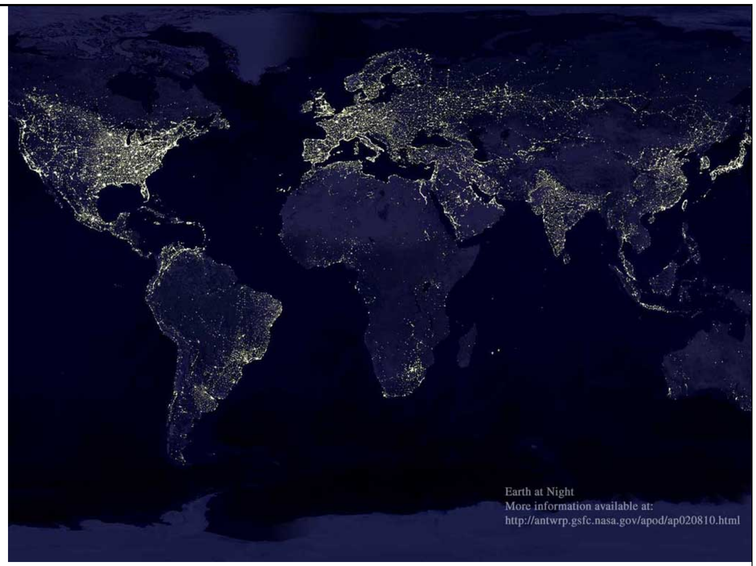
Many Slides Are From Prof. Tom Murphy (with Permission) Thank You Prof. Murphy



Chapter 2: fossil fuels

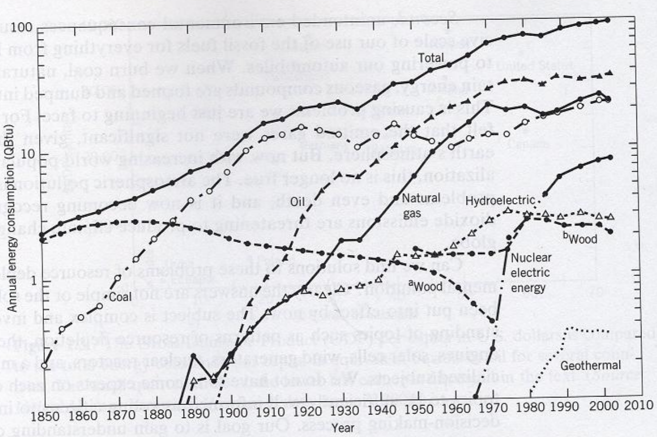
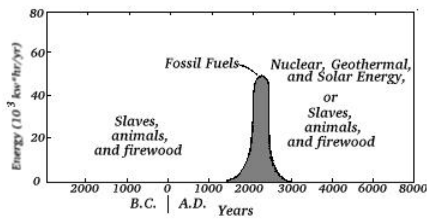


Figure 1.1 Various forms of energy consumed in the United States since 1850. This type of graph is called a semilogarithmic plot, an explanation of the scales is given in the Appendix. *Sources: Historical Statistics of the United States, Colonial Times to 1970*, U.S. Department of Commerce. Bureau of the Census, 1975; U.S. Energy Information Administration, *Annual Energy Review*, 2003. (a) The wood data set from 1850 to 1970 is from the first source. (b) The wood data set from 1950 to 2003 is from the second source; it includes wood, black liquor (a byproduct of the wood-based paper production process), and wood waste.

A brief history of fossil fuels



- Here today, gone tomorrow
- What will our future hold?
  - Will it be back to a simple life?
  - Or will we find new ways to produce all the energy we want?
  - Or will it be somewhere in the middle

