Sustainable Energy:

The Solar Strategy

Summary

The renewed look at the Sustainable Energy results from two irrefutable reasons:

1. The supplies of fossil and mineral resources are limited.
2. The process in which these resources are used in energy services damage and even destroy those limited planetary resources on which our lives depend: water, land and atmosphere.

Concerns about adverse environmental and social consequences of fossil fuel use and about finite nature of supplies have been voiced intermittently for several decades -

"Within a few generations at most, some other energy than that of combustion of fuel must be relied upon to do a fair share of the work of the civilized world." - *Robert H. Thurston - 1901 in the Smithsonian Institution annual report.*

Energy and Power

Energy (in joules) = Force (in newtons) x Distance (in meters)

Power (in watt) = Rate at which energy is converted from one form to the other (in joules per second)

Example: 100 watt light bulb is converting 100 joules of energy into light each second

Power used in a given period is generally used as a measure of energy - kWh

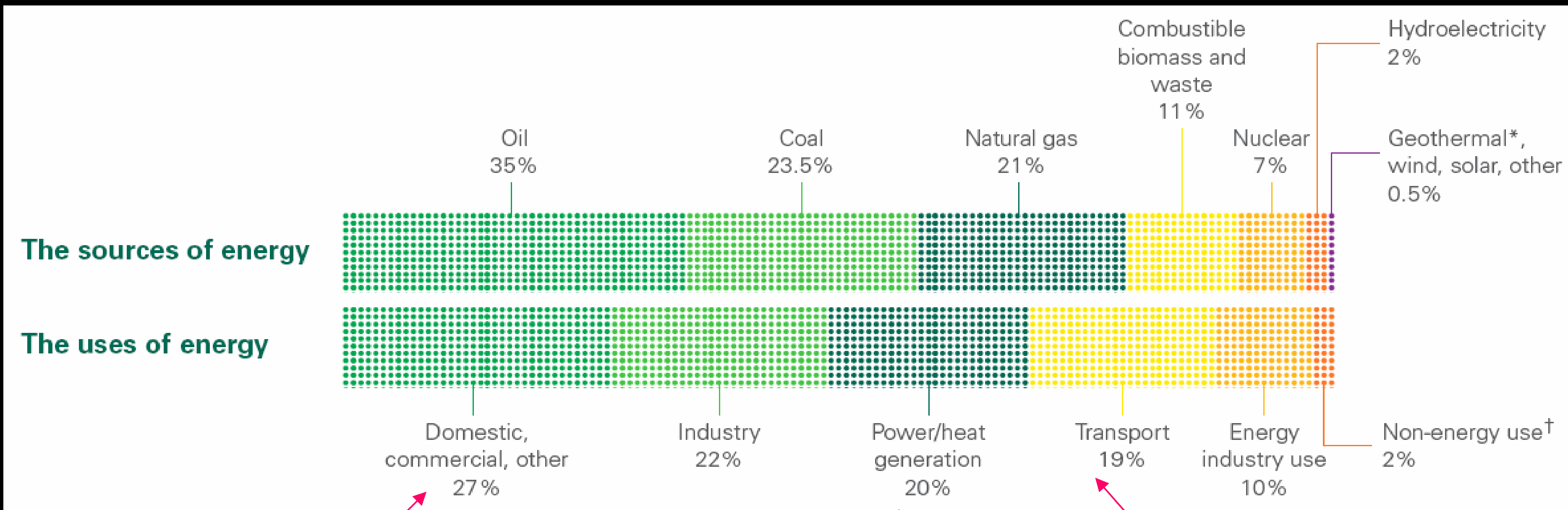
1 kWh = 1000 x 3600 = 3.6 x 10^6 Joules (i.e. 3.6 MJ)

1 Million tonnes of oil equivalent (Mtoe) = 41.9 x 10^{15} Joules (i.e. 41.9 PJ)

Exa - 10^{18}; Peta - 10^{15}; Tera - 10^{12}; Giga - 10^9; Mega - 10^6

1 TW = 31.54 EJ/year

World Sources and Uses Of Energy

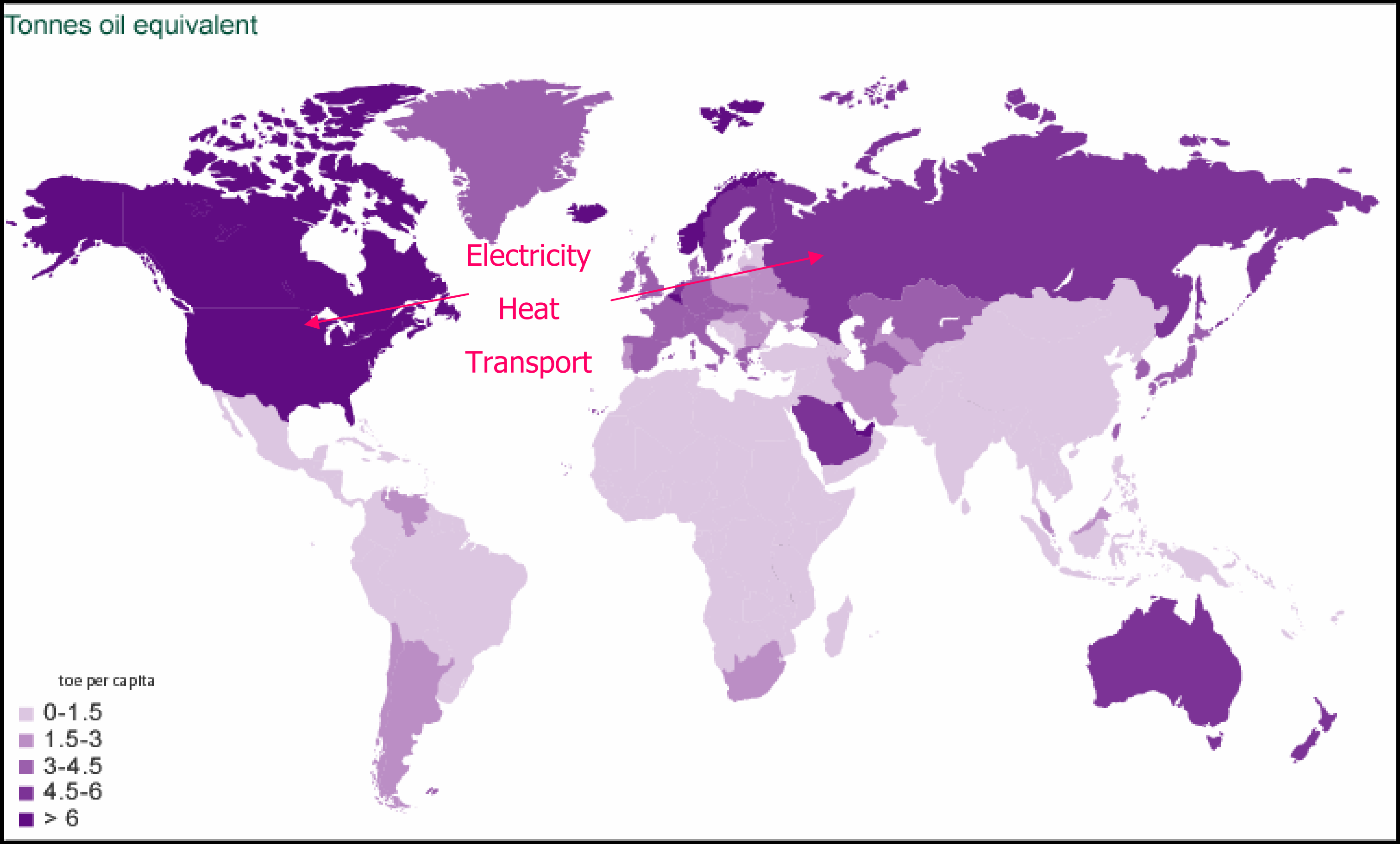


Electricity

Space Heating

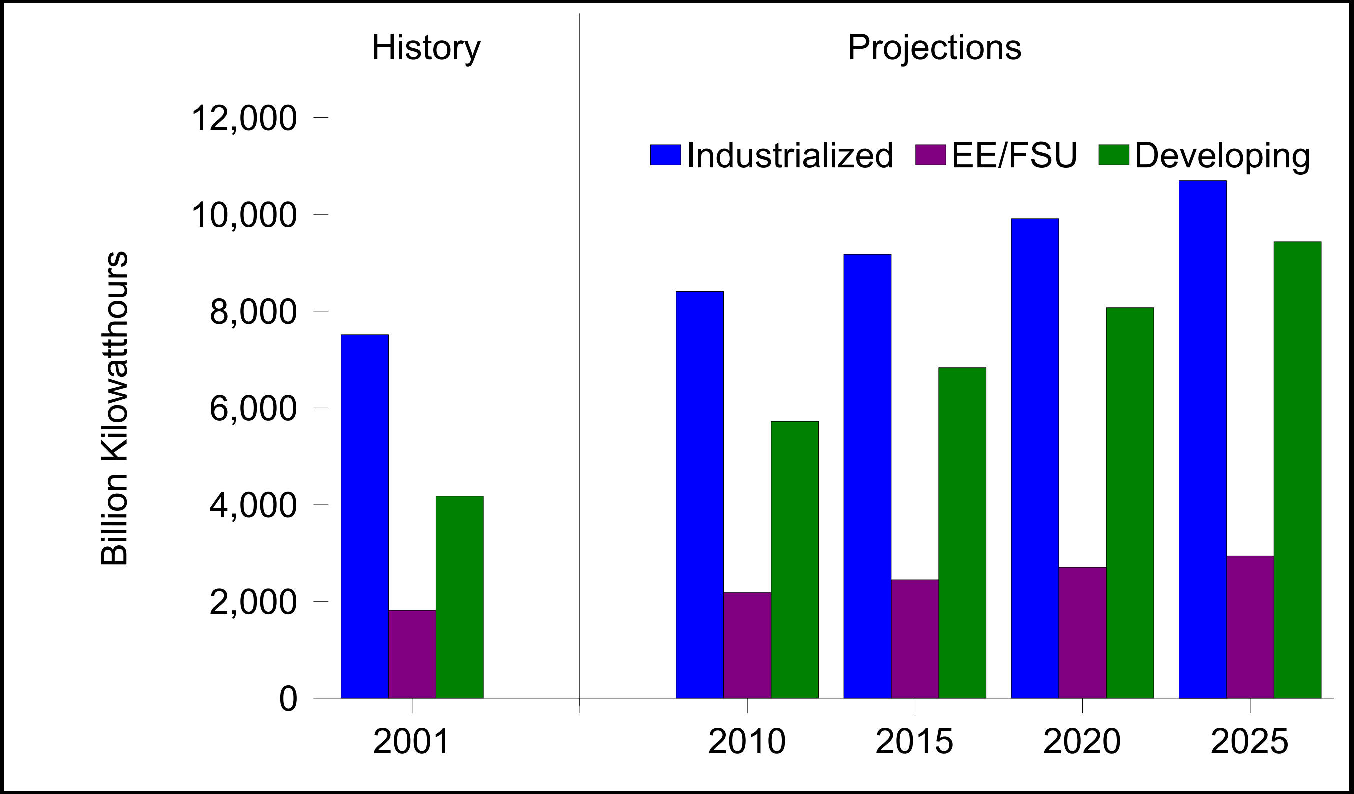
Liquid Fuels

Primary Energy Consumption per Capita



One Tone of Oil Equivalent = 11,639 kWh

Growth in Electricity Demand

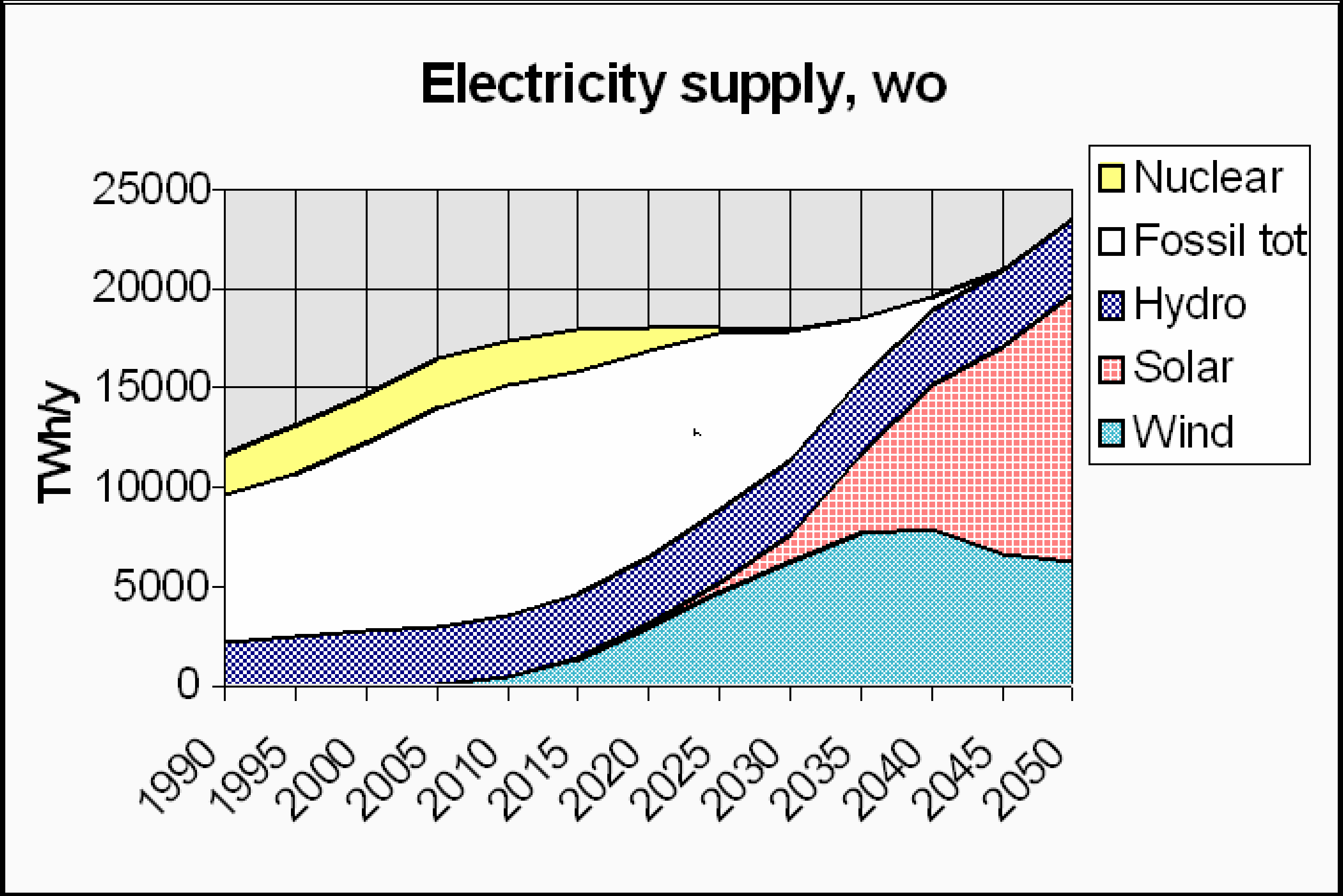


Total:~ 14 TWh

24 TWh

Typical home electricity use in USA = 9000 kWh/year

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

Sustainable Energy Source

Sustainable Energy Source:

One that is not substantially depleted by continuous use

Does not entail significant pollutant emissions or other environmental problems

Does not involve the perpetuation of substantial health hazards or social injustices

Only a few energy sources come close to this ideal

Renewable Energy Sources:

