Bituminous coal
- Key enabling technology for future coal-based power
- Ability to co-produce hydrogen adds potential for:
  - Clean transportation fuel
  - Significant reduction of green house gas emissions
- But questions remain – cost, reliability

EPRI

Source: Stu Dalton, EPRI, 2004

IGCC Environmental Attributes

- Sulfur is removed (98.5-99.99%) from syngas
- NOx emissions are controlled by firing temperature modulation in the gas turbine with SCR possible
- Particulates are removed from the syngas by filters and water wash prior to combustion so emissions are negligible
- Current IGCC design studies plan <3ppmv each of SOx, NOx and CO

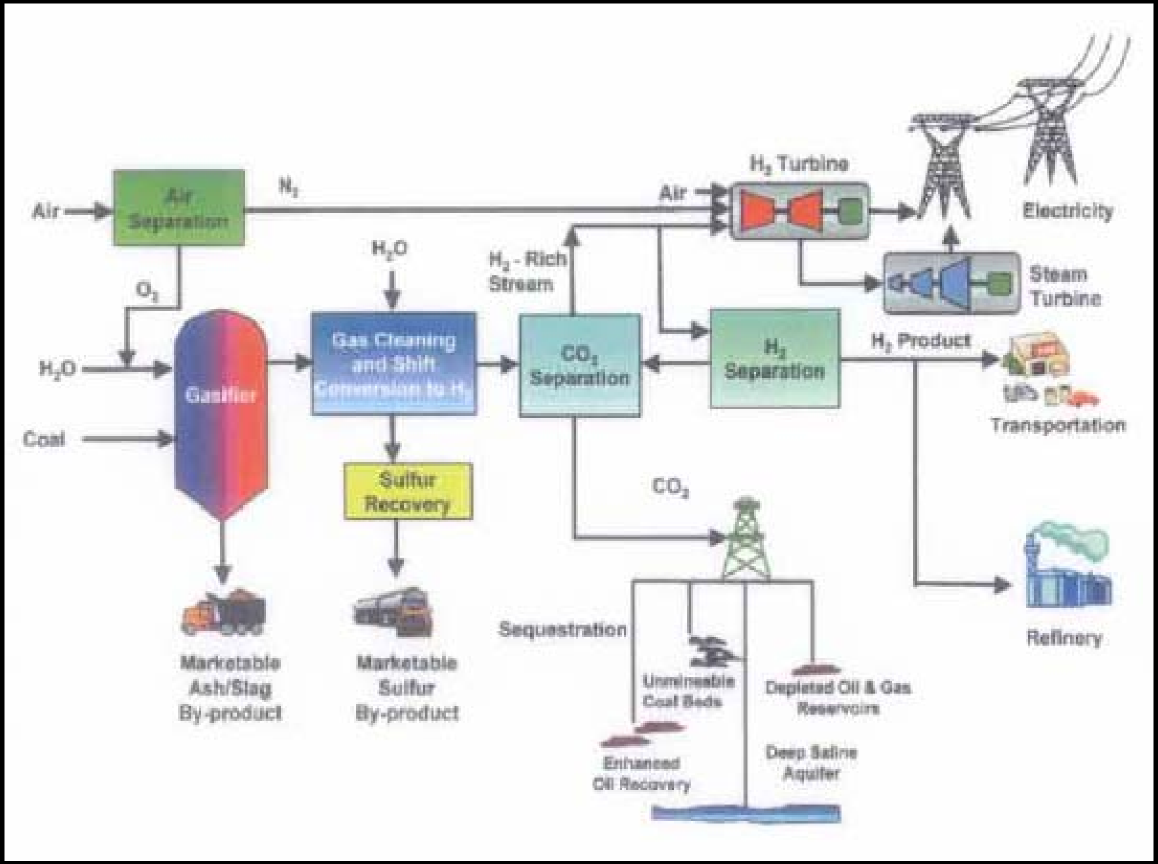
(Hazardous Air Pollutants)

- Mercury and other HAP's removed from the syngas by absorption on activated carbon bed
- Water use is lower than conventional coal
- Byproduct slag is vitreous and inert and often salable
- CO2 under pressure takes less energy to remove

EPRI

Source: Stu Dalton, EPRI, 2004

Future Gen Plant: CO_2 Capture and Storage



Energy Units

1 barrel (bbl) of crude oil= 42 gallons=6.12×10^{9} joules

1 Mtoe =million tons of oil equivalent = 10^{13} joules

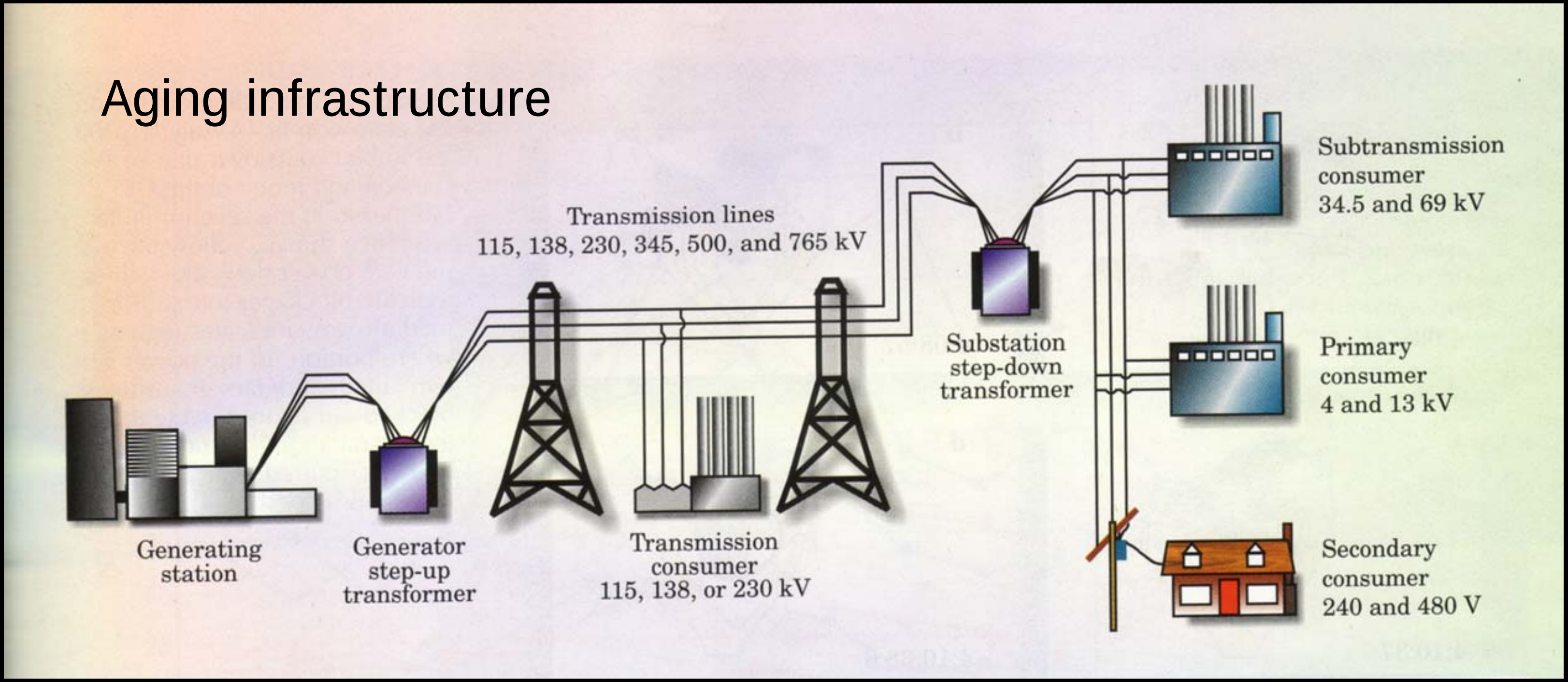
1 MJ = million joules = 274 Wh

kW*capacity factor*annual hours = Kwh

Fuel conversion Factors:

Electricity:	3,412 Btu/kWh
Fuel oil:	138,700 Btu/gallon
Natural gas:	1,030 Btu/ft^3
LPG/Propane:	95,500 Btu/gallon
Coal:	24,580,000 Btu/ton

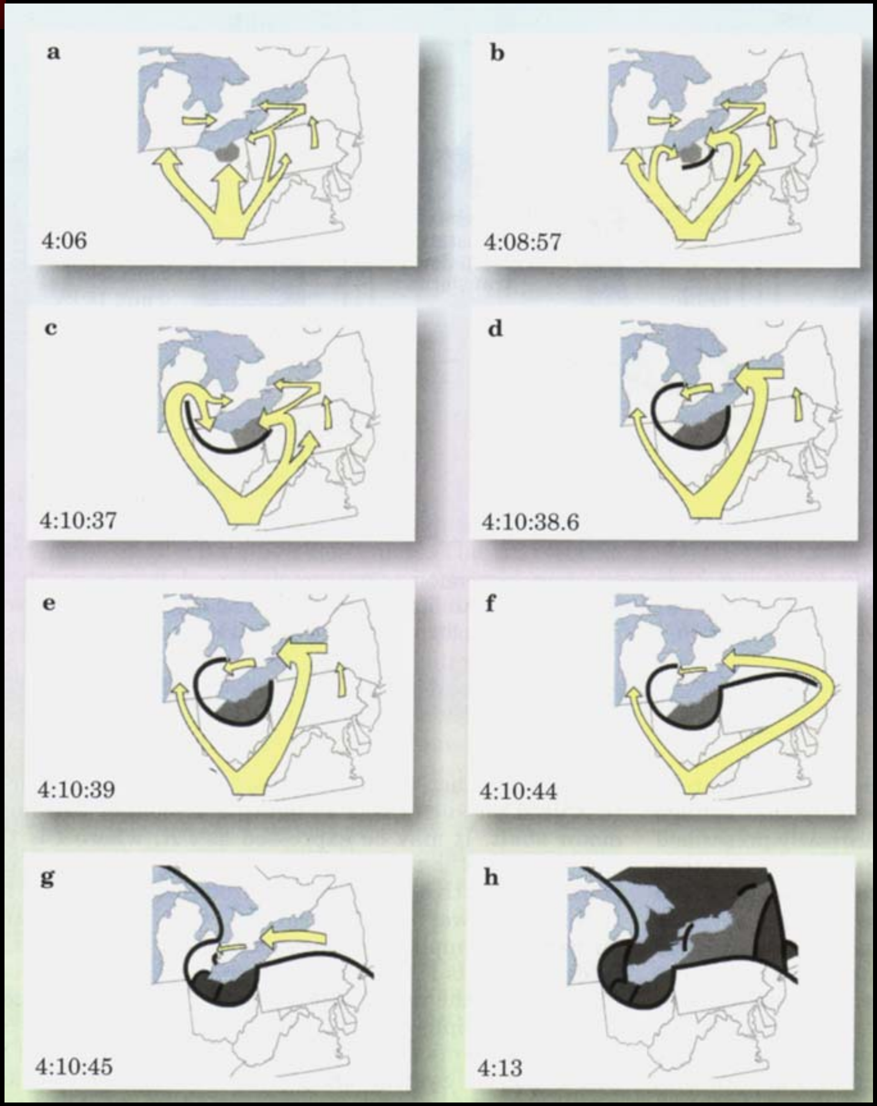
The Electricity Grid



One utility company estimates that it spends $1.50 to deliver power for every $1.00 it spends producing it. Power transmission also incurs some electricity losses. The Energy Information Administration estimates that approximately 9% of the power produced at a central generating plant is lost in delivery.

Source: Transforming the electricity infrastructure by Gellings & Yeager, Physics Today, December 2004.

Cascading Outage

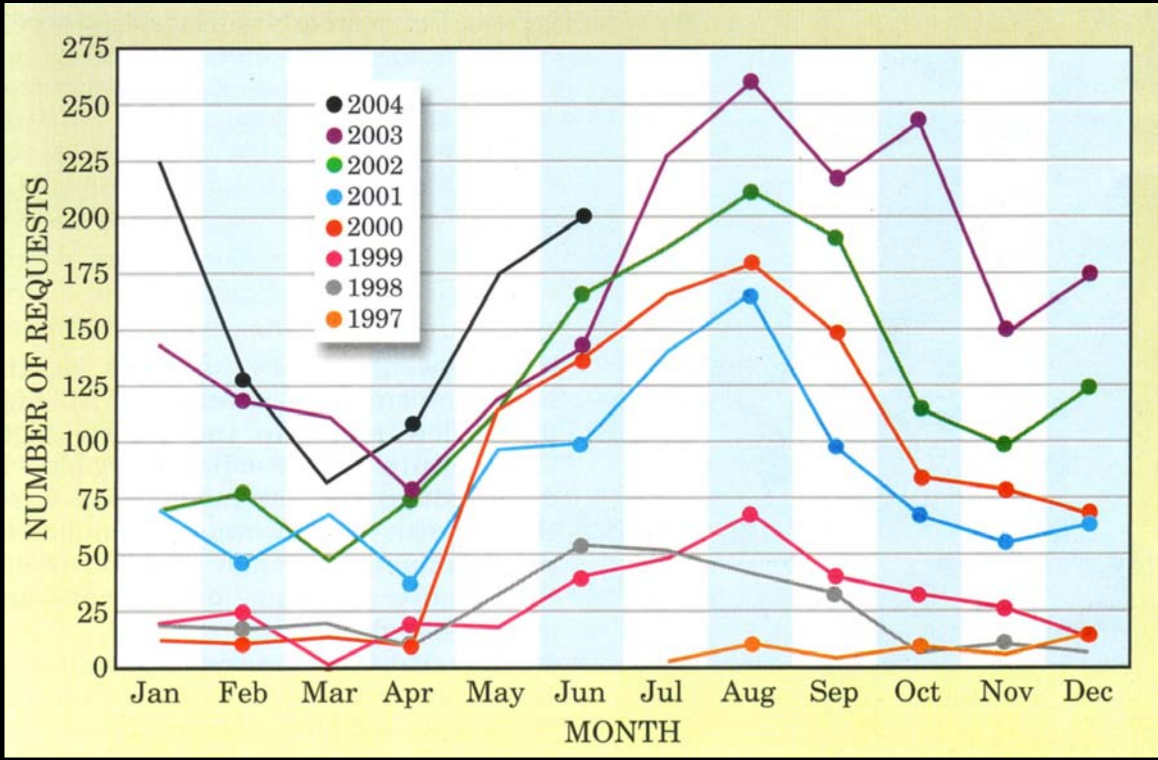


14th August 2003

Blackouts over part of Canada and much of Northeast

Source: Transforming the electricity infrastructure by Gellings & Yeager, Physics Today, December 2004.

