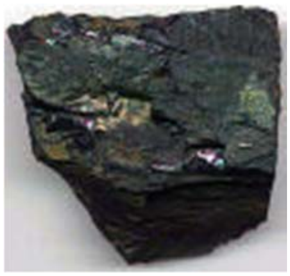
Fuel and Energy

Coal



Dr.-Eng. Zayed Al-Hamamre

Content

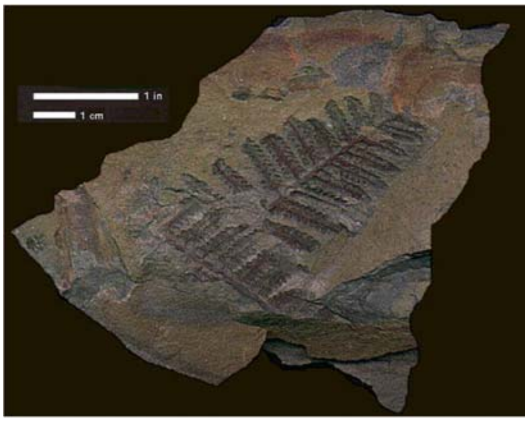
- **Formation of Coal (Coalification)**
- **Demands**
- **Reserves**
- **Side effects**
- **Utilization and processing**

Formation of Coal (Coalification)

- Accumulation of land plant material
- Reducing conditions – coastal and inland swamps

- Organic accumulation is greater than destruction (because of reducing conditions)
- Organic matter builds up to form **peat**

- **Peat** is compressed to form **lignite** – brown coal
- Lignite is compressed and volatile compounds are lost to form **bituminous coal** – soft coal
- Bituminous coal is further compressed and heated to form **anthracite** – hard coal



peat → lignite → subbituminous coal → bituminous coal → anthracite

Coal – what is it?

Elemental Composition	C	65-95%
	H	2-7%
	O	<25%
	S	<10%
	N	1-2%
Proximate Analysis	Char	20-70%
	Ash	5-15%
	H_2O	2-20%
	VM	20-45%

- Inhomogeneous organic fuel formed mainly from decomposed plant matter.

- Over 1200 coals have been classified.

- Coalification forms different coal types:

(Peat)
Lignite
Bituminous coal
Anthracite
(Graphite)

↓ Time, Temperature
Coal Rank

Classifying Coal

- Coal classification is performed using : Chemical analyses and calorific determination.

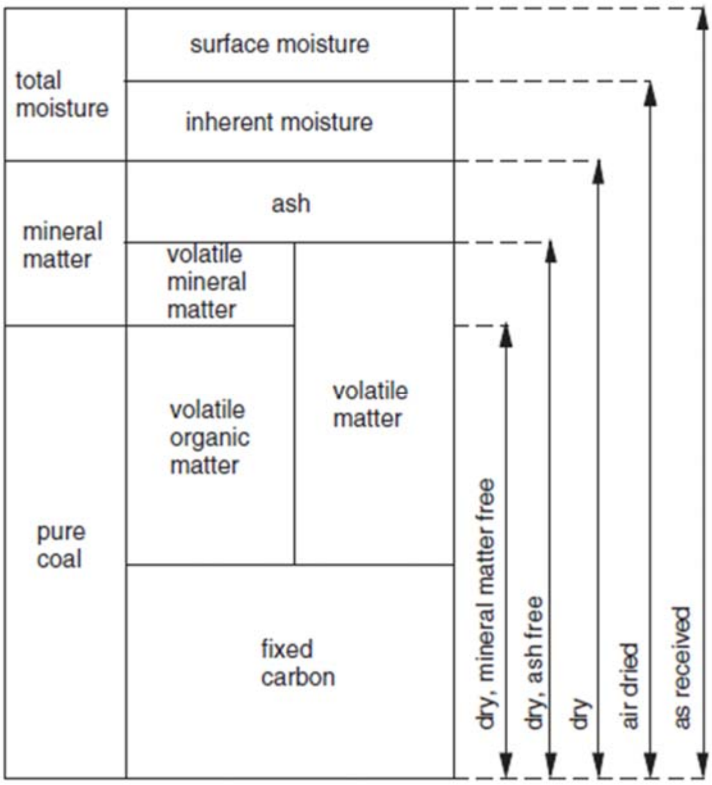
1. The chemical analyses:
   i. The proximate analysis gives the relative amounts of moisture, volatile matter, ash (*i.e.*, inorganic material left after all the combustible matter has been burned off), and, indirectly, the fixed carbon content of the coal.
   ii. The ultimate analysis gives the amounts of carbon, hydrogen, nitrogen, sulfur, and oxygen comprising the coal.

2. The calorific value, also known as heating value, is a measure of the amount of energy that a given quantity of coal will produce when burned.

- The grade of coal refers to the amount of mineral matter that is present in the coal and is a measure of coal quality.
- Sulfur content, ash fusion temperatures (*i.e.*, measurement of the behavior of ash at high temperatures), and the quantity of trace elements in coal are also used to grade coal

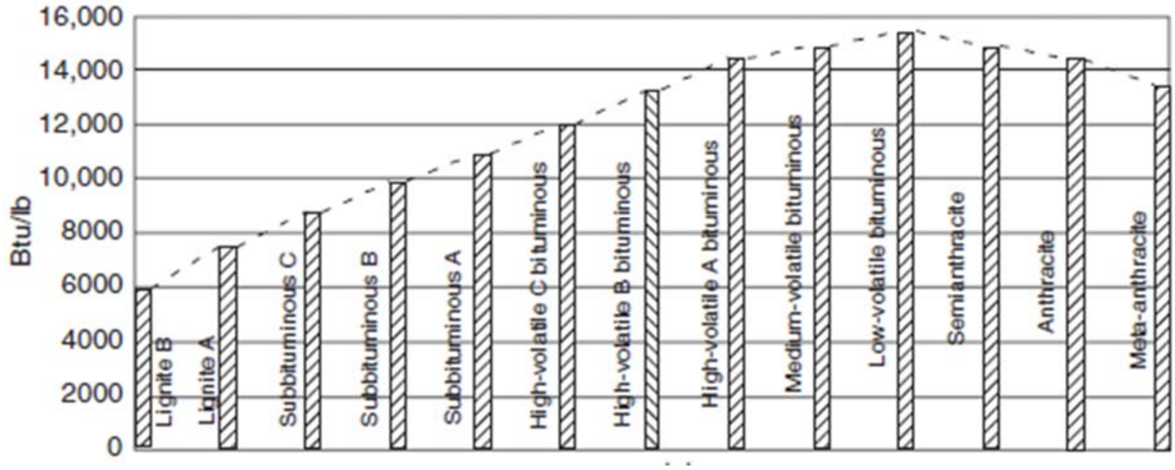
Analytical Data Presentation

- Because moisture and mineral matter (or ash) are extraneous to the coal substance, analytical data can be expressed on several different bases



