Resources – Coal

Outline

- **Coal types**
- **Mining Methods**
- **Reserves**
- **Prices**
- **Emissions**
- **Coal Bed Methane**
- **Oil from Coal or Gas**

Based on

- **The Coal Resource** by World Coal Institute 2005.
- The Coal Resource Base, Chapter 2 of **Producing Liquid Fuels from Coal** by J.T. Bartis, F. Camm and D.S. Ortiz. Published by RAND 2008. ISBN: 978-0-8330-4511-9.
- The Role of Coal in Energy Growth and CO_2 Emissions, Chapter 2 of **The Future of Coal**, an Interdisciplinary MIT Study, 2007.
- **Coal Bed Methane Primer** by ALL Consulting and Montana Board of Oil and Gas Conservation Board, 2004.

Fossil Fuels: Coal

- Coal, like oil and gas, forms from organic materials. Coal formation started during the Carboniferous Period (360-290 million years ago).
- Coal contains much less hydrogen than oil or gas, but it still is a hydrocarbon.

	Carbon molecule ratio	Vitrinite reflectance ratio	BTU per pound	kCal per kg	
Peat	●<40	●<0.20	●<6300	●<3503	**Brown**
Lignite	40<●<50	0.20<●<0.35	6300<●<8300	3503<●<4615	**Brownish**
Bituminous	50<●<85	0.35<●<2.00	8300<●<14000	4615<●<7784	**Black**
Anthracite	85<●<98	2.00<●<4.10	14000<●	14000<●	**Glossy black**
Graphite	98<●	4.10<●	14000<●	14000<●	**Pencil lead**

- Vitrinite reflectance is ability to reflect light (rises with the temperature the rock is exposed to).

- 1 BTU (British Thermal Unit) raises the temperature of 1 pound of water by 1 ^{o}F.
  - This is increasing temperature of 453.6 grams of water by 0.556 ^{o}C.
- 1 Calorie increases the temperature of 1 gram water by 1°C.
  - 1 BTU = 453.6 * 0.556 = 252.2 calories. Compare with the calories in your food.

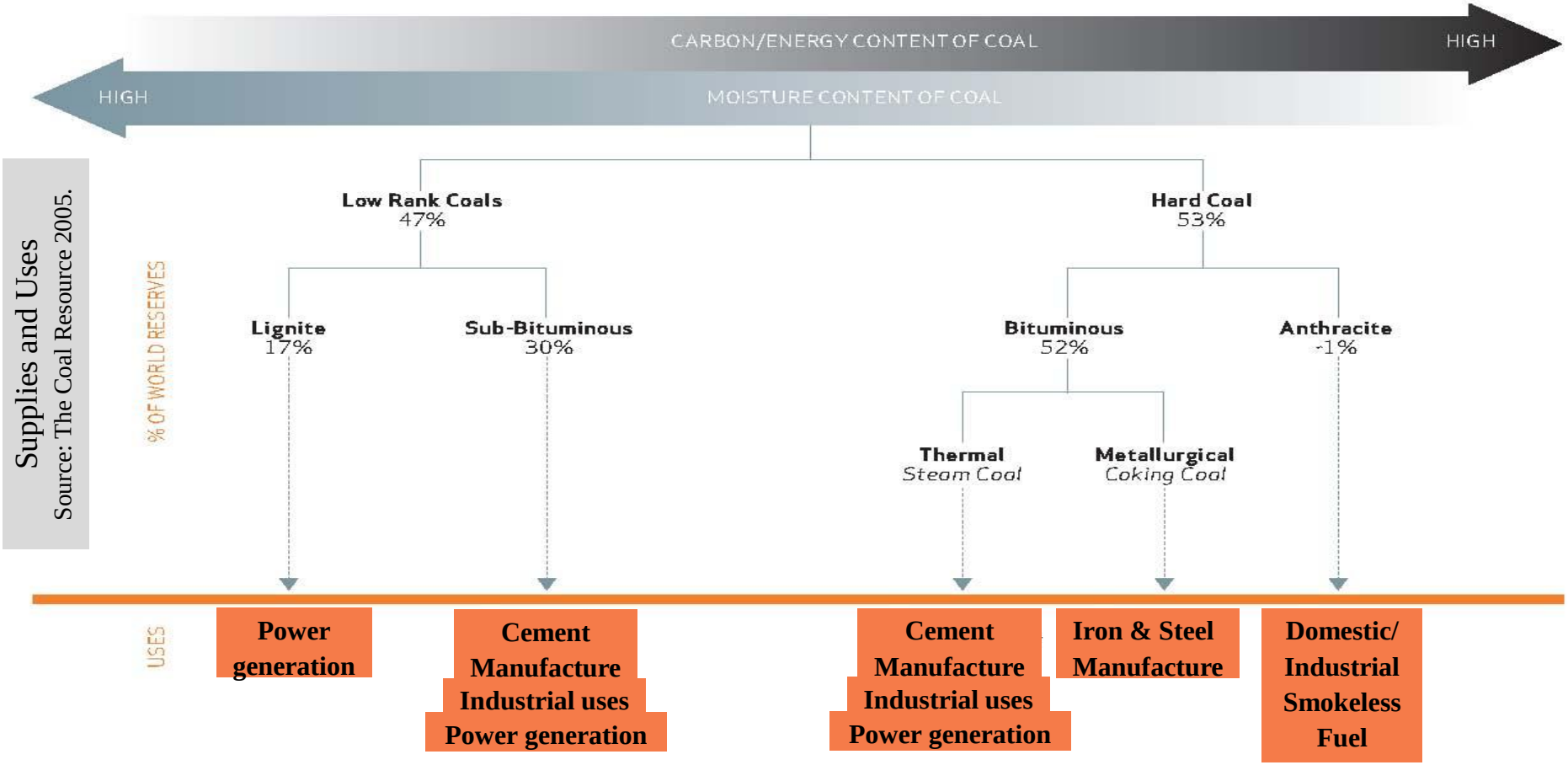
Energy in Terms of Joule

- 1 Joule is the potential energy spent to lift 1 kg by 0.1 meter (=1/9.8).
  - 1 BTU = 1055 joules
  - 1 BTU = 252 calories
  - 238 calories = 1000 joules = 1 kilo joule = 0.001 mega joule
  - To burn 238 Calories lift 1 kg package by 0.1 meter approximately 1000 times.
  - A serving of Hershey chocolate bar has 220 calories, lift 1 kg package by 0.1 meter approximately 925 times.

- 6300 BTU = 6.6465 Mega Joule. 6300 BTU is 6,646,500 (=6,300*1055) joules
- If 1 pound peat gives 6300 BTU, it gives 6.6465 Mega Joule. Then 1 kilogram peat gives 6.6465/0.4536 = 14.653 Mega Joule. Rest of the table below is computed similarly.

	BTU per pound	Mega Joules per kilogram
Peat	●<6300	●<14.7
Lignite	6300<●<8300	14.7<●<19.3
Bituminous	8300<●<14000	19.3<●<32.6
Anthracite	14000<●	32.6<●
Graphite	14000<●	32.6<●

Coal Supplies and Uses

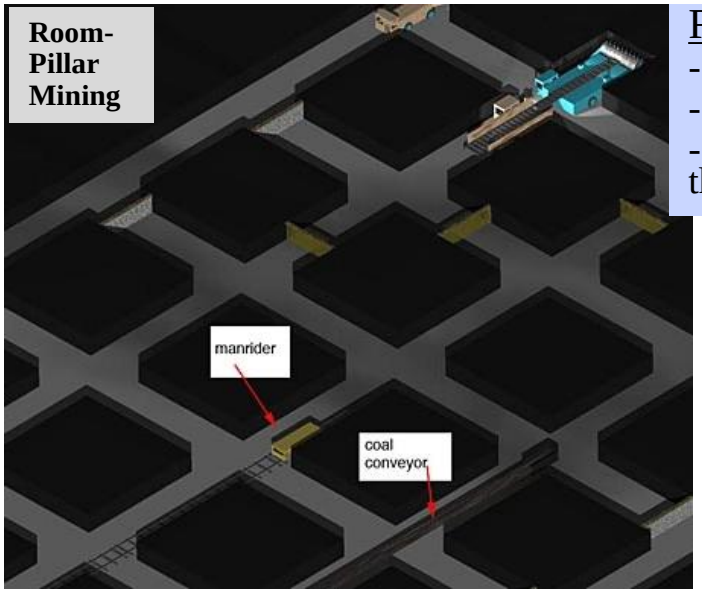


- Significant amount of coal is used for power generation. In 2002, 39% of global electricity is generated from coal. This percentage is expected to drop slightly to 38% in 2030.
- Use of coal depends on country
  - US: 91% of coal for electric generation
  - China: 55% of coal for electric generation