Transmission



Accommodate a request to transmit energy

Source: Transforming the electricity infrastructure by Gellings & Yeager, Physics Today, December 2004.

Fossil and Renewable Energy Domains

Size	Fossil-Fueled	Renewable-Fueled
Large	• Coal-fired Boilers • Coal-fired Fluid Bed • Combined Cycle	• Solar Central Receiver • Wind Farms • Solar Trough • Biomass
Small	• Combustion Turbine • Diesels • Microturbines • Fuel Cells	• Wind Machines • Solar Dish • Photovoltaics • Energy Efficiency

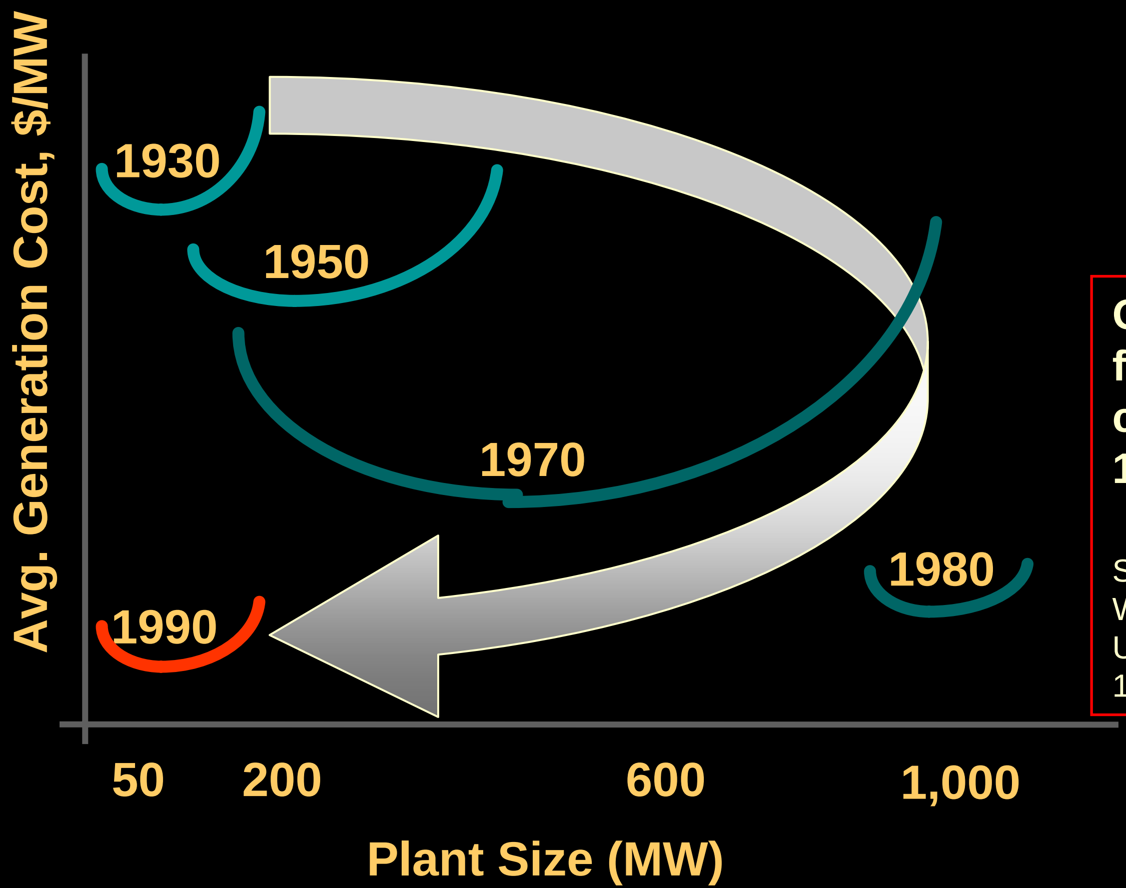
Storage

Large ↕ Small

Fossil-Fueled ↔ Hybrids ↔ Renewable-Fueled

Source: Mervin Brown, NREL

Micropower

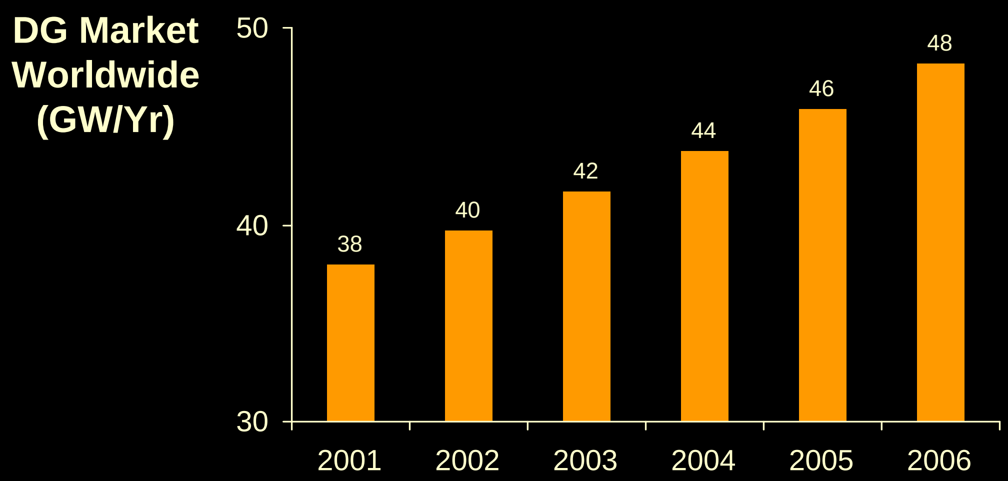


Optimal generation plant size for a single plant based on cost per megawatt [MW], 1930-1990

Source: Charles E. Bayless, "Less is More: Why Gas Turbines Will Transform Electric Utilities." Public Utilities Fortnightly 12/1/94

Source: Mervin Brown, NREL

Global Distribution Generation

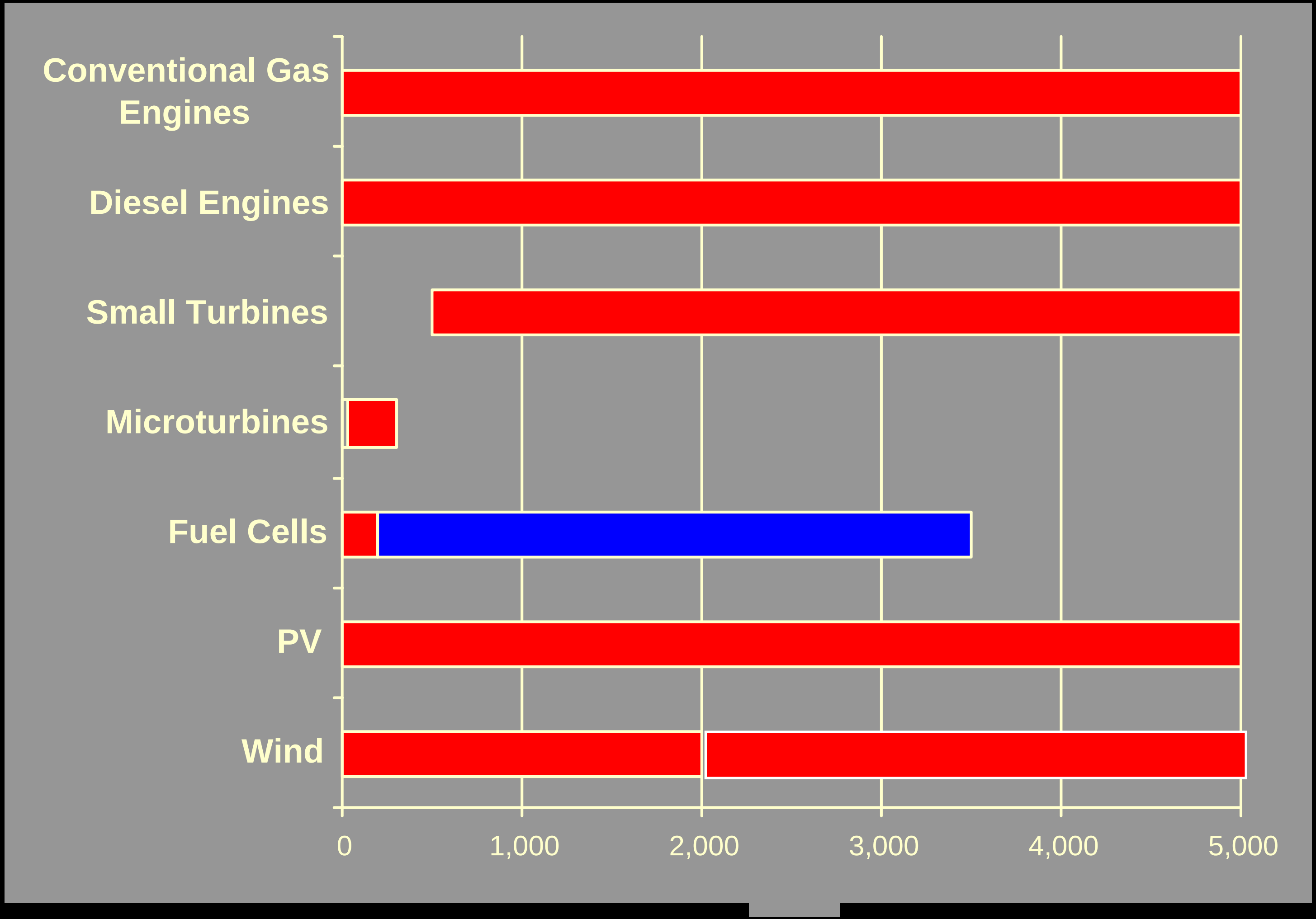


Deregulation
Quality/reliability power demand
Environment concerns
Distribution constraints
Flexibility to add capacity

Siting and Permitting process
Lack of interconnection standards
Back-up tariffs
Near term cost

Source: John Cassidy, United Technologies Corp.

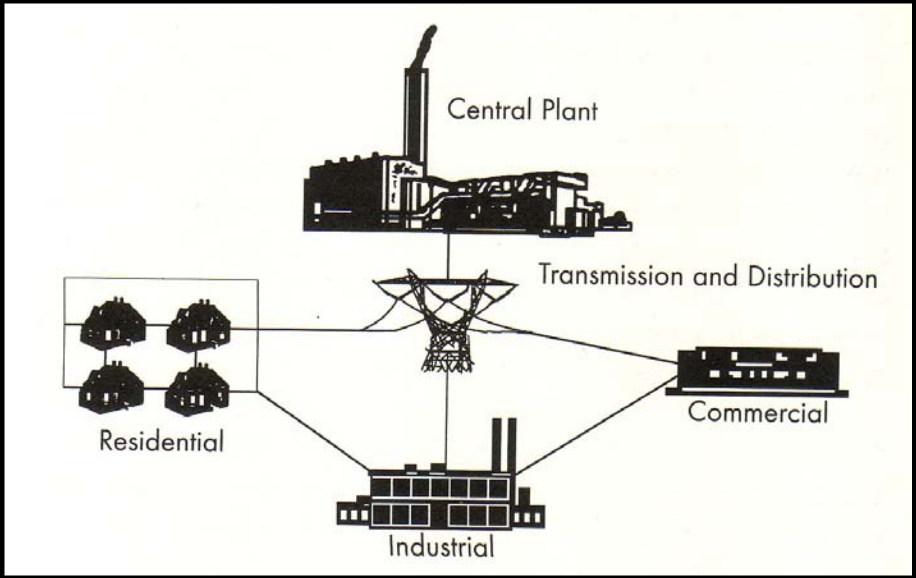
Power Output Ranges



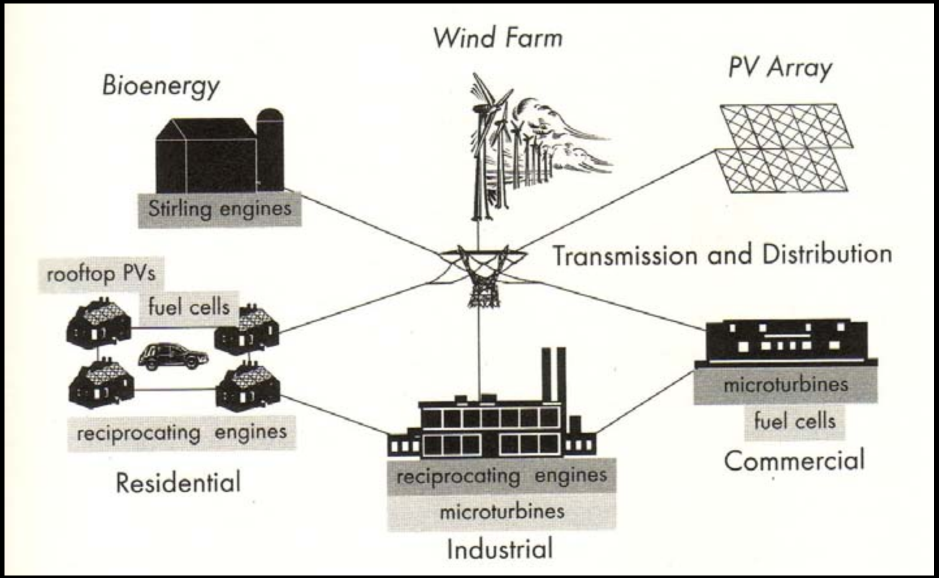
Sources: Arthur D. Little, 01/2000; Resource Dynamics Corp. 02/2001 and UTC estimates

Future Power System

Centralized Power System



Distributed Power System



Power line extension costs anywhere between \$10,000 to \$30,000 per mile.