Generally more sustainable than fossil or nuclear fuels

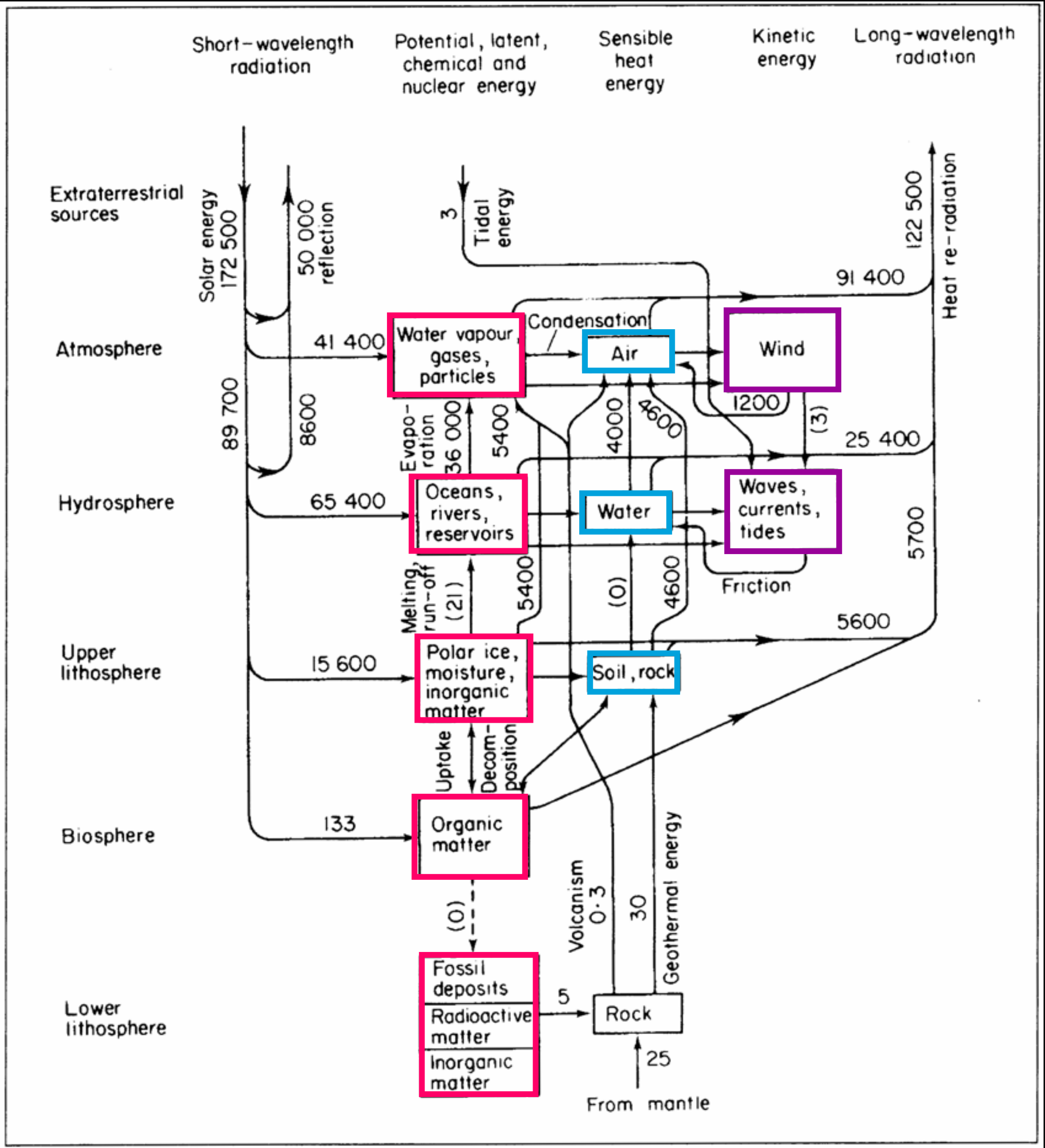
Essentially inexhaustible

Their use entails lower emissions of greenhouse gases or other pollutants

Fewer health hazards

Principal source of renewable energy is solar radiation

Origin of Renewable Energy Flows



Solar radiation (incoming short wavelength):

5.44×10^6 EJ/year

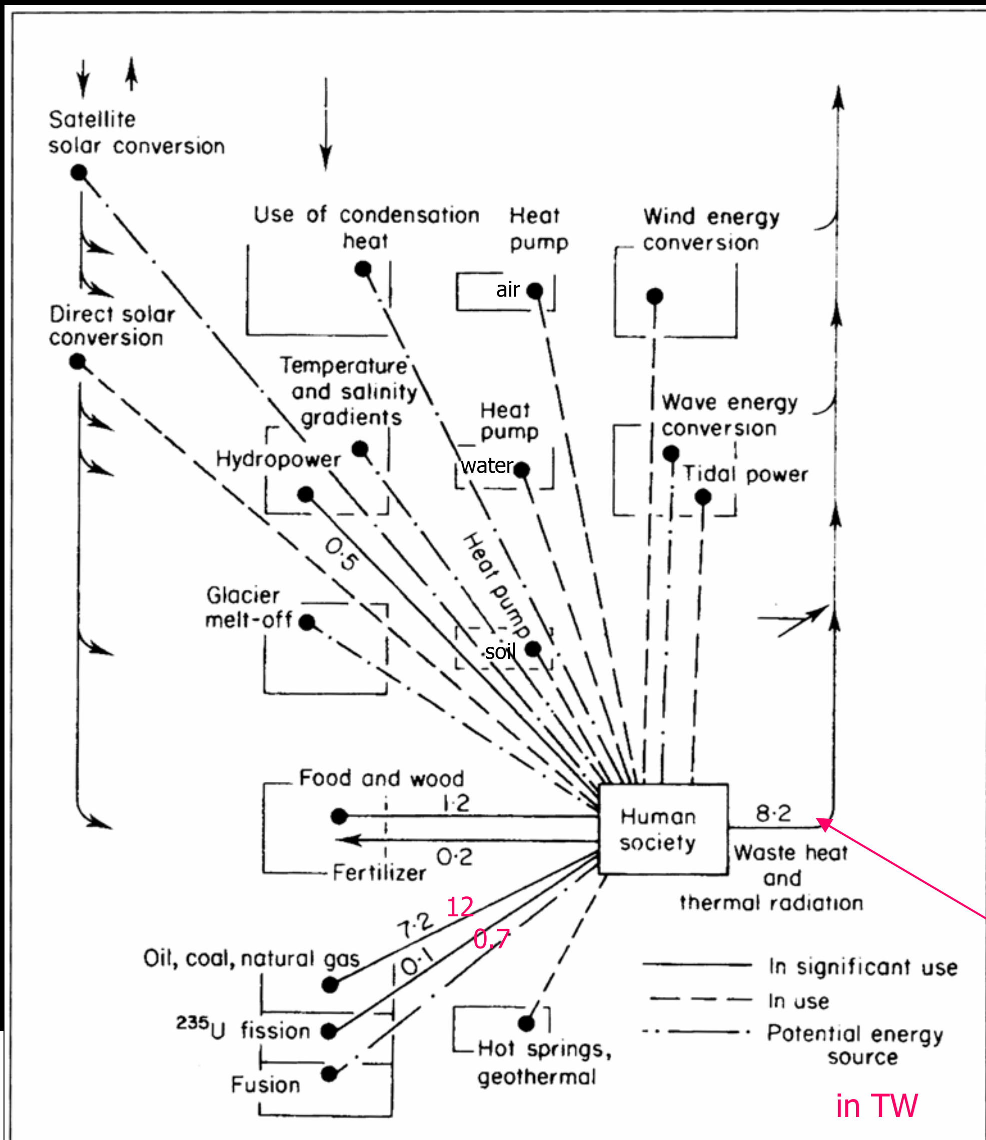
Short wavelength radiation direct reflection to space: ~ 30%

Energy cycle without anthropogenic interference. The energy flows are in TW

1 TW = 31.54 EJ/year

Source: Renewable energy, Brent Sorensen, Elsevier, 2004, p123

Possible Sources of Energy Conversion



Direction conversion to heat in air, earth and oceans: 2.55×10^6 EJ/year

Biomass energy: 4.3×10^3 EJ/year

Wind, waves convection and currents: 11.7×10^3 EJ/year

Convection in volcanoes and hot springs: 9.36 EJ/year

Ocean tides: 93.6 EJ/year

We should pay attention to those areas of energy cycle which have not yet been utilized for which energy conversion methods have been in place.

~ 4.7×10^{-5} of the solar radiation

Maximum relative change during the past 500K years has been 10^{-3}

Solar Electricity

Solar-thermally generated electricity:

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 17%.

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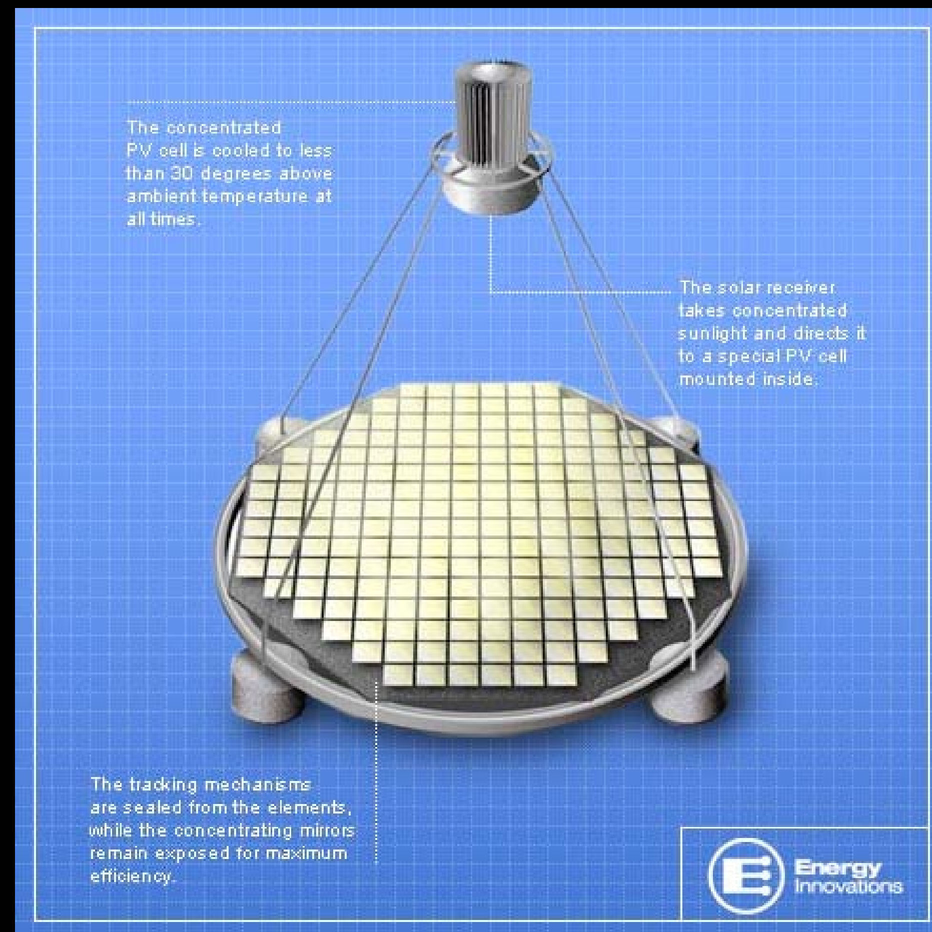
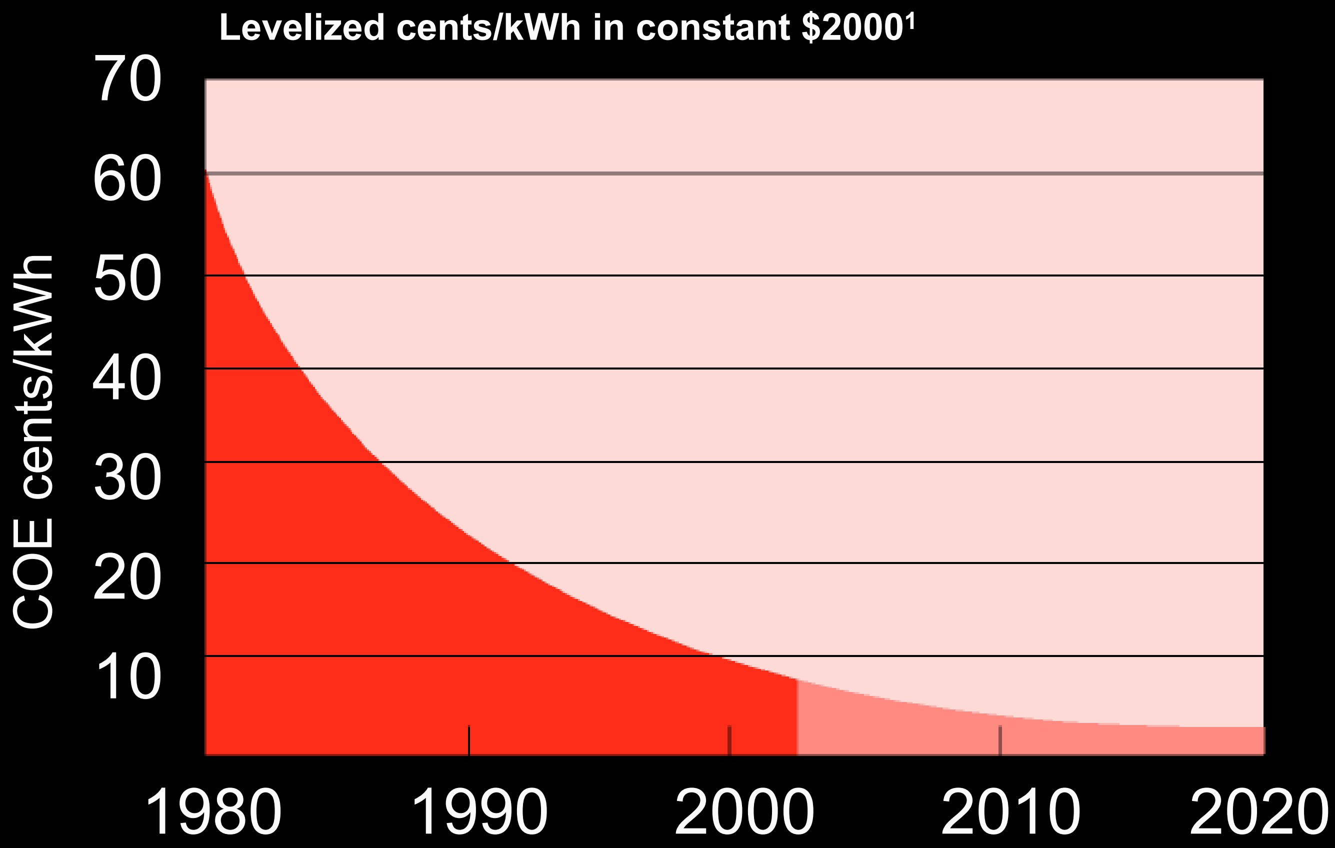
Solar-thermal Power Systems

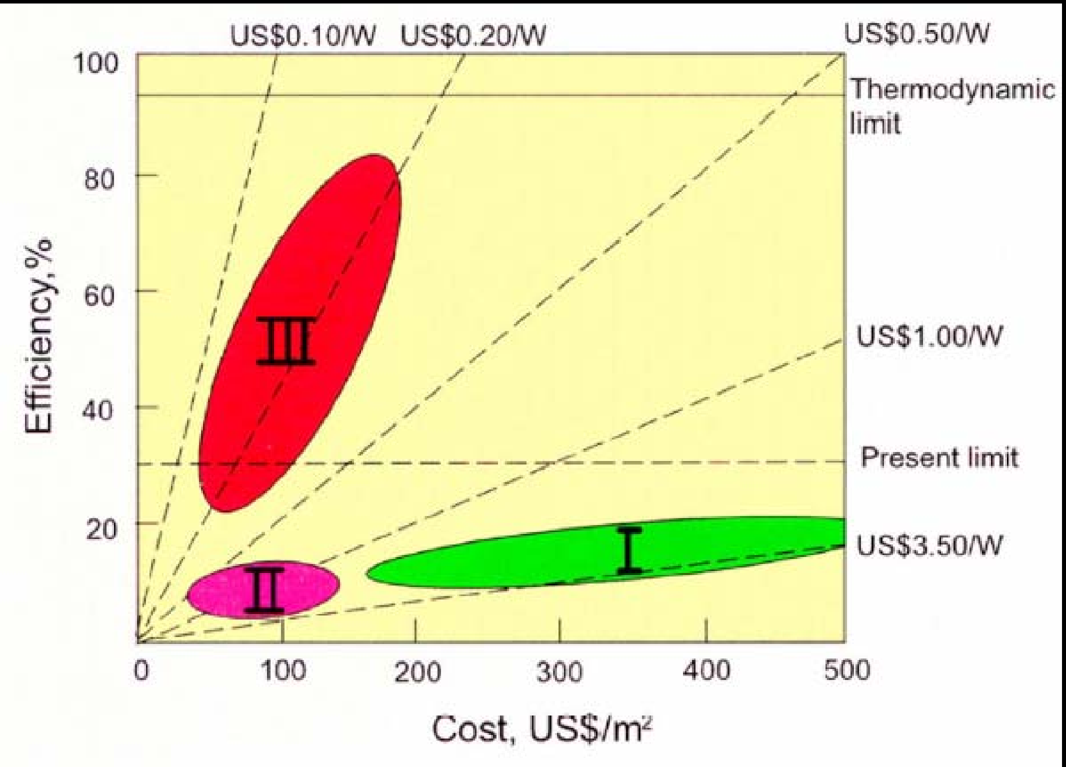


In 1914, Frank Shuman of Philadelphia was planning to build 50,000 km^2 of collectors in Sahara dissert. With present technology, such a plant can generate 2500 GW of electricity.

Solar Thermal



PV Costs



First generation (I): Crystalline PV

Second generation (II): Thin Film PV

Third generation (III): Based on nanotechnology using collections of atoms of semiconducting material. Films containing nanocrystalline structures and nanostructured conducting polymers are designed to absorb much of the solar spectrum. This technology will lead to PV cells made from thinly stacked plastic sheets converting solar energy to electricity with very high efficiency and at very low cost.

Photoelectrochemistry, an area of confluence between solar cell technology and battery or fuel cell technology, is playing role in the development of organic solar cells.

