FOSSIL FUELS' ENERGY
AND THEIR ENVIRONMENTAL IMPACT

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FOSSIL FUELS:

We love to hate …

- The Big Picture, Revisited, why do we care?

- Types, amounts, how long and what are the trends?

- Combustion and reforming, why some chemistry headache?

- Combustion phenomena, where do they fit?

- Burners and Combustors, some hardware?

- Power Cycles, conventional and advanced, what are the trends?

- Emissions and their control, successes or failures?

- Fuel Cell; what do they have to do with fossil?

- Biomass, what is the connection?

THE GLOBAL PICTURE

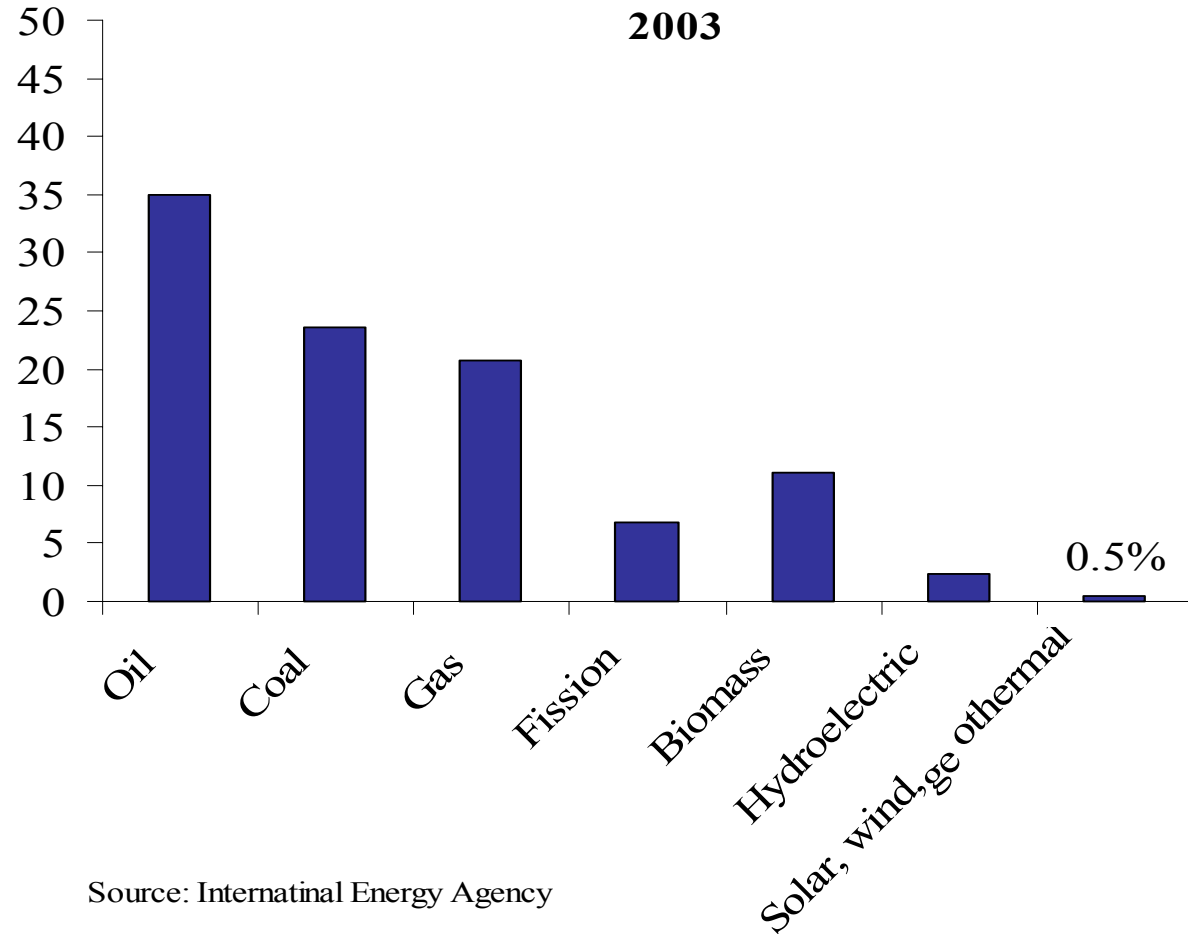# The Terawatt Challenge
R. Smalley*
Rice University

1. **ENERGY**
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

12 Terawatts World wide

(3.3 TW in US)

~ 80% fossil, ~ 90% with biomass

2003

Source: Internatinal Energy Agency

Energy Sources and Demand

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Graph removed for copyright reasons.

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Wigley, Richels and Edmonds, ppmv of CO_2,
pre-industrial concentration is 280 ppmv
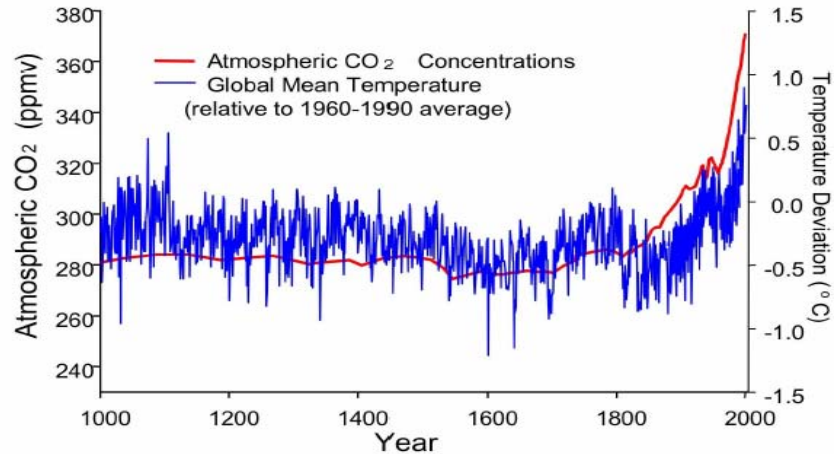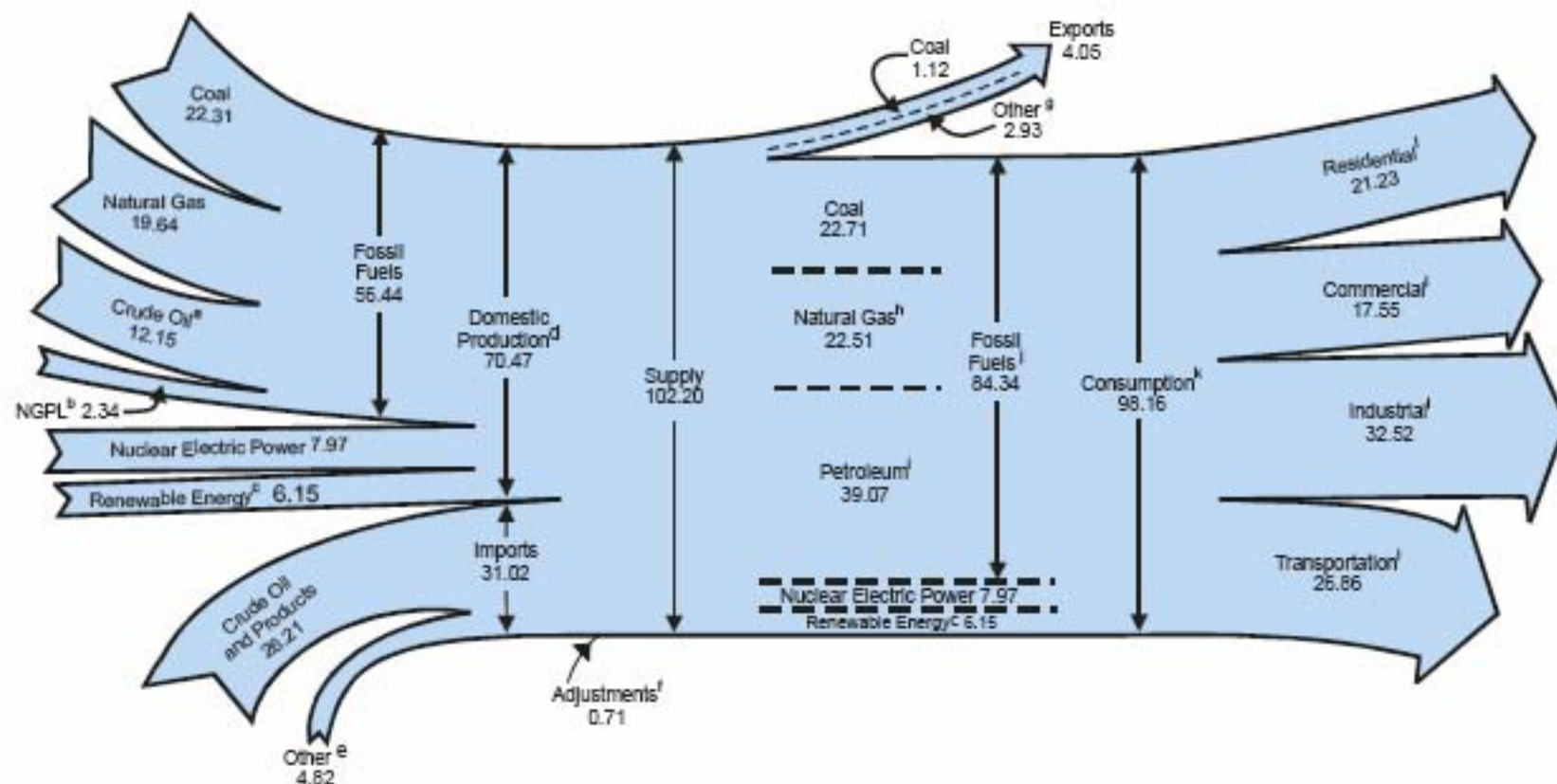
CO2 emissions and Global Temperature!

Figure 1b Increased CO$_2$ Emissions Causing a Rise in Atmospheric CO$_2$ Associated with a Rise in Global Temperature (Sources: CO$_2$ data from Ethridge et al. 2001, Keeling and Whorf 2002; temperature data from Jones et al. 1998, Peterson and Vose 1997)

From "Basic Research Need for a Hydrogen Economy", Report of DOE BES Workshop, May 13-15, 2003

Predictions are always wrong! But it is good to have a plan …

THE DOMESTIC PICTURE

Diagram 1. Energy Flow, 2003
(Quadrillion Btu)

Coal 22.31

Natural Gas 19.64

Crude Oil[a] 12.15

NGPL[b] 2.34

Nuclear Electric Power 7.97

Renewable Energy[c] 6.15

Crude Oil and Products 26.21

Other[e] 4.82

Fossil Fuels 56.44

Domestic Production[d] 70.47

Imports 31.02

Adjustments[f] 0.71

Supply 102.20

Coal 1.12

Other[g] 2.93

Exports 4.05

Coal 22.71

Natural Gas[h] 22.51

Petroleum[i] 39.07

Nuclear Electric Power 7.97

Renewable Energy[c] 6.15

Fossil Fuels 84.34

Consumption[k] 98.16

Residential[l] 21.23

Commercial[l] 17.55

Industrial[l] 32.52

Transportation[l] 26.86

[a] Includes lease condensate.