Power Cost

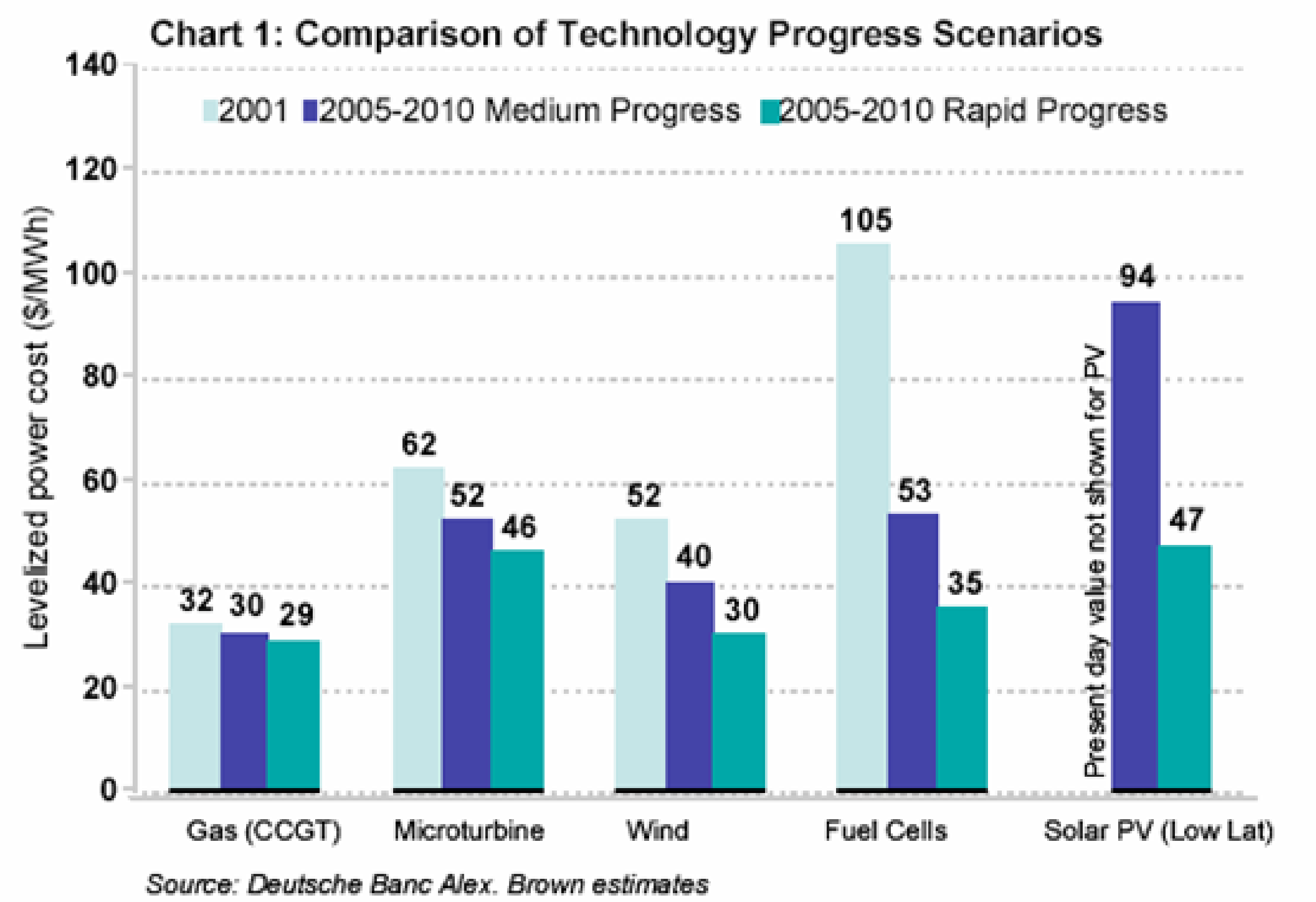
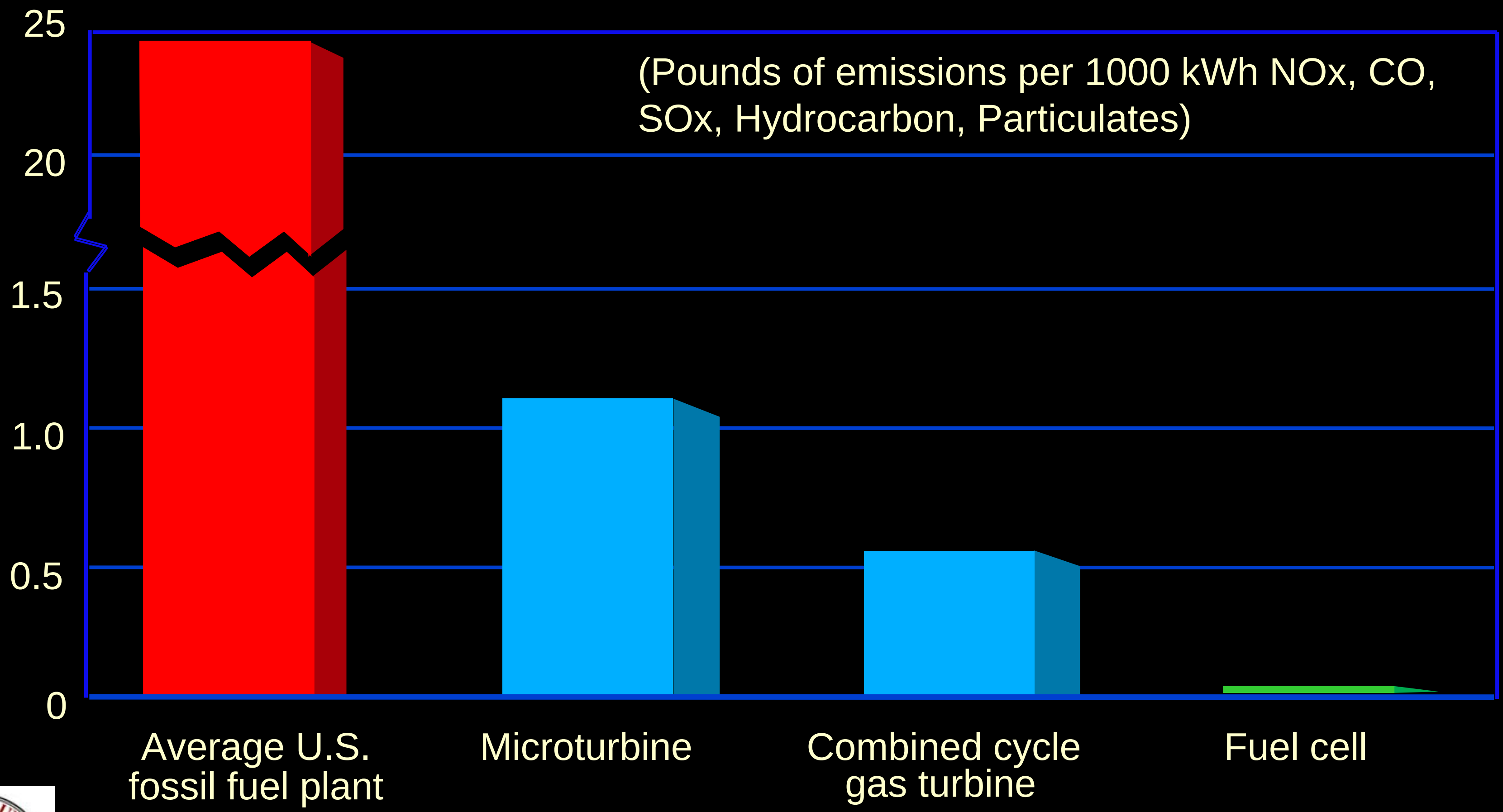


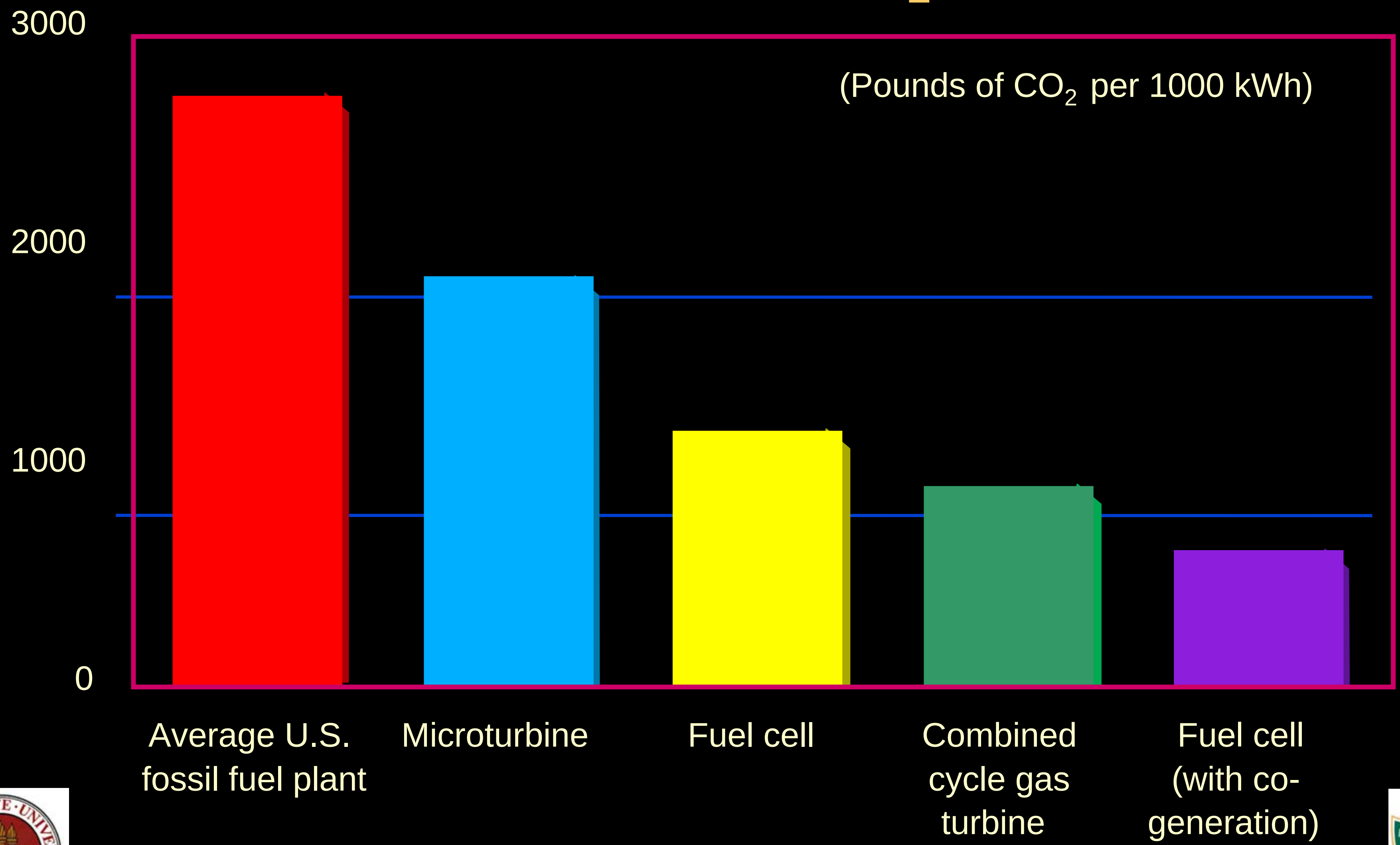
Chart 1: Comparison of Technology Progress Scenarios
2001
2005-2010 Medium Progress
2005-2010 Rapid Progress
Levelized power cost ($/MWh)
140
120
100
80
60
40
20
0
32
30
29
62
52
46
52
40
30
105
53
35
94
47
Present day value not shown for PV
Gas (CCGT)
Microturbine
Wind
Fuel Cells
Solar PV (Low Lat)
Source: Deutsche Banc Alex. Brown estimates

Emissions



25
20
1.5
1.0
0.5
0
(Pounds of emissions per 1000 kWh NOx, CO, SOx, Hydrocarbon, Particulates)
Average U.S. fossil fuel plant
Microturbine
Combined cycle gas turbine
Fuel cell

CO_2 Emissions



Source: UTC estimates

Guiding Energy Principles

Consume less: Energy conservation

Most advanced building codes

Efficient lighting, smart windows etc.