Solar Cell Power Conversion η

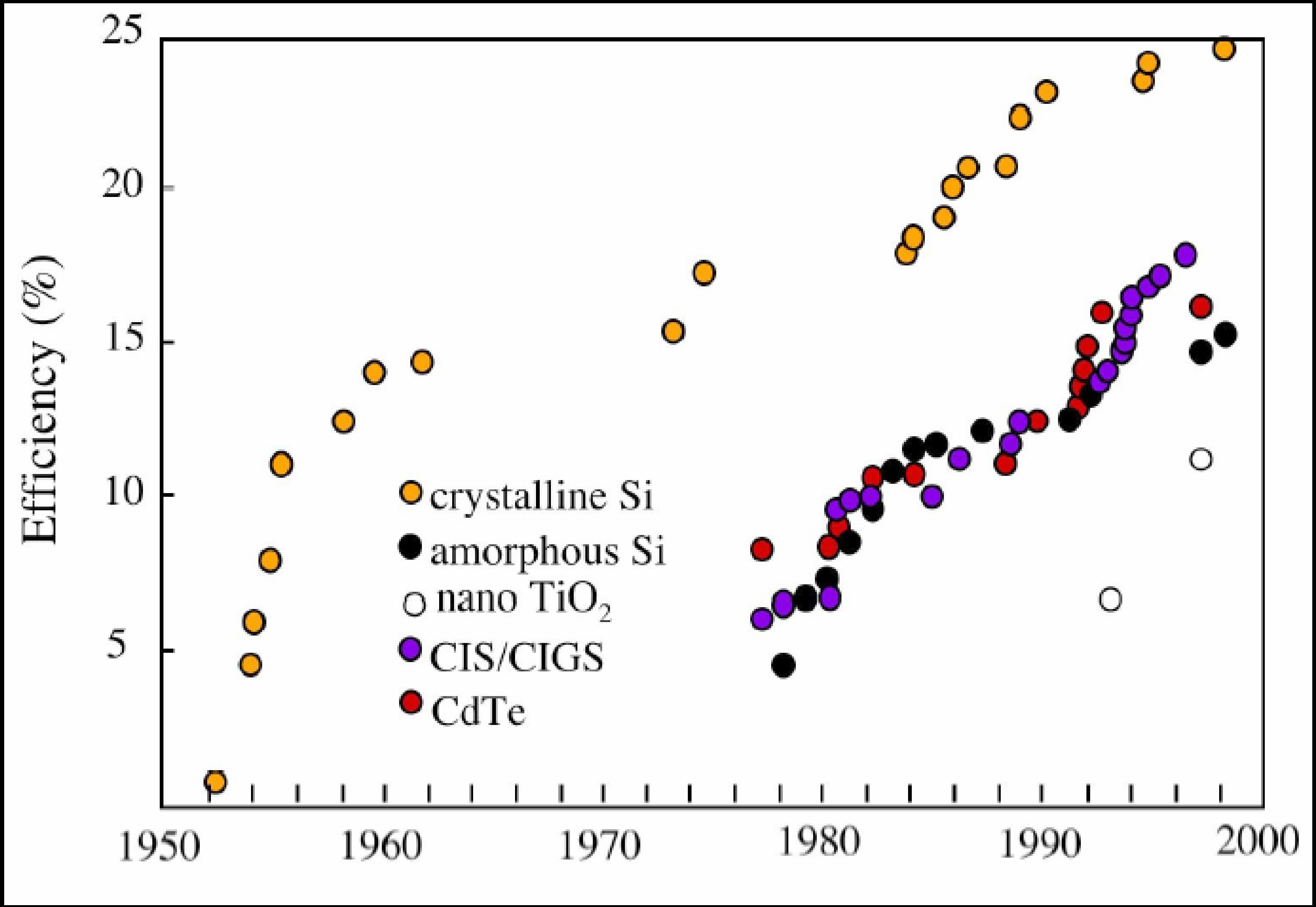
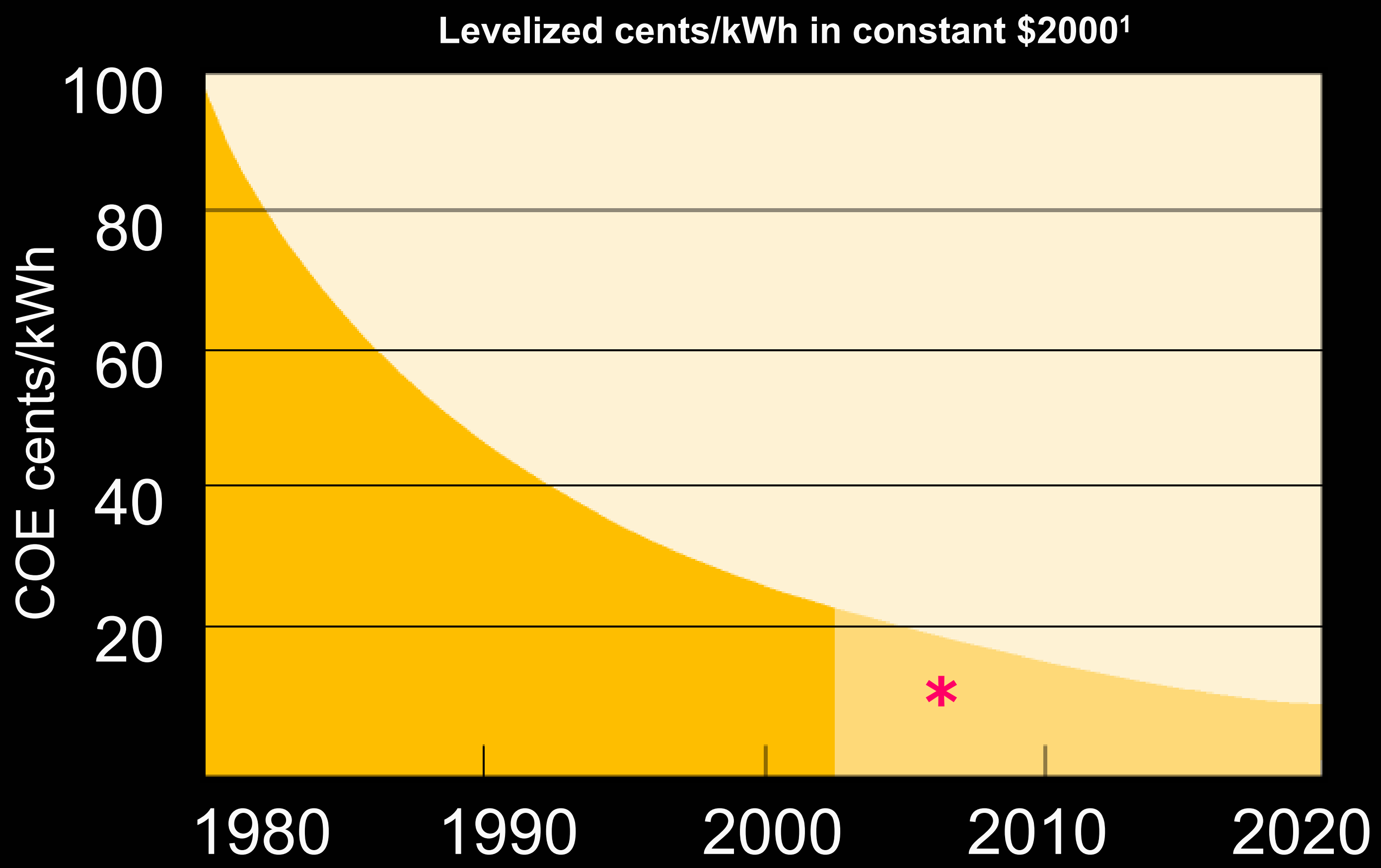


Figure 2 Power Conversion Efficiency Trends over Time for Different Kinds of Photovoltaic and Photoelectrochemical Devices (CIS = cadmium-indium-selenide; CIGS = cadmium-indium-gallium-selenide) (Source: Kazmerski 2001)

Photovoltaics



Cost of Photovoltaic Modules

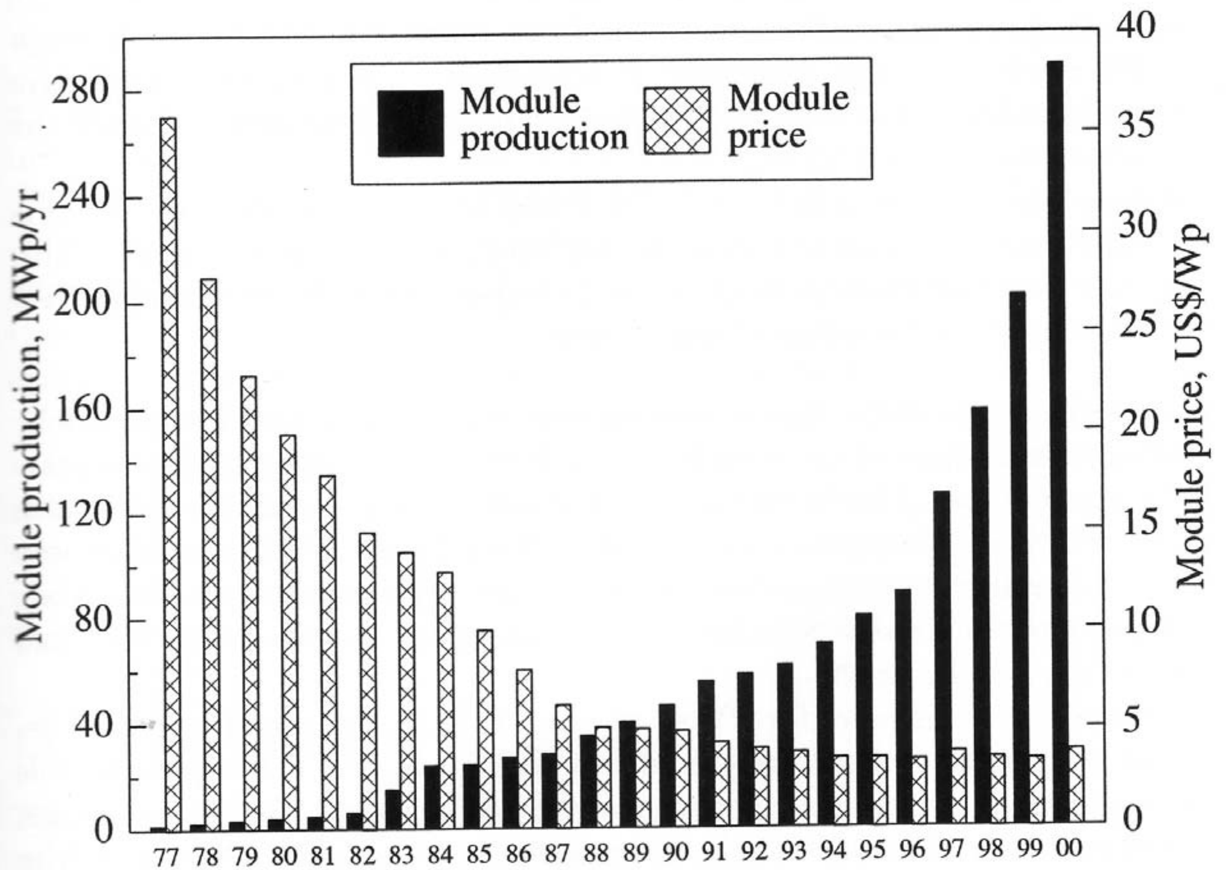


Fig. 1.1. Development of annual global PV module shipments and prices since 1977

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

Renewable Electricity Generation

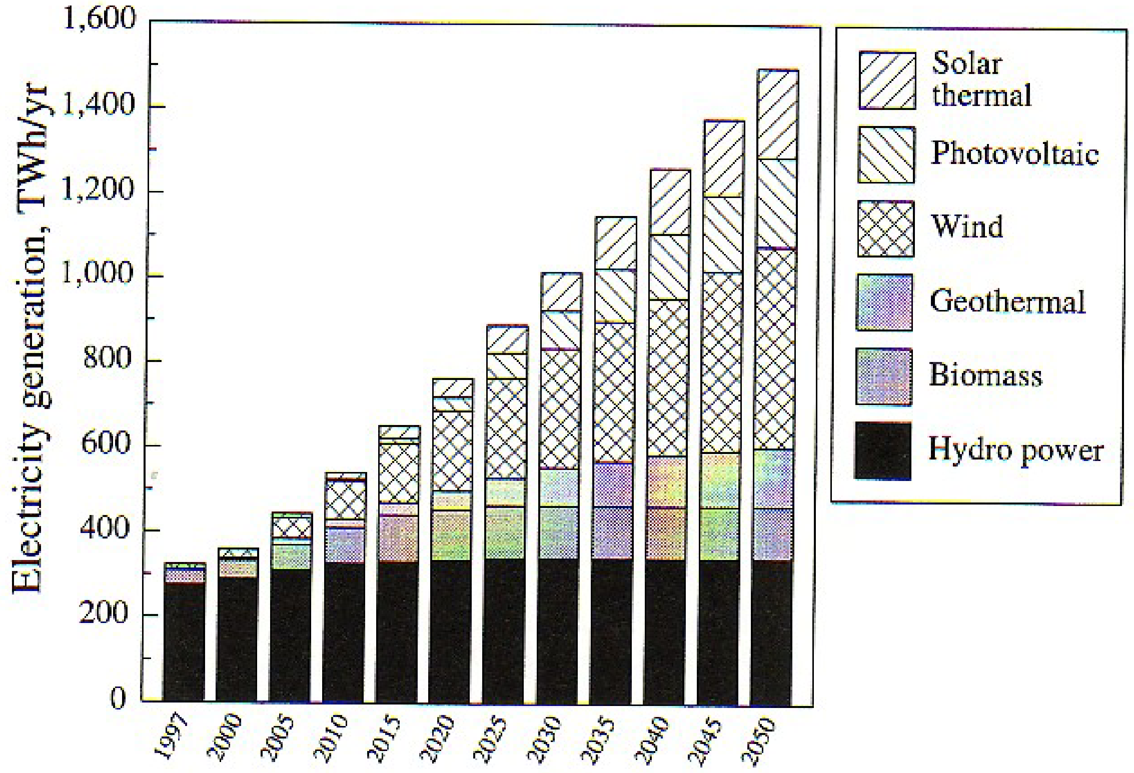


Fig. 1.14. Renewable electricity generation of EU 15 by shares of energy sources

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

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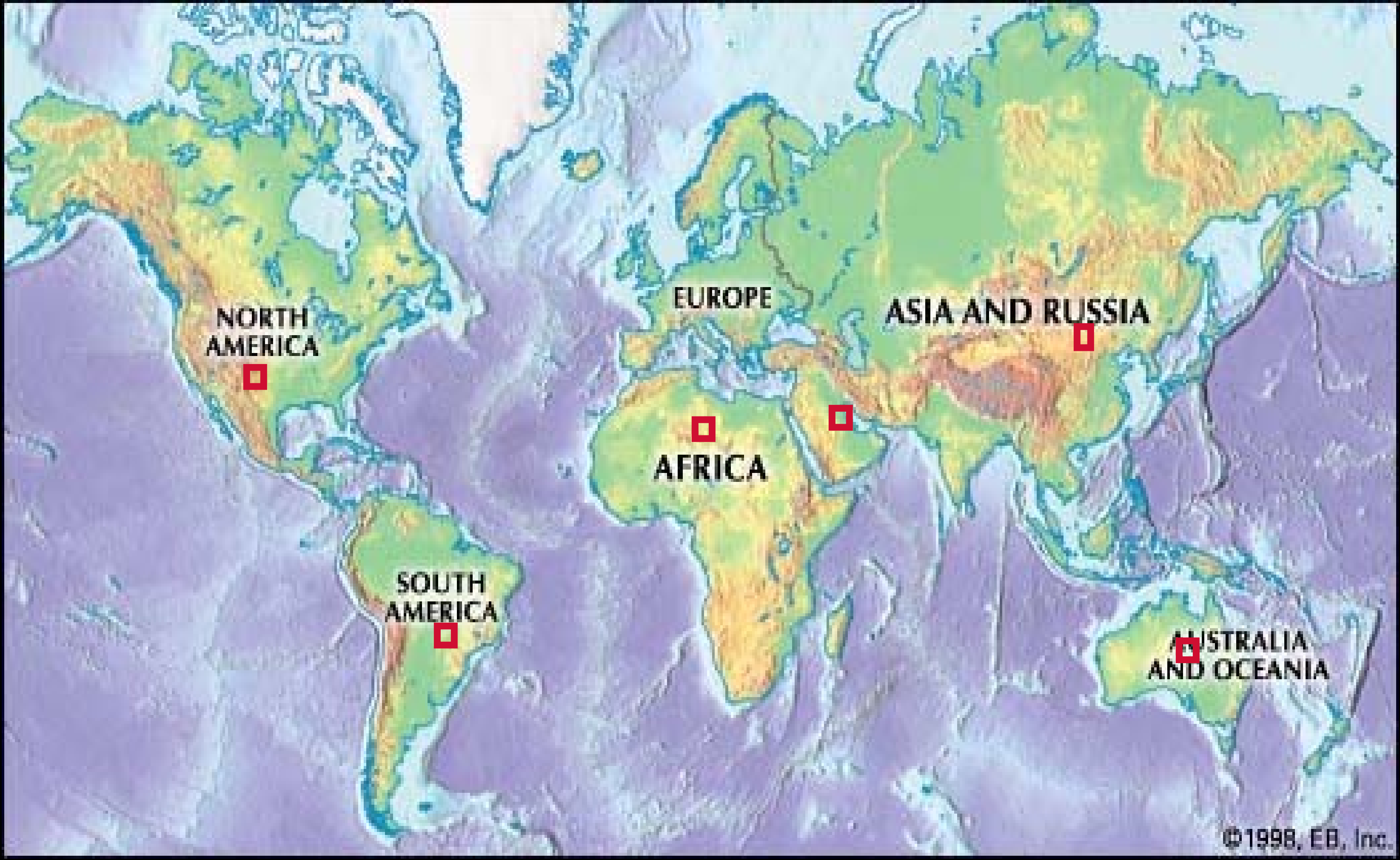
Solar Cell Land Area Required



6 Boxes at 3.3 TW Each = 20 TW

Source: Smalley, 2003

Summary

The solar technology is still in its infancy, comparable with the automobile of 1920's.