Mining

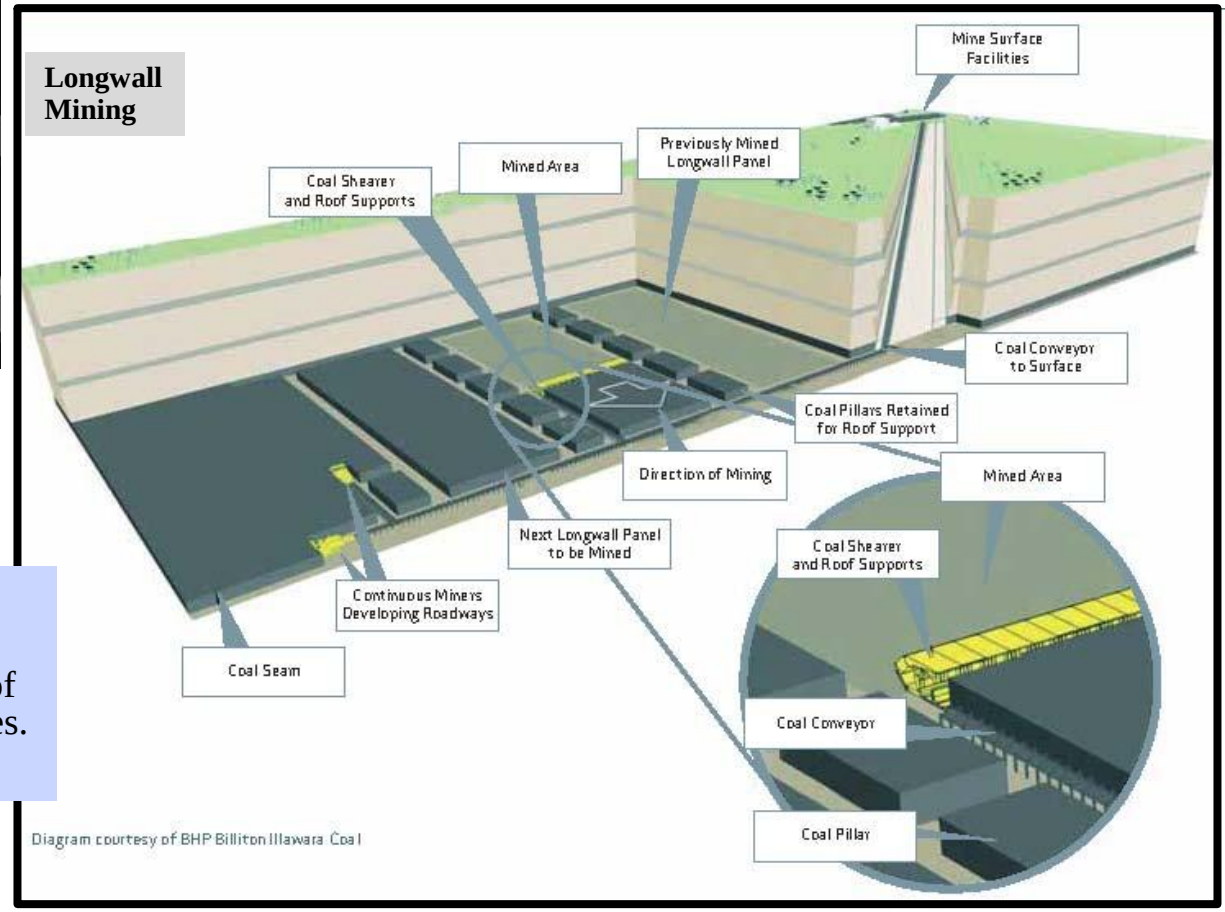
- **Mining Methods**

Production: Coal Mining



Room-Pillar Mining:

- Pillars support the rocks/soil (overburden) above the mine.
- Pillars can consume up to 40% of coal, so 60% coal recovery.
- To improve recovery, use retreat mining: remove coal from pillars as exiting the mine. Dangerous but possible.



Longwall Mining:

- Coal shearer has roof supports.
- After the shearer is done with a panel, roof supports move away and the panel collapses.
- 75% of the coal can be extracted.

Both Retreat and Longwall mining cause a collapse underground; effects over the ground?

Surface Effects of Underground Mine Collapse

Mine Drainage

Mine drainage occurs when old underground mine workings gradually fill up with water, and the water breaks out onto the ground surface usually near a coal outcropping on or near a hillside. Sometimes heavy rains or melting snow can raise the water level in a mine and trigger a mine water breakout.

If such a breakout occurs suddenly and unexpectedly near a building, substantial damage can occur. Although this is not considered mine subsidence, under certain circumstances, building damage from such a mine water breakout would be covered by Mine Subsidence Insurance.

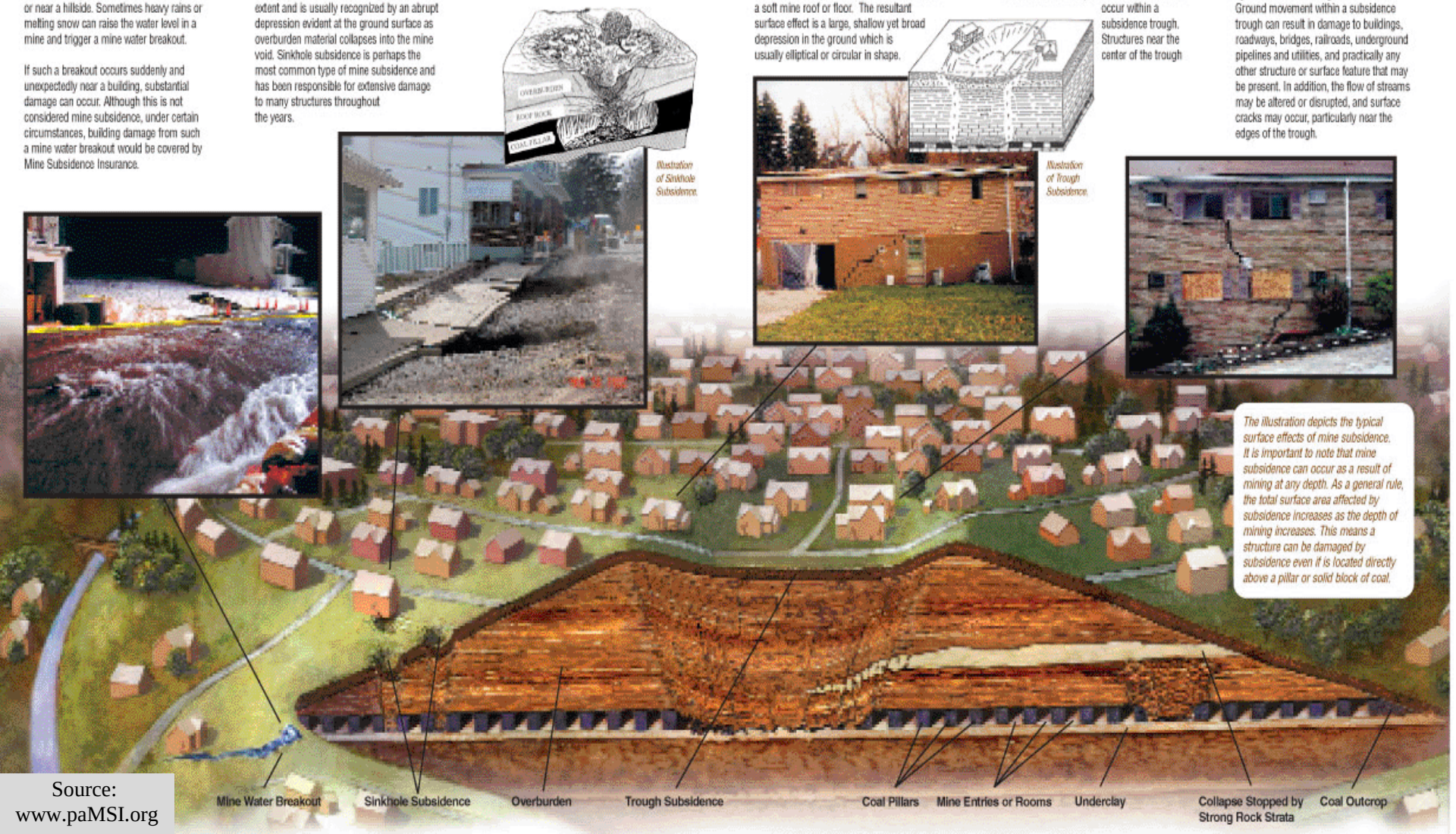
Sinkhole Subsidence

Sinkhole subsidence occurs in areas overlying underground mines which are relatively close to the ground surface. This type of subsidence is fairly localized in extent and is usually recognized by an abrupt depression evident at the ground surface as overburden material collapses into the mine void. Sinkhole subsidence is perhaps the most common type of mine subsidence and has been responsible for extensive damage to many structures throughout the years.