Fuel efficient cars; e.g. hybrid cars

Generate more: Environmentally friendly and affordable

Less carbon/$output

Cogeneration

Renewable energy - wind, solar, biomass etc.

Every 1 mpg improvement in vehicle fleet efficiency saves more than one million metric tones of carbon generation annually.

Wind Energy Potential

Globally: 27% of earth's land surface is class 3 (250-300 W/m^2 at 50 m) or greater

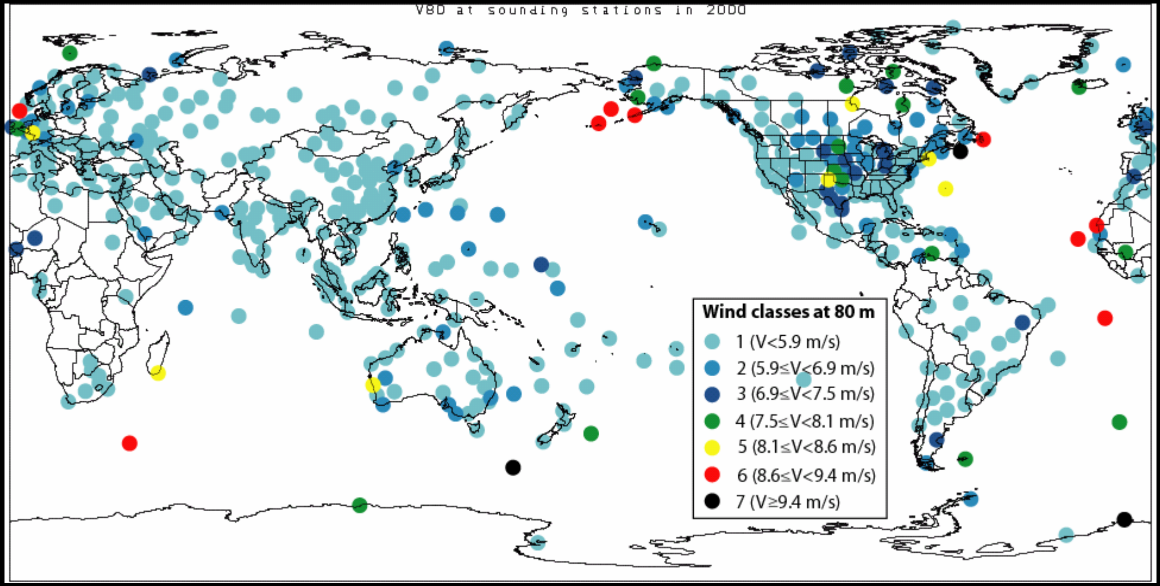
- potential of 50 TW

4% utilization of > class 3 land area will provide 2 TW

US: 6% of land suitable for wind energy development - 0.5 TW

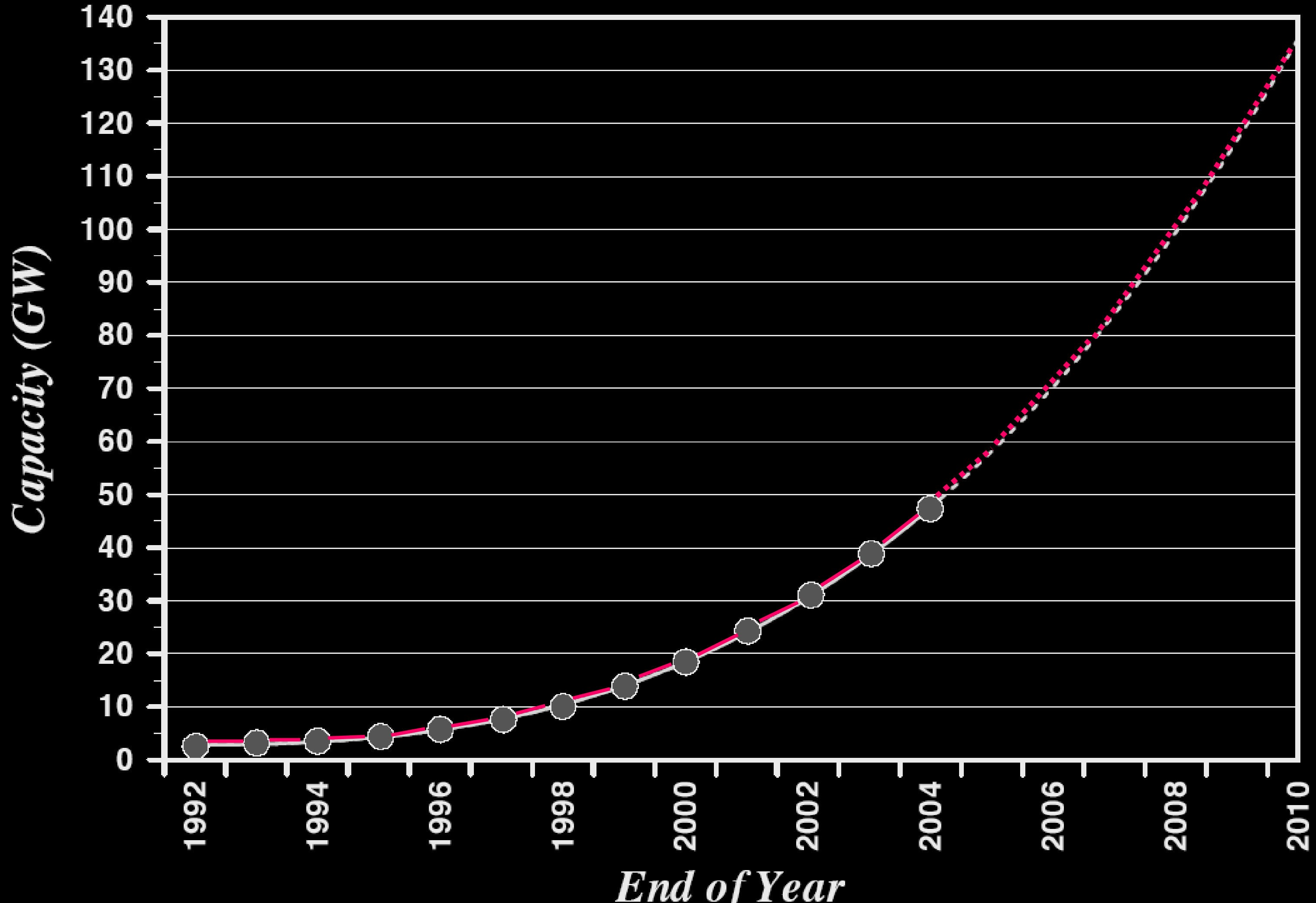
US electricity consumption ~ 0.4 TW

Off shore installations provide additional resource



Cristina L. Archer and Mark Z. Jacobson, Evaluation of Global Wind Power, Stanford University, 2005

Global Wind Energy Growth



Global Wind Energy

Country	2004 MW	% of total
Germany	16,629	35.1
Spain	8,263	17.5
United States	6,740	14.2
Denmark	3,117	6.6
India	3,000	6.3
Italy	1,125	2.4
Netherlands	1,078	2.3
United Kingdom	888	1.9
Japan	874	1.8
China	764	1.6

World Total: 47,317 MW

2004 Installations: 7,976 MW

Growth rate: 20%

2020 Prediction: 1,245,000 MW*

Equivalent to 1000 Nuclear power plants

12% of world electricity generation

* According to Wind Force 12

RE Power 5MW Wind Turbine

Rated Power: 5 MW

Cut-in-speed: 3.5 m/s

Rated Wind speed: 13 m/s

Cut-out speed: 25 - 30 m/s

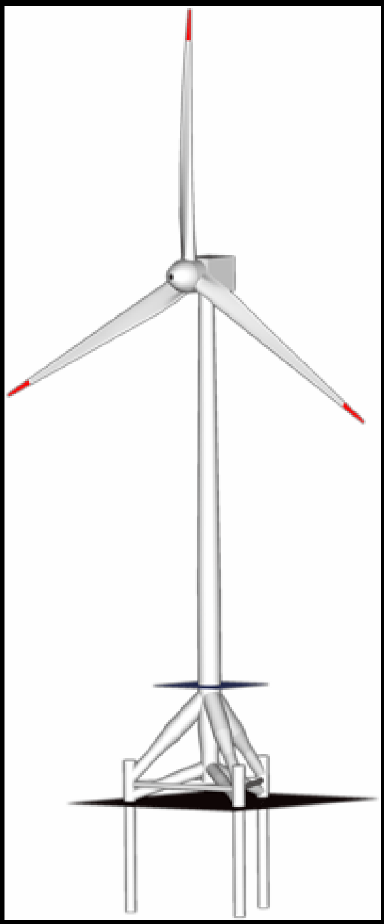
Rotor Diameter: 126 m

Rotor area: 12,469 m^2

Rotor blade length: 61.5 m

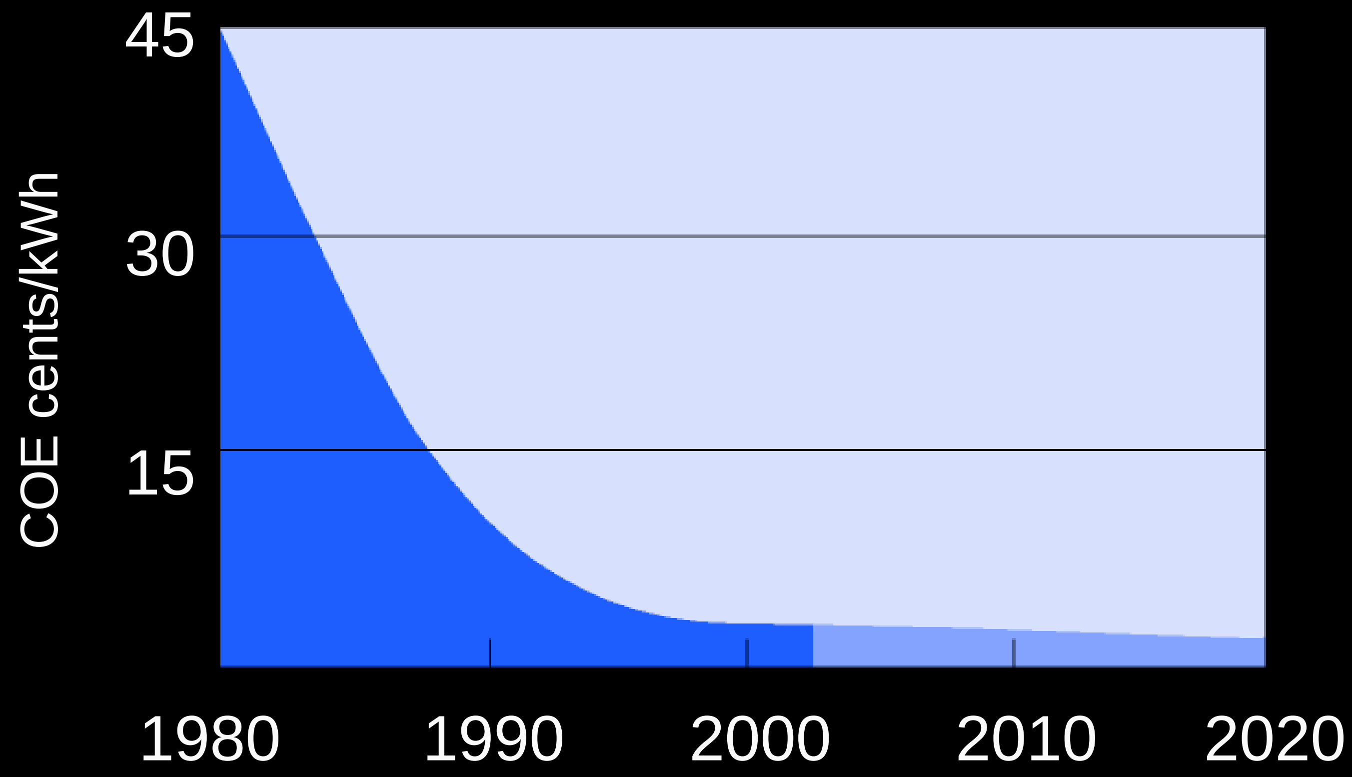
Rotor speed: 6.9-12.1 rpm

Offshore installation



Wind Energy Costs Trends

Levelized cents/kWh in constant $2000[1]



Source: NREL Energy Analysis Office
[1]These graphs are reflections of historical cost trends NOT precise annual historical data.
Updated: June 2002