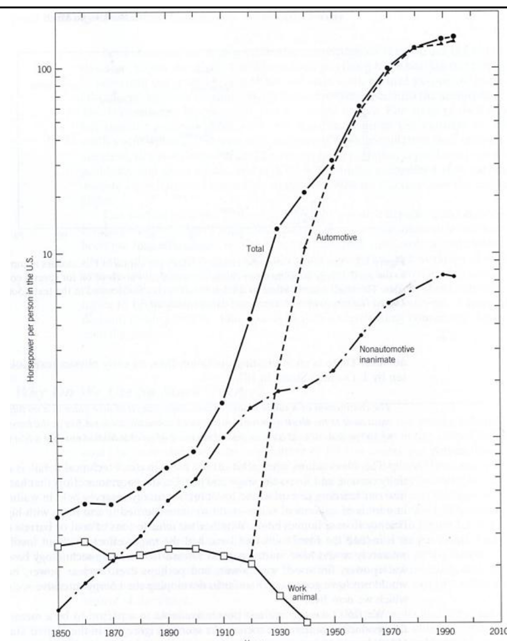


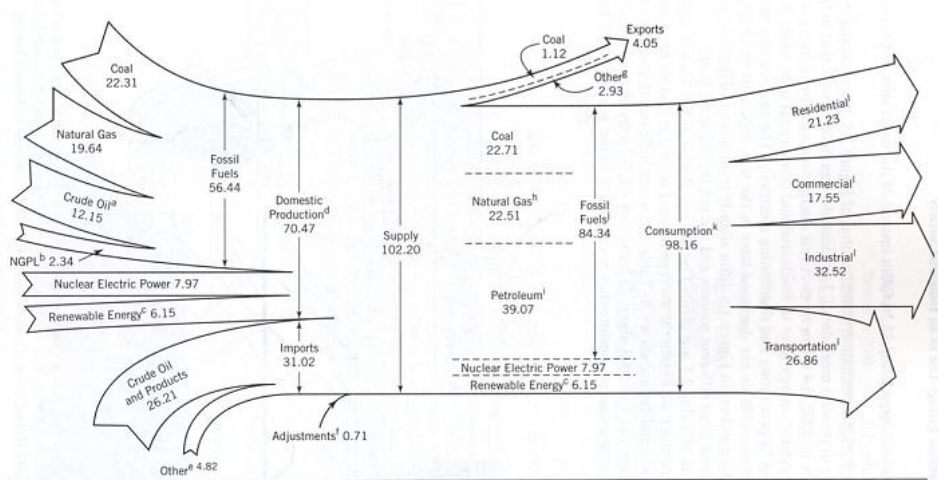
Figure 1.4 Horsepower per capita of all prime movers in the United States since 1850. Only a small fraction of this available horsepower is in use at any given time. (*Source*: *Historical Statistics of the United States, Colonial Times to 1970; Statistical Abstracts of the United States 2003*. Washington, D.C.: U.S. Department of Commerce, Bureau of the Census.)

Source	10^{18} Joules/yr (~QBtu/yr)	Percent of Total
Petroleum*	158	40.0
Coal*	92	23.2
Natural Gas*	89	22.5
Hydroelectric*	28.7	7.2
Nuclear Energy	26	6.6
Biomass (burning)*	1.6	0.4
Geothermal	0.5	0.13
Wind*	0.13	0.03
Solar Direct*	0.03	0.008
Sun Abs. by Earth*	2,000,000	then radiated away

Global Energy: Where Does it Come From?

* Ultimately derived from our sun

Courtesy David Bodansky (UW)



[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 QBtu 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 QBtu of coal coke net imports.
[k] Includes, in QBtu, –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.
Notes: • Data are preliminary. • Totals may not equal sum of components due to independent rounding.

Figure 1.5 Energy flow from source to use in the United States in 2003 in units of QBtu. (*Source*: Washington, D.C.: U.S. Department of Energy, Energy Information Administration, *Annual Energy Review*, 2003.)

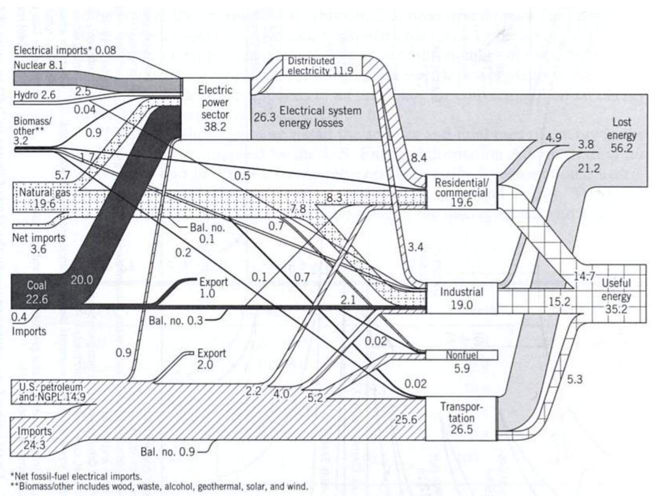


Figure 1.6 Energy flow in the United States in 2002 in units of QBtu, arranged to separate out useful energy from lost energy. (*Source*: Lawrence Livermore National Laboratory (2004) and United States Energy Information Administration, Annual Energy Review 2002.)