The future solar cells will be made of flexible materials capable of converting the entire solar radiation spectrum into electricity.

Cost reductions will result in massive use of solar electricity in a not too distant future.

Source: Smalley, 2003

Sustainable Energy:

The Solar Strategy

(Continued from Lecture 4)

Home work

Due on September 20, 2005

1. Compare the total purchase costs of a nominally 2.5 kW (peak) photovoltaic system for the following three choices of solar modules:

   a) First generation crystalline silicon modules of 15% energy conversion efficiency at a projected cost of $\$240/m^2$;

   b) Second generation thin film modules of 12% conversion efficiency at a projected cost of $\$60/m^2$;

   c) Third generation polymer modules of 50% conversion efficiency at a projected cost of $\$80/m^2$.

   Assume balance of system components, include everything in a photovoltaic system other than the photovoltaic modules, is about 60% of the total module cost.

   (Solar modules are normally given a rating under "peak" sunlight, corresponding to 1 kW/m^2 intensity)

Home work

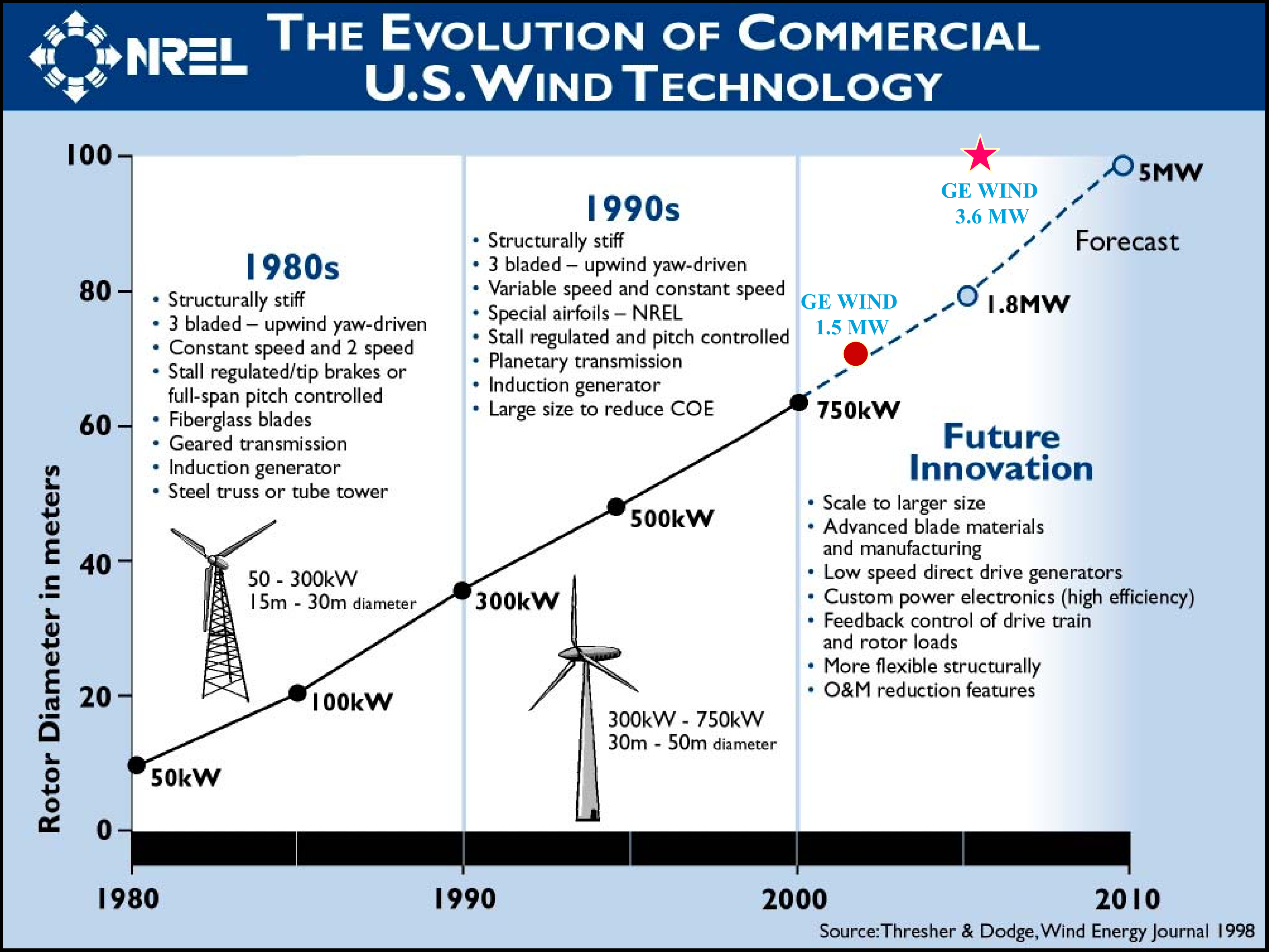
2. Estimate the cost of electricity ($/kWh) produced by two 1 kW BWC XL-1 turbines:

The total cost of the system is $15,000;

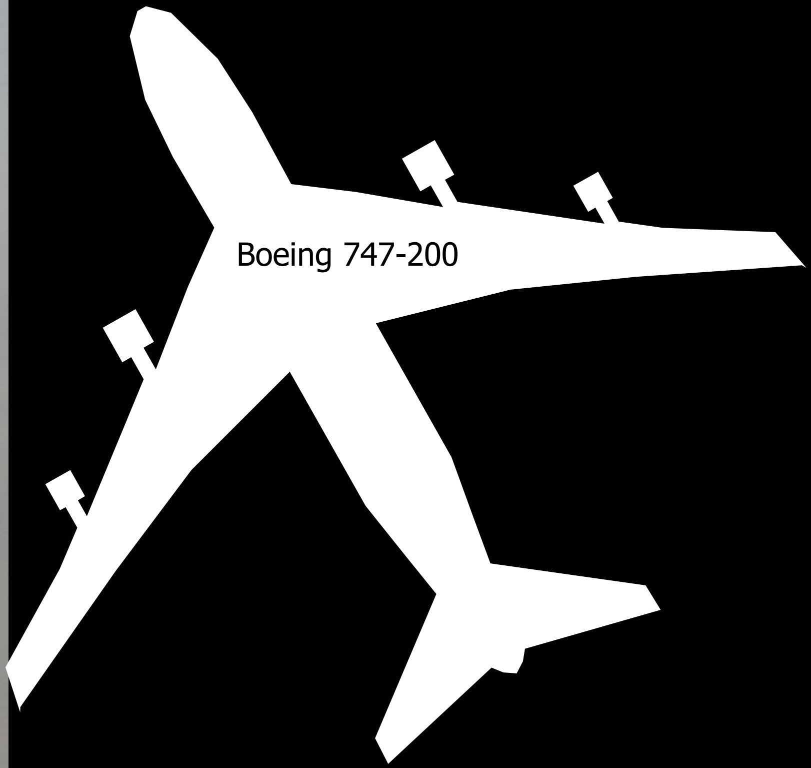
Depending on the wind resource, 160-400 kWh per month is produced;

12 hours to one week of back-up power is provided using battery storage.

Wind Power


NREL
THE EVOLUTION OF COMMERCIAL U.S. WIND TECHNOLOGY
Rotor Diameter in meters
100
80
60
40
20
0
1980
1990
2000
2010
1980s
• Structurally stiff
• 3 bladed – upwind yaw-driven
• Constant speed and 2 speed
• Stall regulated/tip brakes or full-span pitch controlled
• Fiberglass blades
• Geared transmission
• Induction generator
• Steel truss or tube tower
1990s
• Structurally stiff
• 3 bladed – upwind yaw-driven
• Variable speed and constant speed
• Special airfoils – NREL
• Stall regulated and pitch controlled
• Planetary transmission
• Induction generator
• Large size to reduce COE
Future Innovation
• Scale to larger size
• Advanced blade materials and manufacturing
• Low speed direct drive generators
• Custom power electronics (high efficiency)
• Feedback control of drive train and rotor loads
• More flexible structurally
• O&M reduction features
50 - 300kW
15m - 30m diameter
300kW - 750kW
30m - 50m diameter
50kW
100kW
300kW
500kW
750kW
1.8MW
5MW
Forecast
GE WIND 1.5 MW
GE WIND 3.6 MW
Source: Thresher & Dodge, Wind Energy Journal 1998

Large Scale Wind Turbine



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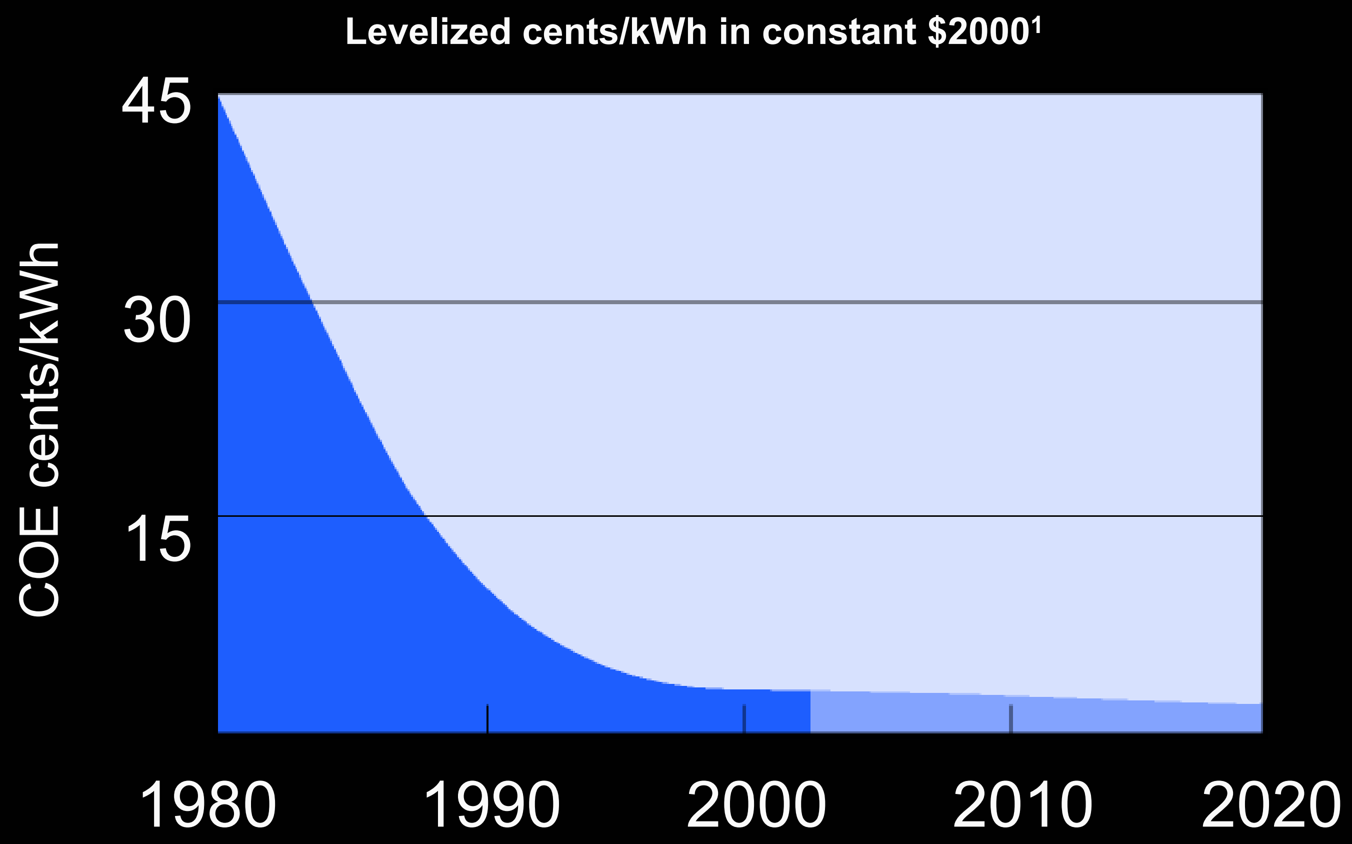
Wind Energy Costs Trends



Source: NREL Energy Analysis Office

[1]These graphs are reflections of historical cost trends NOT precise annual historical data.

Updated: June 2002

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*

12% of world electricity generation

* According to Wind Force 12

US Wind Energy Installations

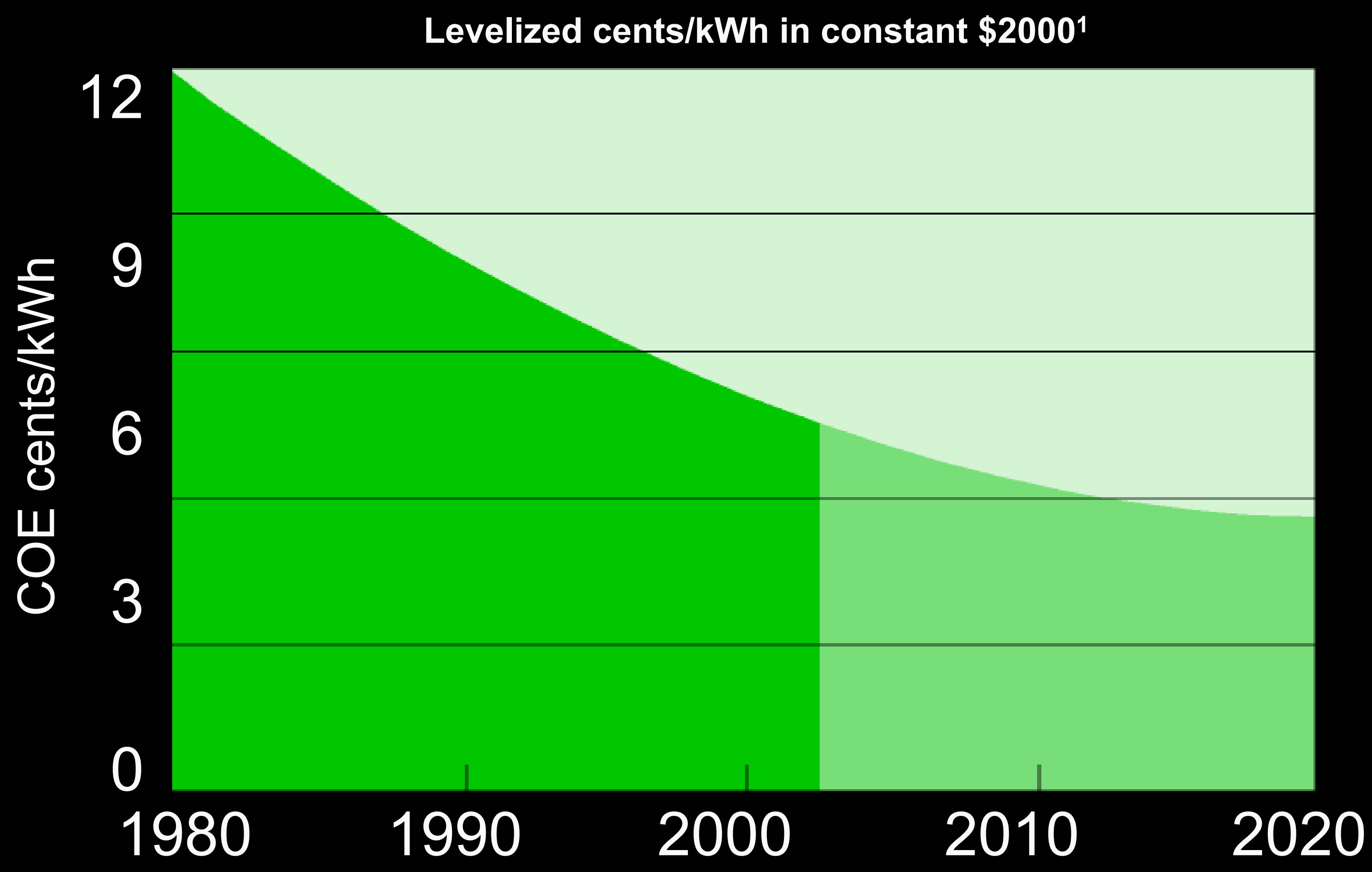
States with most wind energy installed, by capacity (MW)

1 California - 2,096 MW
2 Texas - 1,293 MW
3 Minnesota - 615 MW
4 Iowa - 632 MW
5 Wyoming - 285 MW

Largest wind farms operating the U.S. (MW)

1 Stateline, Oregon-Washington - 300 MW
2 King Mountain, Texas - 278 MW
3 New Mexico Wind Energy Center, New Mexico - 204 MW
4 Storm Lake, Iowa - 193 MW
5 Colorado Green, Colorado - 162 MW
6 High Winds, California - 162 MW

Biomass


Levelized cents/kWh in constant $2000[1]
COE cents/kWh
12
9
6
3
0
1980
1990
2000
2010
2020