Sustainable Energy Science and Engineering Center

Solar Energy Potential

Theoretical: 1.76 x 10^5 TW striking Earth; 0.3 Global mean albedo

Practical: 600 TW

Conversion Efficiency: 10%

Electricity generation potential = 60 TW

Estimated Global Demand in 2050 = 20 TW

Solar Cell Land Area Required

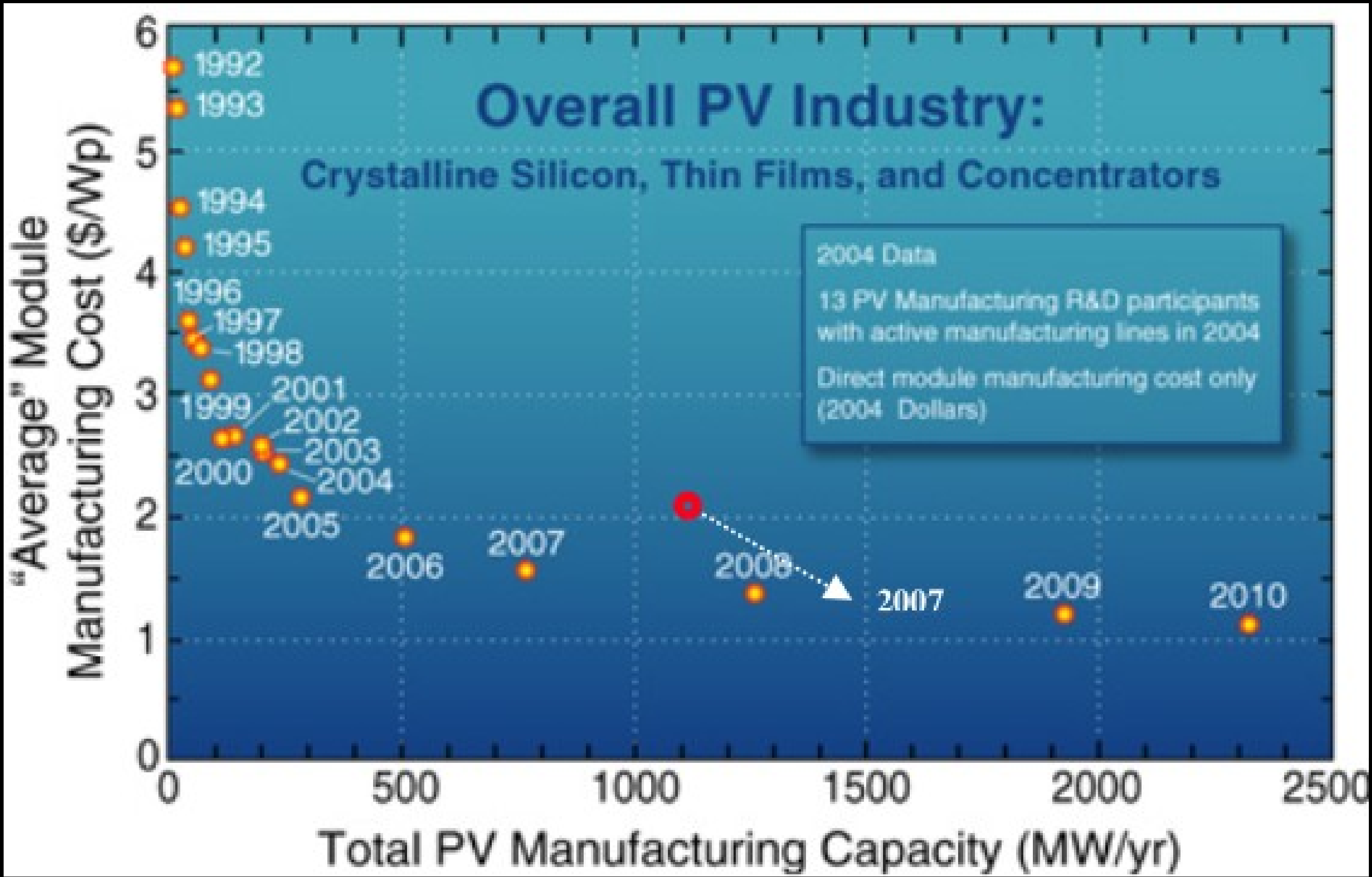
6 Boxes at 3.3 TW Each = 20 TW

Solar Resource Magnitude

- At our latitude, the solar flux at mid-day on a clear day is 1000 W/m^2.
  - The average Including night and clouds is 200 W/m^2.
- The average solar power incident on Continental US is 1.6×10^{15} W.
  - This is 500X the average power consumption in the U.S. (3.3×10^{12} W).
- If we cover 2% of the Continental US with 10% efficient PV systems, we will make all the energy we need.
- For perspective:
  - 1.5% of the Continental US is covered with roads.
  - 40% is used to make food (20% crops, 20% grazing)

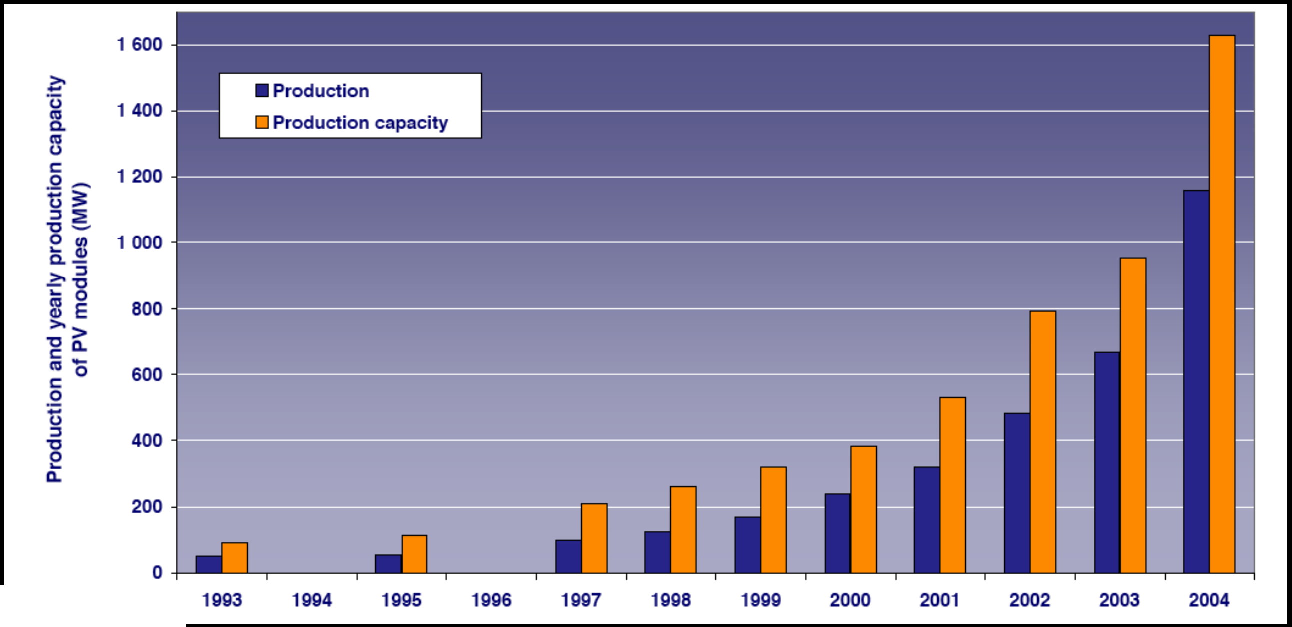
Source: Emanuel Sachs, ME, MIT

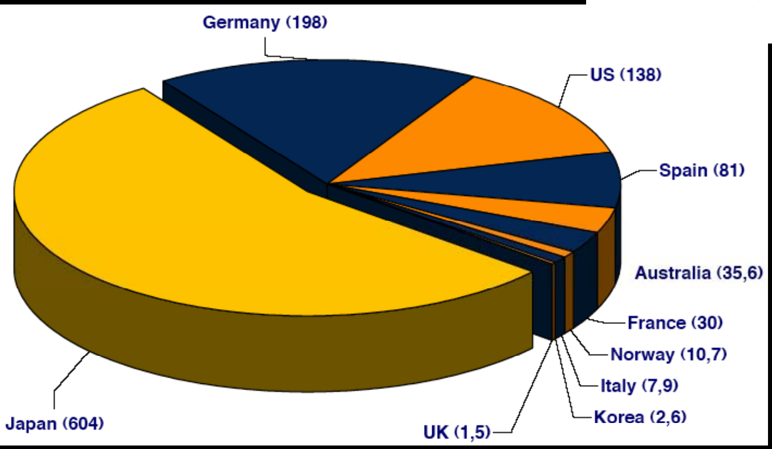
Cost of Photovoltaic Modules



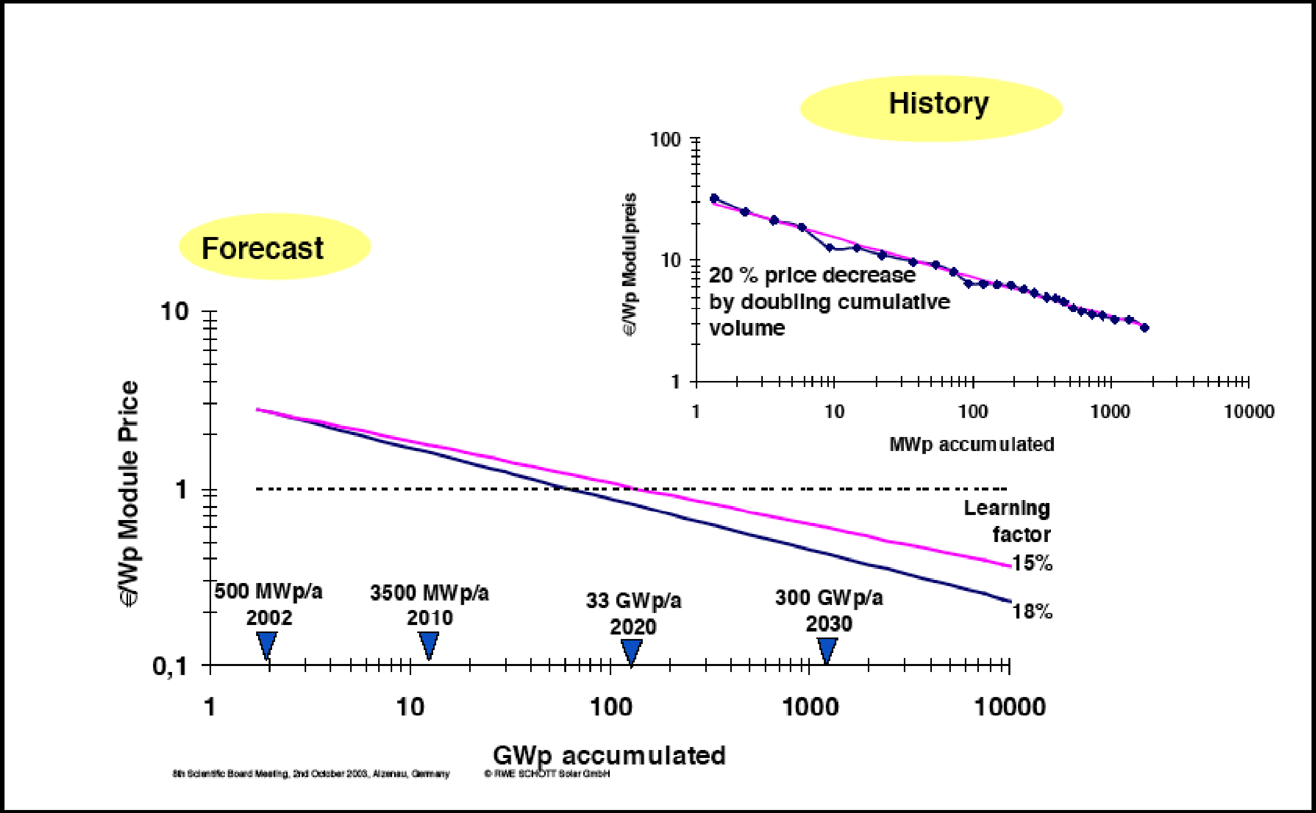
Starting in 2006 China's production: 400 MW_p/year