Rank of Coal

- The degree of coal maturation is known as the *rank* of coal and is an indication of the extent of metamorphism the coal has undergone.
- Rank is also a measure of carbon content as the percentage of fixed carbon increases with extent of metamorphism



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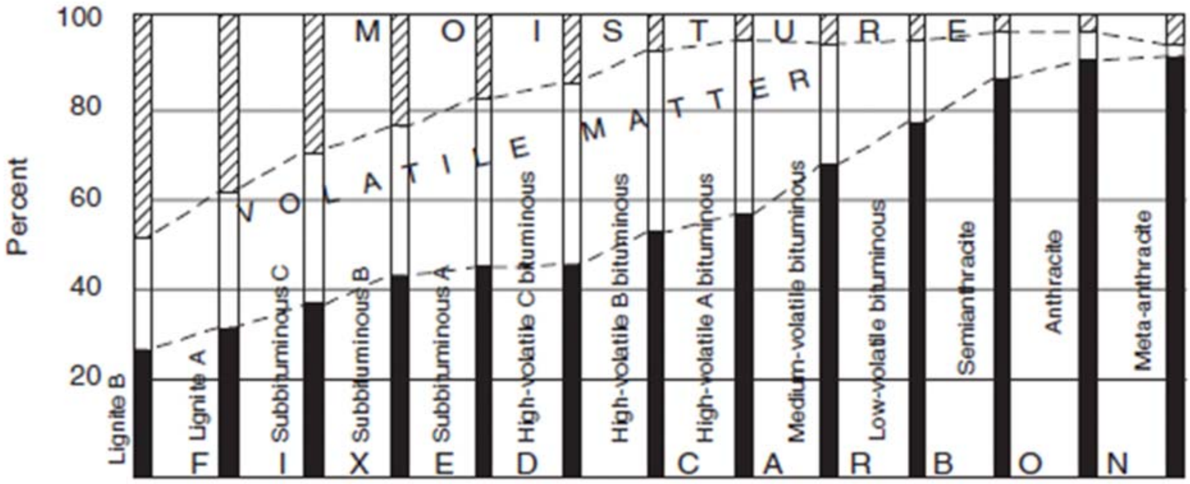
Rank of Coal



Comparison of heating values (on a moist, mineral-matter-free basis) and proximate analyses of coals of different ranks.

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Rank of Coal

ASTM Coal Classification by Rank

Class/Group	Fixed Carbon[a] (%)	Volatile Matter[b] (%)	Heating Value[b] (Btu/lb)
Anthracitic			
Meta-anthracite	>98	<2	—
Anthracite	92–98	2–8	—
Semi-anthracite	86–92	8–14	—
Bituminous			
Low-volatile	78–86	14–22	—
Medium-volatile	69–78	22–31	—
High-volatile A	<69	>31	>14,000
High-volatile B	—	—	13,000–14,000
High-volatile C	—	—	10,500–13,000[c]
Subbituminous			
Subbituminous A	—	—	10,500–11,500[c]
Subbituminous B	—	—	9500–10,500
Subbituminous C	—	—	8300–9500
Lignitic			
Lignite A	—	—	6300–8300
Lignite B	—	—	<6300

[a]Calculated on dry, mineral-matter-free coal. Correction from ash to mineral matter is made by means of the Parr formula: mineral matter = 1.08[percent ash + 0.55(percent sulfur)]. Ash and sulfur are on a dry basis.

[b]Calculated on mineral-matter-free coal with bed moisture content.

[c]Coals with heating values between 10,500 and 11,500 Btu/lb are classified as high volatile C bituminous if they possess caking properties or as subbituminous A if they do not.

Source: Berkowitz, N., *An Introduction to Coal Technology*, Academic Press, New York, 1979. With permission.

C

T

International Classification/Codification Systems

Parameter	Vitrinite Reflectance (Mean Random)		Characteristics of Reflectogram[b]				Maceral Group Composition (mmf) Inertinite[c]		Liptinite		
Digit	1, 2		3				4		5		
Coding	Code	R_{random} (%)	Code	Standard Deviation		Type	Code	Vol.%	Code	Vol.%	Petrographic Tests
	02	0.2–0.29	0	≤1	No gap	Seam coal	0	0 to <10	1	0 to <5	
	03	0.3–0.39	1	>0.1≤0.2	No gap	Simple blend	1	10 to <20	2	5 to <10	
	04	0.4–0.49	2	>0.2	No gap	Complex blend	2	20 to <30	3	10 to <15	
	—	—	3	—	1 gap	Blend with 1 gap	—	—	—	—	
	48	4.8–4.89	4	—	2 gaps	Blend with 2 gaps	7	70 to <80	7	30 to <35	
	49	4.9–4.99	5	—	>2 gaps	Blend with >2 gaps	8	80 to <90	8	35 to <40	
	50	≥5.0	—	—	—	—	9	≥90	9	≥40	

Parameter	Crucible Swelling No.		Volatile Matter[d] (daf)		Ash, Dry		Total Sulfur, Dry		Gross Calorific Value (daf)		
Digit	6		7, 8		9, 10		11, 12		13, 14		
Coding	Code	Number	Code	Wt.%	Code	Wt.%	Code	Wt.%	Code	MJ/kg	Technological Tests
	0	0–0.5	48	≥48	00	0 to <1	00	0 to <0.1	21	<22	
	1	1–1.5	46	46 to <48	01	1 to <2	01	0.1 to <0.2	22	22 to <23	
	2	2–2.5	44	44 to <46	02	2 to <3	02	0.2 to <0.3	23	23 to <24	
	—	—	—	—	—	—	—	—	—	—	
	7	7–7.5	12	12 to <14	20	20 to <21	29	2.9 to <3.0	37	37 to <38	
	8	8–8.5	10	10 to <12	—	—	30	3.0 to <3.1	38	38 to <39	
	9	9–9.5	09	9 to <10	—	—	—	—	39	≥39	
	—	—	—	—	—	—	—	—	—	—	
	—	—	02	2 to <3	—	—	—	—	—	—	
	—	—	01	1 to <2	—	—	—	—	—	—	

[a]Higher rank coals are coals with gross calorific value (maf) of ≥24 MJ/kg, and those with gross calorific value (maf) of <24 MJ/kg provided mean random vitrinitic reflectance ≥0.6%. To convert from MJ/kg to Btu/lb, multiply by 429.23.

[b]A reflectogram as characterized by code number 2 can also result from a high rank seam coal.

[c]It should be noted that some of the inertinite may be reactive.

[d]Where the ash content of the coal is more than 10%, it must be reduced before analysis to below 10% by dense medium separation. In these cases, the cutting density and resulting ash content should be noted.

Source: Van Krevelen, D. W., *Coal: Typology–Physics–Chemistry–Constitution*, Third ed., Elsevier Science, Amsterdam, 1993. With permission.