Trough Subsidence

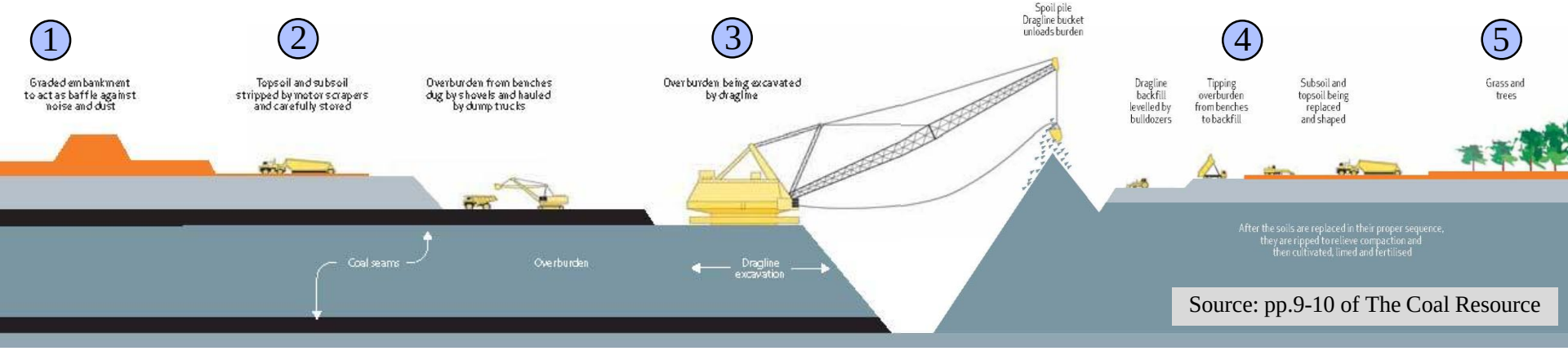
Subsidence troughs over abandoned mines usually occur when the overburden sags downward due to the failure of remnant mine pillars or by punching of the pillars into a soft mine roof or floor. The resultant surface effect is a large, shallow yet broad depression in the ground which is usually elliptical or circular in shape.

Subsidence is usually greatest at the center of the trough and it progressively decreases until the limit of the impacted surface area is reached. Horizontal ground movements also occur within a subsidence trough. Structures near the center of the trough can experience damage caused by the compression of the ground surface, and structures near the edges can be damaged by tension or stretching of the surface. Ground movement within a subsidence trough can result in damage to buildings, roadways, bridges, railroads, underground pipelines and utilities, and practically any other structure or surface feature that may be present. In addition, the flow of streams may be altered or disrupted, and surface cracks may occur, particularly near the edges of the trough.



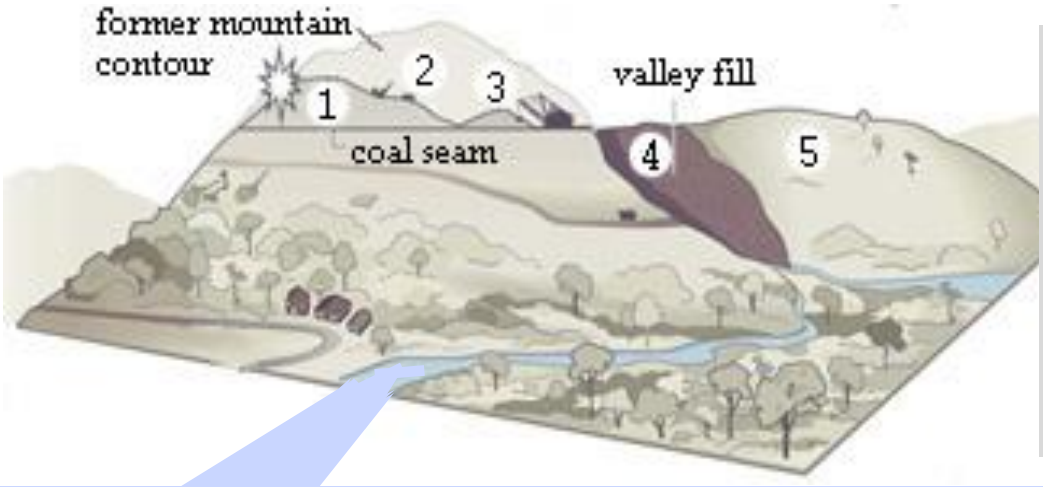
Source: www.paMSI.org

Surface Mining: 5 steps



Source: pp.9-10 of The Coal Resource

Surface mining is safer and can be used when coal I closer to the surface. But it can change the mountain contours.



Source: http://mountainjustice.org

Mountain top removal in West Virginia
Source: www.epa.gov/region3/mtntop/

Water stream(s) can be polluted by dumped waste. Army Corp of Engineers issues permits to dump rock, soil and waste into streams. It did for Spruce 1 mine of Arch Coal in Appalachia in 2007. In 2009, EPA revoked the permit saying "dumping waste would impose unacceptable harms on water quality and wildlife. Arch Coal attempted to take the matter to the Supreme Court which declined to review it in 2014.

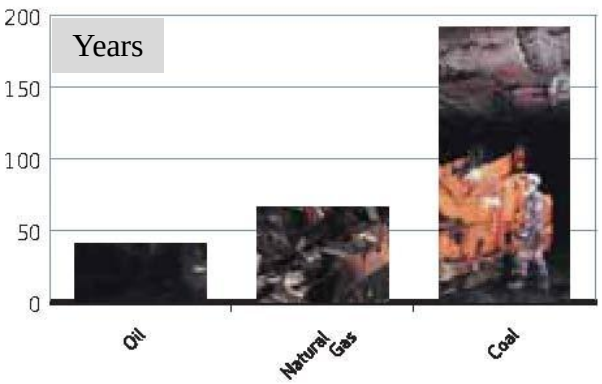
Source: B. Kendall. Supreme court rejects Arch Coal challenge to EPA powers on permits. WSJ, Mar 24, 2014.

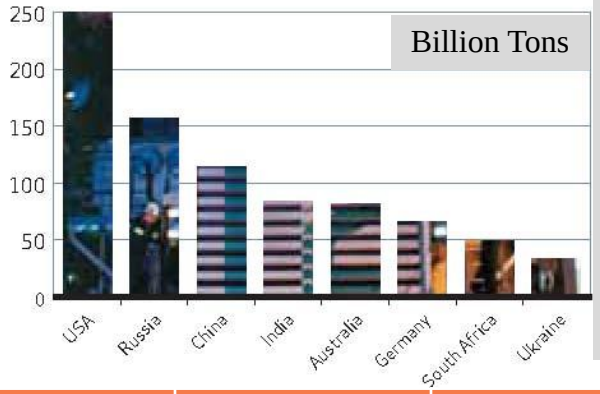
Economics and Environment

- **Reserves: Coal is plenty and shippable**
- **Prices: Coal is cheap**
- **Emissions: Coal is dirty**

Reserves and Production: Coal is Plenty

Sufficient coal reserves for 190 years and most are in the USA.





Source: The Coal Resource by World Coal Institute 2005.

Reserves	% of Global	% Production
US	27.1	17.0
Russia	17.3	5.0
China	12.6	38.4
India	10.2	7.2
Australia	8.6	6.0
South Africa	5.4	4.1
Ukraine	3.8	1.3
Kazakhstan	3.4	1.6
Top 8 countries	88.4	80.6

Source: Ch. 2 of The Coal Resource Base, 2007.

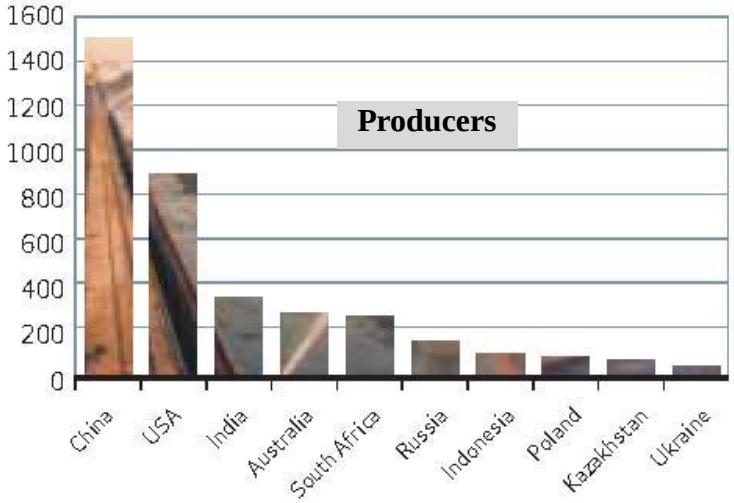
	Reserves in MM tons	Production in MM tons
Montana	74,900	40
Wyoming	40,600	404
Illinois	38,000	32
W. Virginia	18,000	154
Kentucky	14,900	120
Pennsylvania	11,800	67
Ohio	11,500	25
Colorado	9,800	39
Texas	9,500	46
US Total	267,000	1,131

Coal reserves are more uniformly distributed than Oil/Gas: Geographically large countries have large reserves.
2006 coal production is 6.2 billion tons = $125*10^{15}$ Btu = 80% of annual oil production.

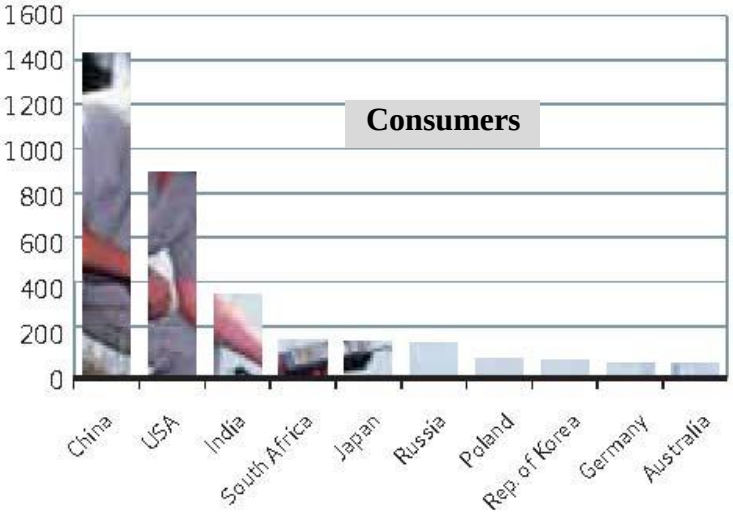
Source: Producing Liquid Fuels from Coal.