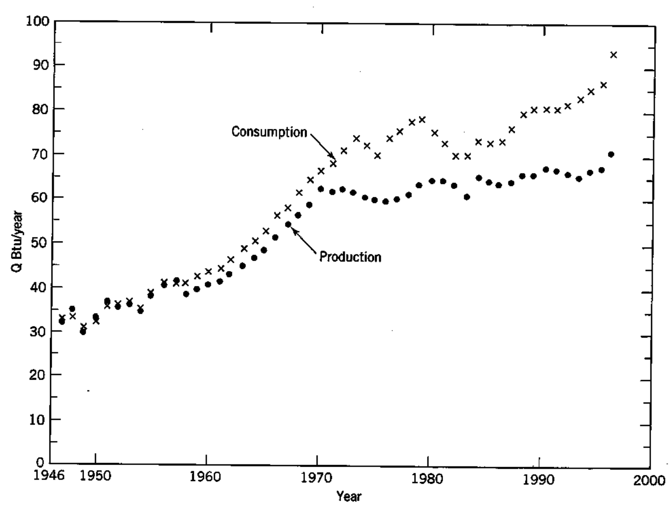
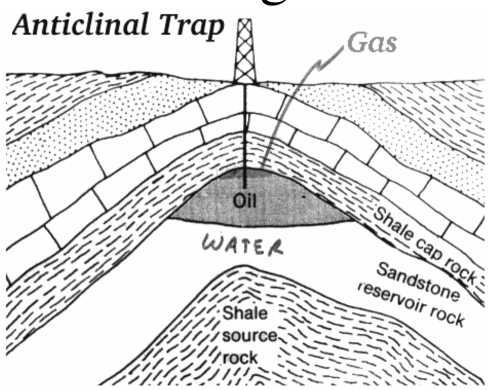


Figure 1.7 The total energy consumption and production in the United States since 1947 in quadrillion British Thermal Units (QBtu) per year. (*Source*: Washington, D.C.: U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 1996*.)

Finding Oil



- Oil is trapped in special (rare) geological structures
- Most of the oil in the world comes from a few large wells
- About one in ten exploratory drillings strike oil
  - and this in places known to be oil-rich: get nothing in most of world

Q

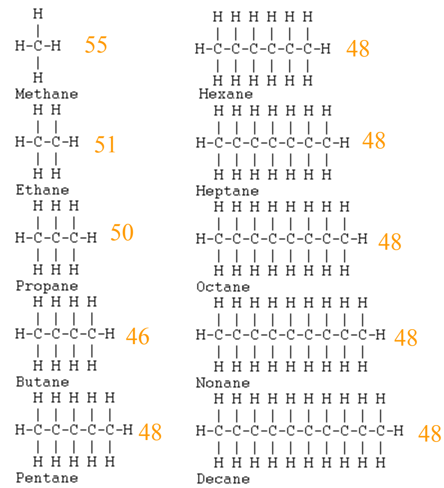
The Oil Window

- Organic material must be deposited without decomposing
  - oxygen-poor environment: usually underwater with poor flow
- Material must spend time buried below 7,500 feet of rock
  - so that molecules are “cracked” into smaller sizes
- But must not go below 15,000 feet
  - else “cracked” into methane: gas, but no oil
- So there is a window from 7,500 to 15,000 feet
- Additional circumstances must be met
  - existence of “caprock” to keep oil from escaping: even a drop per second depletes 20 million barrels per million years
  - source rock must be porous and permeable to allow oil flow

The hydrocarbons

kJ per gram

- All fossil fuels are essentially hydrocarbons, except coal, which is mostly just carbon
- Natural Gas is composed of the lighter hydrocarbons (methane through pentane)
- Gasoline is hexane (C_6) through C_{12}
- Lubricants are C_{16} and up



(1 Cal = 4.184 kJ) Read about Petroleum refining!

Hydrocarbon Reactions

- Methane reaction:

  $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + energy

  1 g 4 g 2.75 g 2.25 g 55 kJ
- Octane reaction:

  $2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$ + energy

  1 g 3.51 g 3.09 g 1.42 g 48 kJ
- For every pound of fuel you burn, you get about three times that in CO_2
  - one gallon of gasoline → ~20 pounds of CO_2
  - occupies about 5 cubic meters (1300 gallons) of space

Q×2

Aside: Carbohydrate Reactions

- Typical carbohydrate (sugar) has molecular structure like: $[CH_2O]_N$, where N is some integer
  - refer to this as "unit block": $C_6H_{12}O_6$ has N=6
- Carbohydrate reaction:

$$[CH_2O]_N + NO_2 \rightarrow NCO_2 + NH_2O + \text{energy}$$

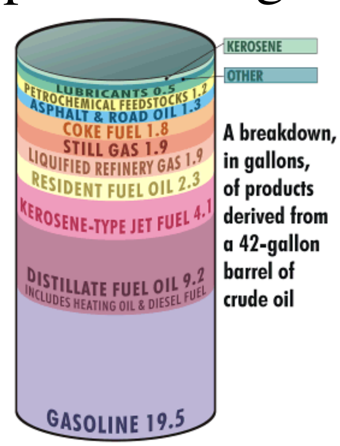
1 g   1.07 g   1.47 g   0.6 g   17 kJ

- Less energy than hydrocarbons because one oxygen already on board (half-reacted already)
- For every pound of food you eat, exhale 1.5 lbs CO_2
  - Actually lose weight this way: 0.5 to 1.0 lbs per day in carbon
  - Must account for "borrowed" oxygen mass and not count it

So where does our petroleum go?