Coal

- Fossilized, condensed carbon-rich fuel

- 10 X reserves of oil/gas,
- last 200 years at present rate

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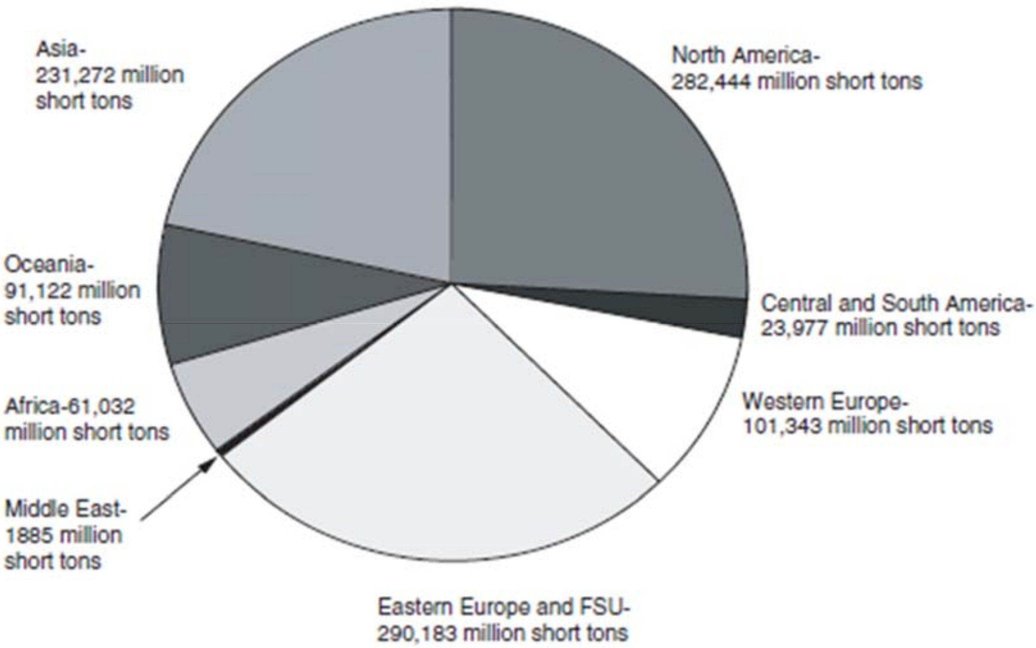
Distribution of recoverable coal reserves in the world



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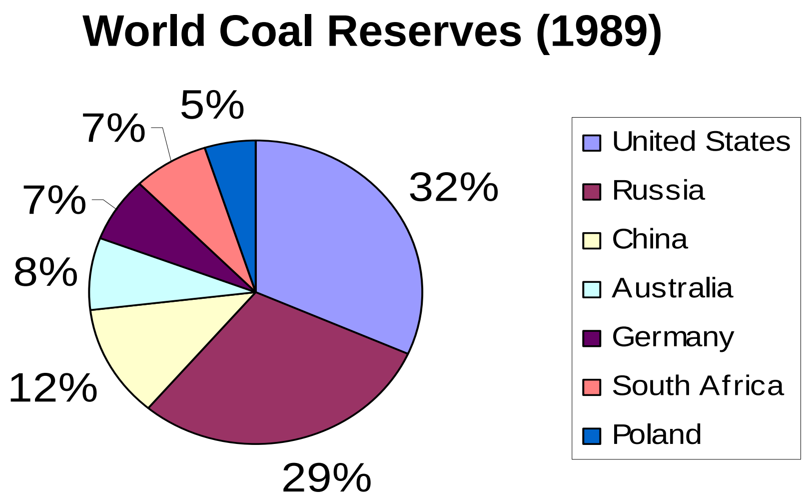
Coal Sources

- Coal is the world's most plentiful fossil fuel.
- Recoverable world coal reserves are estimated at about $1X10^{12}$ tons.



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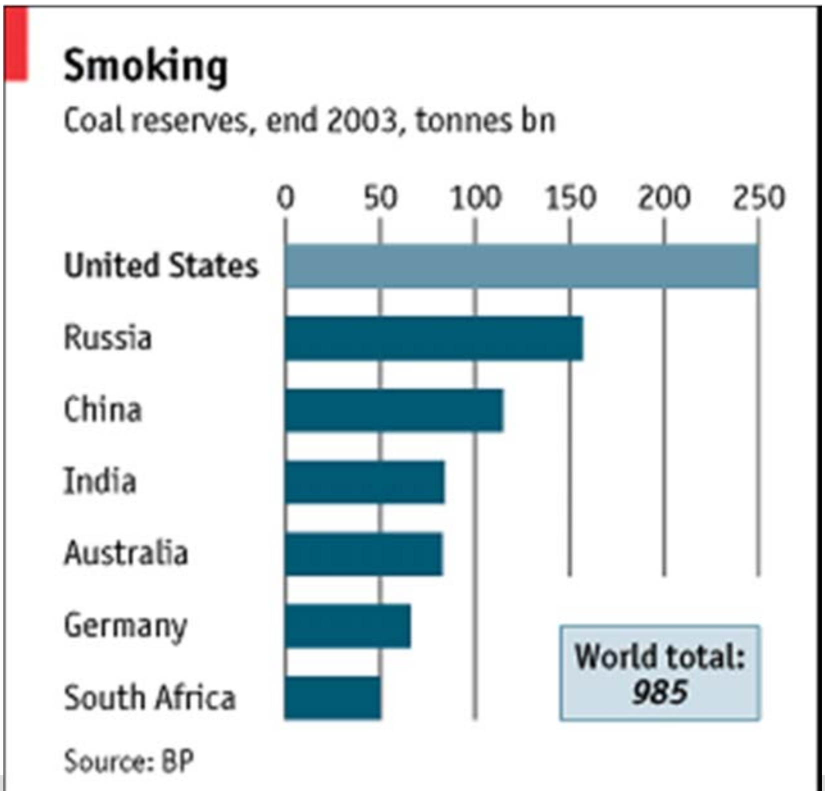
World Coal Reserves



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World Coal Reserves

ESTIMATED WORLDWIDE COAL RESERVES[a]

	Amount (tonne[b])	Percentage of Total	Equivalent Energy[c] (kW • hr)
Former Soviet Union	4.3×10^{12}	56	30.2×10^{15}
United States	1.5×10^{12}	20	10.5×10^{15}
Asia (not including former Soviet Union)	0.68×10^{12}	9	4.8×10^{15}
North America (not including United States)	0.60×10^{12}	8	4.2×10^{15}
Western Europe	0.38×10^{12}	5	2.7×10^{15}
Africa	0.11×10^{12}	1	0.7×10^{15}
Australasia	0.06×10^{12}	1	0.4×10^{15}
South America	0.01×10^{12}	—	0.1×10^{15}
	7.64×10^{12}	100	53.6×10^{15}

[a] According to USGS, 1971.