Power Cost

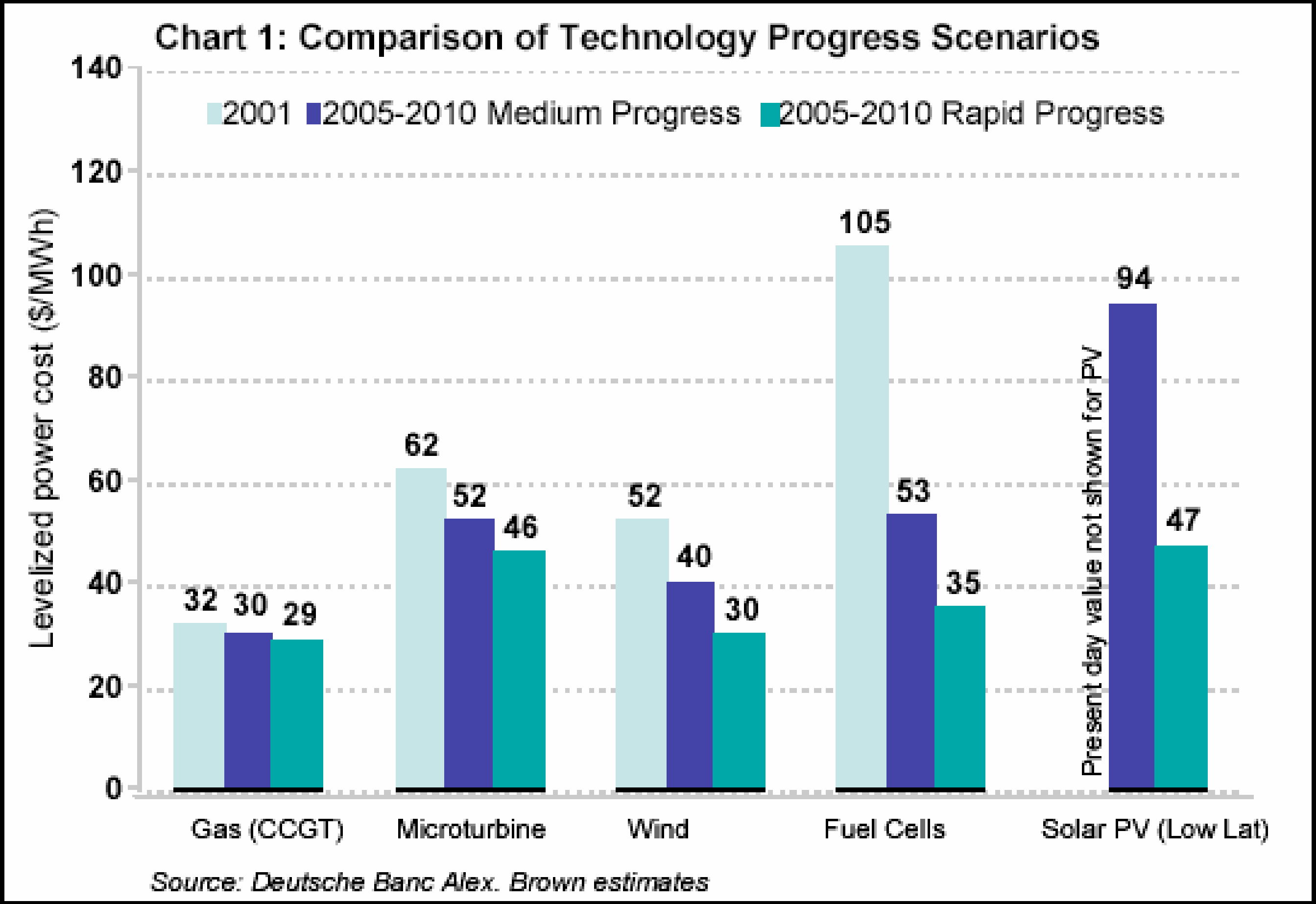


Chart 1: Comparison of Technology Progress Scenarios
2001
2005-2010 Medium Progress
2005-2010 Rapid Progress
Levelized power cost ($/MWh)
140
120
100
80
60
40
20
0
32
30
29
62
52
46
52
40
30
105
53
35
94
47
Present day value not shown for PV
Gas (CCGT)
Microturbine
Wind
Fuel Cells
Solar PV (Low Lat)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

Electricity Generation Costs - 2004

	¢/kWh
Combined cycle gas turbine	3-5
Wind	4-7
Biomass gasification	7-9
Remote diesel generation	20-40
Solar PV central station	20-30
Solar PV distributed	20-50

Non-solar Renewable Energy

Tidal energy:

The power of the tides is harnessed by building a low dam or barrage in which the rising waters are captured and allowed to flow back through electricity generating turbines.

Geothermal energy:

Heat from within the earth is the source. Hot rocks near the surface can heat water in underground aquifers to provide hot water or steam.

Renewable Energy Technologies

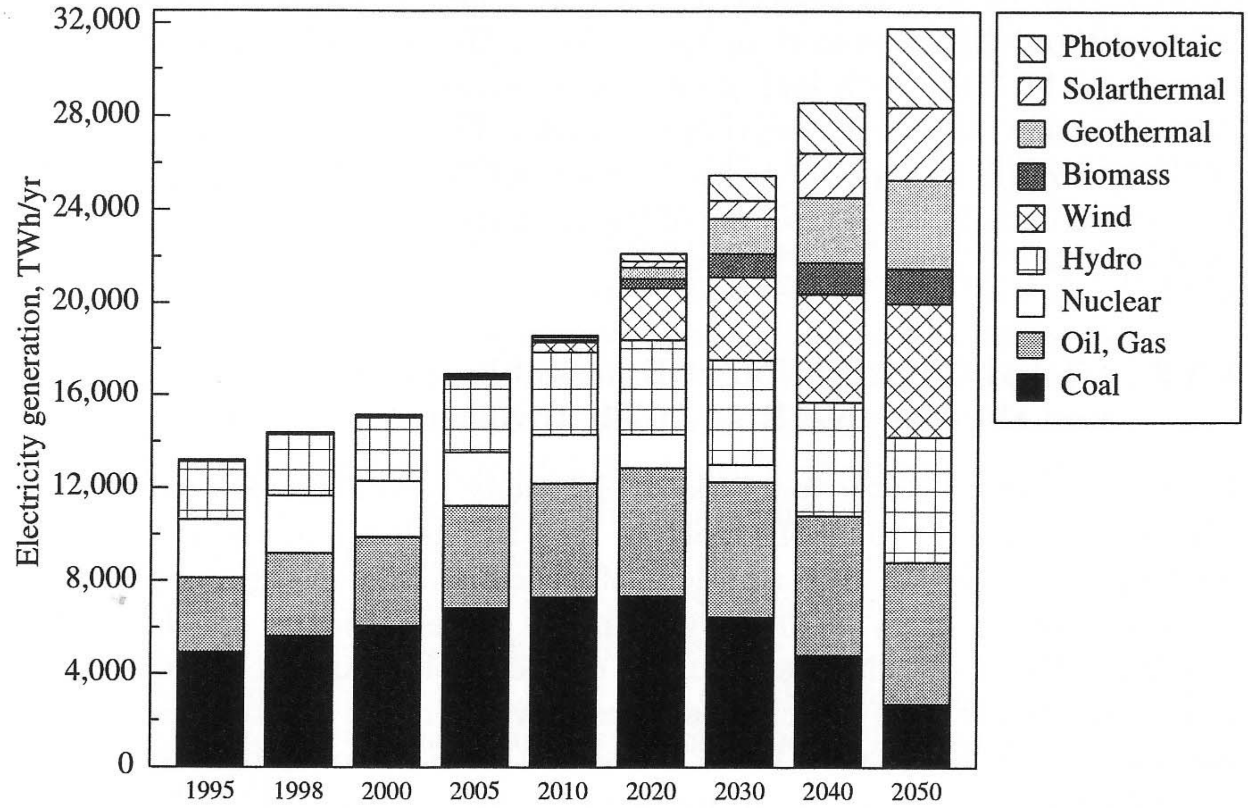


Fig. 1.11. Growth of renewable energy technologies in the "Solar Energy Economy" scenario until 2050

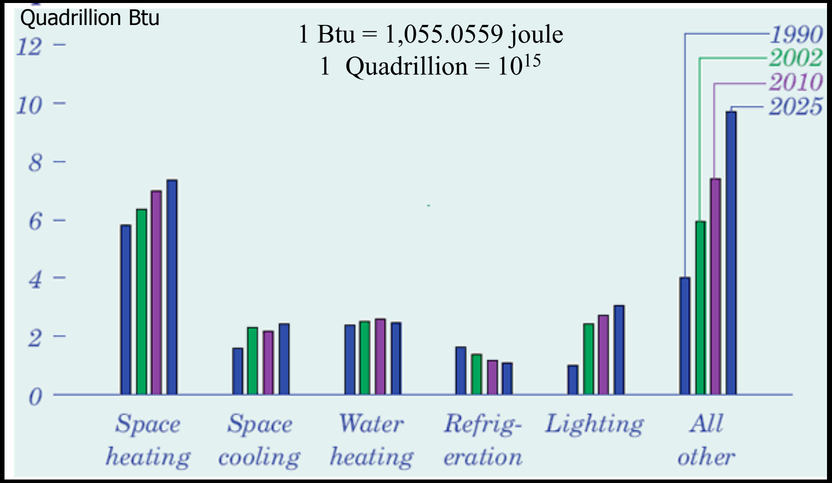
Source: Photovoltaics Guide book for Decision makers by Bubenzer and Luther; Springer, 2003

Solar Heating

Domestic active solar heating:

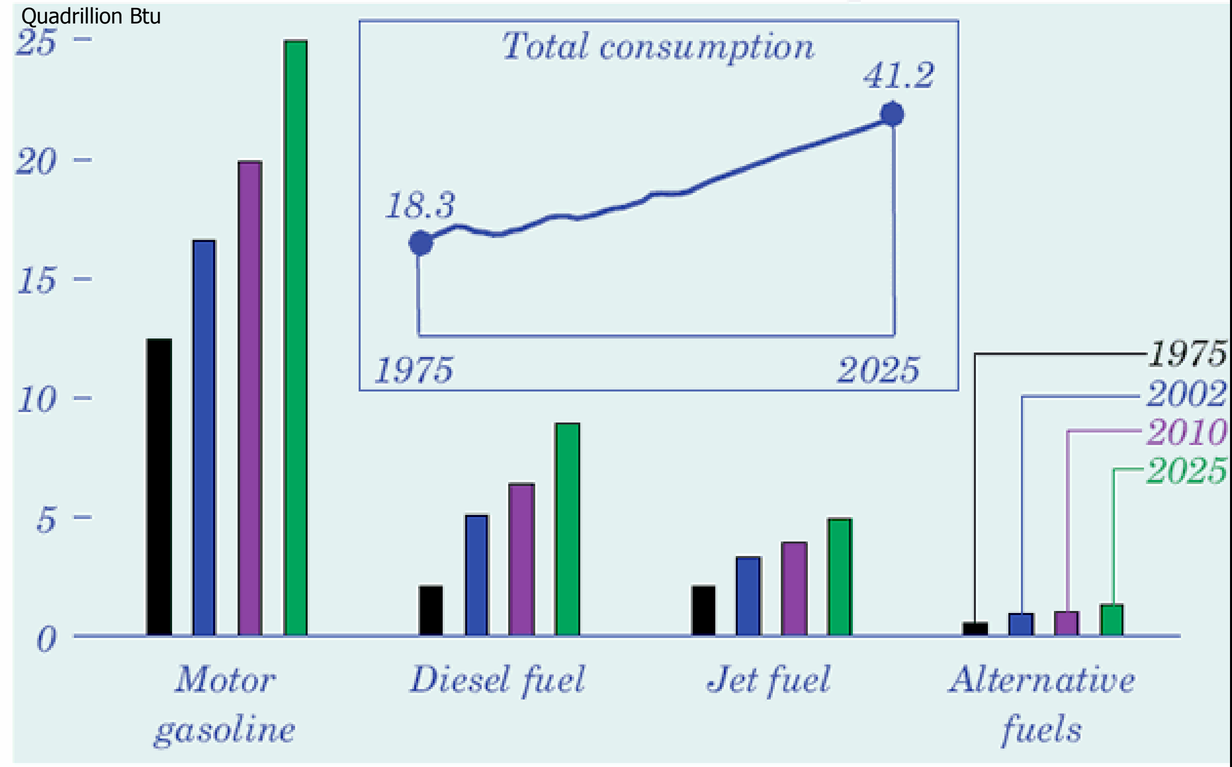
Space heating - Cost effective to invest in home insulation. District heating - distributing heat from waste heat from power generating plants.