- Each barrel of crude oil goes into a wide variety of products
- Most goes into combustibles
- Some goes to lubricants
- Some goes to pitch and tar
- Some makes our plastics

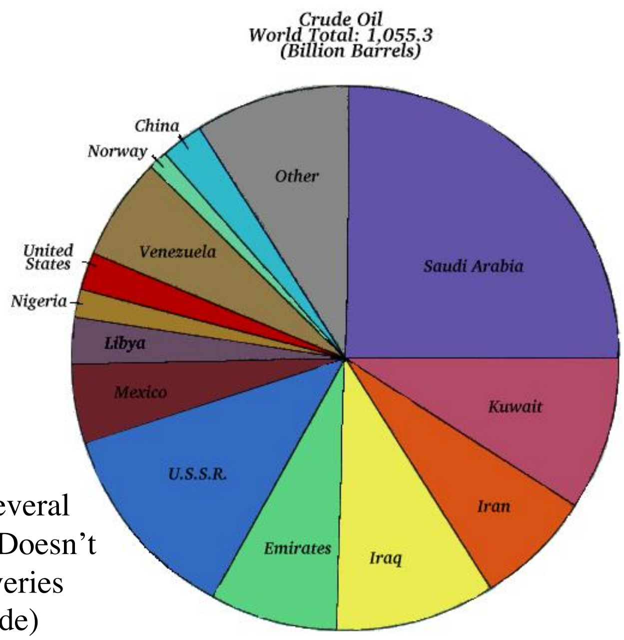
- 40% of our energy comes from petroleum



Participation Questions (write on piece of paper with name and hand in)

1. How long do you think the world's oil will last?
2. What do you think about nuclear energy?
3. Given Fukushima nuclear accident, should I visit Tokyo next month for a conference?

Who's got the crude oil resources?



Data from several years back (Doesn't count discoveries yet to be made)

Countries with top oil reserves (World Oil Journal 2006)

Saudi Arabia	262 Gbbl (Billion barrels)
Iran	132 Gbbl
Iraq	115
Kuwait	101
United Arab Emrites	70
Venezuela	53
Former Soviet Union	48
Nigeria	37
Libya	34
USA	21.7
China	16
Mexico	12.3
Canada	12
Brazil	11.9
Algeria	11.3
Angola	9
Norway	8
Sudan	6.1
Indonesia	5.0
India	4

Let's get our barrels straight

- An oil barrel (bbl) is 42 gallons, or 159 liters
- In the U.S., we use about 24 bbl per year per person
  - average person goes through a barrel in 15 days
  - recall: 60 bbl/yr oil equivalent in all forms of energy: oil is 40% of our total energy portfolio
- That's 7.2 billion bbl/yr for the U.S.
  - 20 million bbl/day
- For the world, it's 25 billion bbl/year
  - 69 million bbl/day
- 100 Qbtu/yr = 17 Gboe/yr: world 400 Qbtu/yr = 69 Gboe/yr (Gboe = billion barrel oil equivalent ~ 5.8 QBtu)

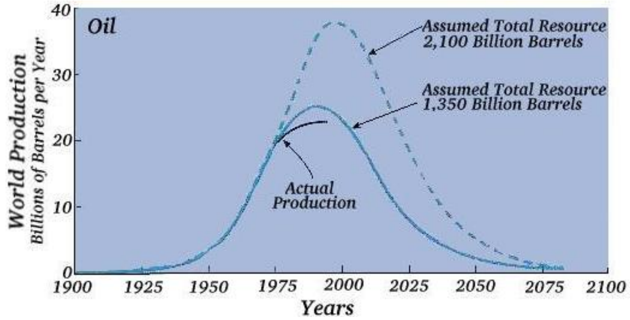
Excerpts from Table 2.2 in book (but in Gbbl/year instead of Mbbl/day)

Country	Prod (Gbbl/ year)	Reserves (Gbbl)	No. Prod. Wells	years left
Saudi Arabia	3.3	262.7	1,560	80
Russia	2.9	69.1	41,192	24
U.S.	2.1	29.4	521,070	14
Iran	1.4	130.7	1,120	96
China	1.2	23.7	72,255	19
Mexico	1.2	16.0		13
Norway	1.0	10.1	833	10
U.A.E.	0.86	97.8		114
Canada	0.81	16.9	54,061	21
Kuwait	0.80	96.5	790	121

Notes on Table 2.2

- Not a single country matching U.S. demand of 7.2 Gbbl/ year
- Reserves:
  - Non-OPEC proved reserves: 173 Gbbl
  - OPEC reserves: 882 Gbbl
  - Total: 1055 Gbbl
- To maintain current production of 25 Gbbl/year…
  - this will last 42.5 years
  - means entries in previous table with longer timescales than this would have to step up production, *if they can*
  - may not be possible to extract oil fast enough for demand
  - Saudi Arabia used to produce at less than 100% capacity, now running full-out