[b] 1 tonne = 1000 kg = 2205 lb = 1.1 ton.

[c] Based on an average of 6400 kW • hr per ton or 7020 kW • hr per tonne.

- from Kraushaar & Ristinen, 1993

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World Coal Reserves

Estimated Worldwide Coal Proved Reserves

Country	Amount (10^9 tonnes)	Percentage of World Total	*R/P* ratio (years)
United States	250	25	260
Former Soviet Union	230	23	≥500
Europe	138	14	300
China	115	12	70
Australia	82	8.3	240
Africa	55	5.6	230
South and Central America	22	2.2	350
North America (not incl. U.S.)	7.7	0.8	110
World total	984	100	192

Proved reserves are the amount recoverable from known deposits under existing economic and operating conditions.
The reserves-to-production (*R/P*) ratio is the number of years that the remaining proved reserves would last if production continues at the present level.
Source: *BP Global Reports*, December 2004. Reserves data from World Energy Council.

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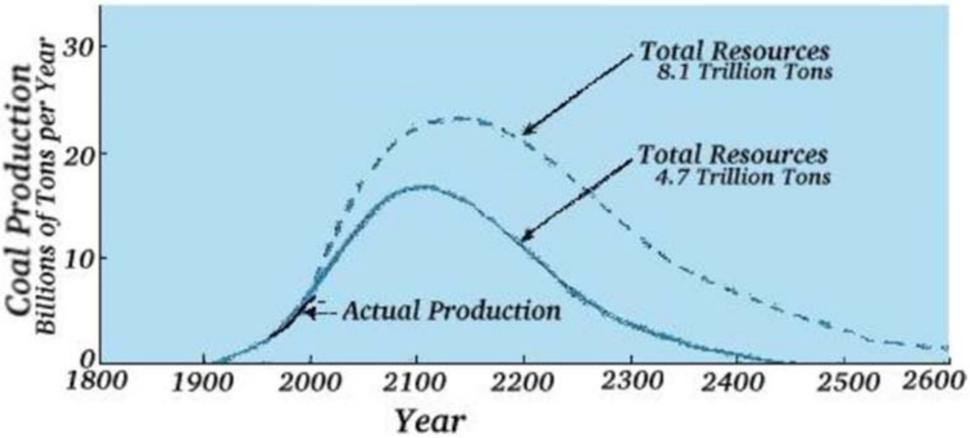
When will coal run out?



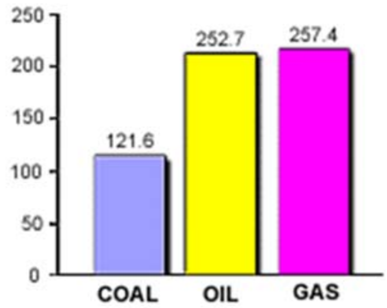
- We use 10^9 tonnes of coal per year, so the U.S. supply alone could last as long as 250 (1500) years at current rate
- Using variable rate model, more like 75–100 (400–600) years – especially relevant if oil, gas are gone
- This assumes global warming doesn't end up banning the use of coal
- Environmental concerns over extraction also relevant

Coal mines

Surface (strip) mine

Underground (shaft) mine,

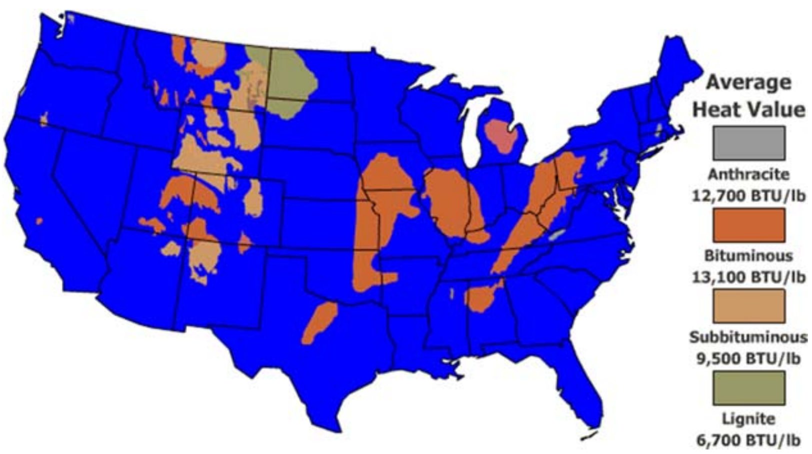
Coal cheaper, but polluting



coal May

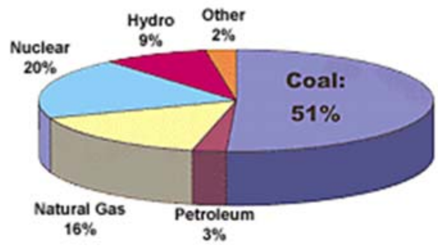
- has high-sulfur content, more expensive to mine
- has low-sulfur content, cheaper to mine
- But mining in semi-arid area more damaging to land.

Heat value of coal types



- Anthracite
- Bituminous
- Subbituminous
- Lignite

- 51% of U.S. use in coal



Energy lost from coal

- 65% lost in power plants
- 10% lost on transmission line (stray voltage)

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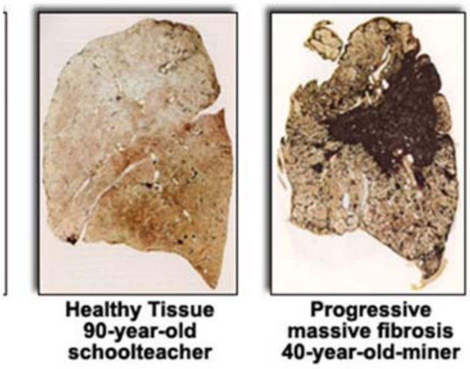
Effects on health



- Black Lung Disease (miners)
- Respiratory illnesses (public)

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Effects on land

Coal sludge releases

Hardpan at strip mines

Huge water use
Slurry pipelines

Mountaintop removal

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Effects on air

- Greenhouse gases
  - 3/4 sulfur dioxide, SO_x
  - 1/3 nitrogen oxides, NO_x
  - 1/2 carbon dioxide, CO_2

- Toxics, Trace metals
  - Mercury
  - Uranium
- Particulate matter
- Organic compounds