Water heating: passive solar thermal systems



Source: Annual Energy outlook - 2004, Energy Information Administration

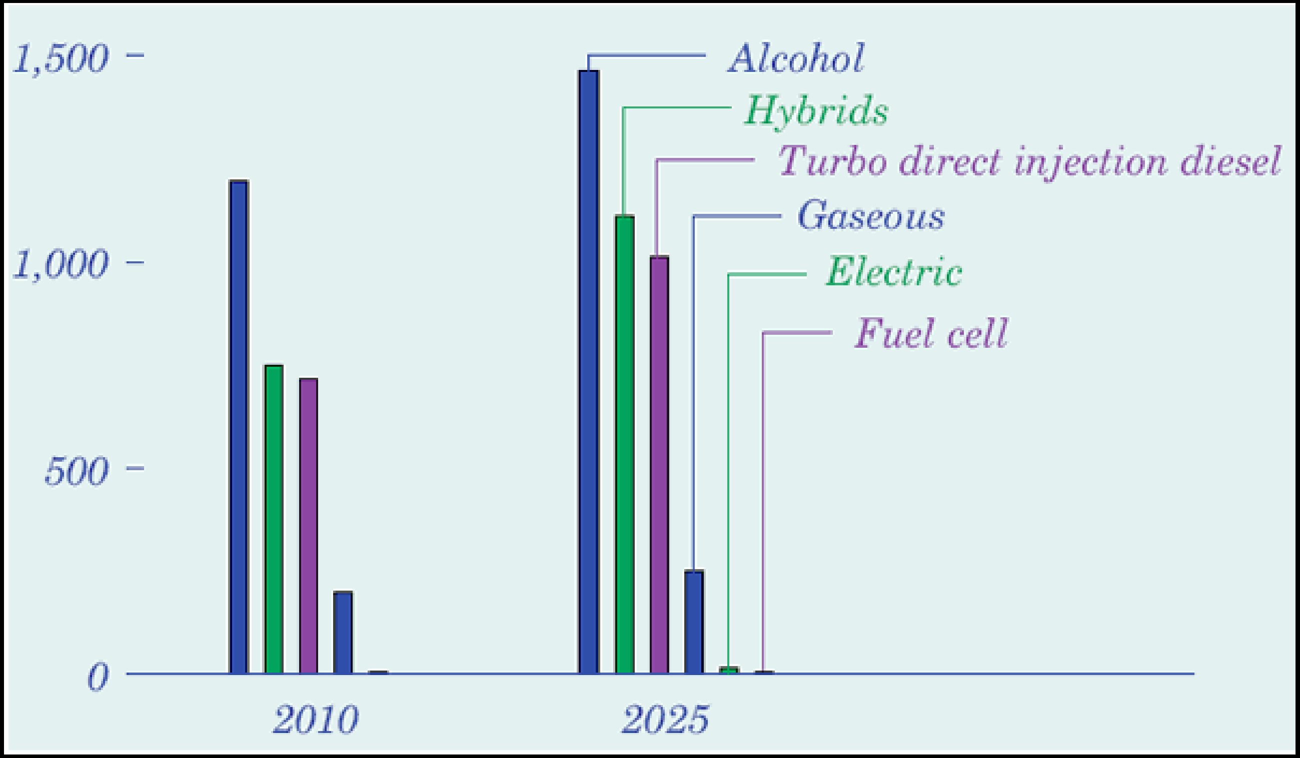
Transportation Energy Consumption



Source: Annual Energy outlook - 2004, Energy Information Administration

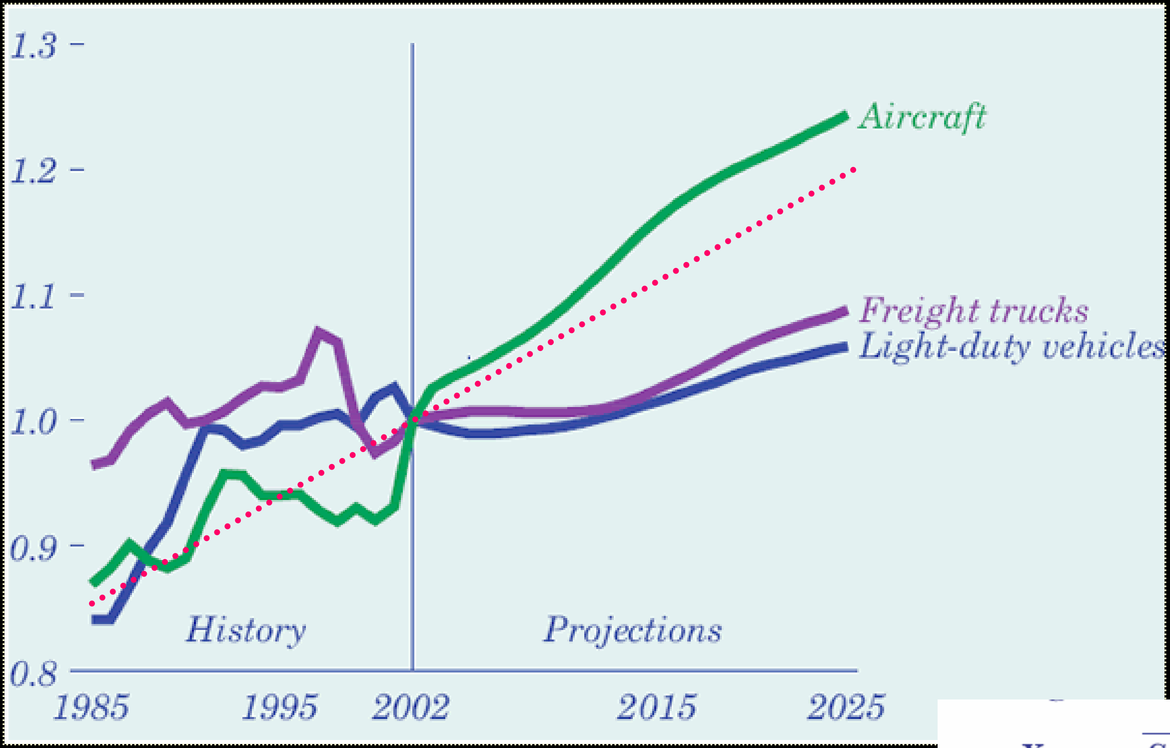
Light Duty Vehicles by Fuel Type

Thousands of Vehicles sold



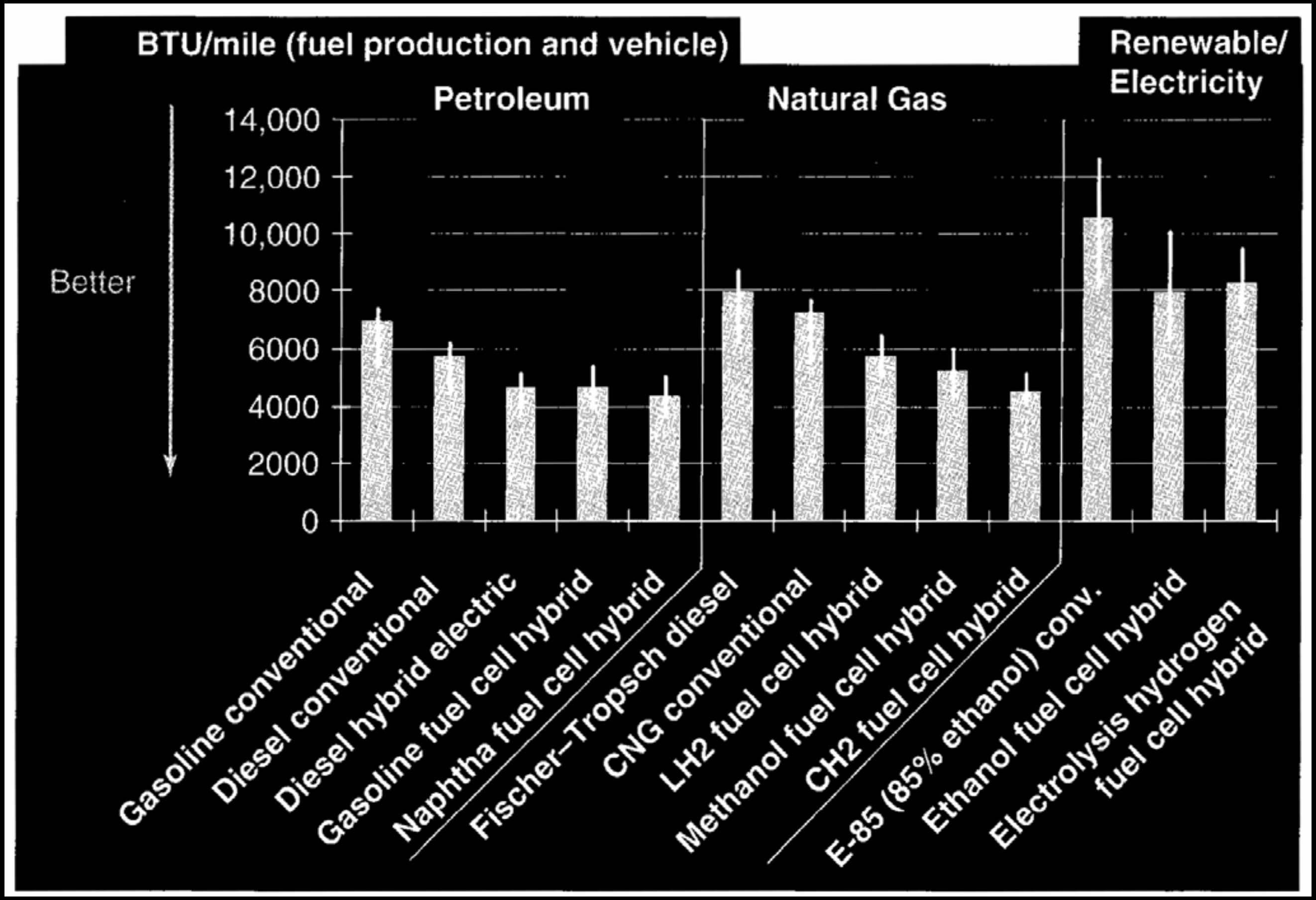
Source: Annual Energy outlook - 2004, Energy Information Administration

Transportation Fuel Efficiency



Year	Cars			Light trucks		
	Small	Medium	Large	Small	Medium	Large
1990						
Horsepower	119	145	176	132	157	185
Sales share	0.60	0.28	0.12	0.48	0.21	0.30
2000						
Horsepower	145	177	221	173	185	229
Sales share	0.50	0.35	0.15	0.30	0.34	0.36
2010						
Horsepower	176	217	251	213	216	280
Sales share	0.50	0.35	0.15	0.30	0.34	0.35
2025						
Horsepower	192	237	269	224	221	286
Sales share	0.50	0.35	0.15	0.30	0.34	0.35

Performance



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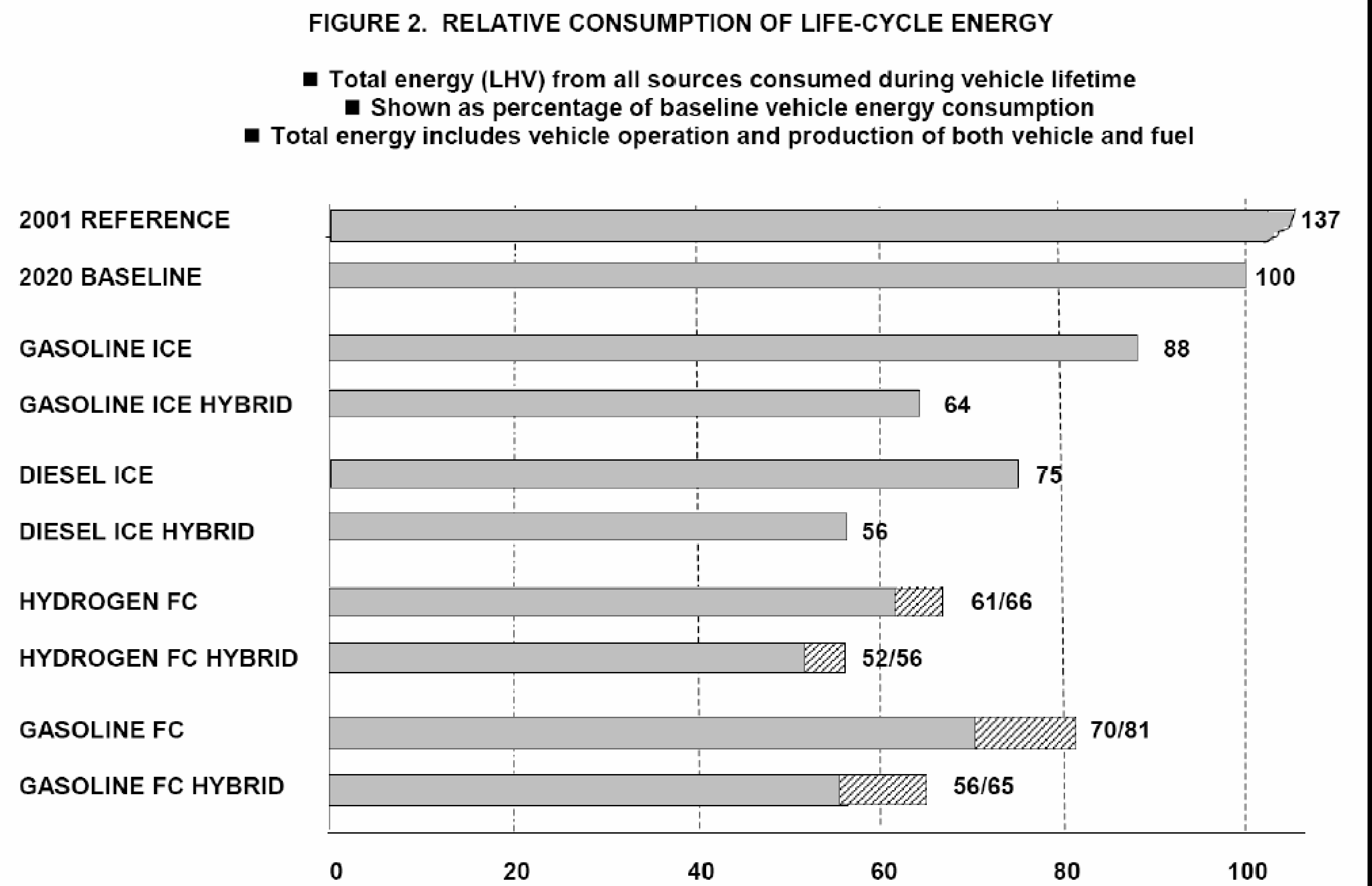
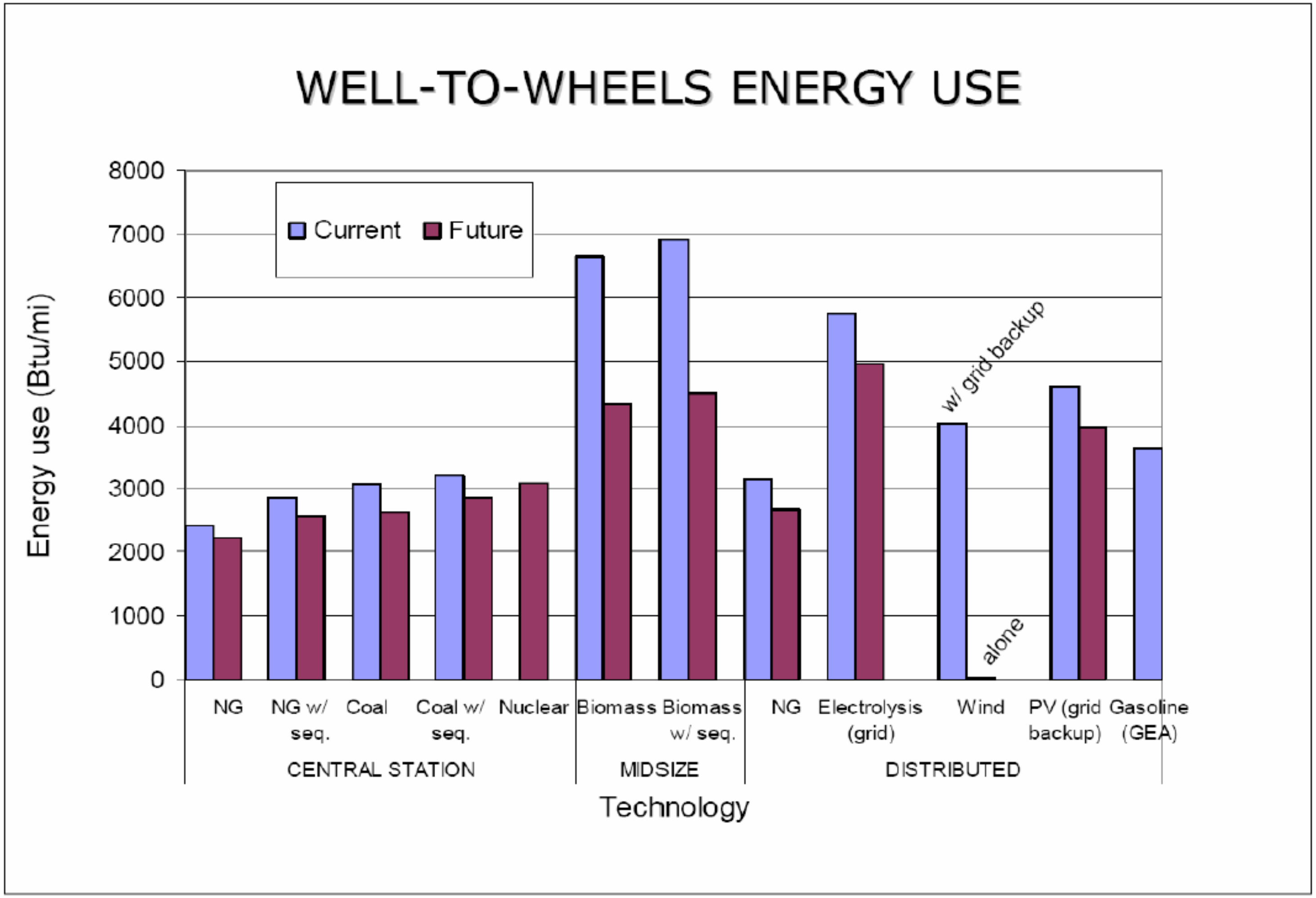
Vehicle Life Time Energy Consumption



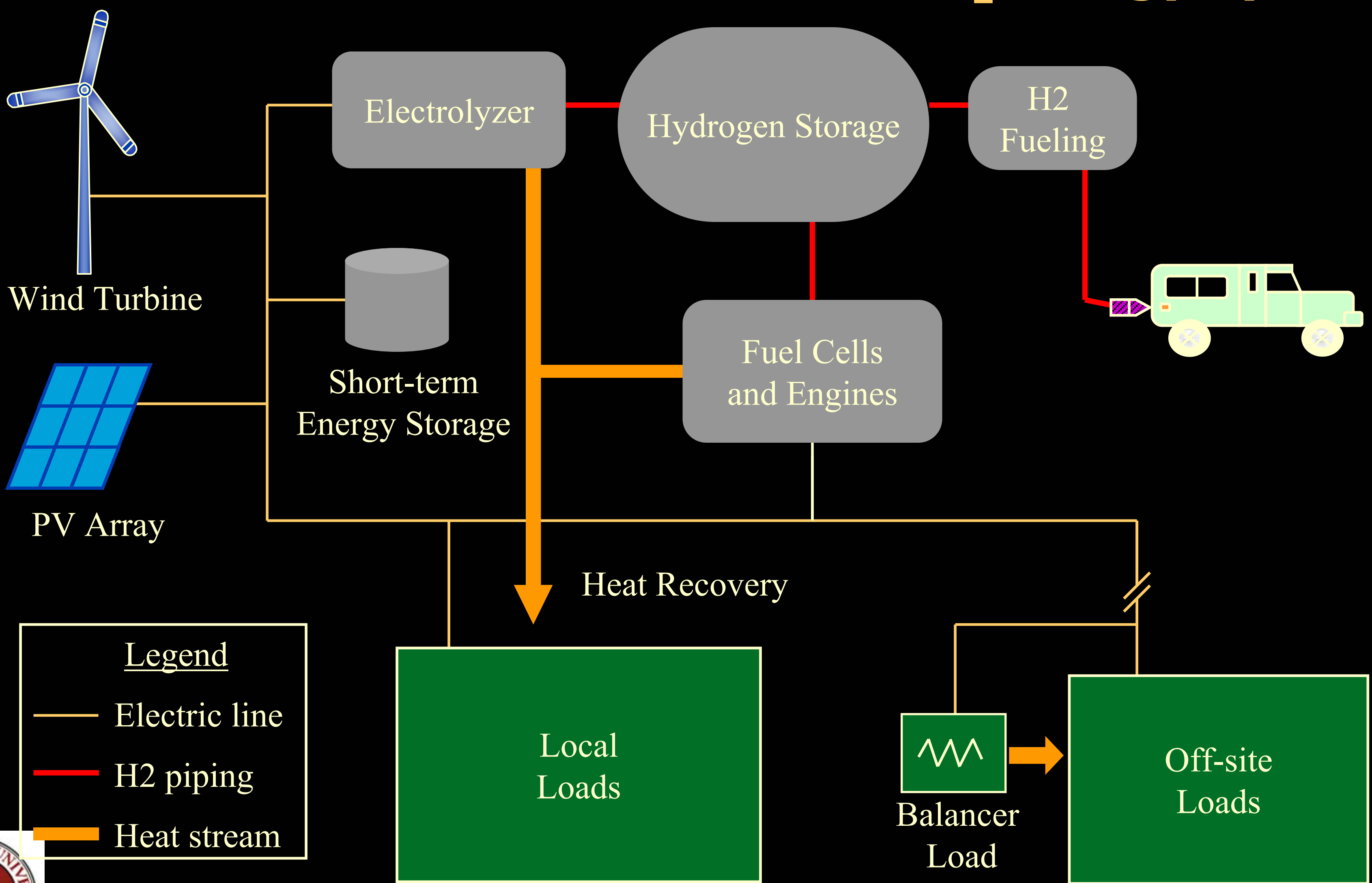
Source: Weiss et al., "Comparative Study of Fuel Cell Cars", MIT Energy Laboratory (2003)

Vehicle Total Energy Use



Source: M. Ramage et al., The Hydrogen Economy…, National Academy of Engineering, 2004