[b] Natural gas plant liquids.

[c] Conventional hydroelectric power, wood, waste, ethanol blended into motor gasoline, geothermal, solar, and wind.

[d] Includes -0.09 quadrillion Btu hydroelectric pumped storage.

[e] Natural gas, coal, coal coke, and electricity.

[f] Stock changes, losses, gains, miscellaneous blending components, and unaccounted-for supply.

[g] Crude oil, petroleum products, natural gas, electricity, and coal coke.

[h] Includes supplemental gaseous fuels.

[i] Petroleum products, including natural gas plant liquids.

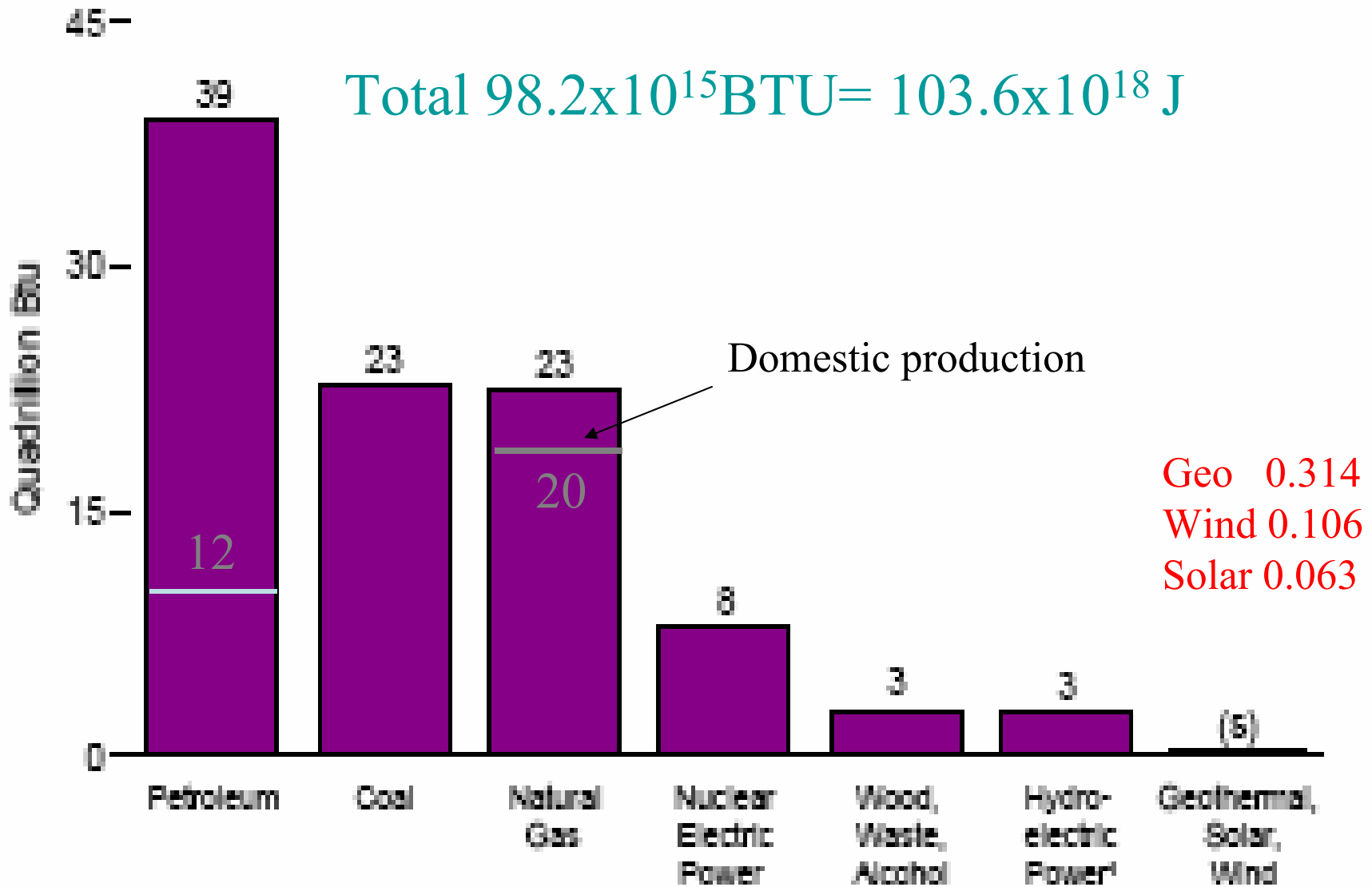[j] Includes 0.05 quadrillion Btu of coal coke net imports.

[k] Includes, in quadrillion Btu, -0.09 hydroelectric pumped storage; -0.24 ethanol blended into motor gasoline, which is accounted for in both fossil fuels and renewable energy but counted only once in total consumption; and 0.02 electricity net imports.

[l] Primary consumption, electricity retail sales, and electrical system energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See note at end of Section 2.
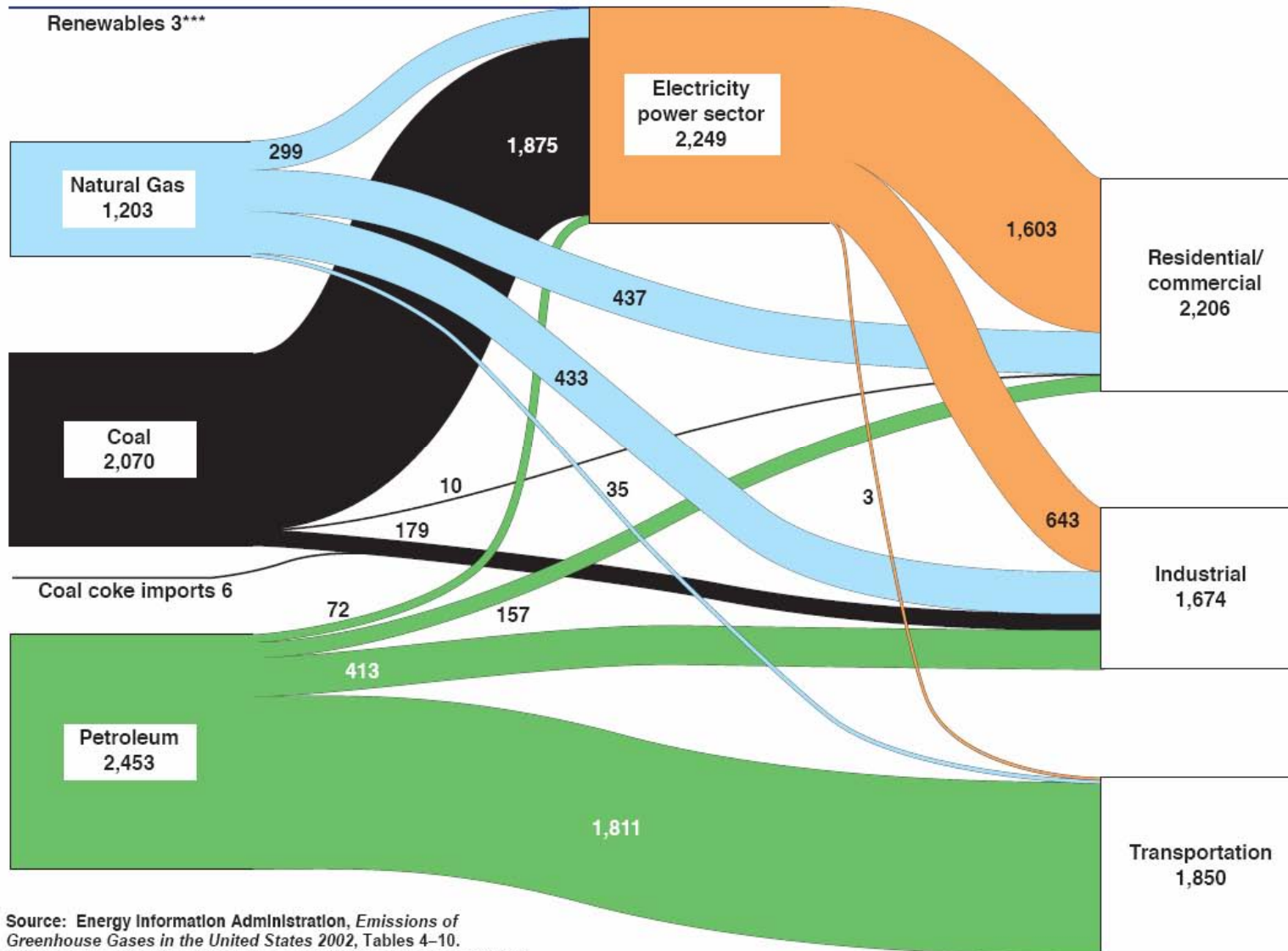
Notes: • Data are preliminary. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.