PV Cell Production in 2004

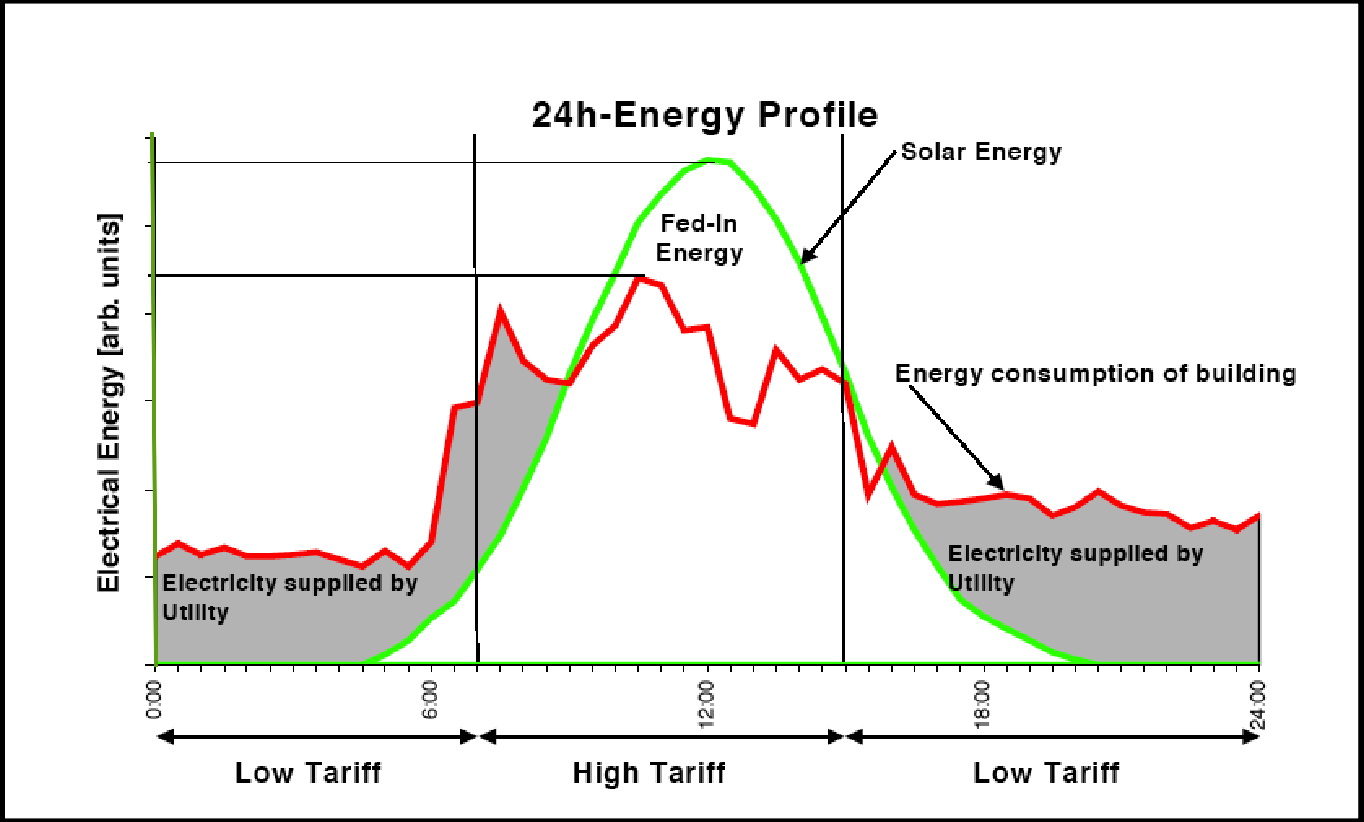




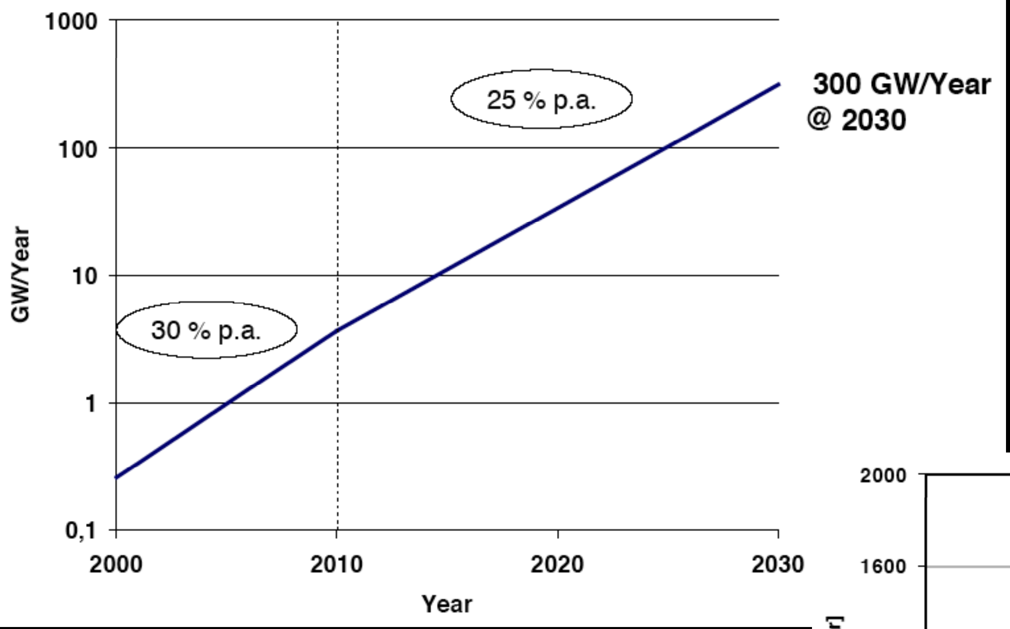
PV Price experience Curve

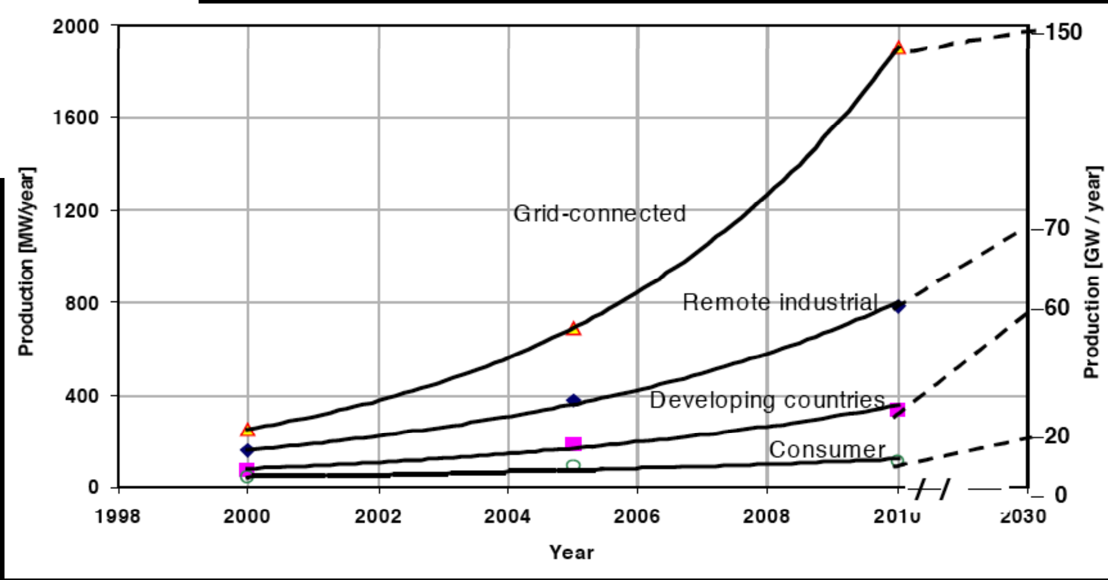


Office Building Energy Profile



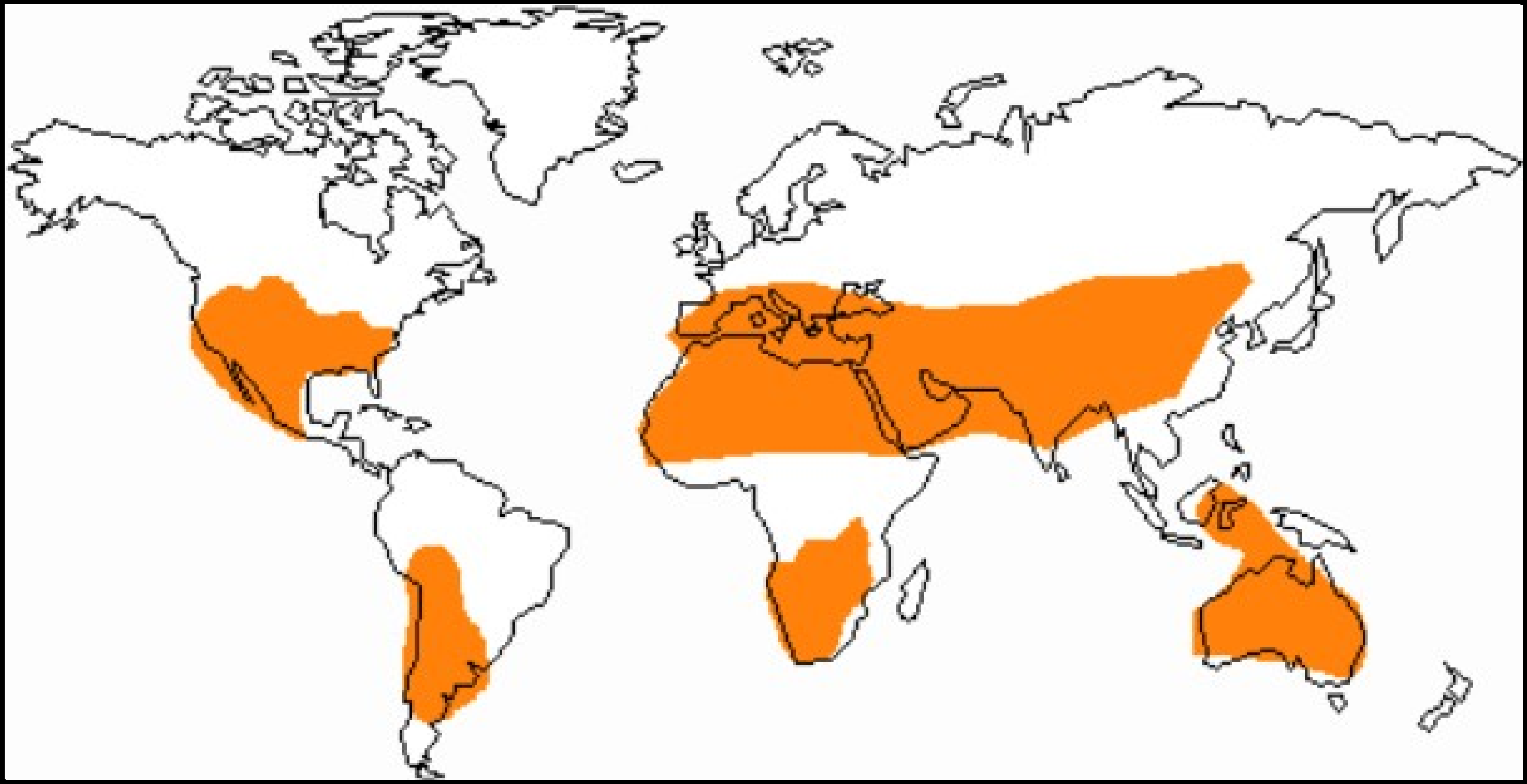
PV Growth


1000
100
10
1
0,1
GW/Year
25 % p.a.
30 % p.a.
300 GW/Year
@ 2030
2000
2010
2020
2030
Year

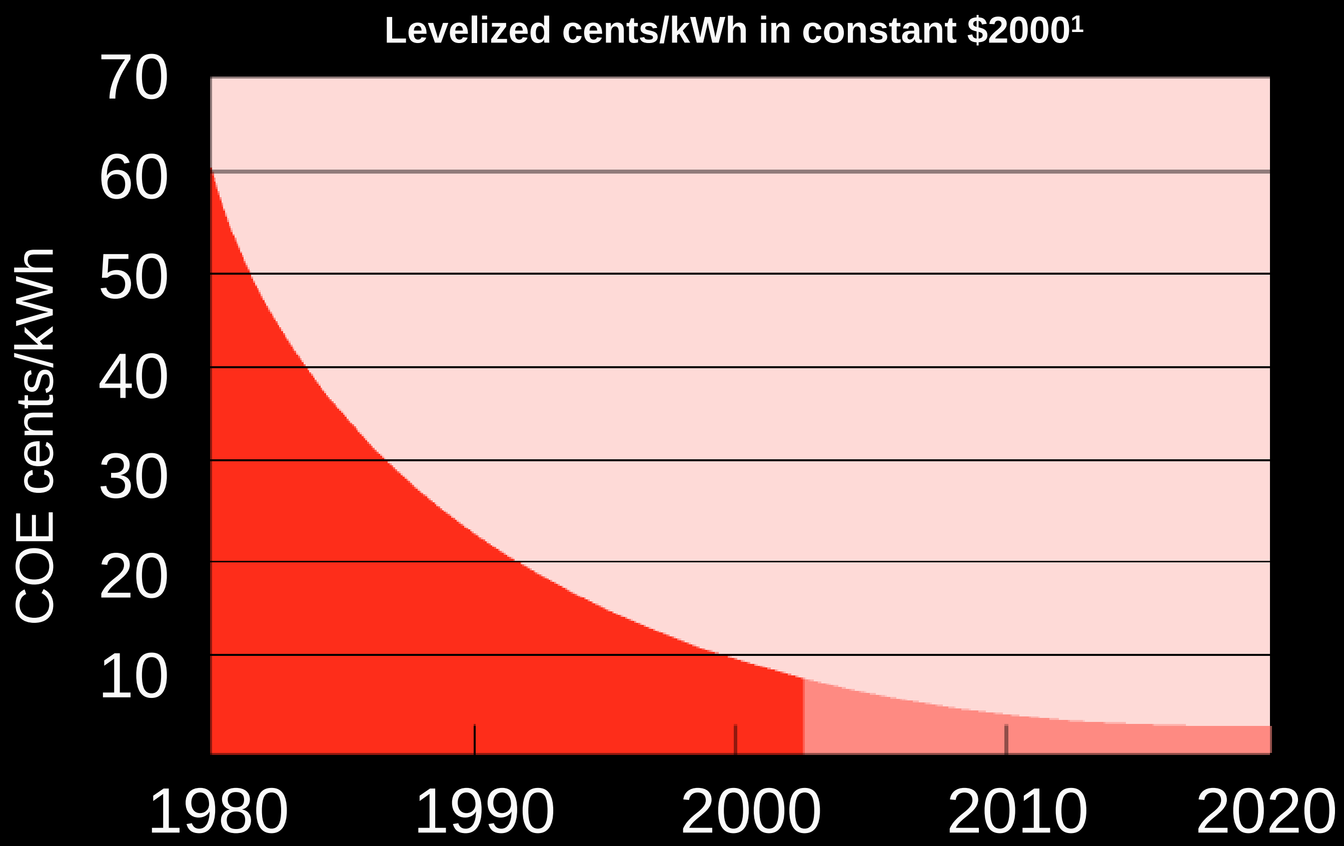

2000
1600
1200
800
400
0
Production [MW/year]
Grid-connected
Remote industrial
Developing countries
Consumer
150
70
60
20
0
Production [GW / year]
1998
2000
2002
2004
2006
2008
2010
2030
Year

Solar Thermal Power Plant Potential

Comparably low power generation costs can be achieved wherever insolation reaches 1,900 kWh per square meter and year or more.