How long will the world oil



- Not as long as you might think/hope
- We'll be spent before the century is done, but we'll have to scale down oil usage before then (in the next few decades)

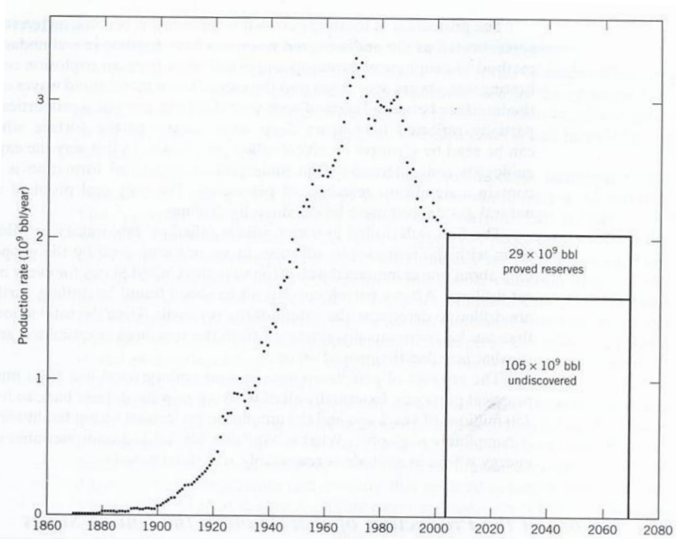
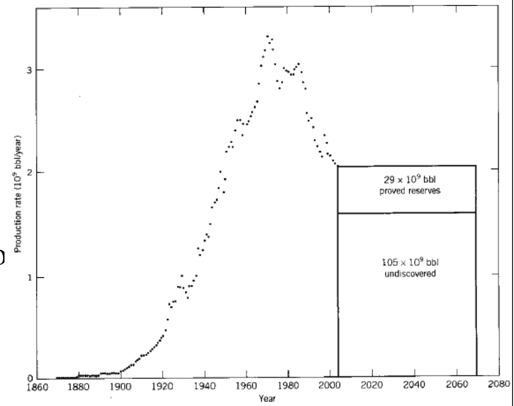


Figure 2.2 Annual rate of petroleum production in the United States, including Alaska. Data through 1996 are from the American Petroleum Institute. Data from 1997 through 2003 are from the U.S. Energy Information Administration. The two data sets do not quite match due to differing definitions of petroleum. The rectangle at the right has an area representing the 134 billion barrels estimated to be remaining for future production. The proved reserves are from Table 2.2. The undiscovered recoverable petroleum is from Table 2.1.

How about the U.S. Supply?

- The estimated total U.S. supply is 230–324 billion bbl (currently used about 200 Gbbl of this)
- We've used >60% of this, leaving 130 billion barrels max
- Production is already down to 60% of peak
- At current rate of production, must be exhausted before 2070
- If we used only U.S. supply, we'd run out in 18 years!!
- If lower total above is right, less time



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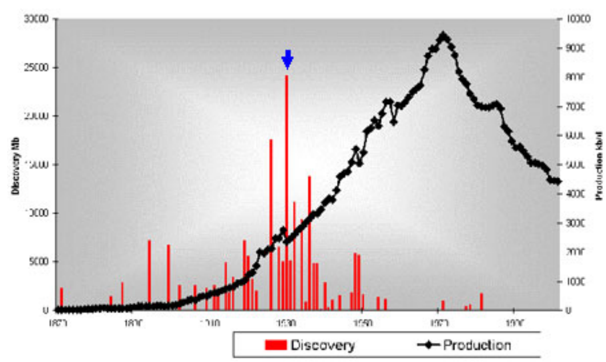
Discovery must lead production

- There must be a lag between the finding of oil and delivery to market
- In the U.S., discovery peaked around 1950, production peaked in 1970