Renewable H_2 Energy System



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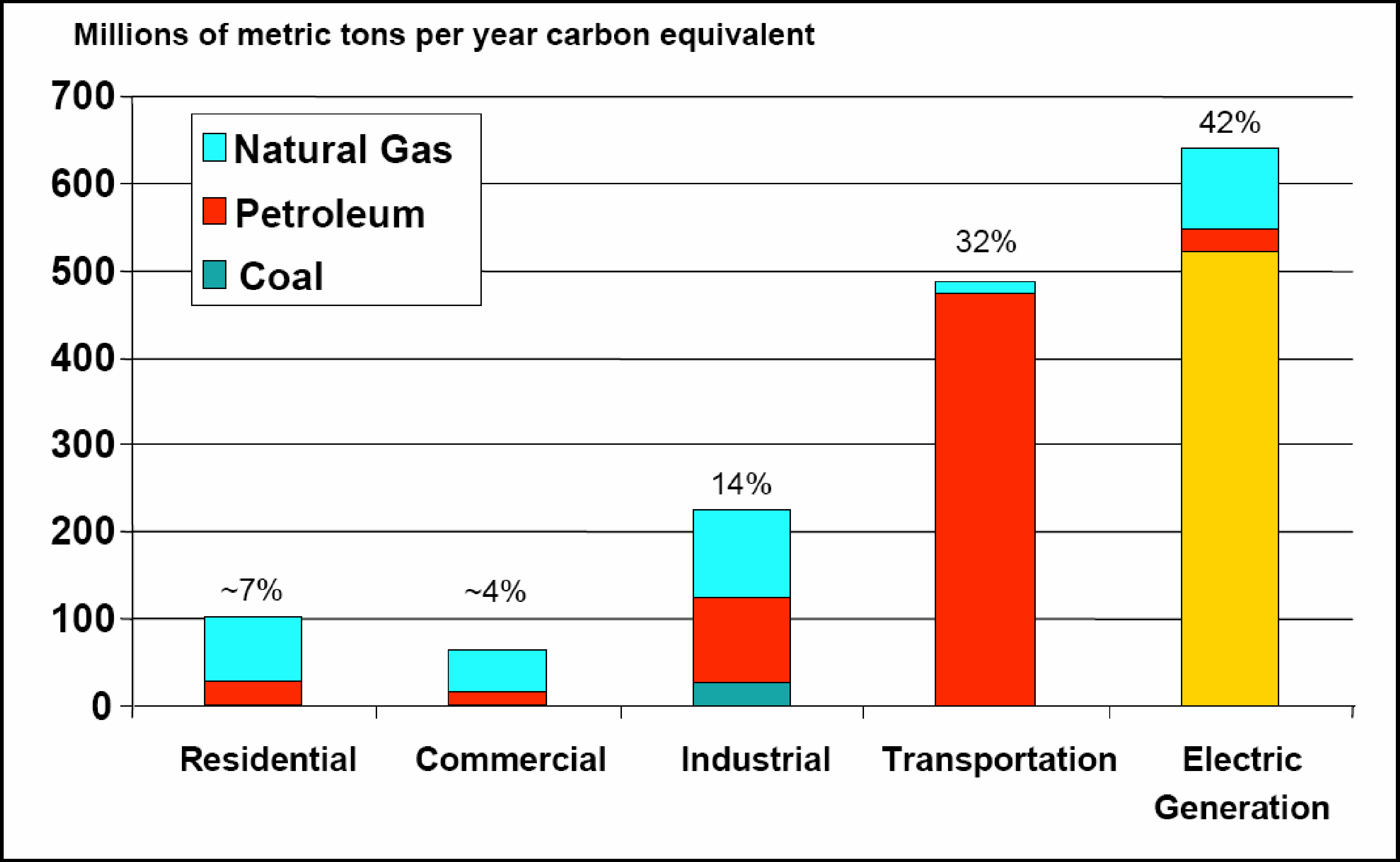
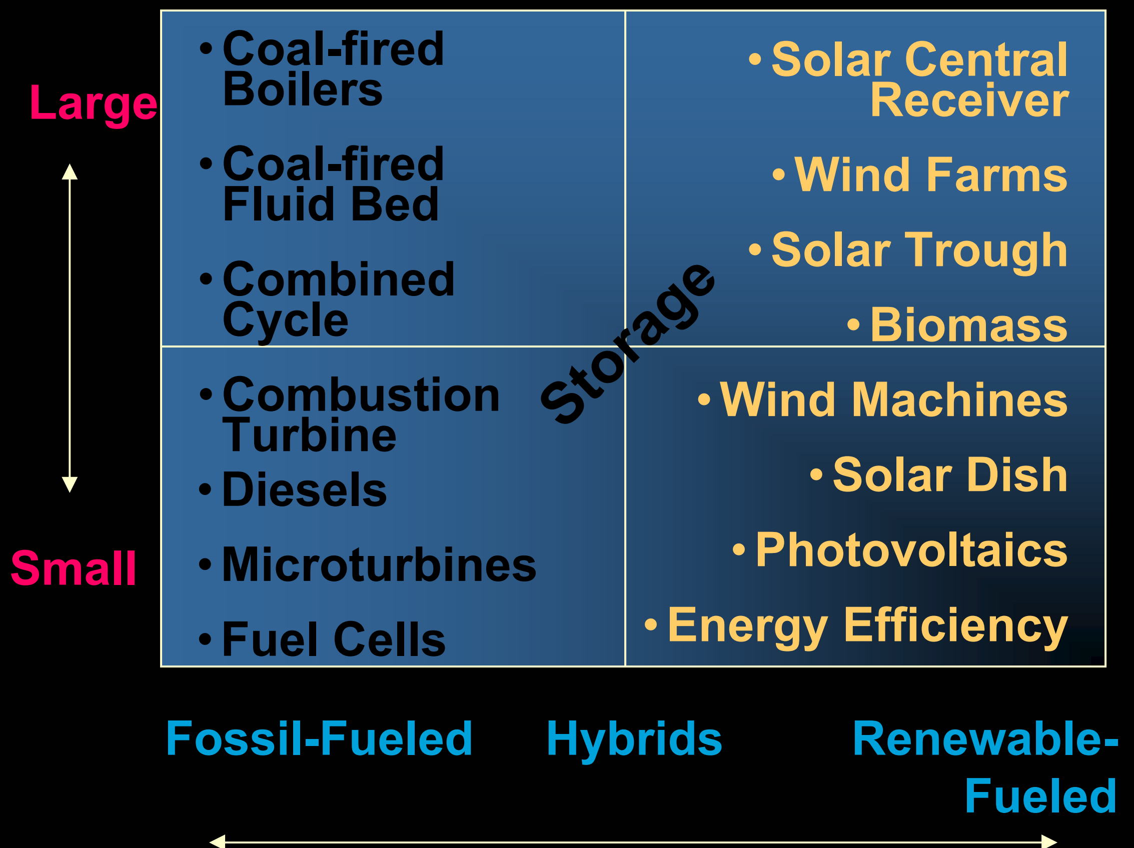
US CO_2 Emissions in 2000

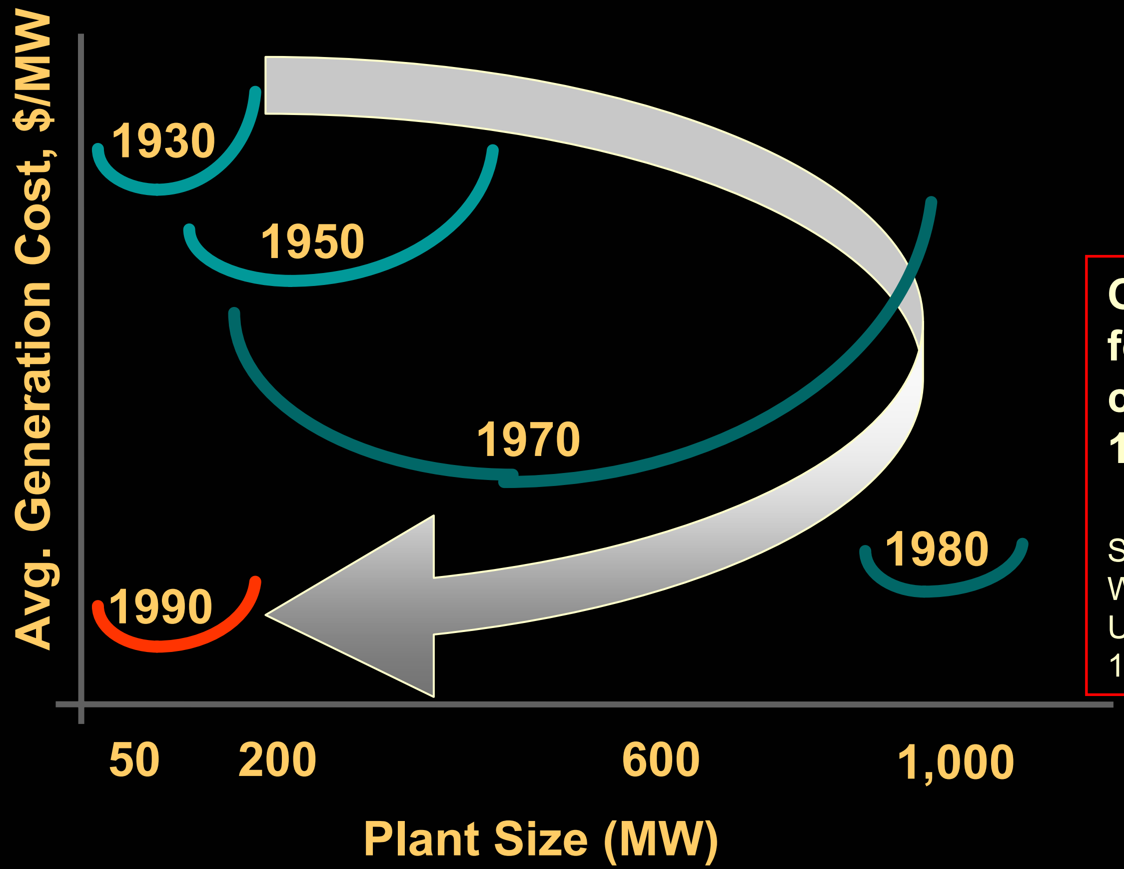


Fossil and Renewable Energy Domains



Source: Mervin Brown, NREL

Micropower

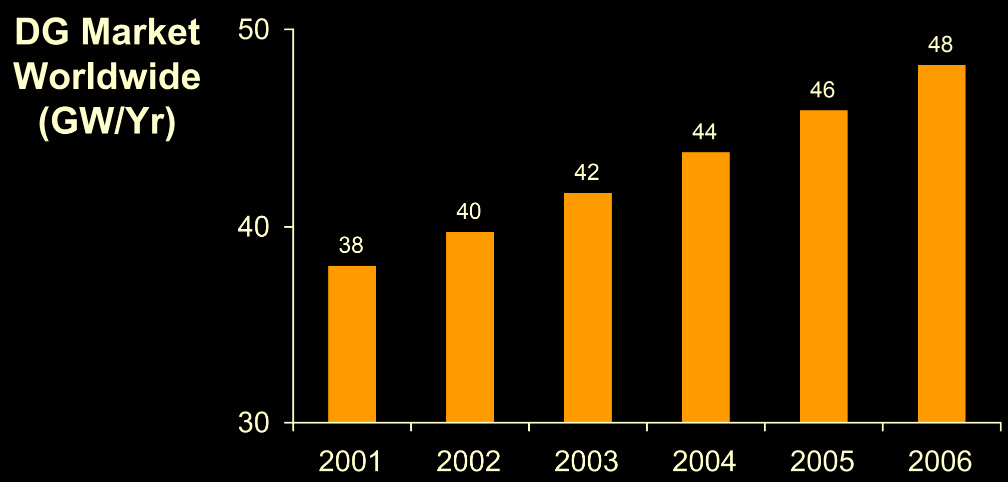


Optimal generation plant size for a single plant based on cost per megawatt [MW], 1930-1990

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

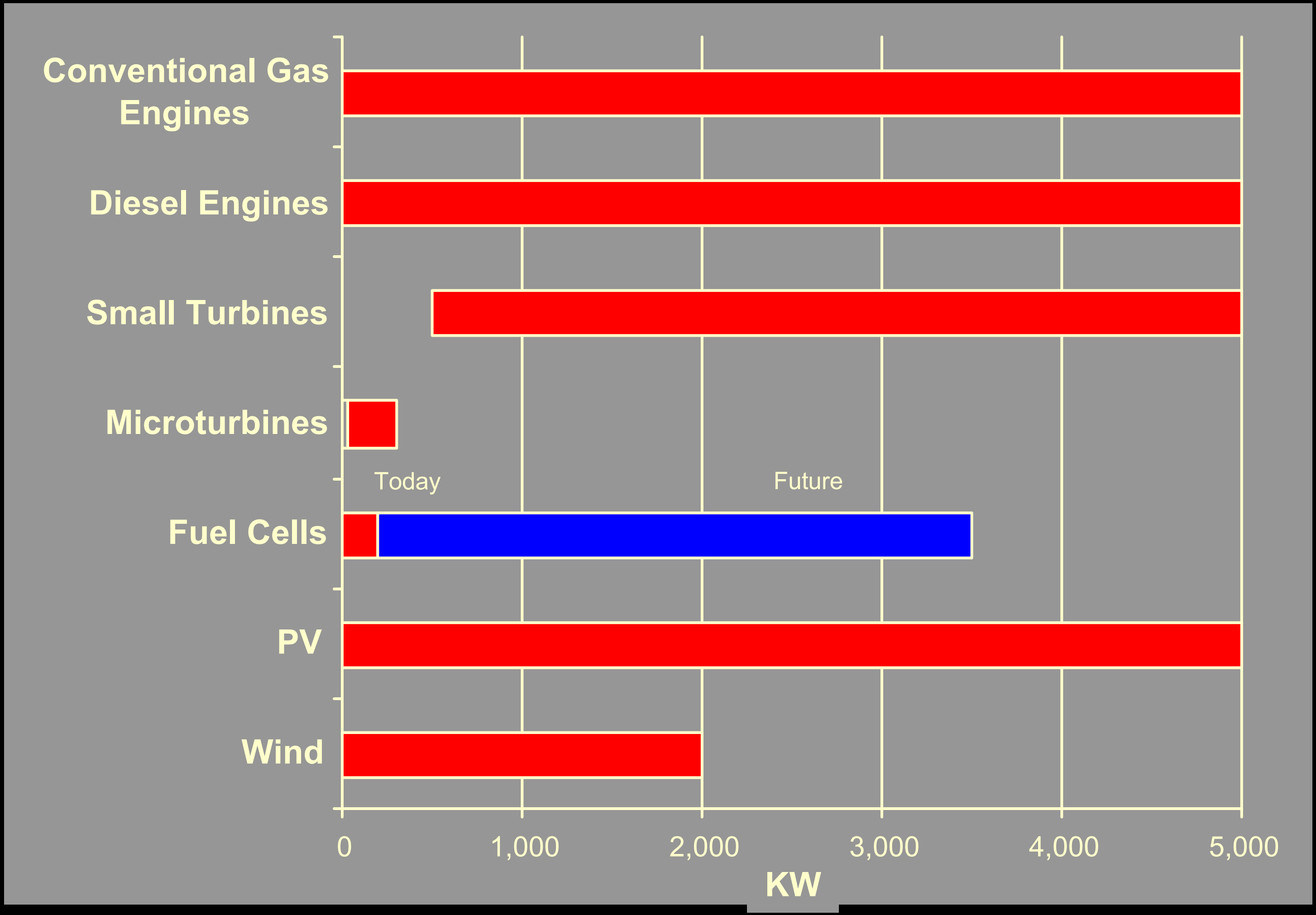


Deregulation
Quality/reliability power demand
Environment concerns
Distribution constraints
Flexibility to add capacity

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

Source: John Cassidy, United Technologies Corp.