By Source, 2003

Total 98.2×10^{15} BTU $= 103.6 \times 10^{18}$ J

Domestic production

Geo   0.314
Wind 0.106
Solar 0.063

Quadrillion Btu

45 —

39

30 —

23   23

15 —   12   20

8

3   3

0

(5)

Petroleum   Coal   Natural Gas   Nuclear Electric Power   Wood, Waste, Alcohol   Hydro-electric Power¹   Geothermal, Solar, Wind

9

Energy Information Administration / Annual Energy Review 2003

U.S. 2002 Carbon Dioxide Emissions from Energy Consumption — 5,682* Million Metric Tons of CO_2**

Renewables 3***

Natural Gas 1,203

Electricity power sector 2,249

299

1,875

1,603

Residential/ commercial 2,206

437

433

Coal 2,070

10

35

3

179

643

Coal coke imports 6

Industrial 1,674

72

157

413

Petroleum 2,453

1,811

Transportation 1,850

Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2002*, Tables 4–10.
*Includes adjustments of 42.9 million metric tons of carbon dioxide from U.S. territories, less 90.2 MtCO2 from international and military bunker fuels.
**Previous versions of this chart showed emissions in metric tons of carbon, not of CO2.
***Municipal solid waste and geothermal energy.
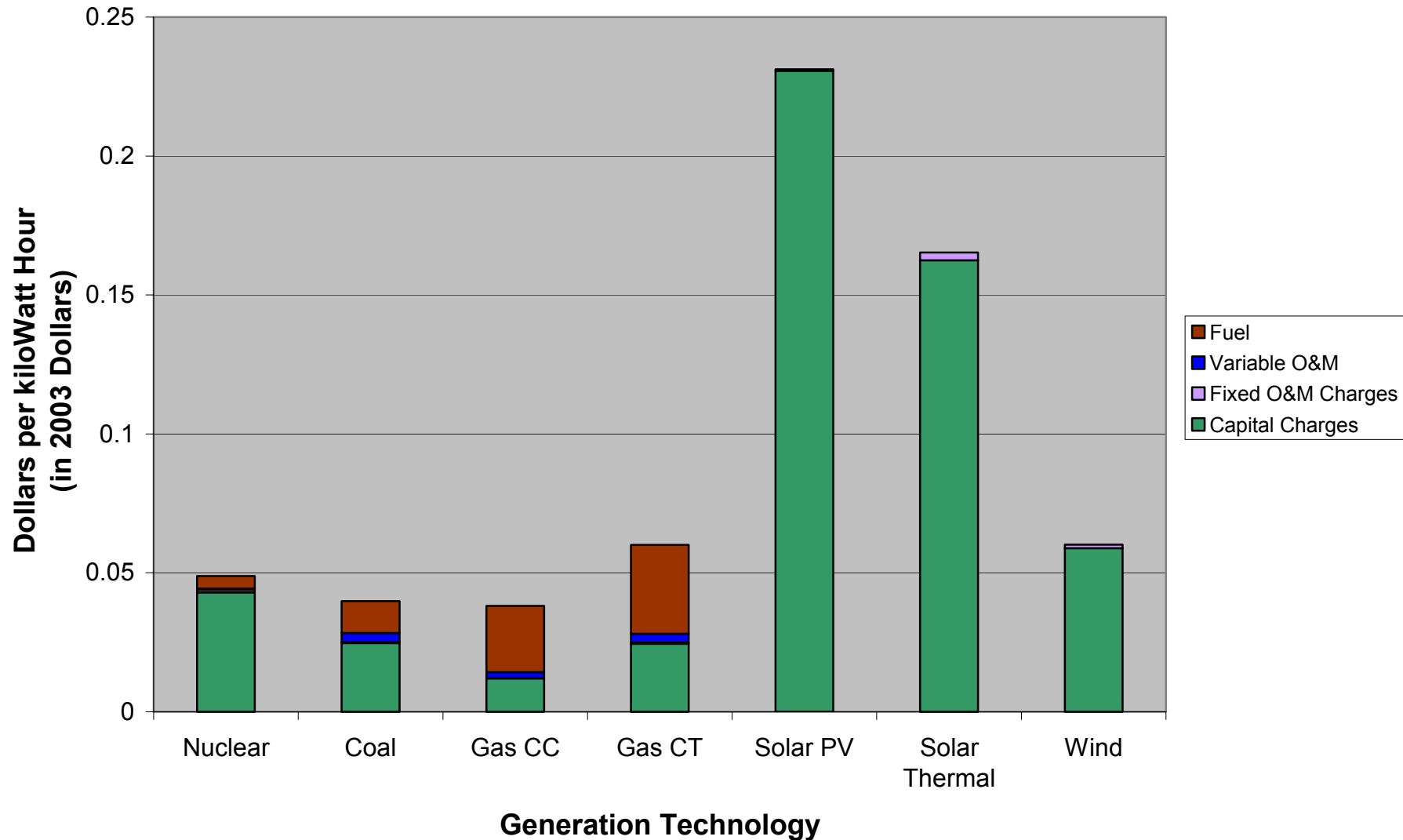Note: Numbers may not equal sum of components because of independent rounding.

Figure 2. Energy consumption by fuel, 1970-2025 (quadrillion Btu)

87-89% fossil based ……

Annual Energy Outlook 2003, Energy Information Agency,
Office of Integrated Analysis and Forecasting, DOE

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Levelized Cost Comparison for Electricity

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FOSSIL FUEL TYPES

FOSSIL/ORGANIC FUELS

COAL, OIL, NATURAL GAS.
OIL SHALE, TAR SAND, PEAT.
"BIOMASS" .. Young, "renewable".

- Formed due to the fossilization of *organic* matter, under ground (although evidence of earth mantel inorganic methane is rising).

- All formed of carbon and hydrogen, some with little oxygen, plus sulfur, mercury and other minerals, and non combustibles.

- Most require some form of processing: sulfur removal, grinding and washing, oil refining, gas desulfurization.

COAL

(fossilized vegetations)
lignite, subbituminous, bituminous, anthracite.

- Coal is carbon + hydrogen (CH_m, m < 1) + sulfur (up to 10% by weight) + nitrogen + ash (non combustibles).

- Some sulfur can be washed away before combustion, but mostly is scrubbed from combustion products using limestone.

- In fluidized bed combustors, pulverized coal is mixed with limestone and burned at lower temperature in blowing air.

- In gasification, rich burning in oxygen and water forms syngas ($CO+H_2$), desulfurization before combustion or gas separation.
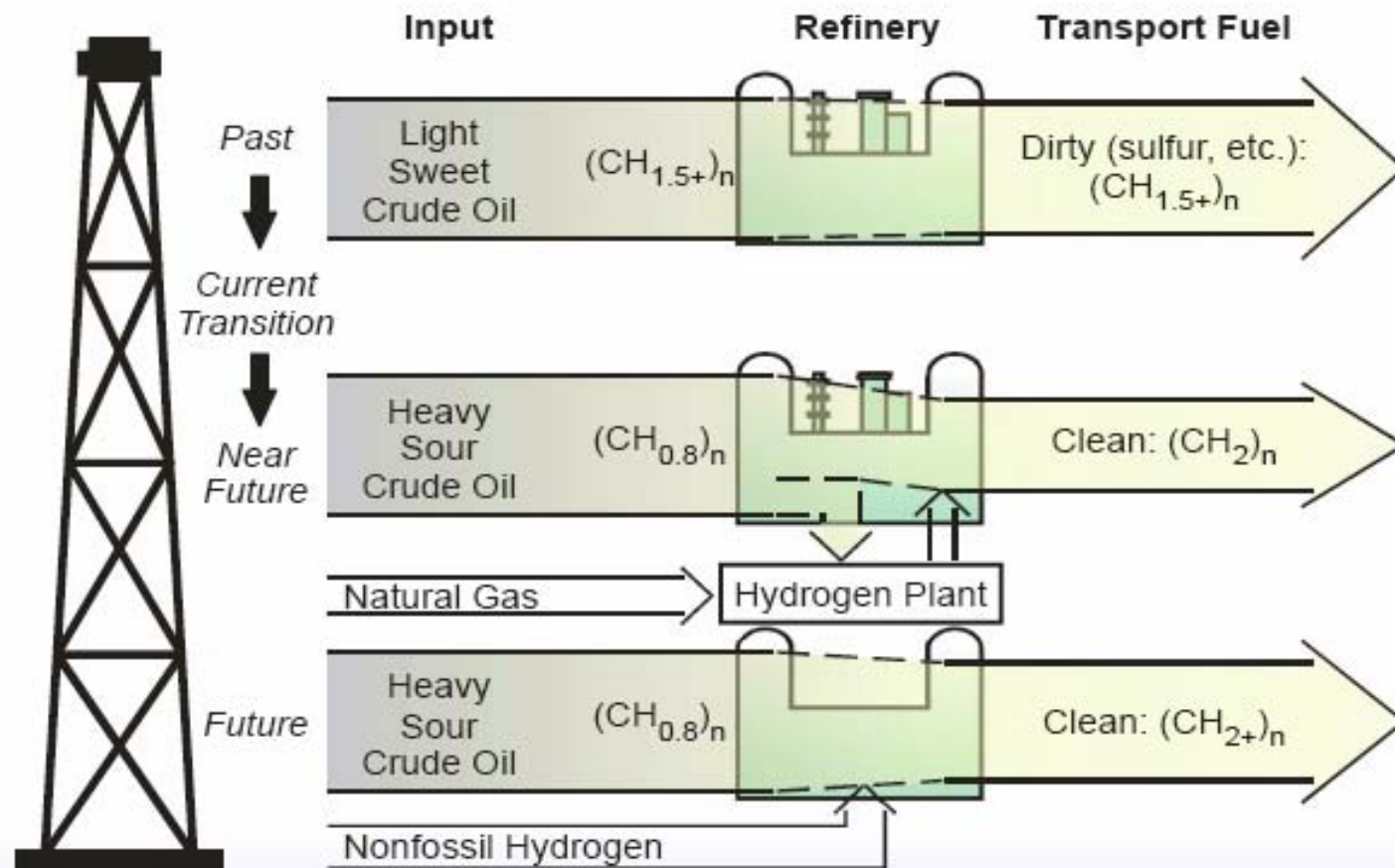
OIL

(or petroleum, liquid rock, fossilized marine life. algae)

- Made up of many organic compounds + hydrogen + nitrogen + sulfur. Sweet and sour refer to the amount of sulfur. CH_m, $1 < m < 2$.

- "Light oil" is generally composed of three hydrocarbon families:

  - Saturated hydrocarbons: paraffins (or normal alkanes), C_nH_{2n+2}, with gas, n = 1-4, liquid, n = 5-15, and solids, n > 15.
  - Unsaturated hydrocarbons, or aromatics, like benzene, C_6H_6, toluene, C_7H_8 and nephthalene, $C_{10}H_8$.
  - Resin and asphaltenes, heavier hydrocarbons rich in nitrogen, oxygen, sulfur and vanadium.

- Refining: distillation (separation of lighter components), catalytic cracking (heating) and reforming (with steam or hydrogen). Products are typically refinery gas, LPG, gasoline (mostly octane C_8H_{18}), aviation fuels (JPx) diesels, heating and lube oils ....

A Large Demand for Hydrogen is due to the Declining Quality of Available Crude Oil

ORNL DWG 2001-107R2

Input	Refinery	Transport Fuel

Past — Light Sweet Crude Oil $(CH_{1.5+})_n$ → Dirty (sulfur, etc.): $(CH_{1.5+})_n$

Current Transition

Near Future — Heavy Sour Crude Oil $(CH_{0.8})_n$ → Clean: $(CH_2)_n$

Natural Gas → Hydrogen Plant

Future — Heavy Sour Crude Oil $(CH_{0.8})_n$ → Clean: $(CH_{2+})_n$

Nonfossil Hydrogen

HTE

Non-Conventional "Heavy" Oil
(all require intensive processing)

Oil Shale:

impermeable hard rock containing (organic, non petroleum) kerogen (pre-oil), which pyrolyzes into oil + (organic, petroleum) bitumen that liquifies with heating.