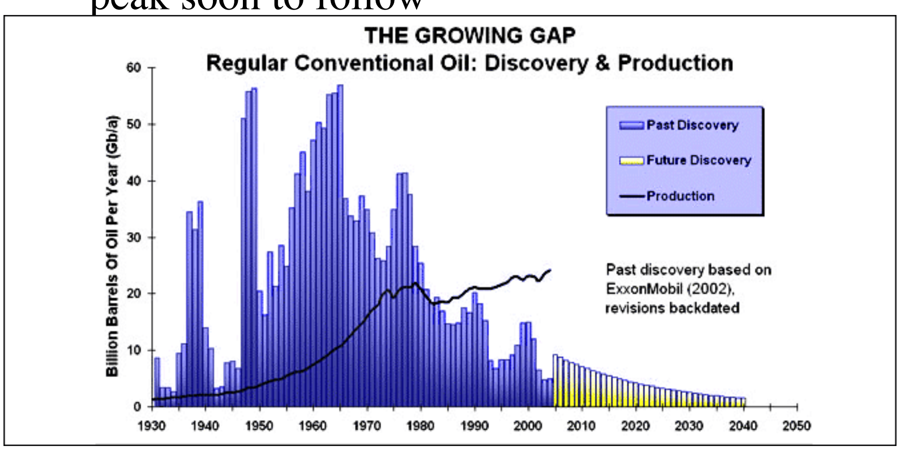
Various Estimates of Oil Remaining

- To date, we've used about 1000 billion barrels of oil worldwide
- We seem to have about this much left
  - halfway through resource
- There will be some future discovery still, but likely small beans
  - ANWR (Arctic National Wildlife Reserve): 5–10 Gbbl ~ 1 years' worth at U.S. consumption rate
- In any case, production unlikely to increase appreciably from this point forward
  - will soon fail to pump as fast as today's demand

Q

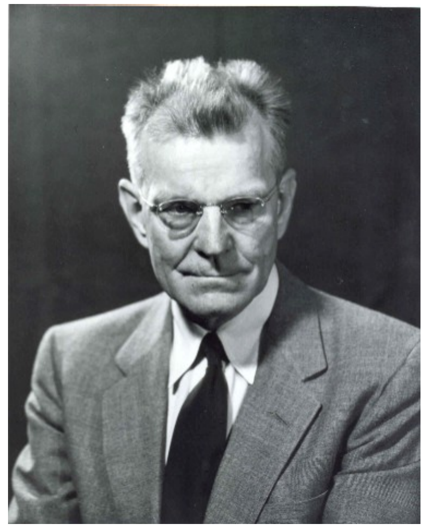
Worldwide Discovery and Production

- discovery peaked before 1970; production peak soon to follow



King Hubbert

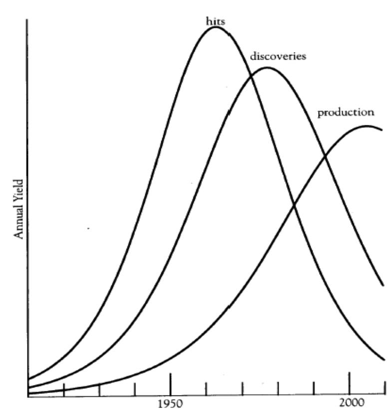
- Geophysicist at the Shell lab in Houston
- In 1956, he presented a paper "Nuclear Energy and Fossil Fuels" at a meeting of the American Petroleum Institute in San Antonio
- He made predictions of the peak year of US oil production based on two estimates of the ultimate production



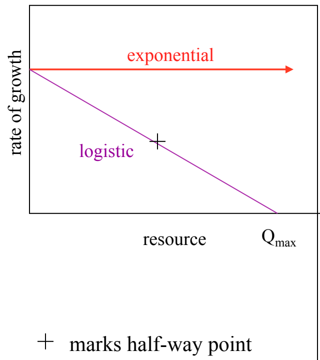
(Dave Rutledge: Caltech 2007)

The Hubbert Peak Idea

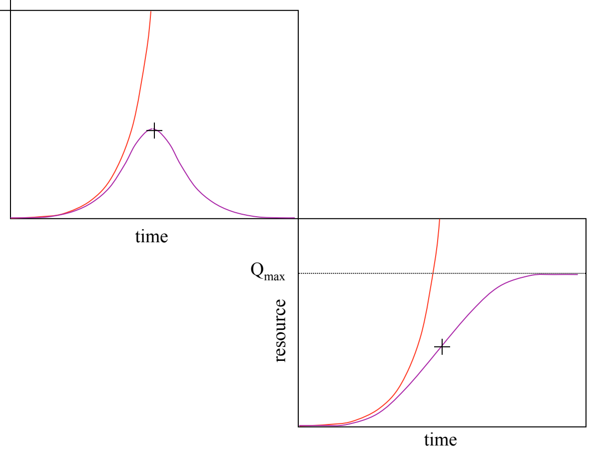
- Hitting new oil field must precede assessment of oil capacity
- Discovery peak (numerical assessment) must follow hits
- Production peak follows discovery (assessment)
- Area under three curves the same (total oil resource)
- Deffeyes estimates that we've hit 94%, discovered 82%, and produced 50% as of about 2005



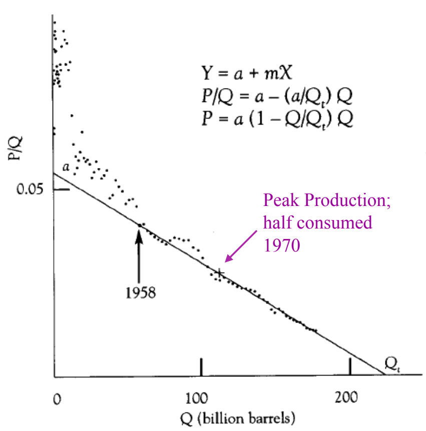
Logistic ("S") curves



Logistic curves result from growth limited by a finite resource: at first exponential, but unable to sustain exponential once resource limits kick in