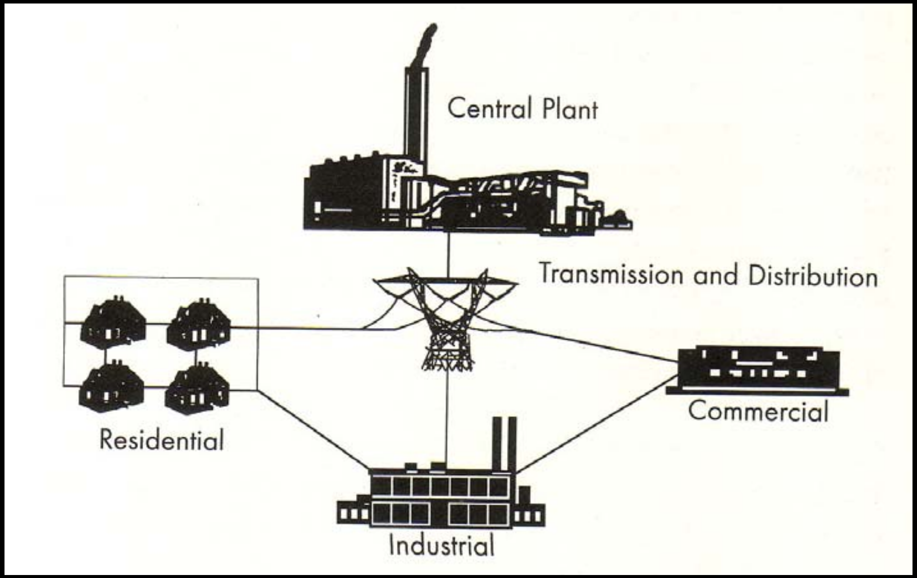
Power Output Ranges



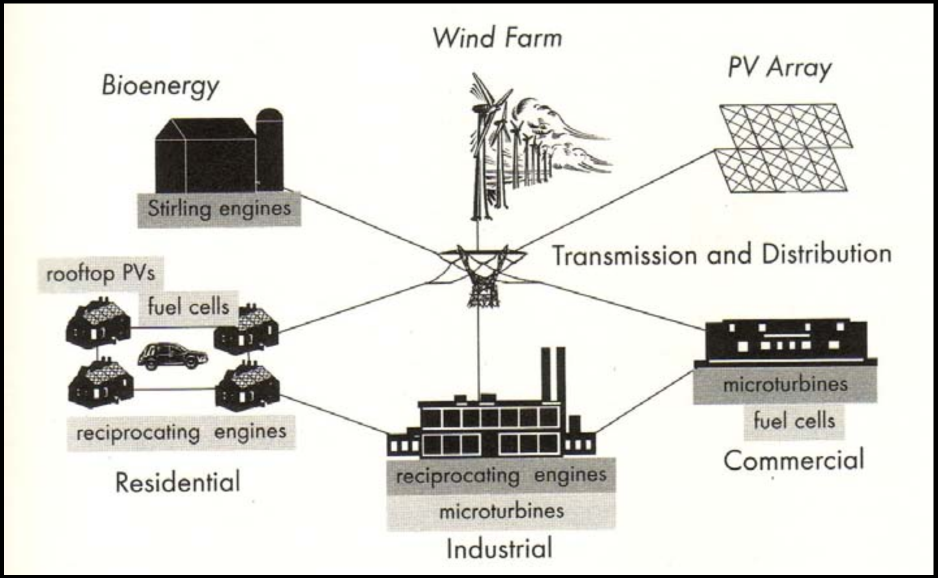
Sources: Arthur D. Little, 01/2000; Resource Dynamics Corp. 02/2001 and UTC estimates

Future Power System

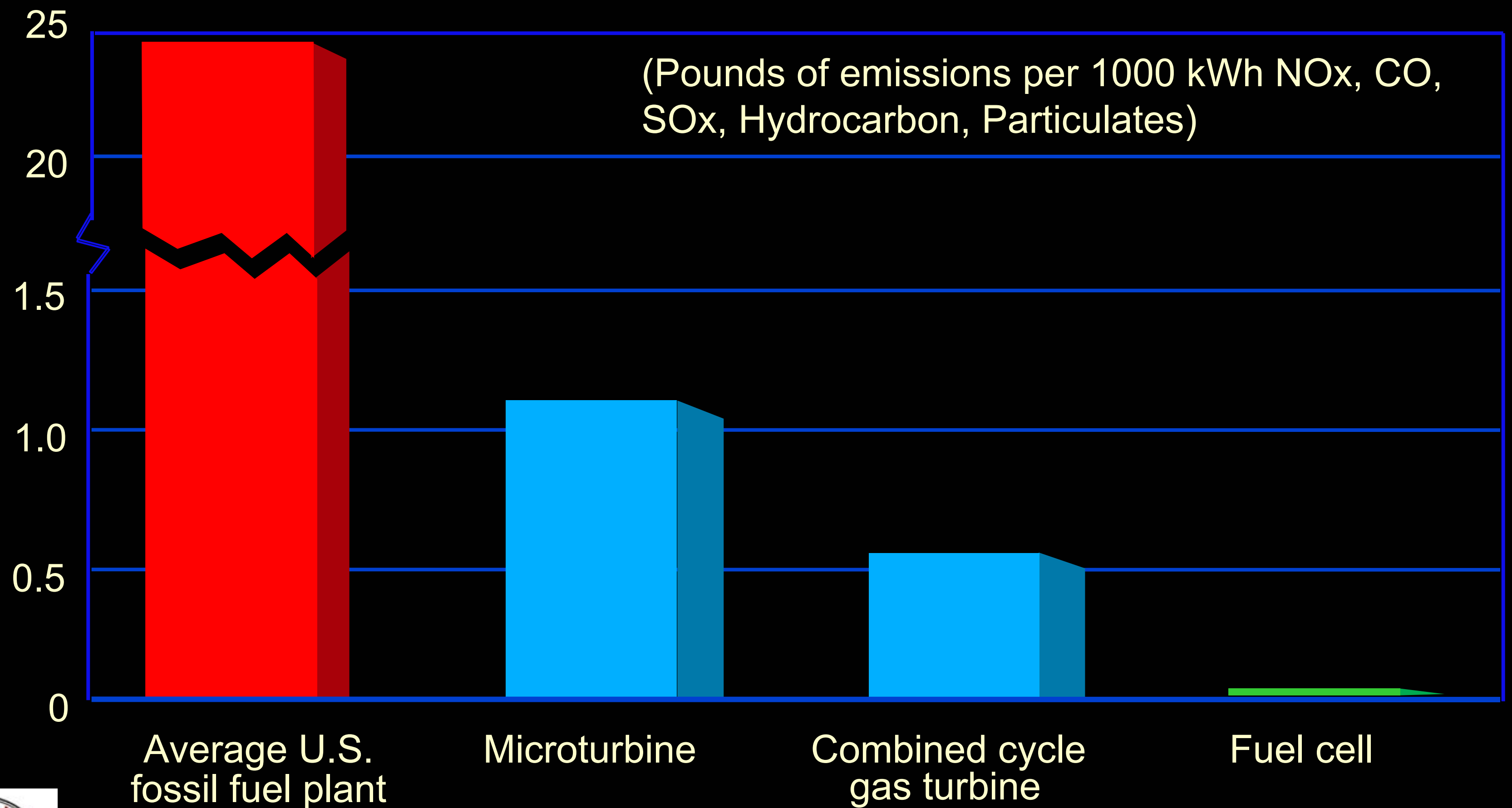
Centralized Power System



Distributed Power System

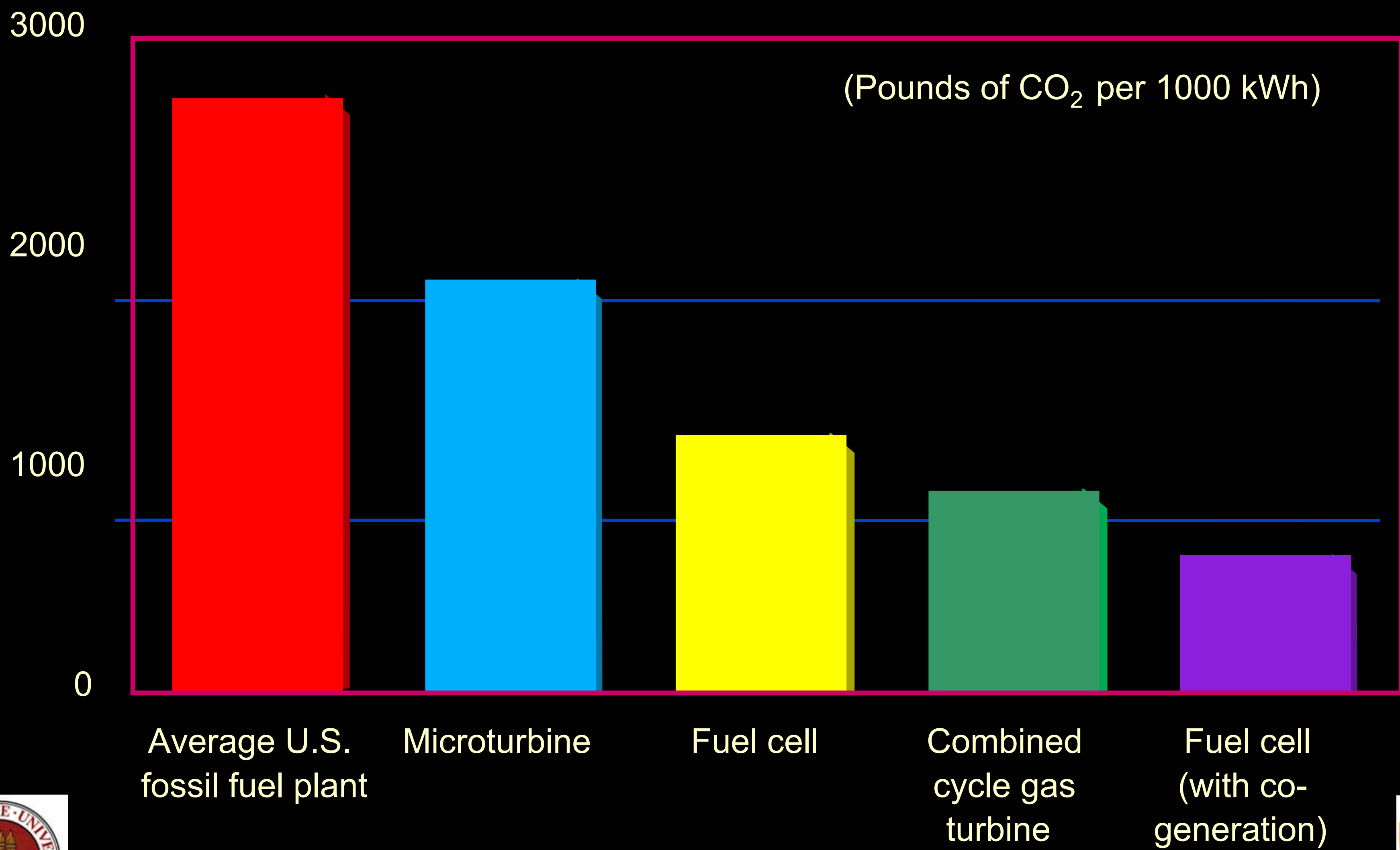


Emissions



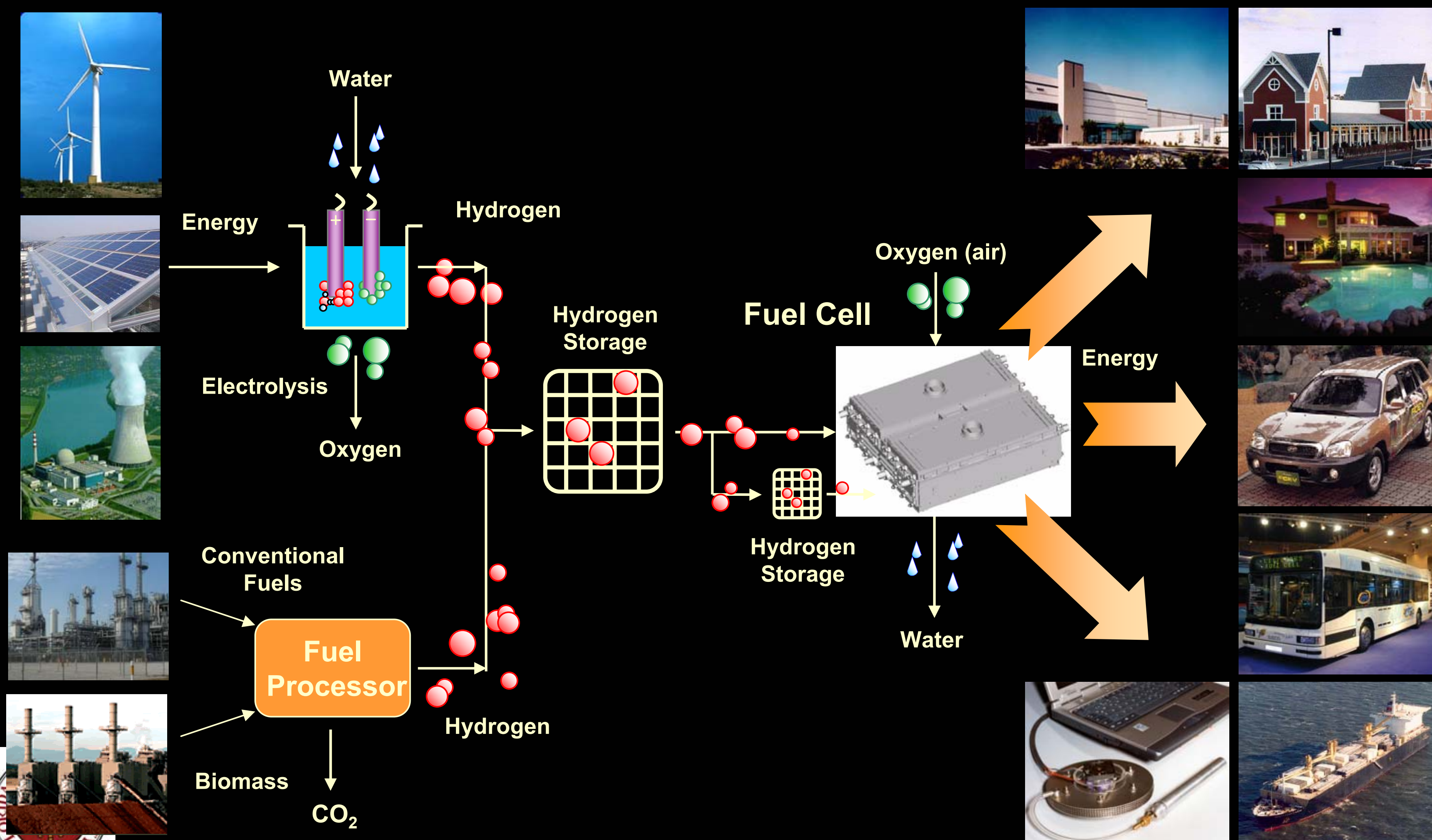
25
20
1.5
1.0
0.5
0
(Pounds of emissions per 1000 kWh NOx, CO, SOx, Hydrocarbon, Particulates)
Average U.S. fossil fuel plant
Microturbine
Combined cycle gas turbine
Fuel cell

CO_2 Emissions



Source: UTC estimates

Hydrogen Economy



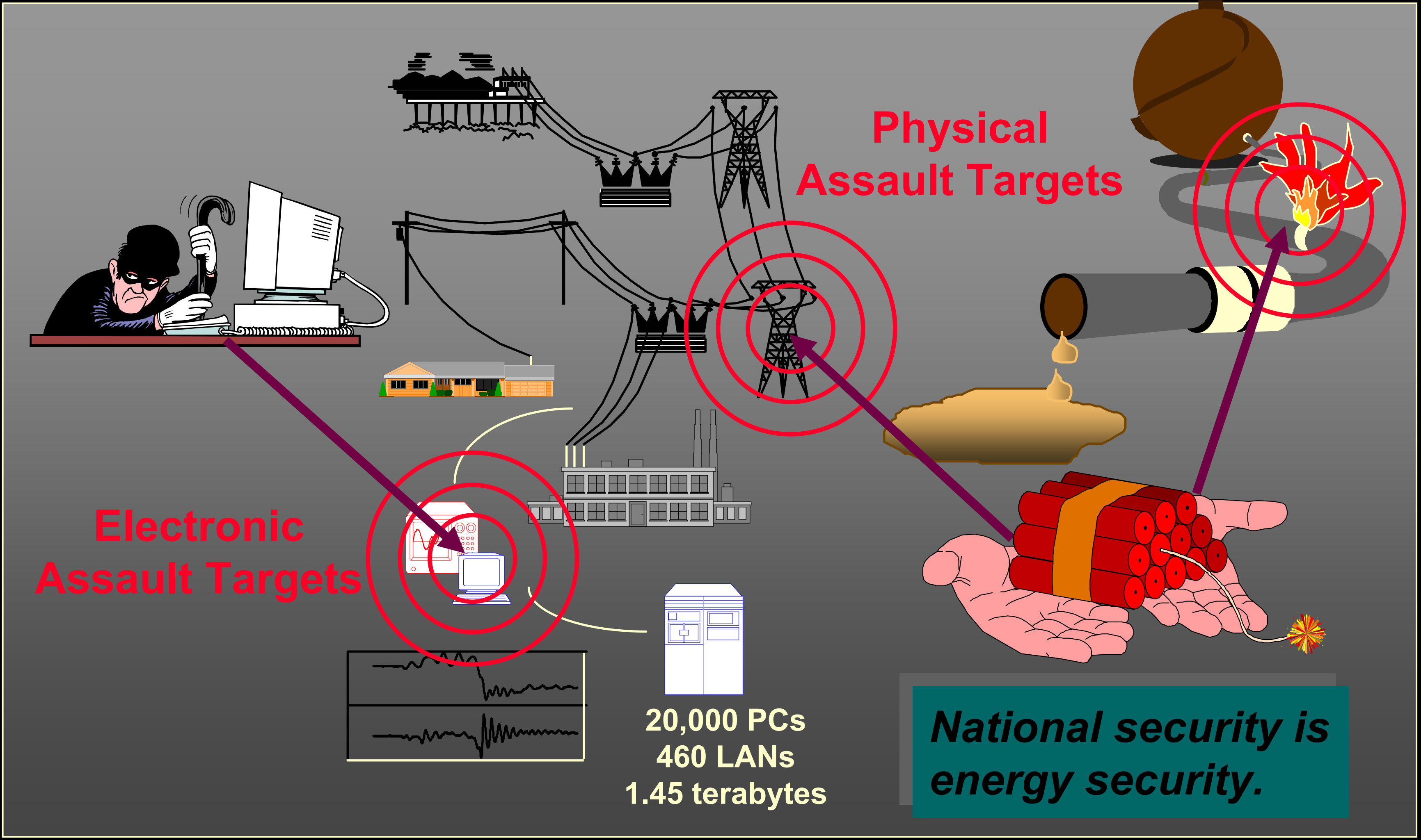
Summary

Edison anticipated a highly dispersed electricity system, with individual businesses generating their own power - Renewable energy is ideally suited to realize this goal.

The cost gap between wind and conventional power continues to close.

New business models will evolve around renewable and micropower technologies.

Energy & Security



Source: Mervin Brown, NREL