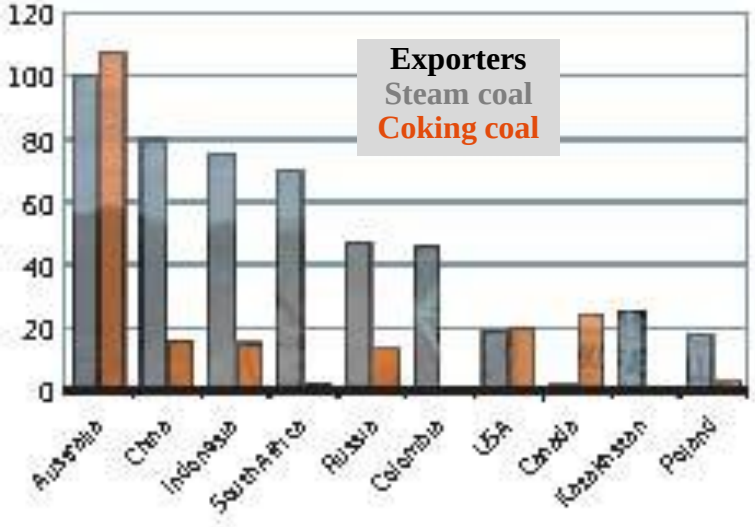
Who are the Producers and Consumers?

From left to right, producers, exporters, importers and consumers. Amounts are in million tons.
Source: The Coal Resource.



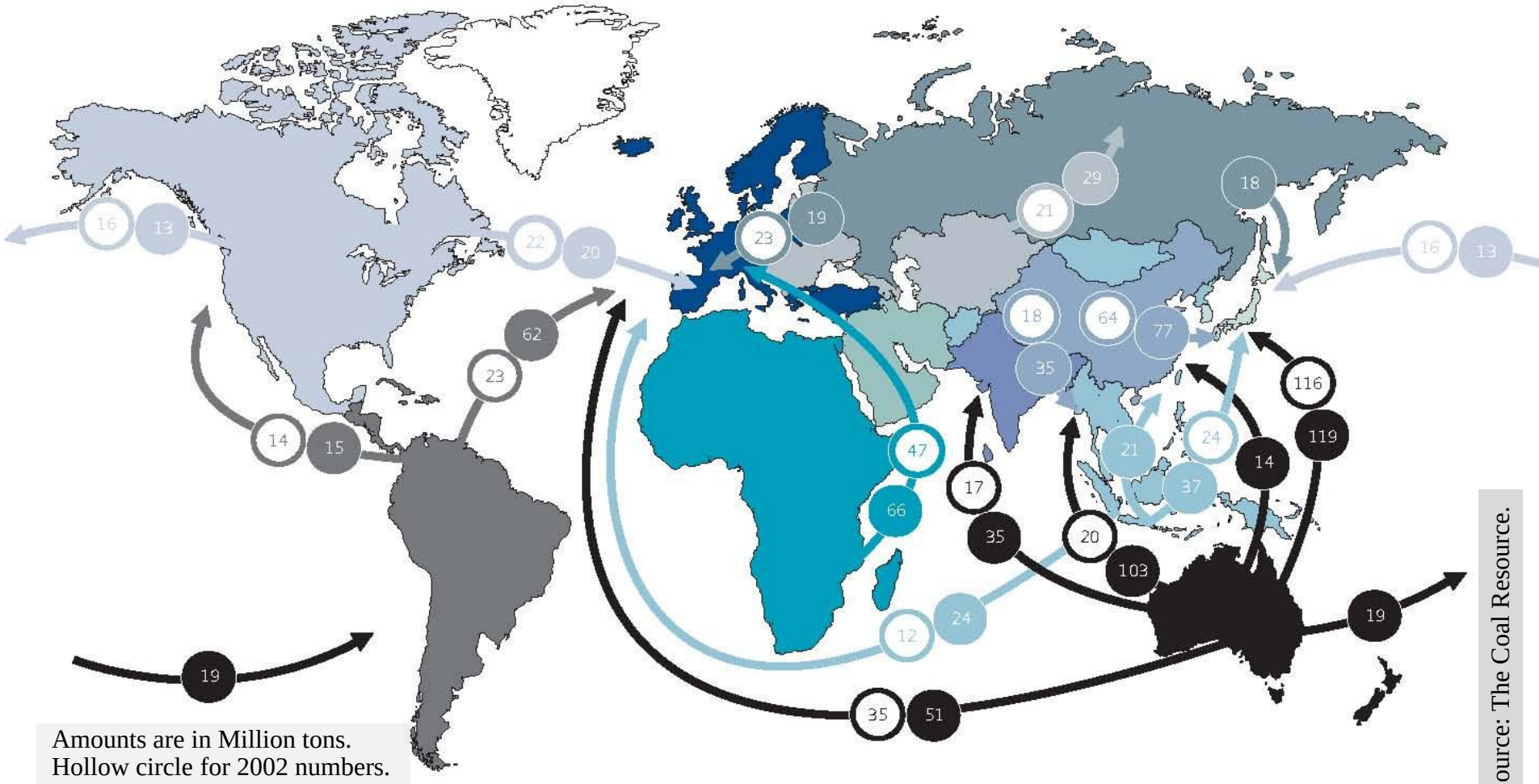
Importing Country	Amount
Japan	162
Korea	72
Taiwan	54
Germany	35
UK	32
Russia	24
India	24
USA	23
Holland	22
Spain	22





- Over 4 Billion ton of coal is produced in 2005.
- Consumption increased to 6.3 Billion tons in 2010.
- Production is expected to reach 7 Billion ton in 2030.

Global Coal Trade: Coal is shippable



Amounts are in Million tons.
Hollow circle for 2002 numbers.
Solid circle for 2030 forecasts.

Source: The Coal Resource.

Largest exporter Australia sells to Pacific Market (Japan, Korea, Taiwan, India).

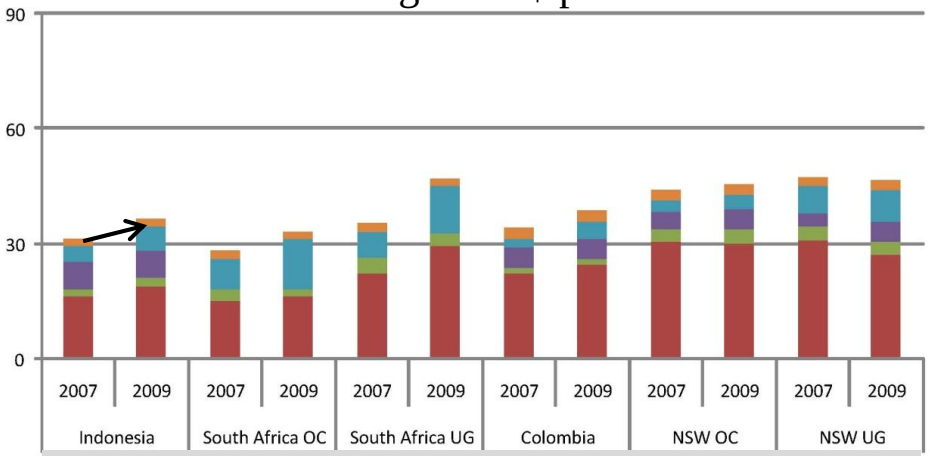
Atlantic Market (UK, Germany, Spain) buys from Africa, Australia, North America, Russia, Indonesia. Atlantic market is expected to get smaller.

Global Coal Market

- Coal demand is uncertain as the recovery from global financial crisis is questionable.
- Chinese domestic coal market >3 the international coal trade. An imbalance in Chinese market strongly affects the global market.
- Demand growth continues but slows down. China in absolute growth and India in relative growth lead the market.
- US is a swing coal producer. It is capable of ramping-up exports quickly and nearly doubling from 2010 to 2012.
- Mongolia and Mozambique are joining the list of major coal exporters.
- Investments into mining fields and transportation infrastructure is solid.

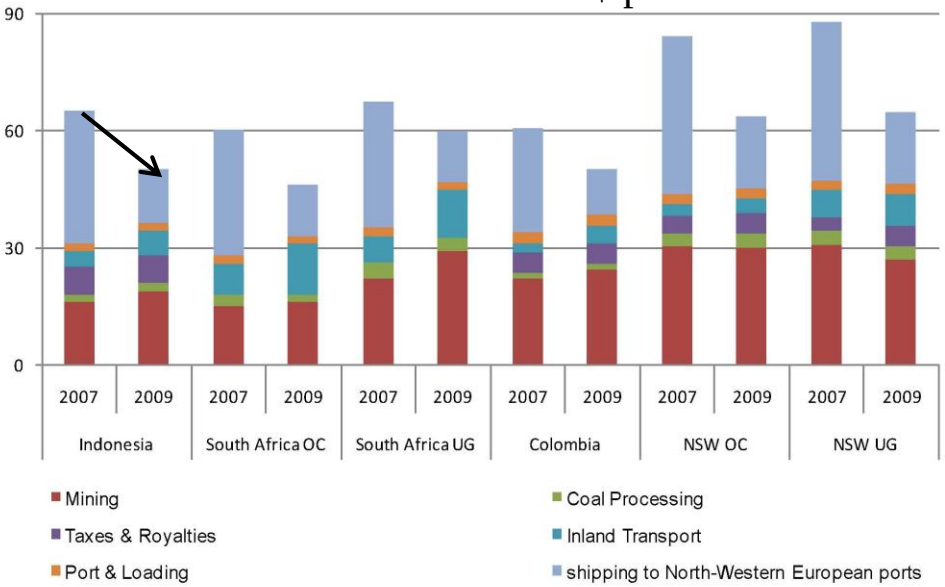
Source: "Executive Summary" of 2011 Medium-Term Coal Market Report by International Energy Agency.