Tar and Tar Sand:

a mixture of sand and bitumen (coal-like) can be reformed into oil components.

Peat:

"Duff" material in forests and woodland ..

NATURAL GAS

- Mostly methane, CH_4, ethane C_2H_6, some propane, C_3H_8, and little butane, C_4H_8, with small fractions of higher hydrocarbons, may contain sulfur, oxygen, CO_2 at small quantities.

- Requires least processing.

- Biogenic Gas: near surface, difficult to exploit.

- **Methane hydrides/hydrates**, found in deep oceans, and permafrost, encapsulated in water (estimated to exceed 2 orders of magnitude of proven gas reserves) in ice like structures.

One way to classify fuels is through their heating value,
In this table it is the *LHV,* in MJ/kg fuel.

Commercial Fuels

Natural gas			36-42
Gasoline			47.4
Kerosene			46.4
No. 2 oil			45.5
No. 6 oil			42.5
Anthracite coal			32-34
Bituminous coal			28-36
Subbituminous coal			20-25
Lignite			14-18

Biomass Fuels

Wood (fir)			21
Grain			14
Manure			13

# Some Combustion Fundamentals: Chemical Thermodynamic

"Classical Thermodynamics is the only physical theory of universal content which …. within the framework of its basic notions, will never be toppled."   Albert Einstein.

HYDROCARBON COMBUSTION IN AIR

$$C_nH_m + \left(n + \frac{m}{4}\right)(O_2 + 3.76N_2) \rightarrow nCO_2 + \frac{m}{2}H_2O + 3.76\left(n + \frac{m}{4}\right)N_2$$
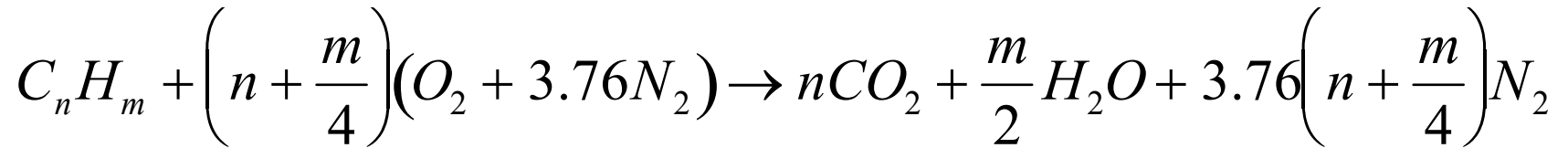
- Hydrocarbons store energy in their chemical bonds. Highest energy storage per unit mass or unit volume (in liquid form).

- Chemical Energy is converted into thermal energy during combustion, or other chemical energy in refining and reforming (processes that require energy).

- In complete, *stoichiometric* combustion of hydrocarbons, the products are water and carbon dioxide.

Ragone plot of Energy Storage
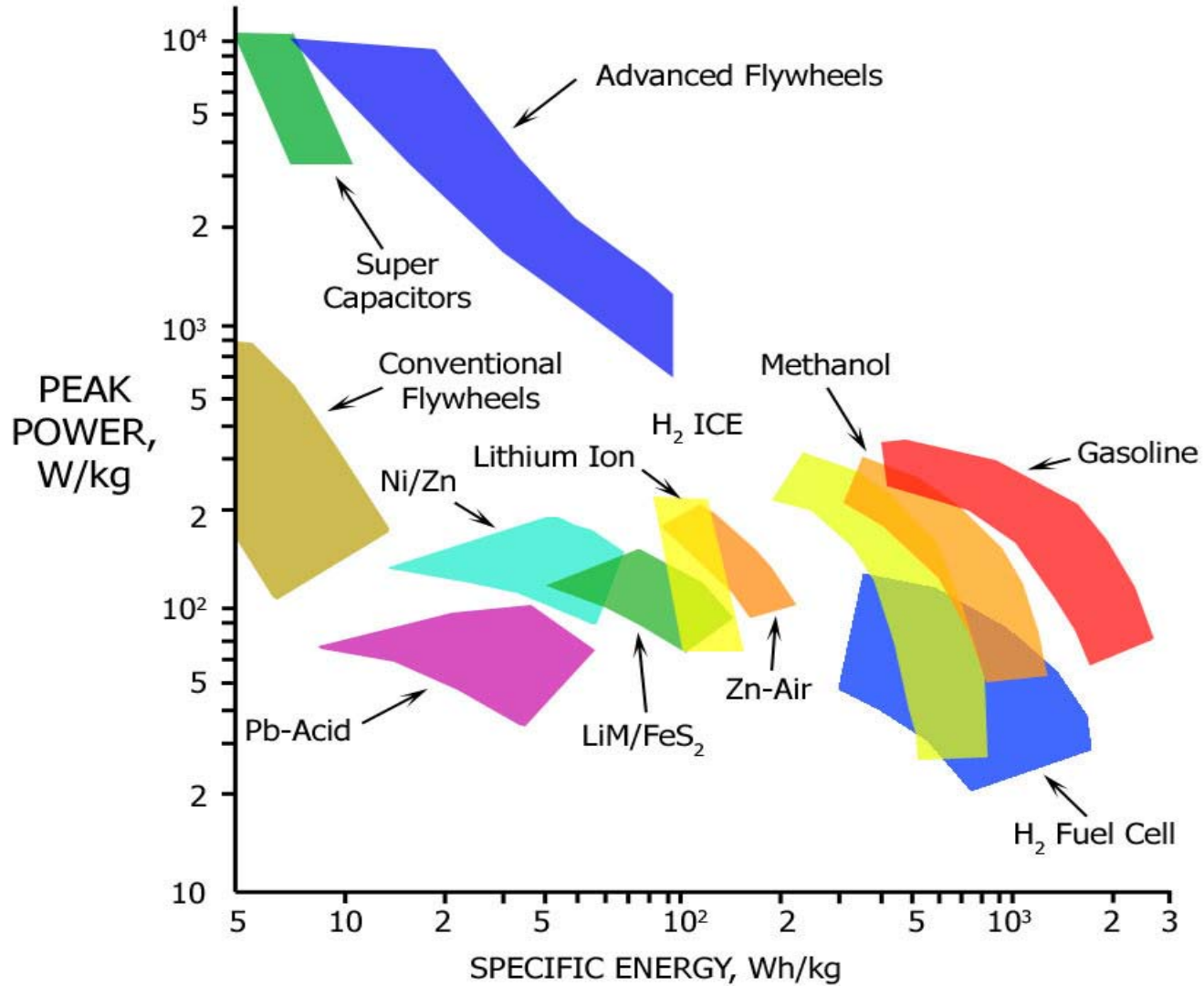
- *Oxyfuel combustion*, that is burning in pure oxygen, is also used to further raise the products temperature, in gasifiers (reformers), or to avoid the formation of nitric oxides.

$$C_n H_m + \left(n + \frac{m}{4} \right) (O_2) \rightarrow nCO_2 + \frac{m}{2} H_2O$$
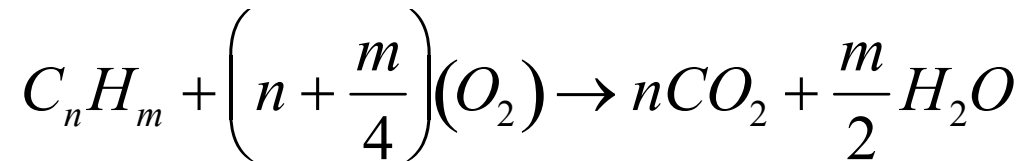
- Even with stoichiometric combustion, carbon monoxide and nitric oxides form, as well very small amounts of hydrocarbons and their fragments (PAH).

- The amount of CO, NOx and "CH" in the products depend on the fuel, combustion conditions, nature of the combustion process, and how fast the products are cooled.

- The amount of heat transferred out this reaction, when burning at constant pressure is known as *the enthalpy of reaction.*

$$H_2 + \frac{1}{2}(O_2 + 3.76 N_2) \rightarrow H_2O + \frac{3.76}{2} N_2 \quad \left\| +\Delta \hat{h}^o_{H2O} \right\|$$
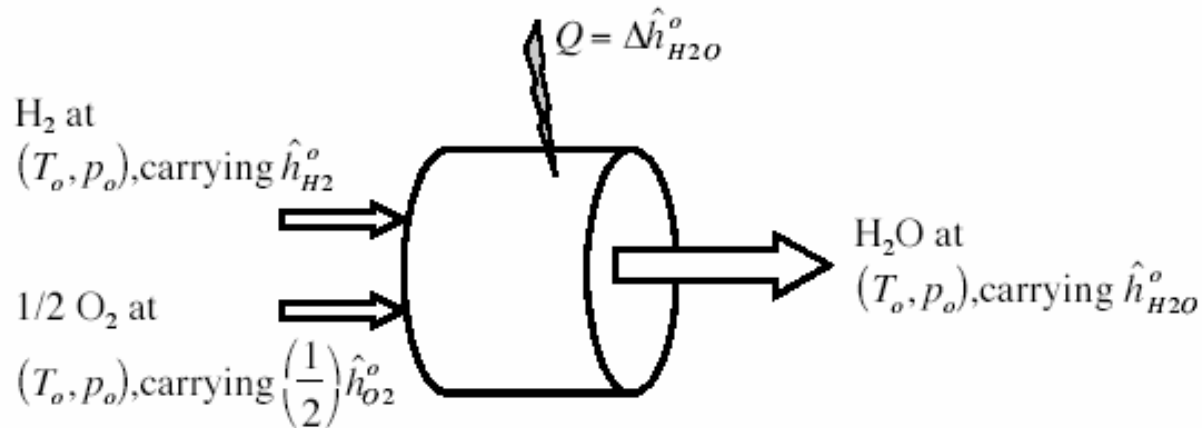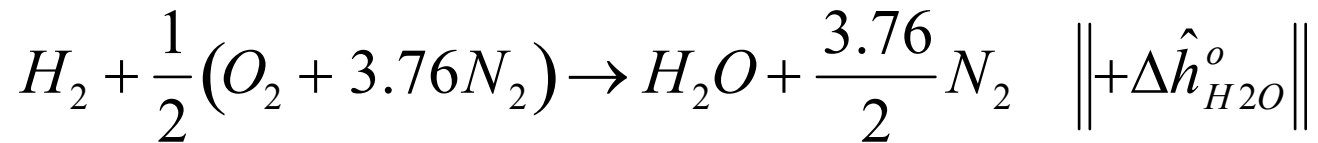