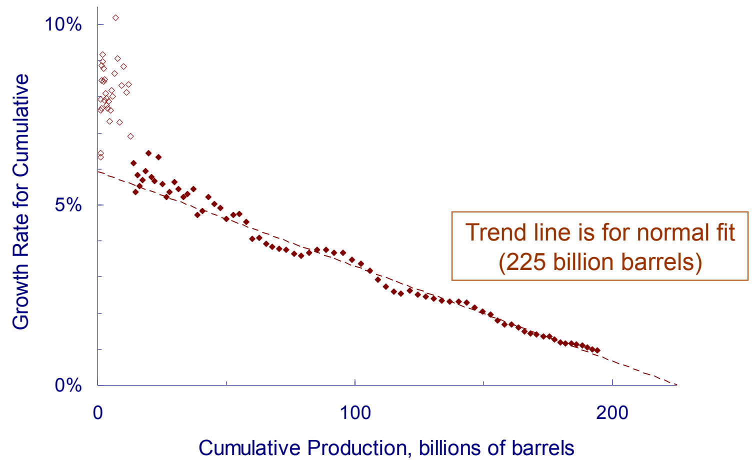


Rate plot for U.S.



- Can plot rate of production (P: annual production) divided by resource (Q: total produced to date) against total resource, Q
  - P/Q is like an interest rate: fractional increase per year
- A "logistic" or S-curve would follow a straight line sloping down
- U.S. oil production does so after 1958
- When you get to zero P/Q, you've hit the end of the resource: no more production

Growth-Rate Plot for US Crude Oil

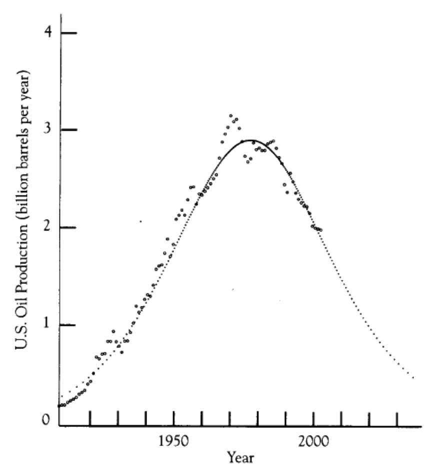


- EIA data (cumulative from 1859, open symbols 1900-1930, closed symbols 1931-2006)

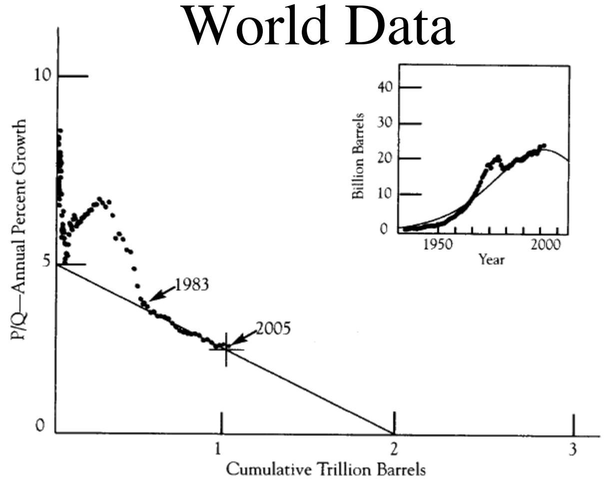
(Dave Rutledge: Caltech 2007)

Same fit, in rate history plot

- The best-fit line on the previous plot produces a decent fit to the rate history of oil production in the U.S.
- Supports the peak position well, and implies a total resource of about 225 Gbbl
- In this case, much proven reserves (22Gbbl) will not increase as many expect!



World Data

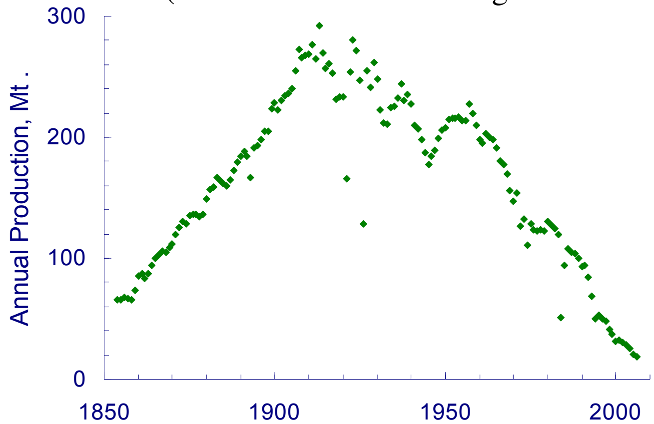


- After 1983, world data follows logistic curve
  - shows us halfway along 2,000 Gbbl at 2005
  - implies we're at the peak right about now