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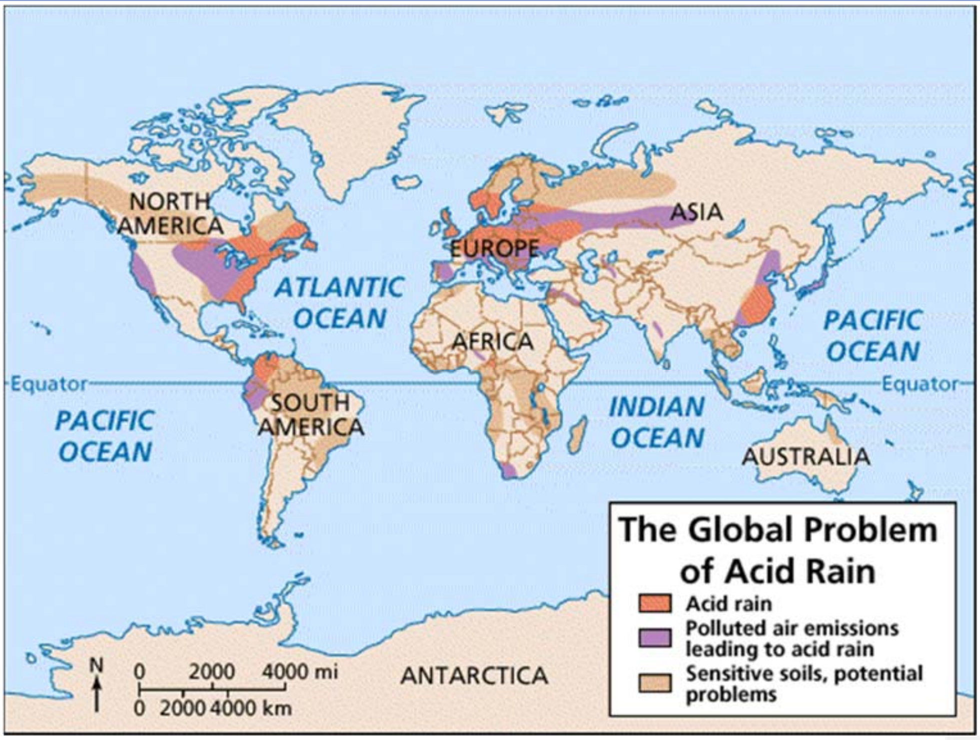
Acid rain



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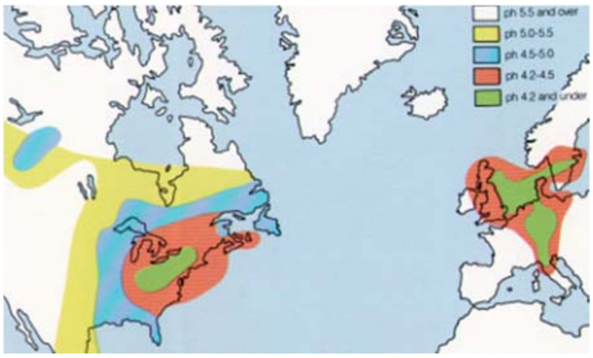
Acidity of rain



- pH of 6.0
  - Kills insects, crabs
- pH < 5.0
  - Kills fish, trees

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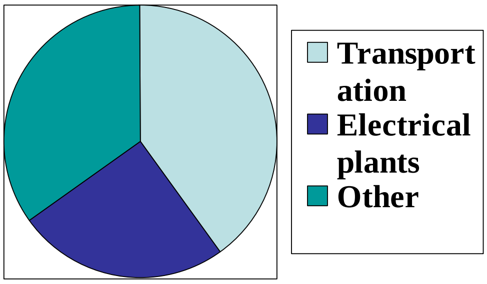
Sources of Nitrogen Oxides



- Nitrogen oxides and sulfur dioxide create acid rain
- Tall stacks deposit farther

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Carbon Oxide

$$C + O_2 \longrightarrow CO_2$$

- Almost 99% of C in coal is converted to CO_2.
- In order to lower CO_2 emission levels, coal power plants will have to leave steam-based systems (37% efficiency) and go towards coal gasification technology (60% efficiency).
- Meanwhile, CO_2 sequestration is being tested.

$$C + ½O_2 \longrightarrow CO$$

- CO is minimized by control of the combustion process (air/fuel ratio, residence time, temperature or turbulence).

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Particulate Matter

Particulate Matter

- **Bottom Ash** is uncombusted granular material, similar to concrete sand, that settles to the bottom of the boiler.
- **Fly Ash** is a fine powder made up of hollow ferroaluminosilicate particles enriched with Ca, K and Na,

➢ PM composition and emission levels are a complex function of:

1. Coal properties,
2. Boiler firing configuration,
3. Boiler operation,
4. Pollution control equipment.

➢ In PC power plants, since combustion is almost complete, the emitted PM is primarily composed of inorganic ash residues.

PM controls (AP-42, EPA)

Mainly post combustion methods:

Electrostatic precipitator (ESP)	99% (for 0.1>d(μm)>10) <99% (for 0.1<d (μm)<10)
Fabric filter (or baghouse)	As high as 99.9%
Wet scrubber	95-99%
Cyclone	90-95% (d(μm)>10)

Trace metals

FORMATION

Concentration of metal in coal, physical and chemical properties of the metal, combustion conditions.

Class 1

Elements that are approximately equally concentrated in the fly ash and bottom ash (Mn, Be, Co, Cr)

Class 2

Elements that are enriched in fly ash relative to bottom ash (Ar, Cd, Pb, An)

Class 3

Elements which are emitted in the gas phase (mainly Hg).

CONTROL

Control of total particulate matter emissions

Collection of fine particles.

Sorbents ???

Organic Compounds

- Include volatile, semivolatile and condensable organic compounds either present in the coal or formed as a product of incomplete combustion.
- Characterized by hydrocarbon class: alkanes, alkenes, aldehydes, alcohols and substituted benzenes.
- The main groups of environmental concern are:

1) tetrachloro- through octachloro- dioxins and furnans.
2) Polycyclic organic matter (POM).

- Emissions dependent on combustion behavior in the boiler (air/fuel ratio, residence time, temperature or turbulence).

Sulfur in coal (<10%)

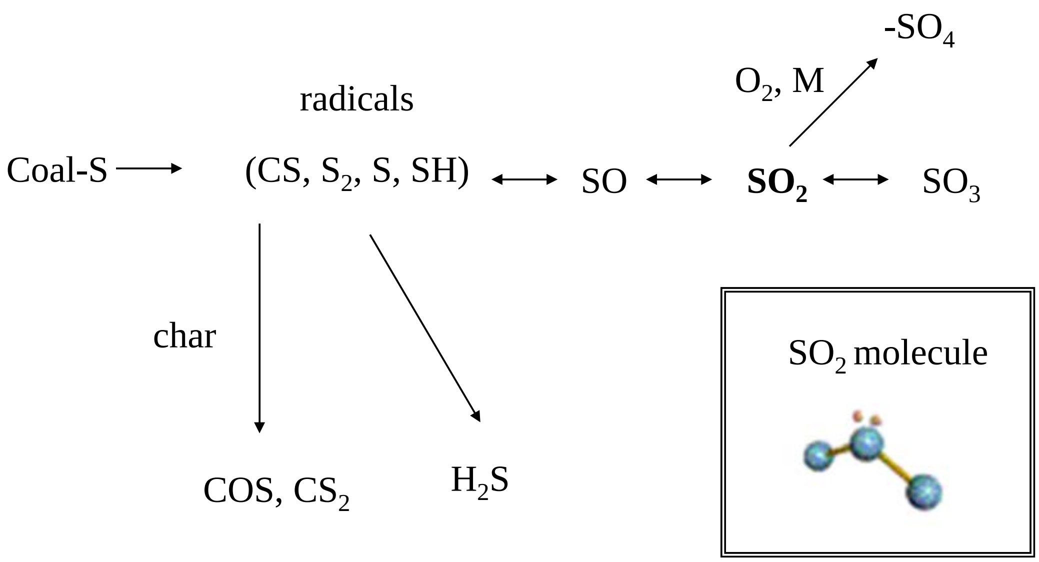
Organic sulfur (40%)

- Chemically bonded to the hydrocarbon matrix in the forms of thiophene, thiopyrone, sulfides and thiol.