- For most hydrocarbon the enthalpy or reaction per unit mass of fuel is 45 - 50 MJ/kg, for hydrogen it is 123 MJ/kg.
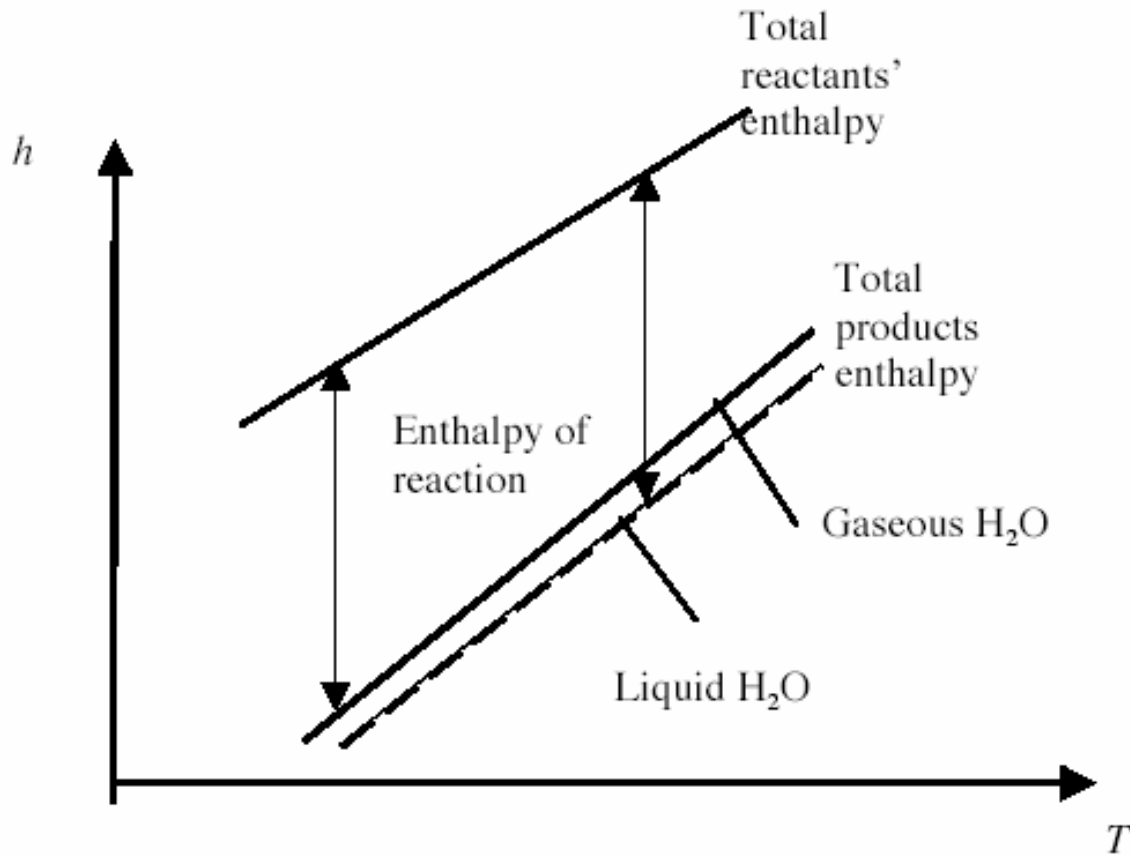
This is also the *Higher Heating Value*, if water in the products is in the liquid phase, or the *Lower Heating Value*, if it is in the gaseous phase (getting either depends on T and p of the process).

Thermodynamic Properties of Fuel Combustion at 25°C and One Atmosphere Pressure[a]
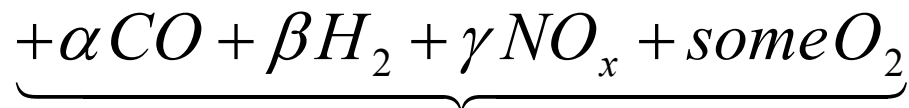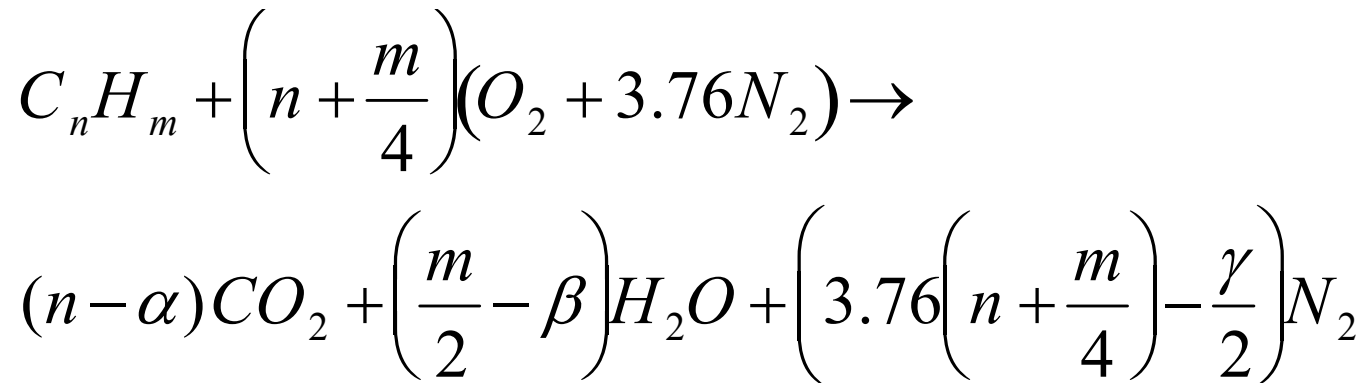
Fuel	Symbol	Molecular Weight (g/mol)	FHV[b] (MJ/kg fuel)[c]	$(A/F)_{st}$	$(h_r\text{-}h_p)$[b] (MJ/kg product)	Δf (MJ/kg fuel)	FHV[b] (MJ/kg C)
Pure Compounds[d]							
Hydrogen	H_2	2.016	119.96	34.28	3.400	117.63	NA[e]
Carbon (graphite)	$C_{(solid)}$	12.01	32.764	11.51	2.619	32.834	32.764
Methane	CH_4	16.04	50.040	17.23	2.745	51.016	66.844
Carbon monoxide	CO	28.01	10.104	2.467	2.914	9.1835	23.564
Ethane	C_2H_6	30.07	47.513	16.09	2.780	48.822	59.480
Methanol	CH_4O	32.04	20.142	6.470	2.696	22.034	53.739
Propane	C_3H_8	44.10	46.334	15.67	2.779	47.795	56.708
Ethanol	C_2H_6O	46.07	27.728	9.000	2.773	28.903	53.181
Isobutane	C_4H_{10}	58.12	45.576	15.46	2.769		53.142
Hexane	C_6H_{14}	86.18	46.093	15.24	2.838		54.013
Octane	C_8H_{18}	114.2	44.785	15.12	2.778		53.246
Decane	$C_{10}H_{22}$	142.3	44.599	15.06	2.778		52.838
Dodecane	$C_{12}H_{26}$	170.3	44.479	15.01	2.778		52.567
Hexadecane	$C_{16}H_{34}$	226.4	44.303	14.95	2.778		52.208
Octadecane	$C_{18}H_{38}$	254.5	44.257	14.93	2.778		52.102
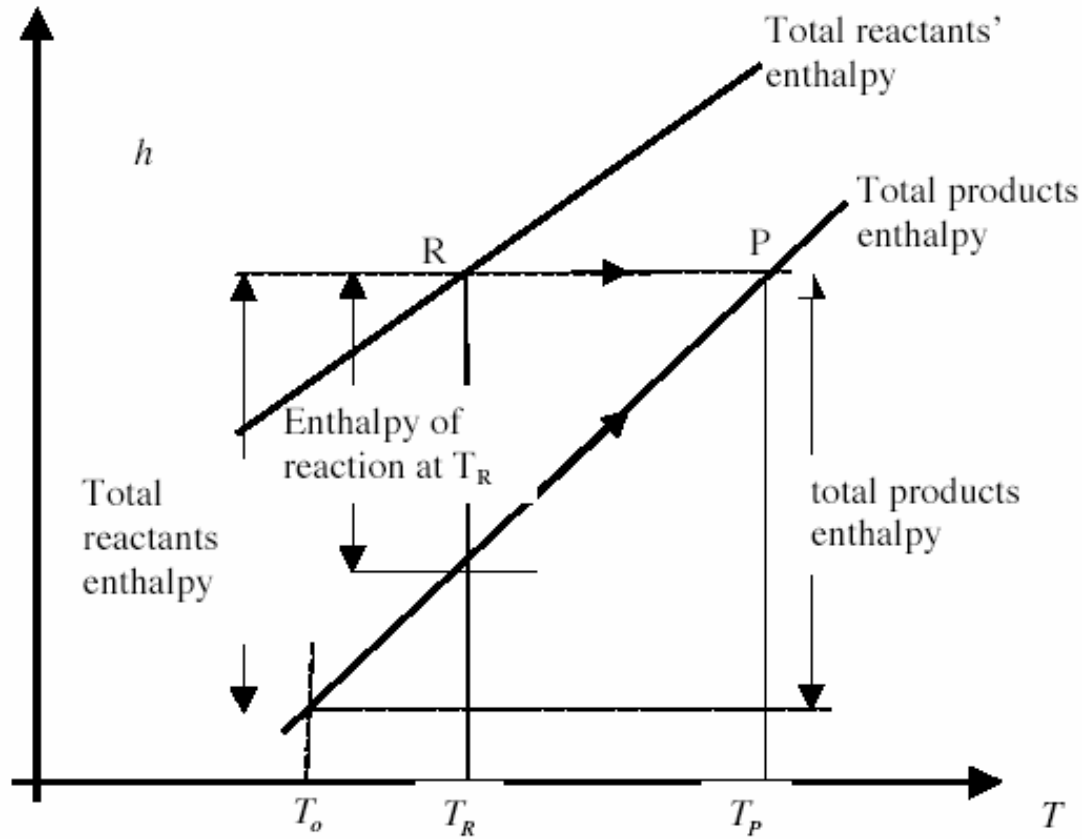
Under adiabatic conditions, the products' temperature is high ~ 2000 C (depending on the initial temperature and the process). It is called the *Adiabatic Flame Temperature*.