Mining costs $ per ton



OC: Open cast; UG: Underground; NSW: New South Wales, Australia

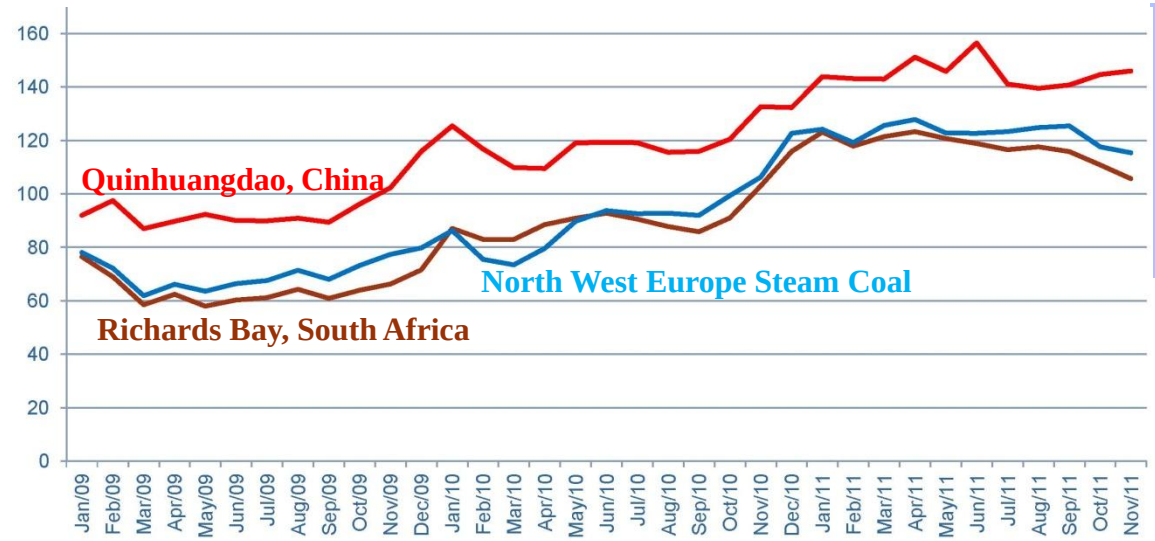
Costs at destination $ per ton



Source: D. Houssin presentation on Jan 11, 2012
Based on Medium-term Coal Market report 2011.

Mining costs increased from 2007 to 2009 but freight costs dropped.

Coal is Cheap
Coal Prices $ per ton

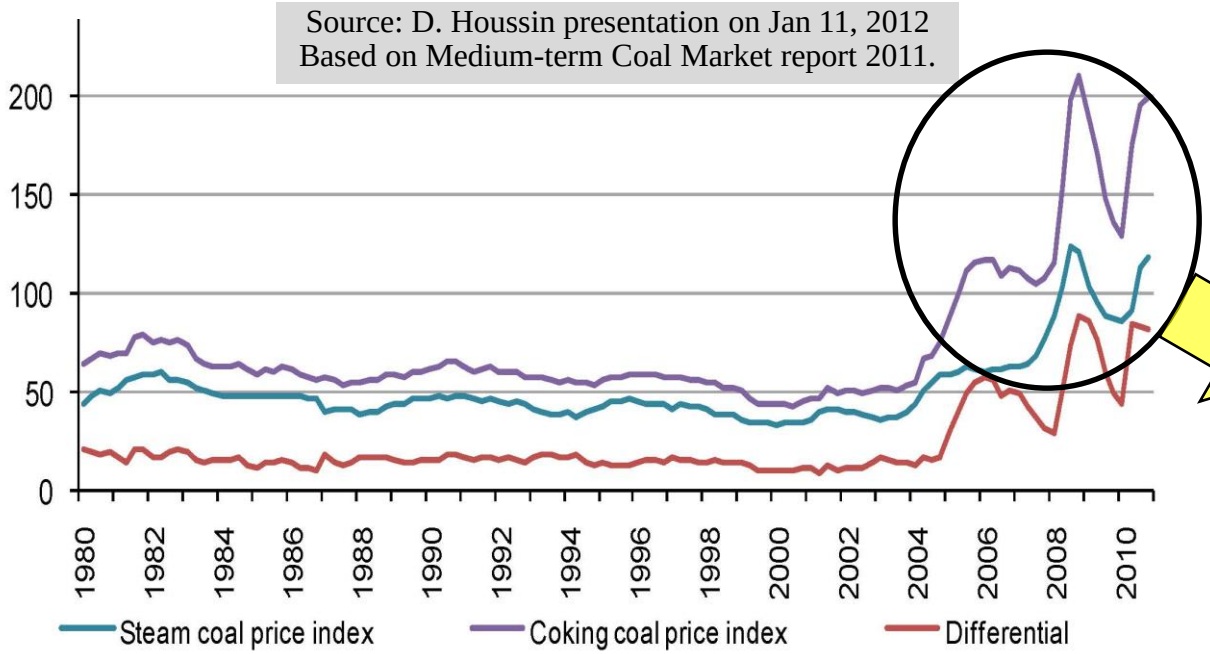


Price is $ per ton for Mid-range Bituminous coal that gives about 6400 kCal per kg.
Or 11500 Btu=0.0115 MMBtu per pound.
Or about 0.025 MMBtu per kilogram.
Or 25 MMBtu by paying about $120/ton.
Or 1 MMBtu bt paying $4.80.

For 1 MMBtu,
- Pay $35 for gasoline;
- Pay $3-16 for natural gas;
- Pay $4-5 for coal.

- Gas is now the cheapest!!
- Gasoline is the most expensive.

Source: D. Houssin presentation on Jan 11, 2012
Based on Medium-term Coal Market report 2011.



Steam coal for power generation,
Coking coal for iron & steel manuf.

Steam coal is appreciating faster than coking coal. Steam and coking coal prices are decoupling!

A cheap substitute for steam coal?

Coal is Dirty
Who Emits More now and in the future?

Coal combustion (burning coal) generates carbon dioxide, a greenhouse gas.

According to 2006 estimates on p.7 of The Future of Coal by MITEI.

	TOTAL EMISSIONS (BILLION METRIC TONS CO_2)			EMISSIONS FROM COAL (BILLION METRIC TONS CO_2)			COAL % OF TOTAL
	OECD (U.S.)	NON-OECD	TOTAL	OECD (U.S.)	NON-OECD	TOTAL	
1990	11.4 (4.98)	9.84	21.2	4.02 (1.77)	4.24	8.26	39
2003	13.1 (5.80)	11.9	25.0	4.25 (2.10)	5.05	9.30	37
2006							
2010	14.2 (6.37)	16.1	30.3	4.63 (2.35)	7.30	11.9	39
2015	15.0 (6.72)	18.6	33.6	4.78 (2.40)	8.58	13.4	40
2020	15.7 (7.12)	21.0	36.7	5.06 (2.59)	9.76	14.8	40
2025	16.5 (7.59)	23.5	40.0	5.42 (2.89)	10.9	16.3	41
2030	17.5 (8.12)	26.2	43.7	5.87 (3.23)	12.2	18.1	41

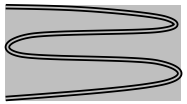
- Carbon Dioxide emission of non-OECD countries is expected to surpass OECD countries.
- Non-OECD coal-based emission was more than that of OECD in 1990.
  - There are more non-OECD (Russia, China, India) countries than OECD countries, is this grouping sensible?
- Coal's contribution to Carbon Dioxide emissions is increasing to 41%.
  - » Penalties for Coal consumption? See appendix.

Unconventional Coal

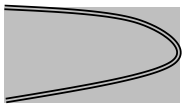
- Unconventional reserve: Coal bed methane
- Unconventional use: Fischer Tropsch Process

Coal Bed Methane (CBM)
Coal or Methane, or both?