Inorganic sulfur (60%)

- Imbedded in the coal, as loose pyrite - FeS_2 or marcasite, and calcium/iron/barium sulfates.
- Sources of sulfur in coal: Seawater sulfates, Limestone

SO_x Formation



SO_x reduction

- Pre combustion removal:
  - Physical cleaning (30-50% removal inorganic sulfur)
  - Chemical and biological cleaning (90% removal organic sulfur)
- Combustion configuration:
  - **No benign sulfur species!**
  - gasification combined-cycle systems (IGCC systems)
- Post-combustion removal:
  - Wet Flue Gas Desulfurization (FGD) (80-98%)
- In situ sulfur capture:
  - Dry Sorbent Injection (DSI) (50%)

Nitrogen in Coal (1-2%)

Name	Structure	~ Relative amount	Stability
Pyridine[1]	[redacted]	15-40%	More stable
Pyrrole[1]	[redacted]	60%	Less stable
Aromatic amines	[redacted]	6-10%	Stable

- [1]Including structures made up of 2-5 fused aromatic rings.

Main NO Mechanisms

1. Thermal NO
2. Prompt NO
3. Fuel NO: volatiles-NO and char-NO

Thermal NO (Zeldovich mechanism)

$$N_2 + O \leftrightarrow NO + N$$

$$N + O_2 \leftrightarrow NO + O$$

- ➢ Strong temperature-dependence: >1300-1500°C
- ➢ Not a major source of NO in coal utility boilers.

Main NO Mechanisms

Prompt NO

$$N_2 + CH_x \leftrightarrow HCN + N + \ldots$$

$$N + OH \leftrightarrow NO + H$$

- ➢ Prevalent only in fuel-rich systems.
- ➢ Not a major source of NO in coal utility boilers.

Fuel NO (-N in volatiles)

$$\text{Fuel-N} \xrightarrow{\text{volatiles}} \mathbf{HCN}/NH_3$$

$$HCN/NH_3 + O_2 \longrightarrow NO \quad \text{(formation)}$$

$$NO + HCN/NH_3 \longrightarrow N_2 \quad \text{(destruction)}$$

- ➢ The major source of NO in coal utility boilers (>80%).

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Main NO Mechanisms

Char NO (-N in the char)

$$\text{Char-N} + \tfrac{1}{2}O_2 \rightarrow NO \qquad \text{(formation)}$$

$$\text{Char-C} + NO \rightarrow \tfrac{1}{2}N_2 + \text{Char(O)} \qquad \text{(destruction)}$$

[char-NO = ~25%] < [volatiles-NO = ~75%]

NO Reduction

Combustion controls:

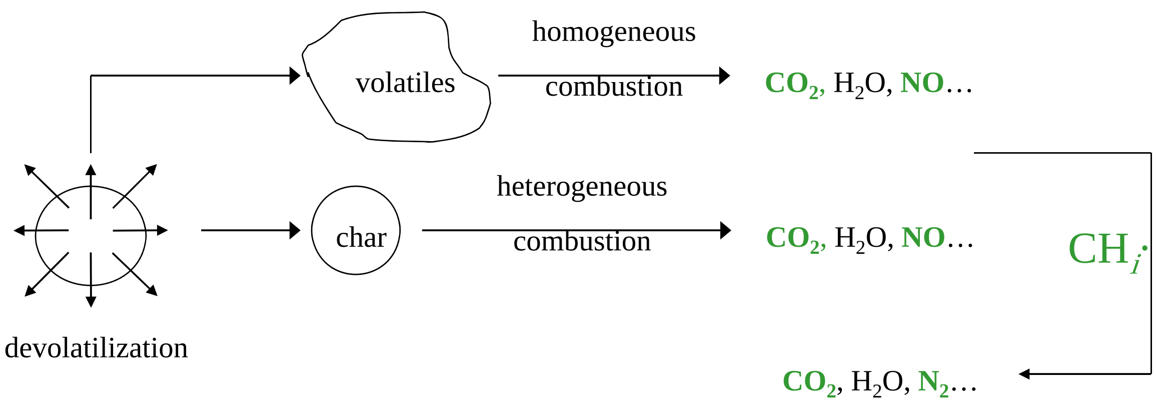
1. Modification of combustion configuration:
   - Reburning
   - Staged Combustion (air/fuel)

Post combustion controls:

1. Injection of reduction agents in flue gas.
2. Post-combustion denitrification processes.

Reburning

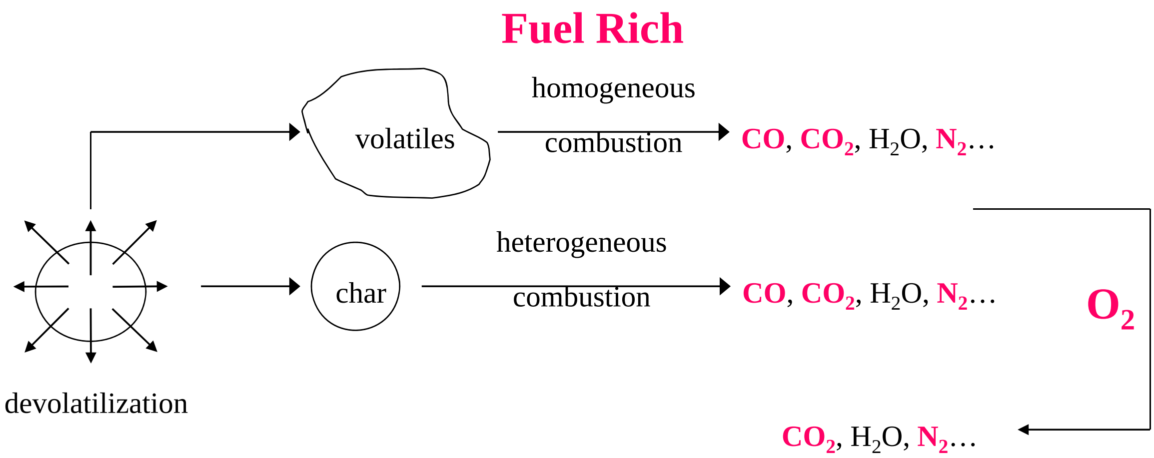
Excess air



$$CH_i^{\cdot} + NO \leftrightarrow HCN$$

$$HCN + NO \leftrightarrow N_2 + \ldots$$

Staged Combustion



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NOx control options(from AP-42, EPA)