Products Composition
in Equilibrium Combustion

There is no complete combustion!

$$C_nH_m + \left(n + \frac{m}{4}\right)(O_2 + 3.76N_2) \rightarrow$$

$$(n-\alpha)CO_2 + \left(\frac{m}{2} - \beta\right)H_2O + \left(3.76\left(n + \frac{m}{4}\right) - \frac{\gamma}{2}\right)N_2$$

$$\underbrace{+\alpha CO + \beta H_2 + \gamma NO_x + some O_2}_{}$$
$$equilibrium\ dissociation\ and\ NOx\ formation$$

Impact of Equivalence Ratio and Initial Temperature On Flame Temperature

Graph removed for copyright reasons. Figure 11 in Docquier, N., and S. Candel. "Progress in Energy and Combustion." *Science* 28 (2002) 107-150.

- COMBUSTION PROCESSES
- COMBUSTION DEVICES
- COMBUSTORS
- BURNERS

Power, what is it and what controls it ..

Two photos removed for copyright reasons. Donkeys pulling cart and a fuel cell car.

Power Density in Combustion Processes

Coal: pulverized 0.01 GW/m^3

       fluidized bed 0.04

SI engine 0.1

Gas boiler 0.2

Aero engine (overall) 2.0

           (primary) 4.0

Vehicle brakes 5

Premixed flame (peak) 6

Spark 10

WSR (at T*) 10-50

Hydrocarbon Oxidation Mechanisms …..

Figure by MIT OCW.
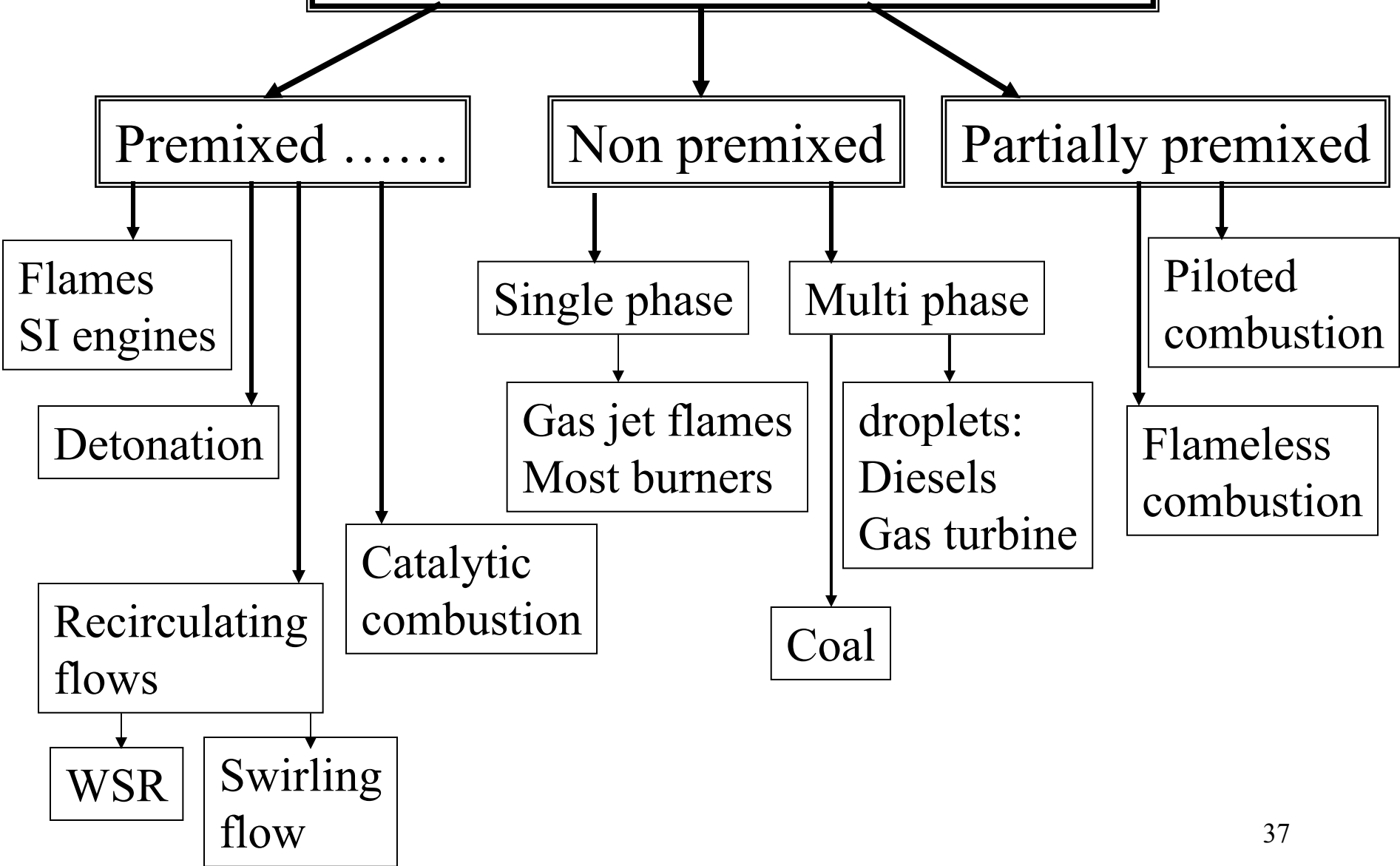
Flame Types

A rich, long, sooty, jet diffusion flame, heavy HC or coal, strong radiation, typical in boiler burners

Photos removed for copyright reasons.

A well mixed (swirling) compact flame of a lighter HC, typical of modern burners, gas turbines, etc.

FOSSIL BASE ENERGY CONVERSION: ADVANCED POWER SYSTEMS

The fuel does not matter much!!

Do we have an Energy or an *Entropy Crisis*?

$$\eta_{carnot} = 1 - T_L / T_H$$

"Nature, in providing us with combustibles on all sides, has given us the power to produce, at all times and in all places, heat and the impelling power which is the result of it. To develop this power, to appropriate it to our uses, is the object of heat engines. The study of these engines is of greatest interest, their importance is enormous, their use is continually increasing, and they seem destined to produce a great revolution in the civilized world."

Sadi Carnot, Reflection On The Motive Power Of Heat And On Machines Fitted To Develop That Power, 1824.

Gas turbine Open (Brayton) Cycles

State 1
Air

fuel

State 3,
Combustion
products

combustor

State 2
Compressed
air

Turbine
work

Compressor
work

State 4,
Products

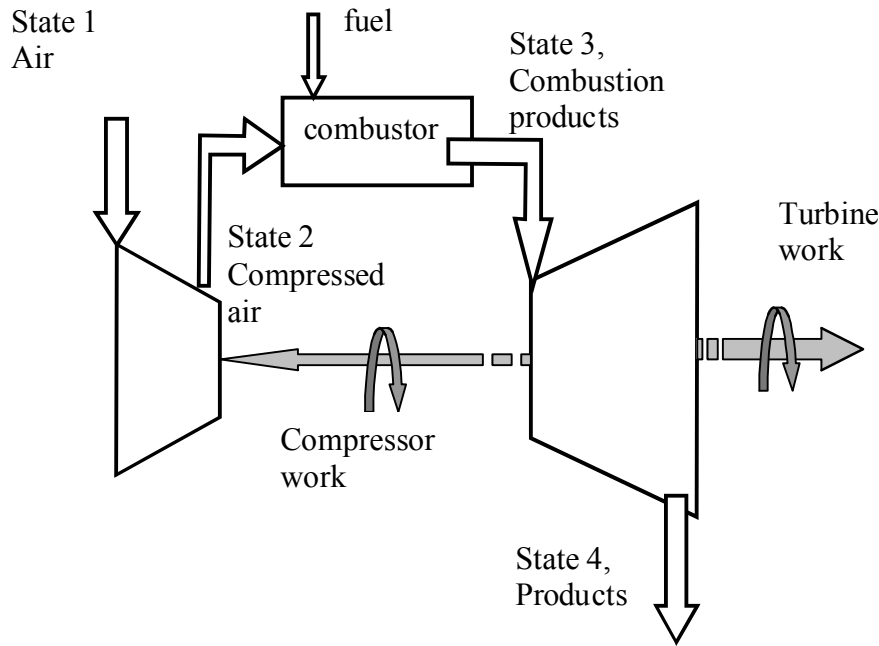Figure 1. The components and states in a Brayton combustion gas turbine cycle.

$$\frac{T_{2s}}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$$

$$\frac{T_3}{T_{4s}} = \left(\frac{p_3}{p_4}\right)^{\frac{k-1}{k}} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$$

$$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}}$$

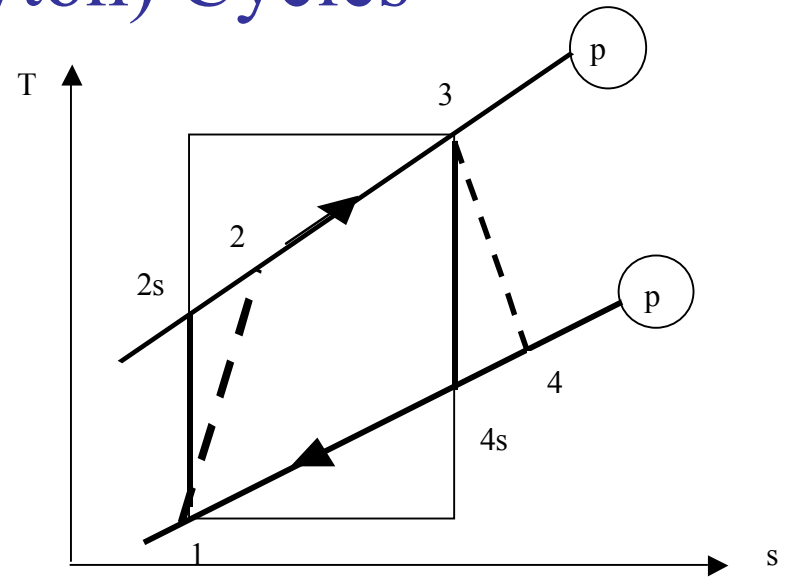Figure 2. the temperature entropy diagram of an ideal Brayton cycle, and one with finite isentropic efficiencies for the work transfer components. A Carnot cycle is superposed between the two extreme temperatures.

$$Q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$$

$$W_{net} = (h_3 - h_4) - (h_2 - h_1)$$
$$= c_p[(T_3 - T_4) - (T_2 - T_1)]$$

$$\eta_{cycle} = \frac{\text{net mechanical work out}}{\text{heat transfer in}}$$

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Gas turbines have advantages in electric power generation:

1. They operate at high temperatures.
2. They can are capable of meeting peak load demands.
3. They are compact and easy to operate, and take advantage of aerospace propulsion applications.
4. They operate at relatively low pressures.
5. Many installations burn natural gas, or in dual fuel mode burning NG and/or oil.
6. They do not handle wet gases, and are not as vulnerable to corrosion as steam turbines.
7. Combustion gas turbines do not require heat transfer equipment on the low-temperature side, and no coolant either.