- Recall Oil and Gas have H along with C; while coal has mostly C.
- **Coal Bed Methane:** H remains as methane gas CH_4 in a coal reserve.
- CBM is natural, common and causes explosion in coal mines.
- Coal has more surface area than other reservoir rocks

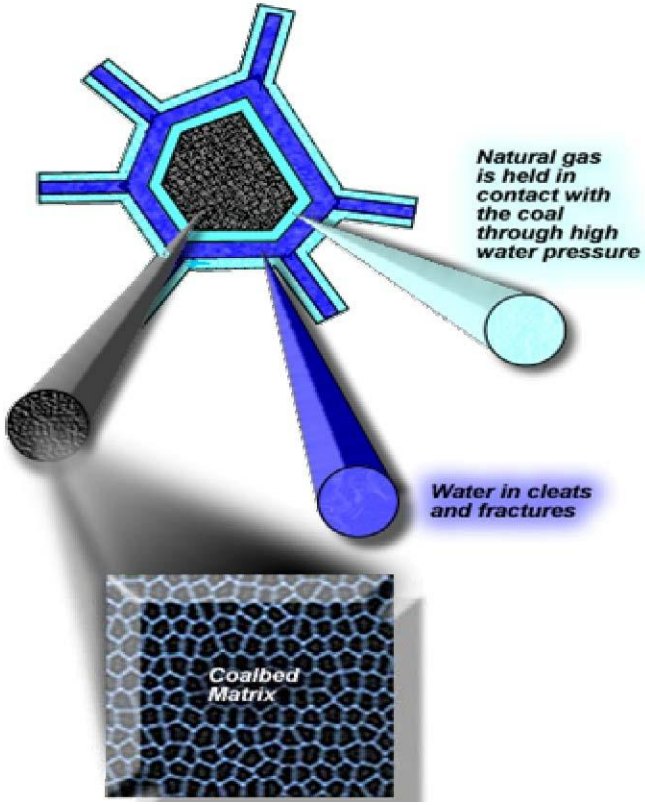


More surface area
per unit volume



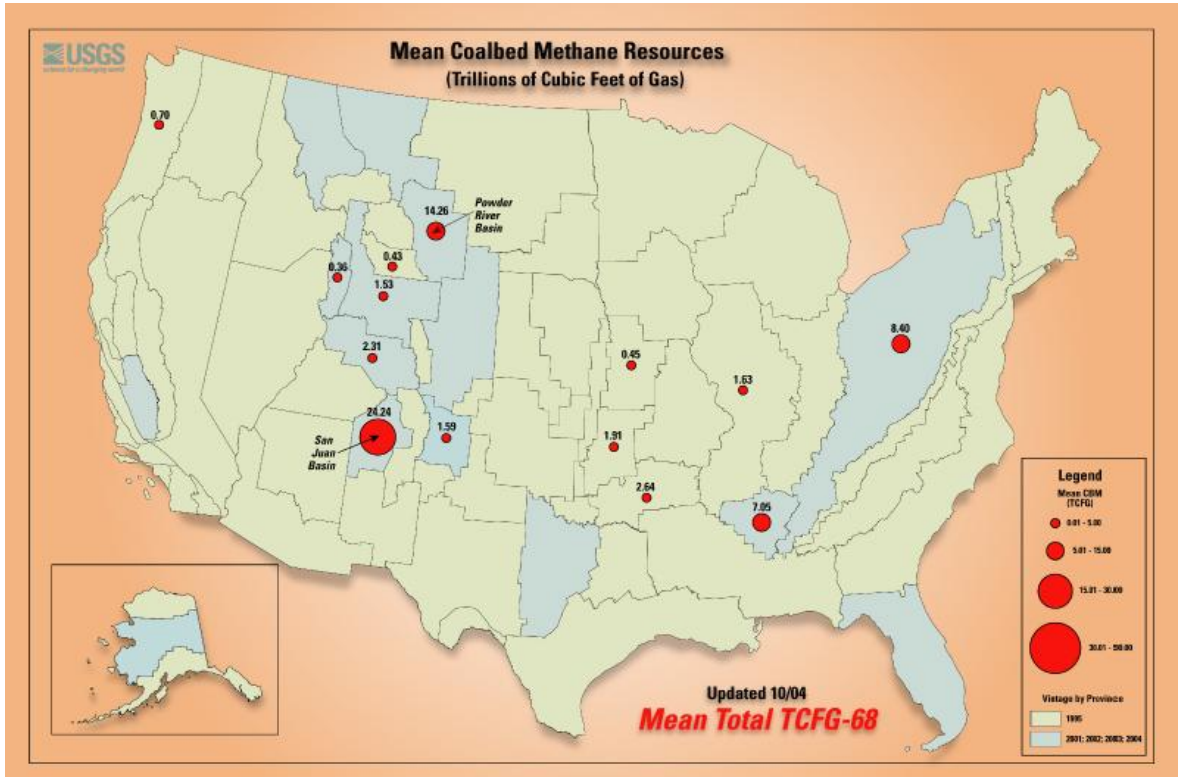
Less surface area
per unit volume

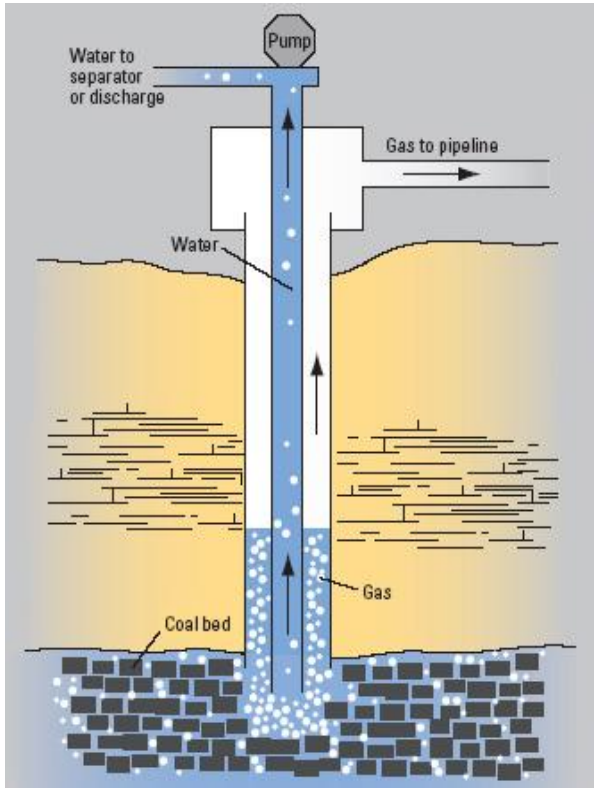
- With its more surface area, coal can hold a lot of methane:
  - 6-7 times more gas than conventional gas reservoir.
- CBM exists in three forms:
  - Free methane gas
  - Gas dissolved in the water in coal reserve
  - Gas absorped on the solid coal surface
- Think of water as the prison guard of the gas around coal.
  - If the guard is removed, gas wants to escape provided that coal permits;
  - The coal seam (reserve) should have high permeability.
- In summary, commercial and profitable CBM reserves should have
  - More gas: Saturated with gas. 500-600 cubicfeet per ton of coal is very favorable for commercial production. Amount of gas is more in mature coal such anthracite and bituminous coal, less in lignite or peat.
  - Permeable coal: Peat and lignite are more permeable than bituminous coal.
  - Tradeoff between amount of gas and ease of extraction.



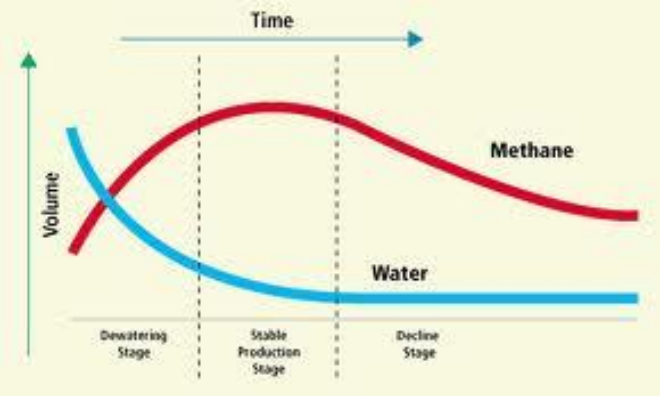
Source: Coal Bed Methane Primer, Feb 2004. Prepared for DoE by ALL Consulting and Montana Board of Oil and Gas Conservation

CBM Reserves and Production





- CBM production in Western US is from bituminous coals; that in Eastern US is from higher rank coals.
- Production is by pumping the water out to reduce the pressure in the reserve. This releases gas which goes up to the surface.
  - Initially in overwatering stage, more water is pumped than gas
  - Water declines fast later and more gas is extracted.
- The water has higher salinity with metals and salts dissolved within. It may not be released to agricultural fields without processing.



Is This an Oil Well, Gas Well or CBM Well?

This well is named CZ Fee A No. 114.
It is in Winn Parish, Louisiana; about 100 kms southeast of Shreveport.
It is drilled by Vintage Petroleum to 3114 feet in January 2004.
Perforated about 2,730 to 2,734 feet in an Paleocene-Eocene coal bed.
Average monthly production is 450,000 cubic feet .

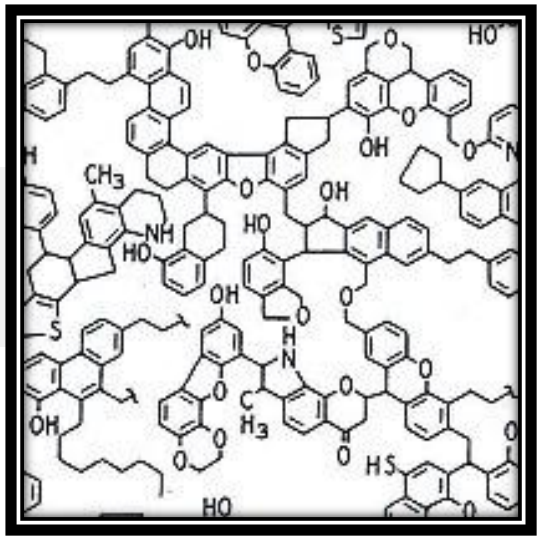
Fossil fuels require drilling.