Solar Thermal



Renewable Energy Technologies

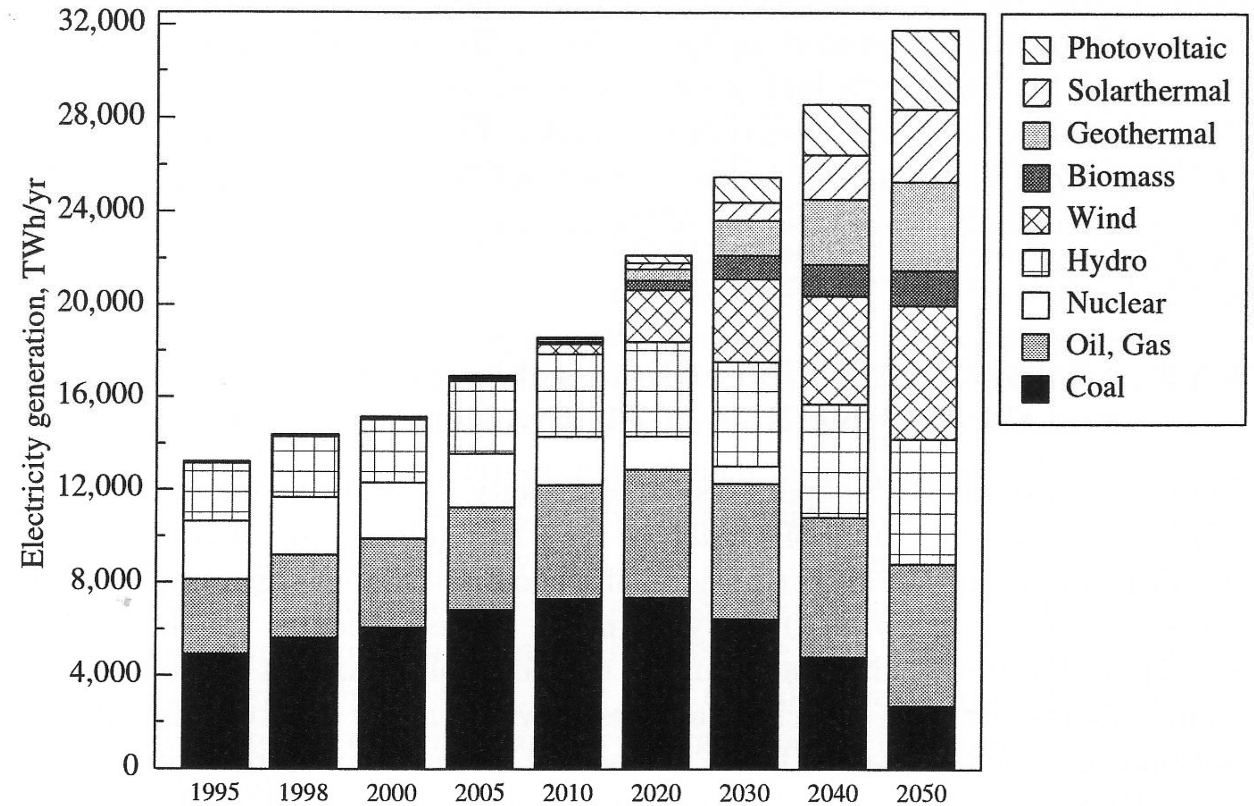
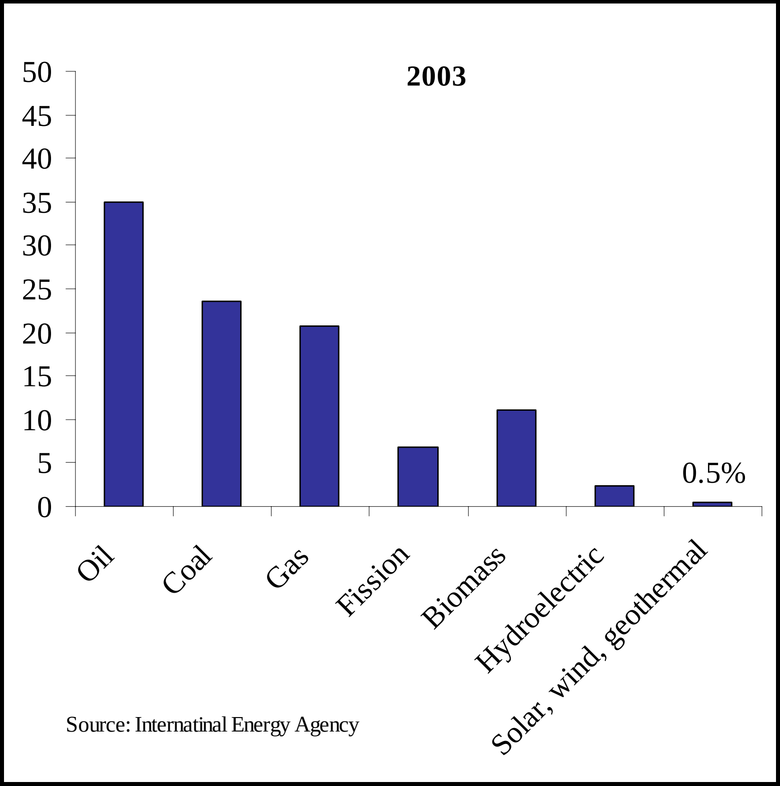
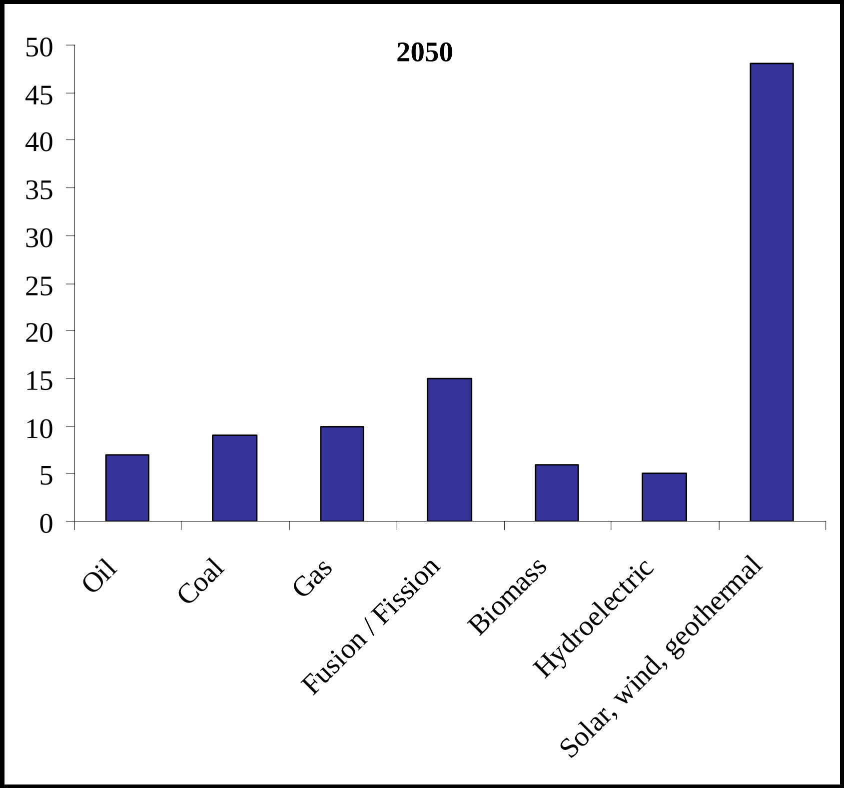


Fig. 1.11. Growth of renewable energy technologies in the "Solar Energy Economy" scenario until 2050

Source: Photovoltaics Guide book for Decision makers by Bubenzer and Luther; Springer, 2003

Why Solar Electricity?





165,000 TW (10^{12} W) of sunlight hit the earth every day

Solar Electricity

Solar-thermally generated electricity: Lowest cost solar electric source.

Complex collectors to gather solar radiation to produce temperatures high enough to drive steam turbines to produce electric power.

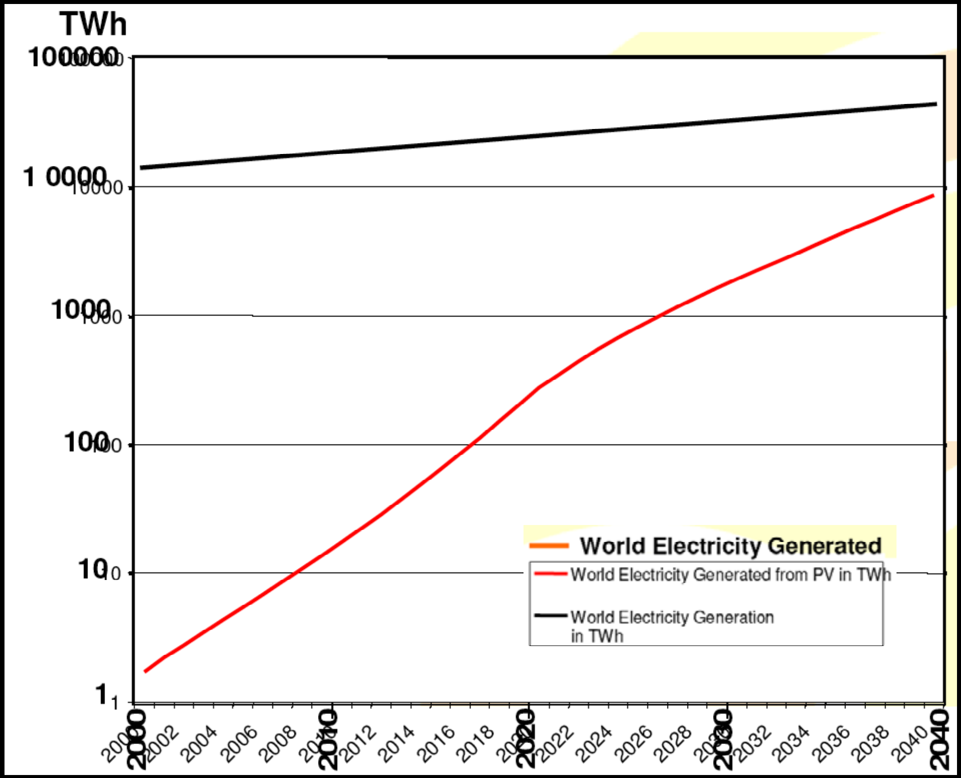
For example, a turbine fed from parabolic trough collectors might take steam at 750 K and eject heat into atmosphere at 300 K will have a ideal thermal (Carnot) efficiency of about 60%. Realistic overall conversion (system) efficiency of about 35% is feasible.

Solar Photovoltaic energy:

The direct conversion of sun’s rays to electricity.

The efficiency (the ratio of the maximum power output and the incident radiation flux) of the best single-junction silicon solar cells has now reached 24% in laboratory test conditions. The best silicon commercially available PV modules have an efficiency of over 19%.

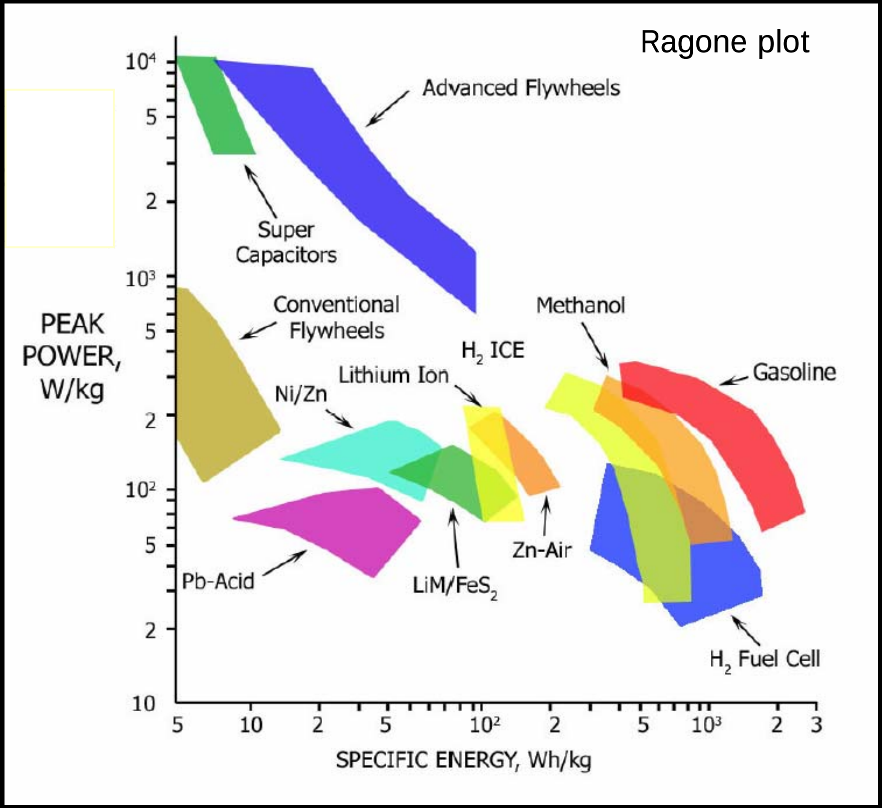
Global PV Electricity Generation



Renewable Energy Storage

Solar and wind energy sources are intermittent and regional.