However, gas turbines suffer from several limitations:

1. They have relatively low efficiency since their maximum temperature is limited by material.
2. Their efficiency is low because of the high compressor work, and low efficiency of compressors.
3. Open cycle turbines are limited by the high exhaust temperature, which limits the turbine work.
4. They cannot be used with "dirty" fuels, such as coal, since sulfur oxides can damage their blades.

Steam, or vapor Rankine cycles overcome some of these limitations, and hence have been very popular in electric power generation.

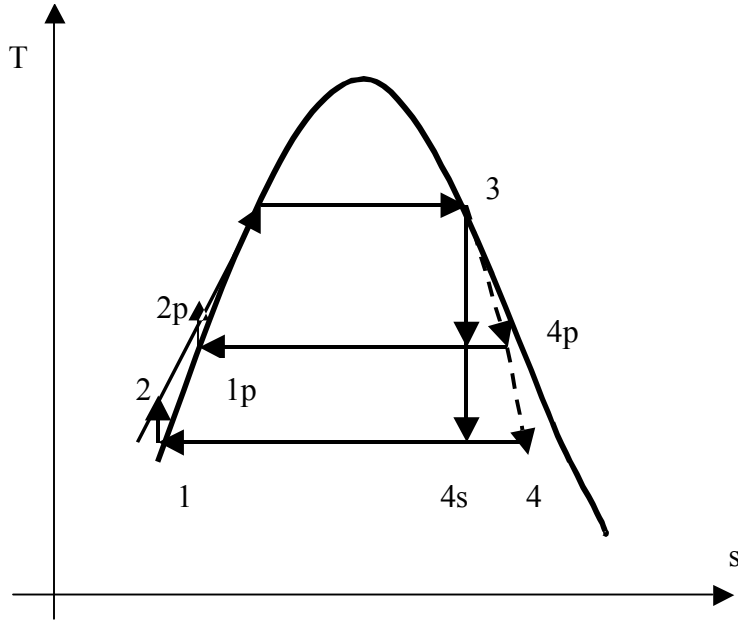# Rankine (Vapor) Cycles:

T

3

2p

4p

2

1p

1

4s   4

s

Figure 12. the T-s diagram of an open Rangine cycle, 1p-2p-3-4p, and a closed Rankine cycle, 1-2-3-4, with subatmospheric pressure

3

turbine

2

pump   boiler

1

condenser

4
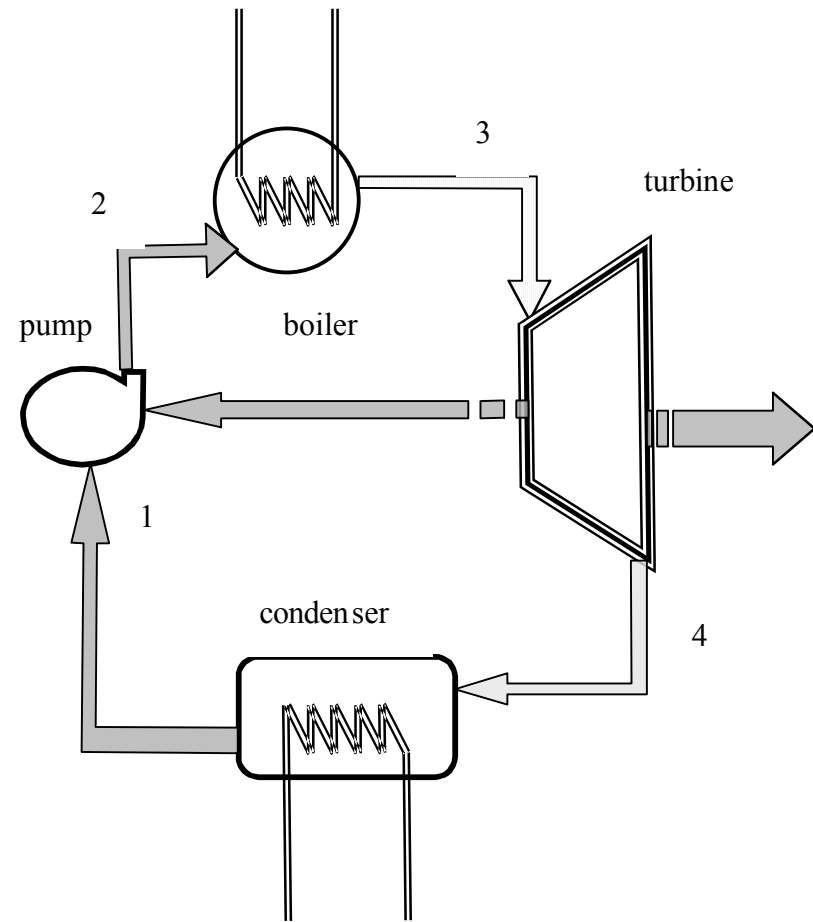
Figure 12. The components of a Rankine cycle.

Critical point: $T_c = 374$ C, $P_c = 22.088$ MPa
Cooling available at: $T = 15$ C, where $P_{sat} = 5.63$ kPa

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Rankine cycles:

1. Fuel flexible, works well with coal (closed cycle).
2. High efficiency, low pumping power.
3. Lower flow rate (latent enthalpy).
4. Run at low T (works with geothermal and solar), but high p.
5. Works well with nuclear energy:

    Pressurized WR: T = 350 C

    Boiling WR: T = 400-500 C

    Gas Cooled R: T = 600-800 C

    High Temperature GR T > 800 C

BUT
1. High inertia, good for base load but not for load following.
2. Require cooling, big condensers, .. Water …

COMBINED CYCLES:

Figure 18. A supercritical steam cycle, and a "matching" gas turbine cycle for use in a combined cycle plant.
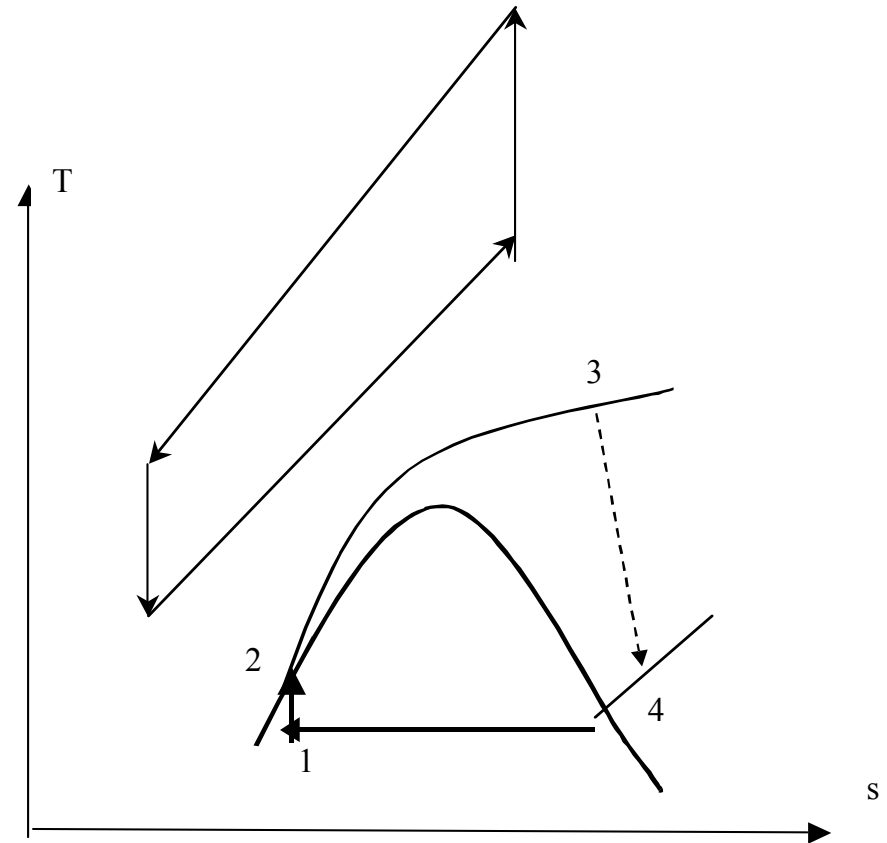
Combined cycles take advantage of high T gas turbine exhaust.

Combined cycle efficiency: $\eta_{com} = \eta_{top} + \eta_{bot}\left(1 - \eta_{top}\right).$

For: $\eta_{top} = 0.25$ and $\eta_{bot} = 0.4$, $\eta_{com} = 0.55$

Table 2.1: Efficiency of current power plant types and efficiency potential stemming from possibilities for improvement and for future power plant cycles [22][4]

Year of Initial Operation	Example	Operating Characteristics	Efficiency in %
Natural Gas-Fired Power Plant Cycles			
1998	Gas turbine simple cycle	TIT approx. 1190°C (ISO 2314)[5]	approx. 38-40
1997	GT with reheat		approx. 38
1998	GT with recuperation		approx. 40
1996	GT with steam injection (STIG/Cheng)		<45
>1998	Humid Air GT (HAT)		approx. 58-59
>>2000	GT with chemical recuperation (CRGT)		55-62
1998	Gas / steam turbine combined cycle power plants	TIT approx. 1190°C (ISO 2314)[5]	58-59
1995 / >2000 >2000 / >2005	Fuel cells, natural gas-fired: PAFC / PEMFC MCFC / SOFC combined cycle plant	[23, 24] [23, 24, 25]	approx. 40 55 ... >60

Courtesy of U.S. DOE.
Source: Gottlicher. "The Energetics of Carbon Dioxide Capture in Power Plants." *DOE*, 2004.

Coal-Fired Steam Power Plants			
Operational since 1998	Coal-fired steam power plant (seawater cooling system) Nordjyllandsvaerket [26]	Steam: 285 bar/580°C/580°C/580°C Feedwater preheating: 300°C Condenser pressure: 0.023 bar 10 feedwater preheating stages	47
Planned for 1999 (adjusted)	Coal-fired steam power plant (wet cooling tower system) Gelsenkirchen-Heßler[27]	Steam: 275 bar/580°C/600°C Feedwater preheating: 300°C Condenser pressure: 0.037 bar 9 feedwater preheating stages	45 to 45.5
Planned for 2001-2005	Coal-fired steam power plant (seawater cooling system) Avedoere 2 [28, 29]	Steam: 300 bar/580°C/600°C Condenser pressure: 0.023 bar	50

Courtesy of U.S. DOE.
Source: Gottlicher. "The Energetics of Carbon Dioxide Capture in Power Plants." *DOE*, 2004.