Know-how obtained in Oil & Gas drilling can be used in CBM drilling; or vice versa.

An integrated understanding of Oil, Gas, Coal and CBM is useful.

Fischer-Tropsch Process

Empirical formulas such as
$C_{137}H_{97}O_9NS$ for bituminous coal,
$C_{240}H_{90}O_4NS$ for high-grade anthracite.



- Fischer-Tropsch technology is an assembly operation. It assembles H_2 to CO to obtain CH_2 groups, long-chain HCs.
- The first two steps involve the manufacture of synthesis gas (**CO** and **H_2**) from coal.
- In 1925, Franz Fischer and Hans Tropsch developed a catalyst to convert CO and H_2 at 1 atm, 300 ^oC to liquid HCs.
- By 1941, Fischer-Tropsch plants produced ~ 700,000 tons of petroleum per year in Germany. Total of 9 plants, the largest in Ruhland-Schwarzheide with capacity of 180,00 tons per year.
- Post WW II, Fischer-Tropsch technology was under study in most industrial nations. The low cost and high availability of crude oil, led to a decline in interest in liquid fuels made from coal. The technology leader is Sasol, South Africa.
- 2015, Sasol has a Lake Charles, LA plant project to turn natural gas into ethylene. A bigger project to turn natural gas to diesel fuel cancelled in 2015 due to low oil prices.

Coal Gasification

$$\textbf{COAL} + O_2 + H_2O \longrightarrow \textbf{CO} + \textbf{H}_2$$

Separated vertical rooms for external heating gasification.

Some systems are required to decrease the sulfur amount. Sulfur causes

$SO_2 + H_2O \rightarrow H_2SO_4$ acid corresion

In order to reduce the sulfur: Wash of coal in advance with some chemicals, use some additives during the burning and sulfur traps (shower systems).

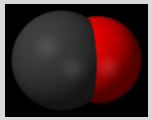
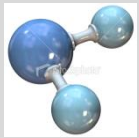
Hydrogen insufficiency: Generally gasification system results in 0.7 mol of hydrogen out of 1 mol CO. Theoretically, that ratio must be 2.

Mitigation of Hydrogen Insufficiency: Gas Water Shift reaction (next page) may be used to compansate for the hydrogen insufficiency and provide some hydrogen for cracking process.

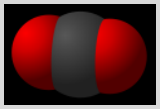
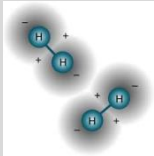
Water Gas Shift (WGS) Reaction

Reaction temperature depends on catalysts. Generally, high temp 150-600°C, 3MPa or more. This is an exothermic (-41.2 kJ/mol) reaction so it releases heat.

$CO + H_2O \xrightarrow{\text{High Temperature, Pressure}} CO_2 + H_2$

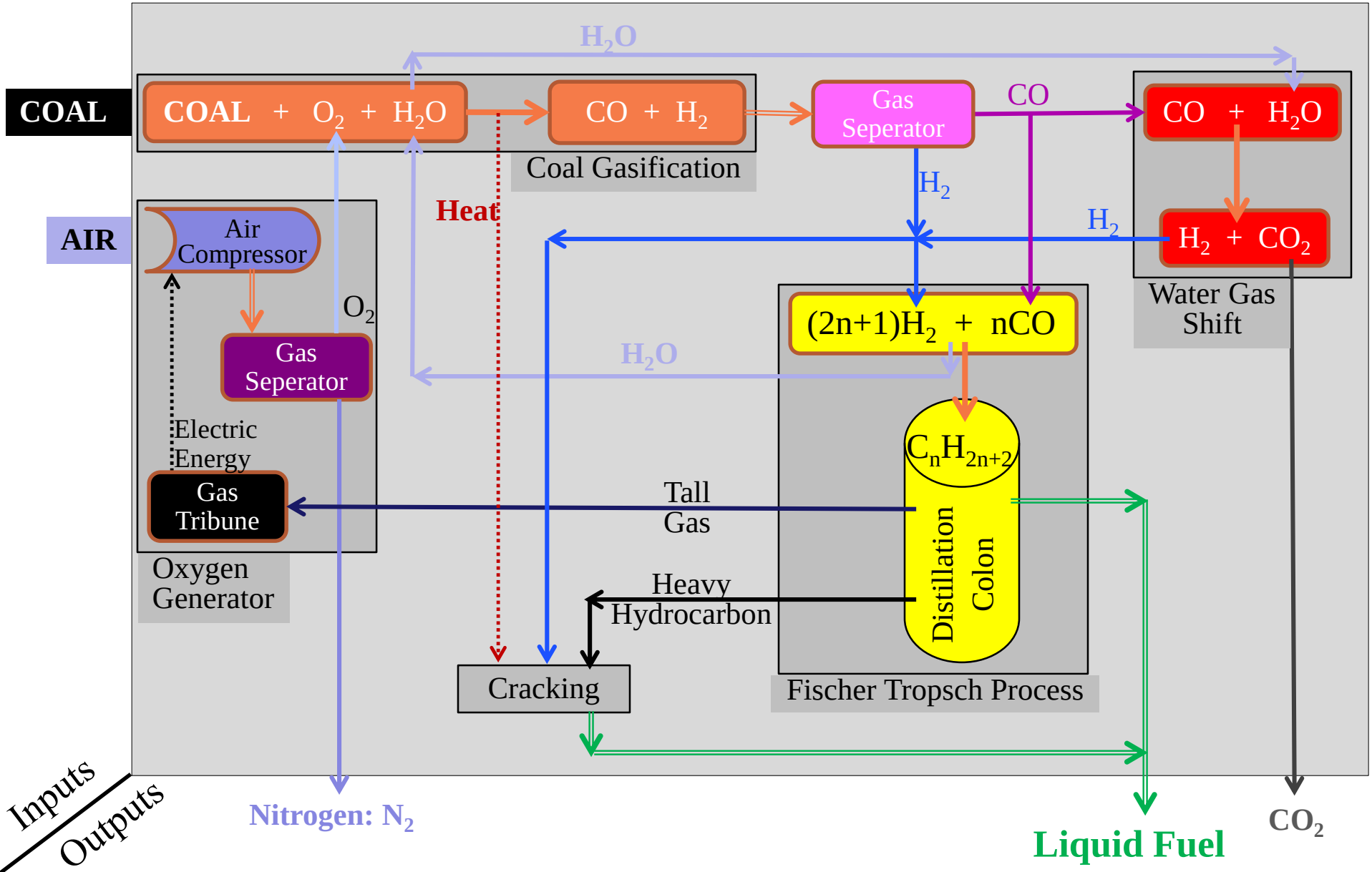
[Fe, Cu, Co] / [Al_2O_3, ZnO, CeO_2]
Catalysts / Supports
Iron, Cupper, Cobalt / Aluminum, Zinc, Cerium oxides

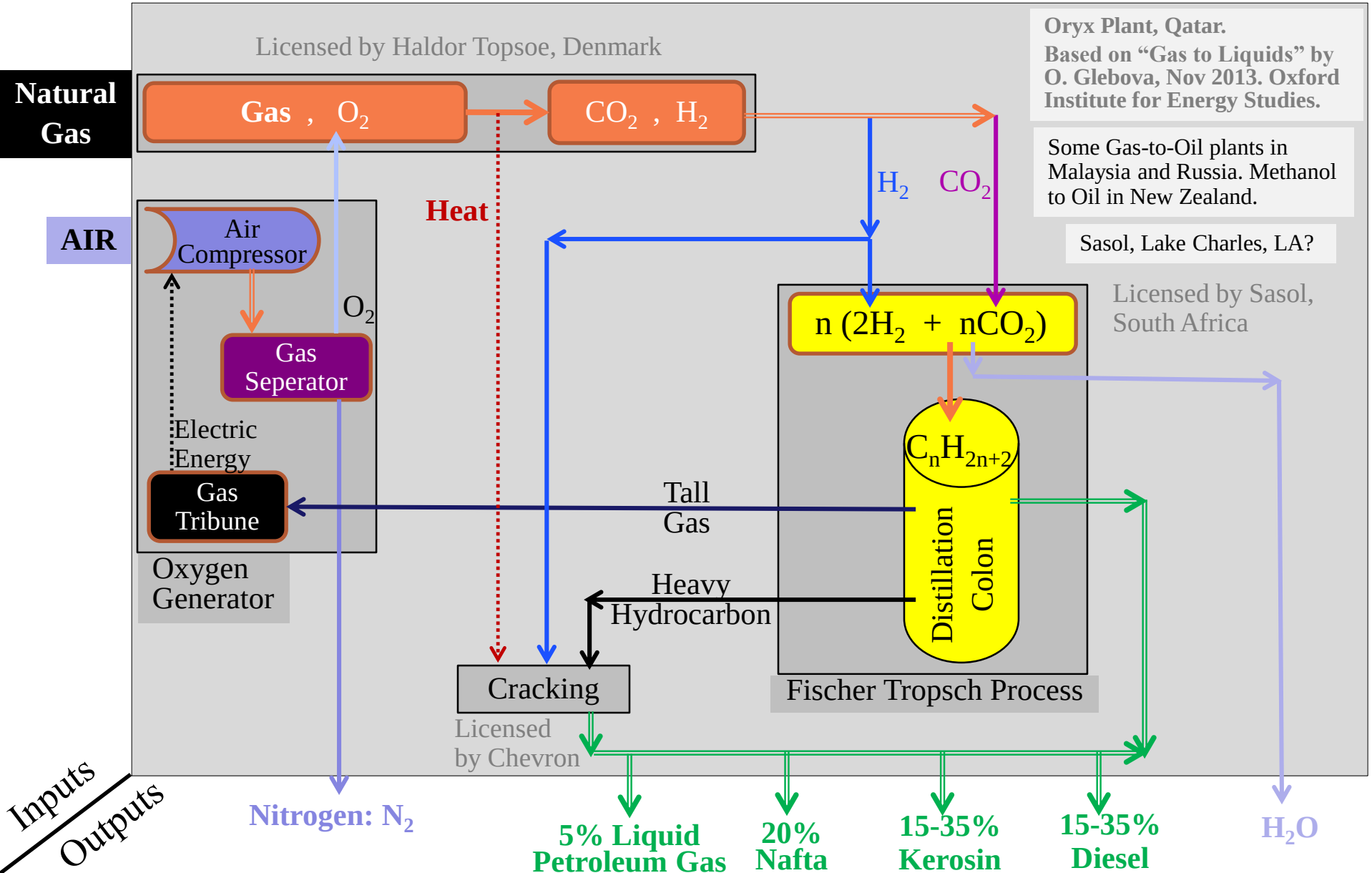
To obtain the WGS reaction, highly selective catalysts and supports are necessary. Otherwise side reactions below are likely.