Control Technique	NO Reduction Potential(%)
Overfire air (OFA)	20-30
Low Nox Burners (LNB)	35-55
LNB + OFA	40-60
Reburn	50-60
SNCR (Selective Non Catalytic Reduction)	30-60
SCR (Selective Catalytic Reduction)	75-85
LNB with SCR	50-80
LNB with OFA and SCR	85-95

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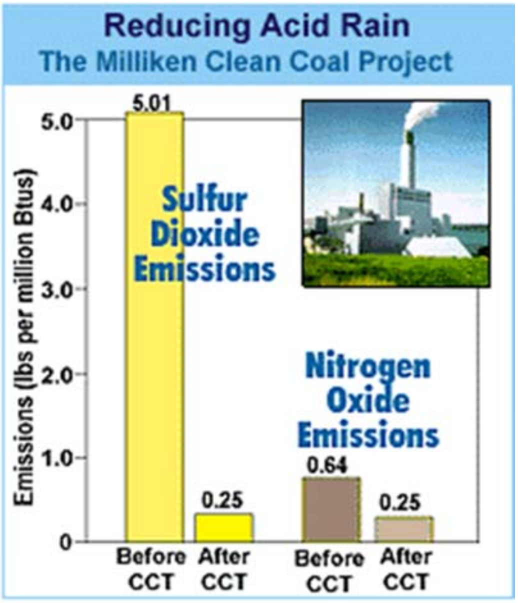
Coal scrubbers



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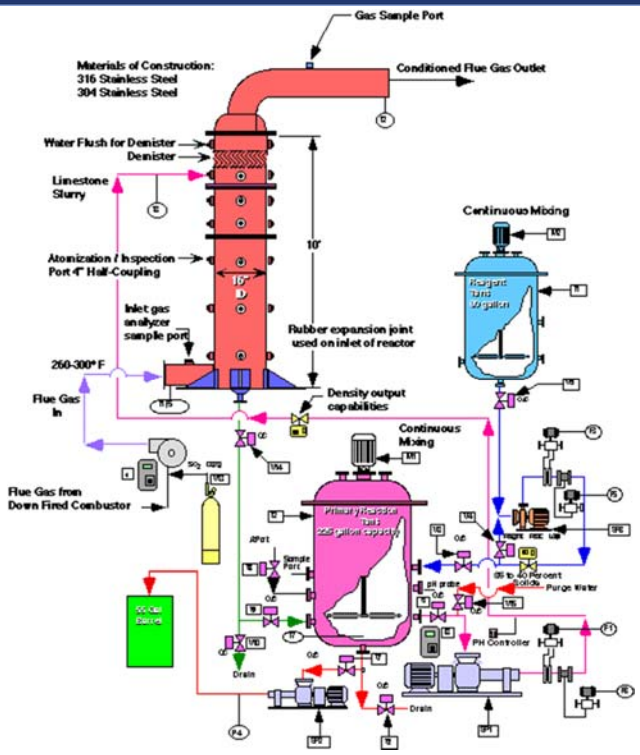
Coal scrubbers



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Fire is the best of servants:

But what a master

Carlyle

Gasification Activities

SNAP SHOT OF WORLDWIDE GASIFICATION ACTIVITY*

STATUS	AMERICAS**		ASIA**		AUSTRALIA**		EUROPE**			AFRICA/M. EAST**	
	USA	REST	CHINA	REST	AUSTRALIA	REST	GERMANY,	UK	REST		
OPERATIONAL	26	15	98	28	4	2	19	5	33	5	6
UNDER CONSTRUCTION	10	9	10	2	1	0	0	3	4	0	2
PROPOSED & PLANNED	113	23	58	38	22	3	3	20	13	1	10
SUB TOTAL	149	47	166	68	27	5	22	28	50	6	18
TOTAL	196		234		32		100			24	
	**Brazil, Canada, Chile, Dom. Repub., Trinidad/Tobago		**India, Japan, Malaysia, S. Korea, Singapore, Taiwan, Vietnam		**New Zealand		**Austria, Belgium, Czech Rep., Finland, France, Italy, Netherlands, Norway, Poland, Portugal, Serbia, Spain, Sweden			**Qatar, Oman, Egypt, Nigeria, UAE, Saudi Arabia	

*Source, July 28 2010 Zeus Syngas Refining Report

Simplified Schematic of Gas Path Systems

GASIFICATION → SHIFT CONV. → GAS CLG. → RECTISOL → METHANATION → GAS DRYING → SNG COMP.

↓ ASH (from GASIFICATION)

↓ O/T LIQUIDS SEPARATION (from SHIFT CONV. and GAS CLG.)

↓ NAPTHA (from RECTISOL)

OVERALL ENERGY BALANCE

	ENERGY IN		ENERGY OUT
COAL	8,189	SNG	5,577
POWER	273		

COAL GAS EFFICIENCY	OVERALL PLANT EFFICIENCY	WITH APX 50% CCS
5,577/8,189=68.1	5,588/8,462=65.9	5,577/8,605=64.8

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What is Coal Gasification ?

- The process of gasification is the conversion of carbonaceous fuels into gaseous product that has a useable heating value
- Gasification is NOT combustion as the gas released from combustion has no useable heating value
- The definition includes the processes of pyrolysis and substochiometric partial oxidation
- Can be applied to solid, liquid and gaseous feedstocks

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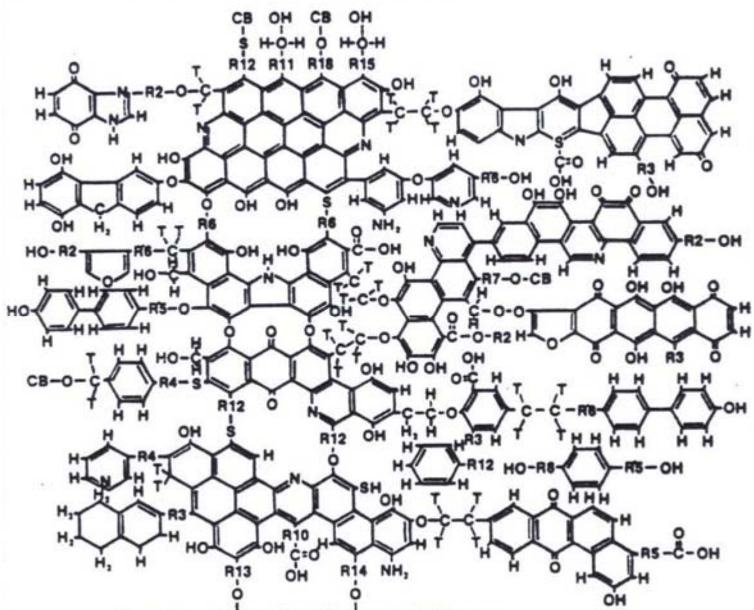
What is Coal Gasification ?