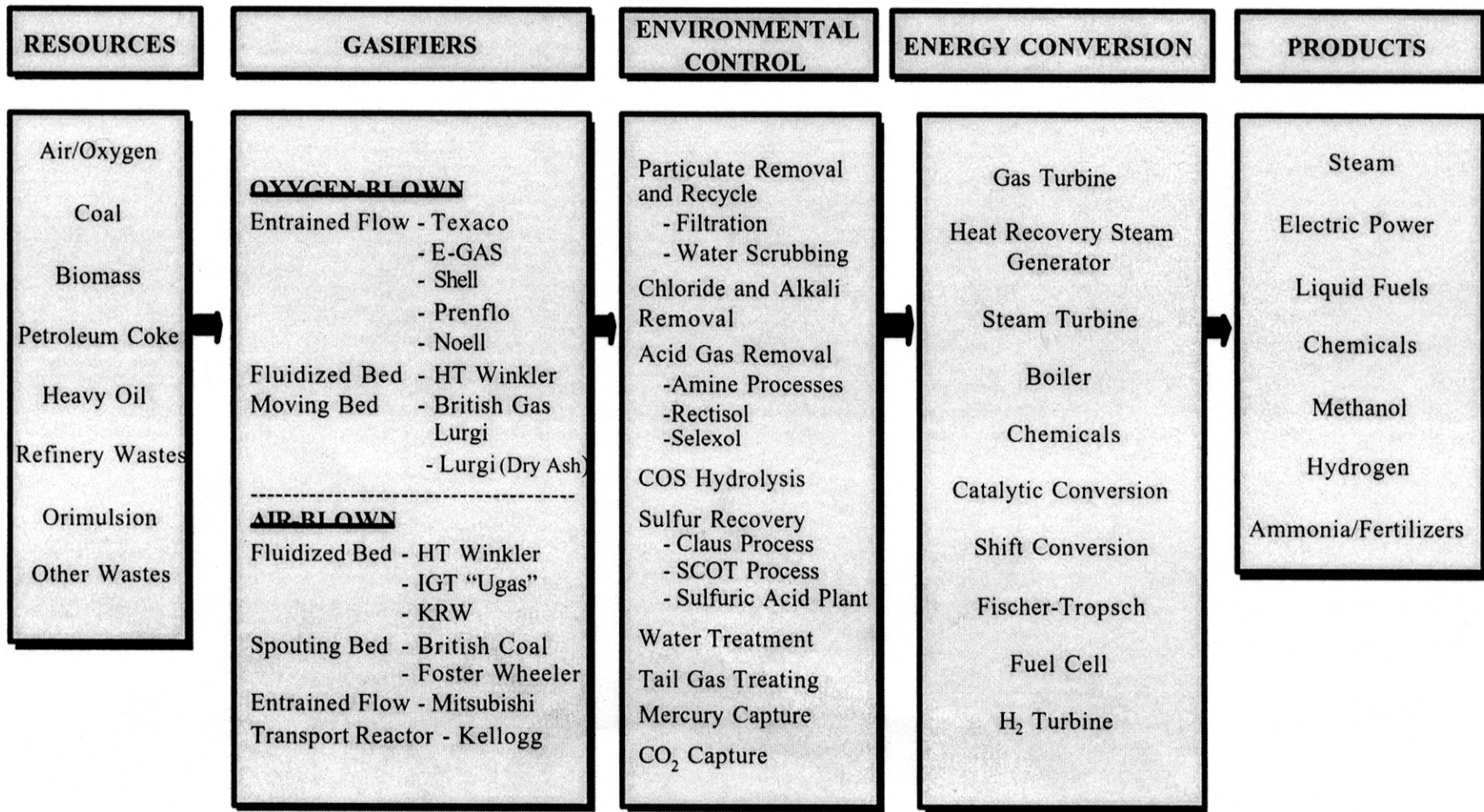| Coal-Fired Combined Cycle			
1994	Pressurized Fluidized Bed Combustion (PFBC) combined cycle	Gas turbine: 860°C/12 bar	36-40 (1999: >45)
>2010	Pressurized Pulverized Coal-Fired combined cycle power plant (with hot gas clean up or warm gas clean up according to heat exchanger)		>50
	Magneto Hydro Dynamic generator (MHD) + steam cycle		50-60

1993 1998 >1998	IGCC Power plant
	  Buggenum (NL)
	  Puertollano (E)
	  Study, ready for construction in 1998 [21]
		TIT 1050°C (ISO 2314)[5]
		TIT 1120°C -"-
		TIT >1190°C -"-
			43.2
			45
			51.5

≥1998 >2000 >2005	IGFC (IGCC with fuel cells): PAFC (split fuel stream) / GT combined cycle plant MCFC combined cycle plant SOFC combined cycle plant	[31] [32] [32]	approx. 50 > 55 > 55
	Multiple steam cycles		50-51
	Kalina cycle		>47

Source: Gottlicher. "The Energetics of Carbon Dioxide Capture in Power Plants." *DOE*, 2004.

TEMPA ELECTRIC POLK IGCC POWER PLANT

250 MW, 35.3 % efficiency, 2500 TPD coal, 200 TPD sulfuric acid, built 1996, $600M

Facility schematic diagram removed for copyright reasons.

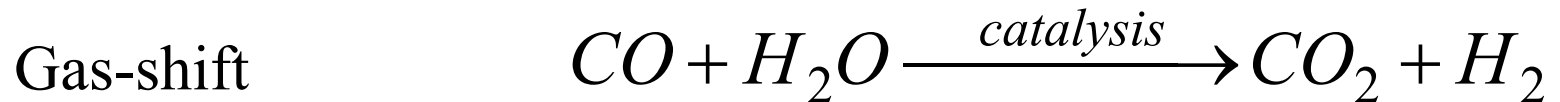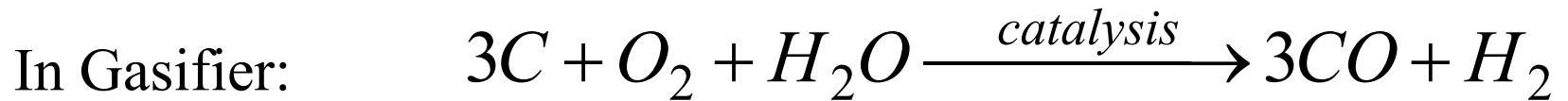| RESOURCES	GASIFIERS	ENVIRONMENTAL CONTROL	ENERGY CONVERSION	PRODUCTS

Air/Oxygen
Coal
Biomass
Petroleum Coke
Heavy Oil
Refinery Wastes
Orimulsion
Other Wastes
	OXYGEN-BLOWN
	Entrained Flow - Texaco
	   - E-GAS
	   - Shell
	   - Prenflo
	   - Noell
	Fluidized Bed - HT Winkler
	Moving Bed - British Gas
	   Lurgi
	   - Lurgi (Dry Ash)
	--- 	
	AIR-BLOWN
	Fluidized Bed - HT Winkler
	   - IGT "Ugas"
	   - KRW
	Spouting Bed - British Coal
	   - Foster Wheeler
	Entrained Flow - Mitsubishi
	Transport Reactor - Kellogg
		Particulate Removal and Recycle
		  - Filtration
		  - Water Scrubbing
		Chloride and Alkali Removal
		Acid Gas Removal
		  -Amine Processes
		  -Rectisol
		  -Selexol
		COS Hydrolysis
		Sulfur Recovery
		  - Claus Process
		  - SCOT Process
		  - Sulfuric Acid Plant
		Water Treatment
		Tail Gas Treating
		Mercury Capture
		CO_2 Capture
			Gas Turbine
			Heat Recovery Steam Generator
			Steam Turbine
			Boiler
			Chemicals
			Catalytic Conversion
			Shift Conversion
			Fischer-Tropsch
			Fuel Cell
			H_2 Turbine
				Steam
				Electric Power
				Liquid Fuels
				Chemicals
				Methanol
				Hydrogen
				Ammonia/Fertilizers

- Tampa Electric 250 MW, Florida
- PSI energy (Cinergy) 262 MW, Indiana
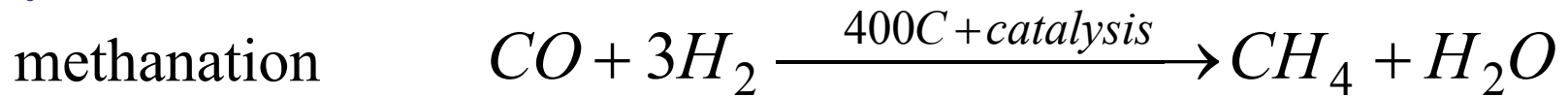- Dow Chemical 160 MW, Louisiana
- S. Cal Edison 100 MW, California

- MHI built 250MW in Japan, 56.5%
- They are building a 500 MW coal.
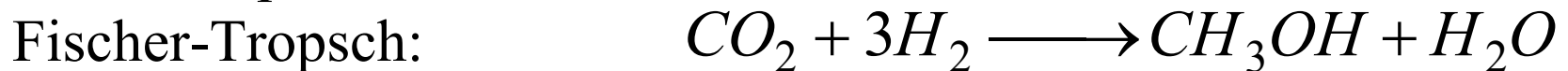- China market ..
- India ..

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Environmental assessment of IGCC Power, Ratafia et al, SAIC and DOE/NETL, 2002

Reforming, Gasification & Synthesis

From Fossil: Coal/Tar Sand/Biomass

In Gasifier:
$$3C + O_2 + H_2O \xrightarrow{\text{catalysis}} 3CO + H_2$$

Gas-shift
$$CO + H_2O \xrightarrow{\text{catalysis}} CO_2 + H_2$$

Synthesis

methanation
$$CO + 3H_2 \xrightarrow{400C + \text{catalysis}} CH_4 + H_2O$$

Synthesis+Liquefaction

Methanol production
Fischer-Tropsch:

$$CO + 2H_2 \longrightarrow CH_3OH$$

$$CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O$$

Probstein and Hicks, Synthetic Fuels, 1990.

Fuel Reforming and Synthesis: Efficiencies, and Fuel life Cycle Analysis

Thermal Efficiencies of Synthetic Fuel Production

FUEL	PRODUCT	EFFICIENCY* (%)
Coal	Synthesis	72-87
Coal	Methane	61-78
Coal	Methanol	51-59
Coal	Hydrogen	62
Oil	Hydrogen	77
Methane	Hydrogen	70-79
Coal, Oil, or Gas	Hydrogen (Electrolytic)	20-30
Oil Shale	Oil and Gas	56-72
Methanol	Oil and Gas	86
Wood	Gas	90
Corn	Ethanol	46
Manure	Gas	90

*Thermal efficiency is the ratio of the heating value of the synthetic product divided by the heating value of the parent fuel.