Possible Side Reactions of the Water Gas Shift Reaction	
$2CO \leftrightarrow C + CO_2$	$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$
$CO + H_2 \leftrightarrow C + H_2O$	$C + 2H_2 \leftrightarrow CH_4$
$CO_2 + 2H_2 \leftrightarrow C + 2H_2O$	$4CO + 2H_2O \leftrightarrow CH_4 + 3CO_2$
$2CO + 2H_2 \leftrightarrow CO_2 + CH_4$	$CH_4 + 2CO \leftrightarrow 3C + 2H_2O$
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	$CH_4 + CO_2 \leftrightarrow 2C + 2H_2O$

Putting Them Together: Coal to Oil



Putting Them Together: Gas to Oil



Oryx Plant, Qatar.
Based on "Gas to Liquids" by O. Glebova, Nov 2013. Oxford Institute for Energy Studies.

Some Gas-to-Oil plants in Malaysia and Russia. Methanol to Oil in New Zealand.

Sasol, Lake Charles, LA?

Summary – Coal

- Coal types
- Mining Methods
- Reserves
- Prices
- Emissions
- Coal Bed Methane
- Oil from Coal or Gas

Oil, Gas, Coal are similar molecules and are fossil fuels.

They all have to be pumped, drilled and mined.

They all emit greenhouse gasses in combustion.

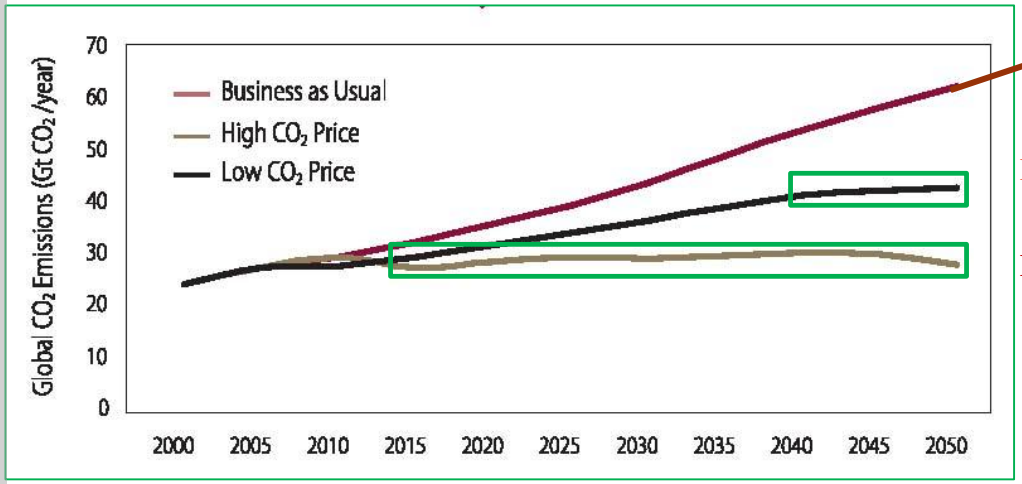
Their combustion can be used to create pressured water vapor to turn turbines at power plants.

Appendix: Carbon Dioxide Penalty and Emissions

- Penalty for emitting Carbon Dioxide can be
  - » Low penalty: Starting in 2010, $7 per ton, increasing at 5% per year, and reaching about $50 per ton in 2050.
  - » High penalty: Starting in 2015, $25 per ton, increasing at 4% per year, and reaching about $100 per ton in 2050.
- Nuclear reactor capacity expansion
  - » Limited capacity: 261 GW in 1997 and 327 GW in 2050. 1 GW $=10^9$ W = 3.4* 10^9 Btu/hr
  - » Expanded capacity: 261 GW in 1997 and 1000 GW in 2050.

Results of Emissions Predictions and Policy Analysis (EPPA) model: http://globalchange.mit.edu/igsm/eppa.html

Source: p. 10 of The Future of Coal.



Business as usual and emissions continue to rise.

Low Penalty: Emissions stabilize ~ 2040 at ~ 42 Billion tons per year (2 x the level in 2000).

High Penalty: Emissions stabilize about 2015 at about 28 Billion tons per year.

These are all scenarios which have not happened!

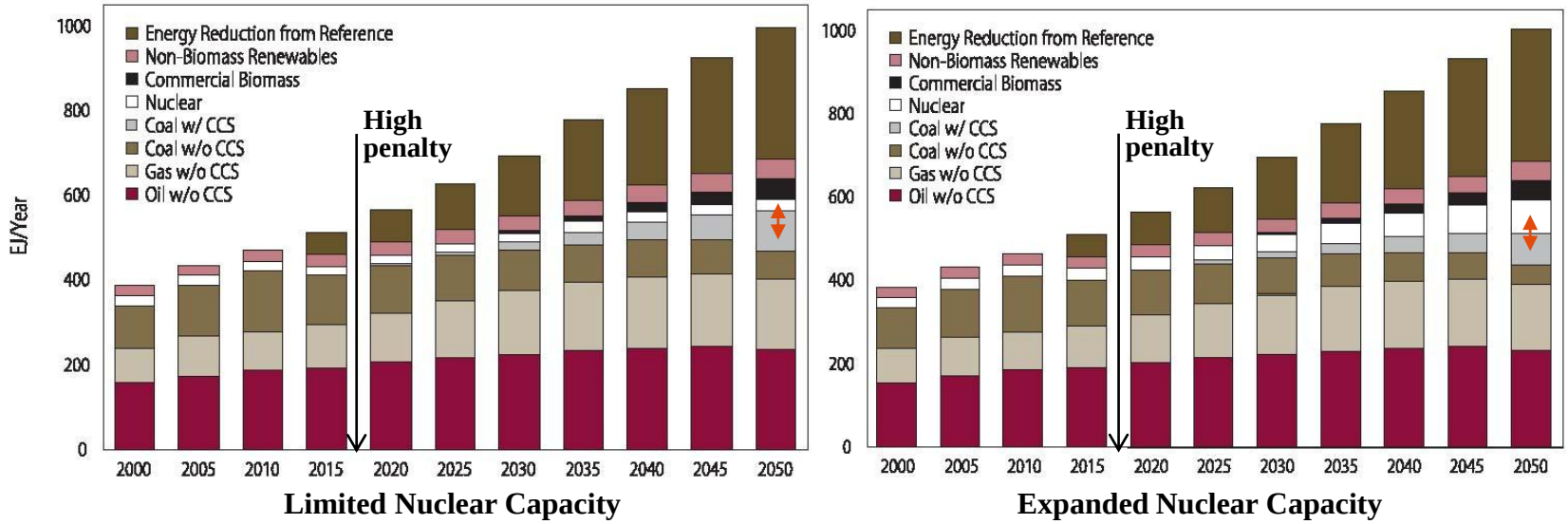
No penalty in 2012 or in the near future. Nuclear capacity is 375 GW ($=10^9$ W) in 2010.

Countries do not participate in these penalties such as carbon-cap and trade.

Appendix: Penalty and Emissions with Carbon Capture and Storage (CCS)

- High penalty becoming effective in 2015 can **reduce energy consumption** with respect to no penalty.

Source: p. 11 of The Future of Coal.



- High penalty can change the composition of energy sources:
  - » Coal consumption without CCS drops
  - » Coal consumption with CCS
    - increases in the Limited Nuclear Capacity case.
    - decreases in the Expanded Nuclear Capacity case – Nuclear can substitute coal!
  - » Oil consumption is stable and Gas consumption is increasing
  - » Renewables increase

CCS is more important under high penalty and limited nuclear capacity when coal is expensive and needed.
Limited nuclear capacity in the USA but expansions abroad; neither limited nor expanded capacity.