They will become major sources of power if we find efficient ways to store and transport their energy.



Source: J.W.Tester, Sustainable Energy, MIT, 2005

Renewable Energy Storage and Fuel for Transportation

Hydrogen, the simplest molecule, can be used for storing energy and make it available where and when it is needed.

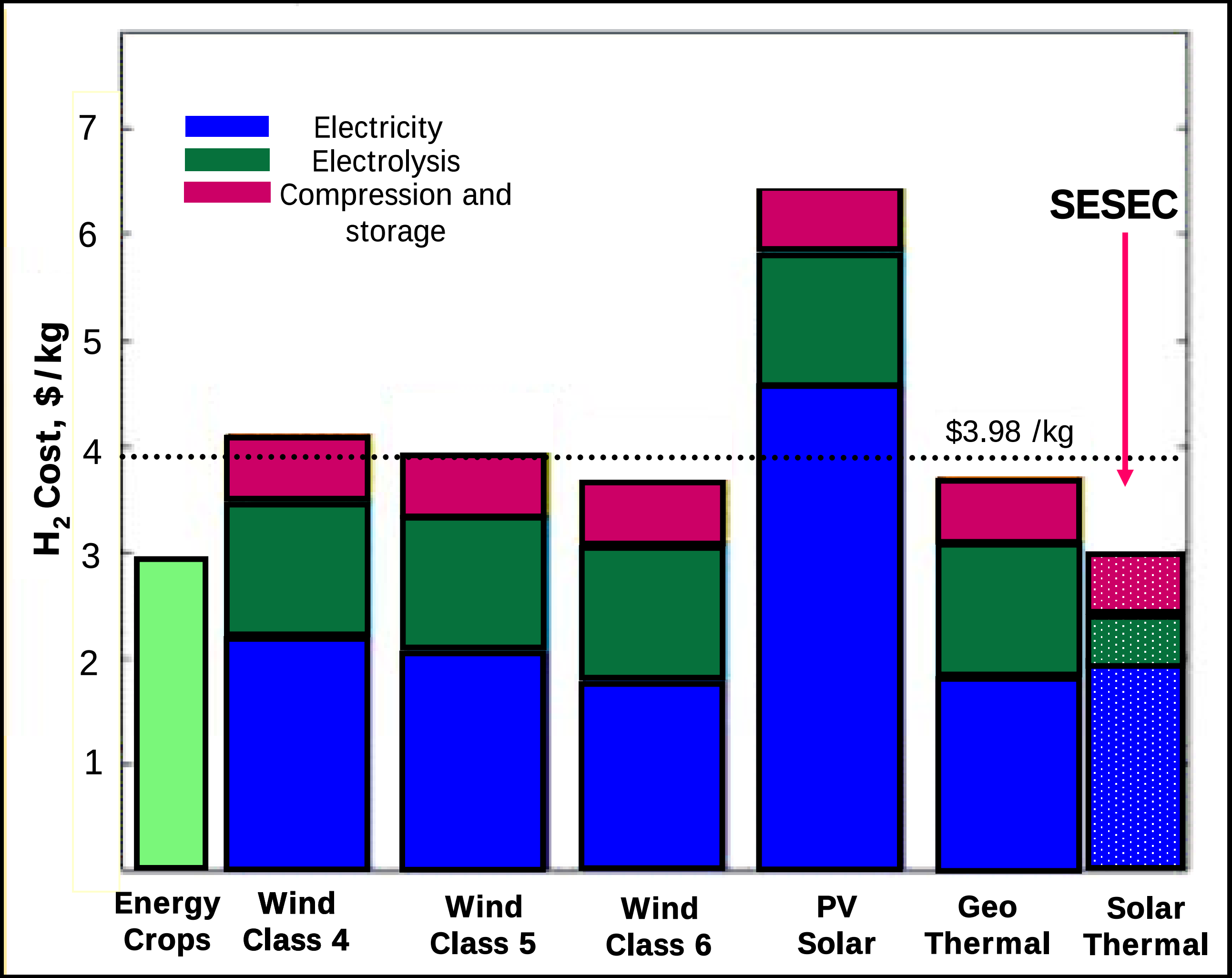
When used as a chemical fuel, it does not pollute

Hydrogen is not an energy *source* , but it is an energy *carrier* that has to be manufactured like electricity.

Hydrogen can be manufactured from many primary sources (from clean water and solar energy) - reduces the chances of creating a cartel.

Hydrogen Cycle: electrolysis → storage → power conversion

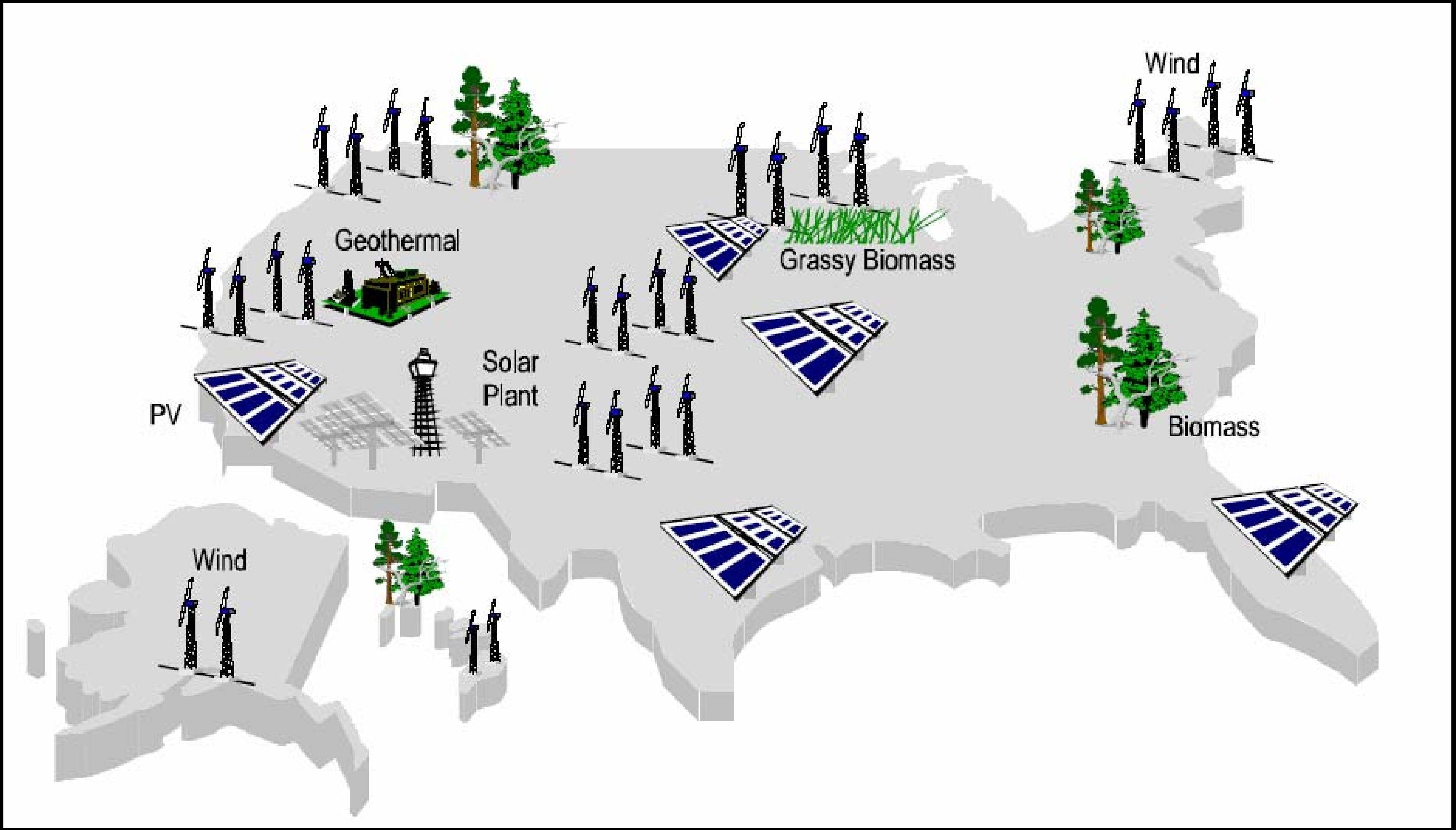
Renewable Hydrogen Cost



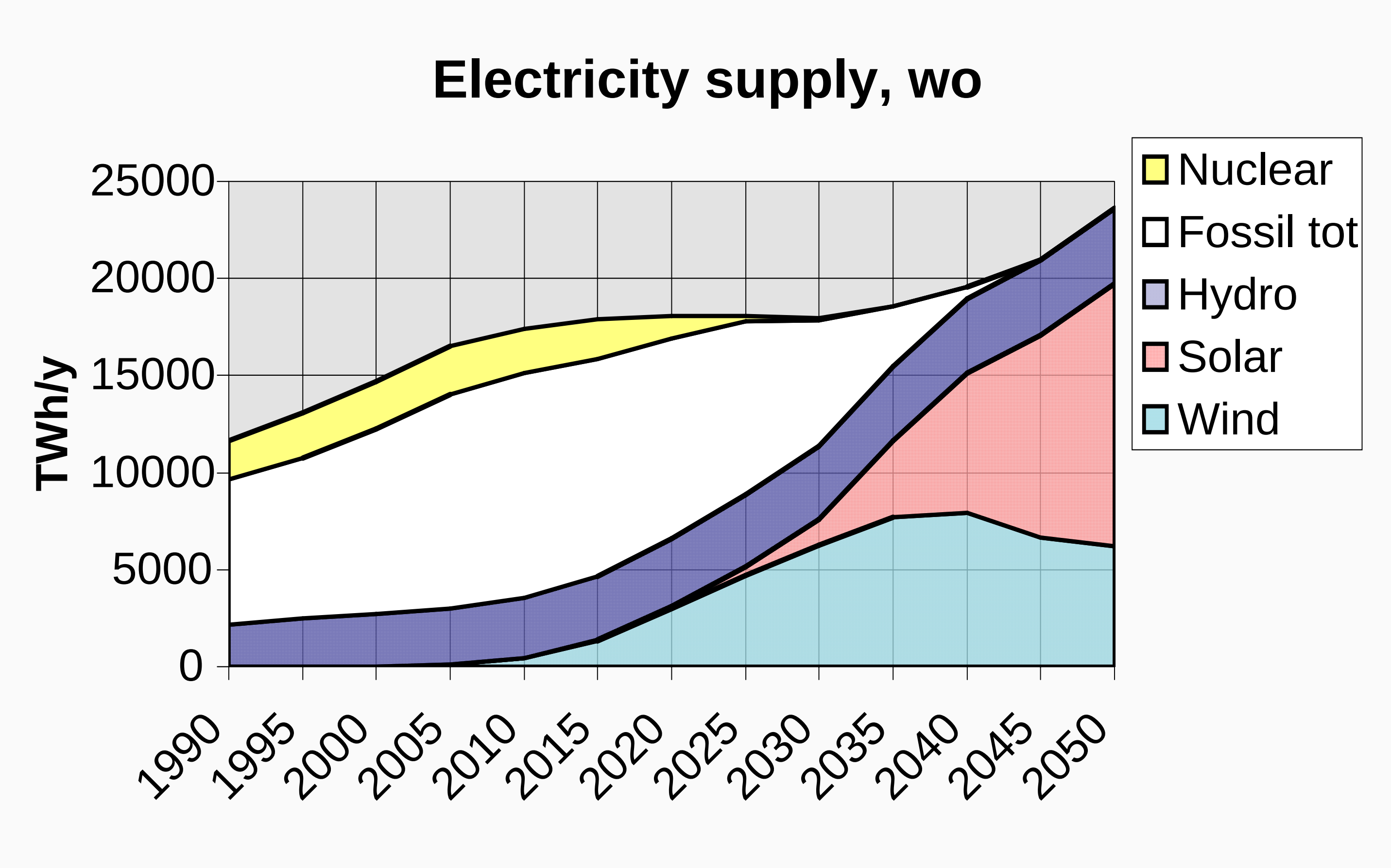
One Kg of hydrogen has roughly the same amount of energy as in one gallon of gasoline

Duane B. Myers et al., 2003, Hydrogen from Renewable sources, Direct Technologies, inc, Arlington, VA 22201

Sustainable Energy Future



Sustainable Energy Vision



Source: Sustainable energy vision 2050, **Gunnar Boye Olesen**, INFORSE-Europe coordinator, Gl. Kirkevej 56, DK 8530 Hjortshoej, Denmark, email ove@inforse.org. Rio 2002

Solar Energy Vision

Among renewable energy sources, only solar energy has a large enough resource base to meet a major fraction of the global energy needs. The rest of energy sources such as wind, biomass, geothermal and hydro do not have adequate global resources to do so - but they should be used to meet the fraction of the energy supply.

The solar radiation with about 125,000 TW of global incident light can be harnessed to meet the global energy needs - an opportunity and societal responsibility. Hence, the subject of this course.

JFK'S Words

"We choose to go the moon in this decade and do other things not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win"

President John F. Kennedy's words when he summoned US to go to the moon on September 12, 1962