- Starting point: Coal

  HHV ~13,000 Btu/lb



Cross Bonding to More Heterocyclic Groups

What is Coal Gasification ?

- Product: Combustible Gas (Syngas)

Constituent	Heating Value (1) Btu/ft^3
Methane	911
Carbon Monoxide	321
Hydrogen	275

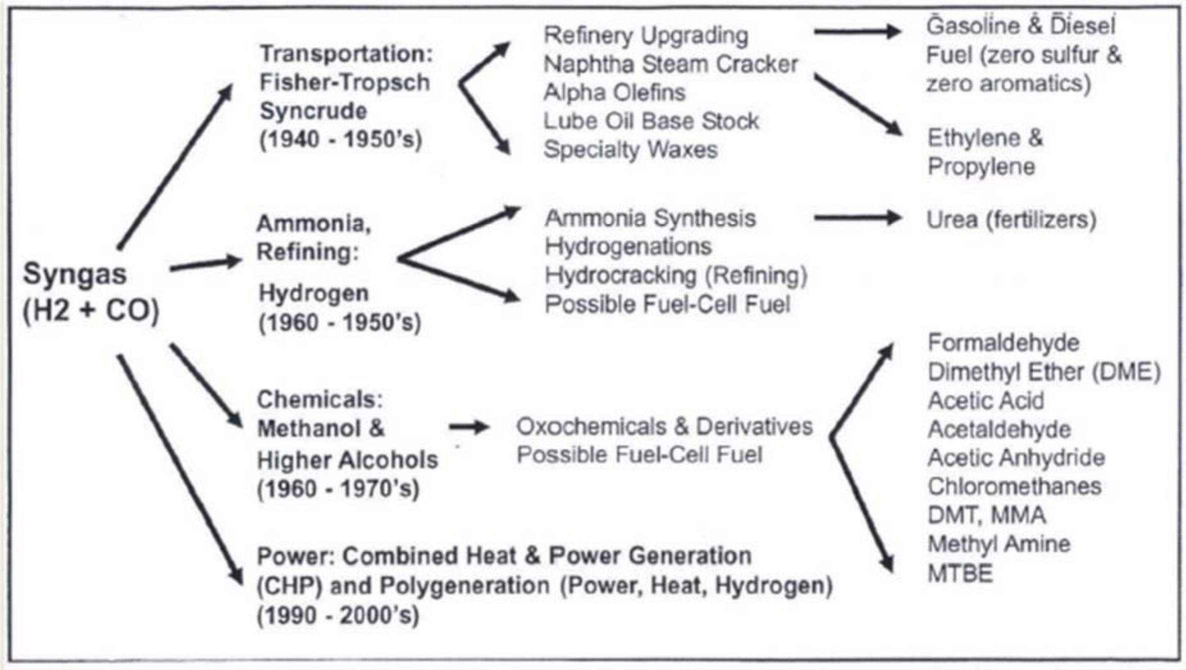
(1) Net heating value

Composition of Cleaned Syngas

Constituent	Volume %
Carbon monoxide	42.7
Hydrogen	38.3
Carbon dioxide	14.4
Methane	0.1
Water	0.3
Nitrogen	3.3
Argon	0.9
Hydrogen sulfide	200 ppmv
Carbonyl sulfide	10 ppmv
Ammonia	0.0 ppmv

Why is Coal Gasification Important ?

➢ Products:



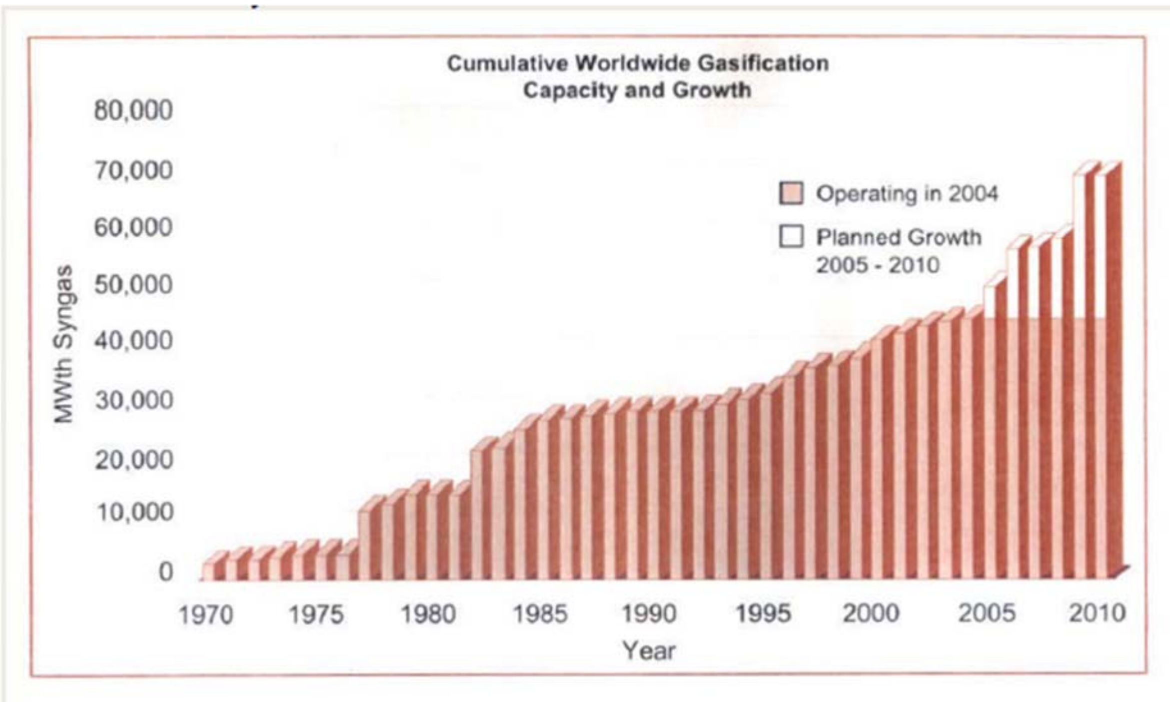
Why is Coal Gasification Important ?

Other drivers:

- ➢ Ability to use fuel feedstocks of low quality but more available than traditional fuels
- ➢ Overall higher efficiency
- ➢ Consequently less CO_2 emissions because of higher efficiency
- ➢ IGCC process capable of capturing CO_2
- ➢ Capable of capturing mercury at much lower costs than traditional coal plants
- ➢ Polygeneration capabilities

Costs: Estimated construction cost 10 – 20 % higher than conventional pulverized coal power plant

Status for Gasification



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