2×Q

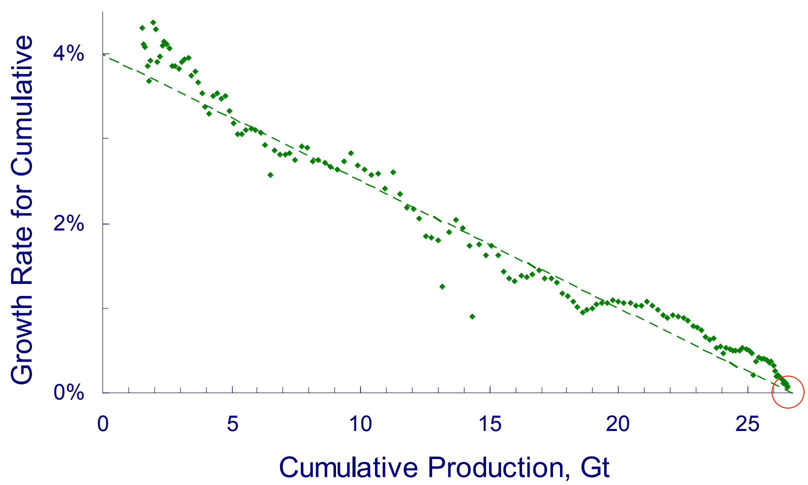
British Coal Production

(Slides from Dave Rutledge: Caltech: 2007)



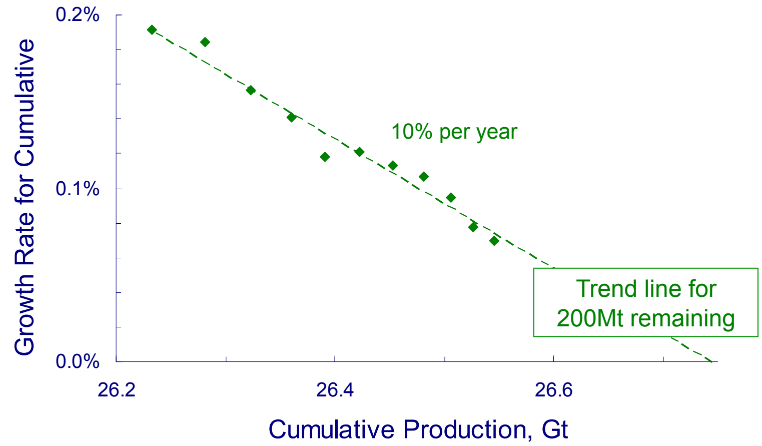
- Data from the US National Bureau of Economic Research (1854-1876), the Durham Coal Mining Museum (1877-1956), and the British Department of Trade and Industry (1957-2006)
- In the peak production year, 1913, there were 3,024 mines

Growth-Rate Plot for British Coal



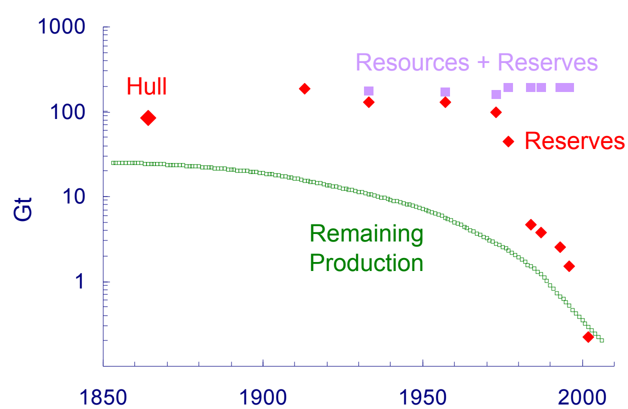
- 1854-2006, 1853 cumulative from William Jevons, *The Coal Question*
- Already near the trend line in 1854

Remaining Production for British Coal



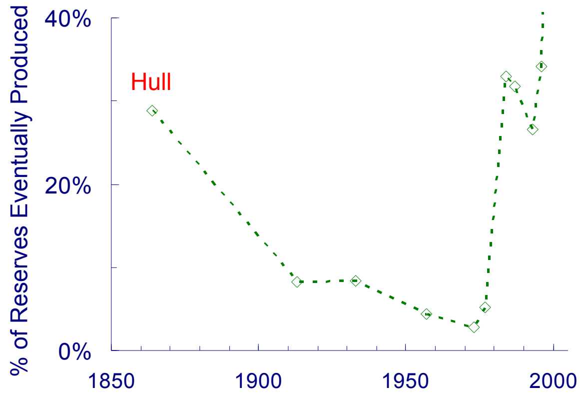
- Data from the UK Department of Trade and Industry (1993-2006)
- 6 producing underground mines — several with less than ten years of coal
- 35 strip mines are producing, but there are difficulties in getting permits for new mines

Reserves vs Remaining Production



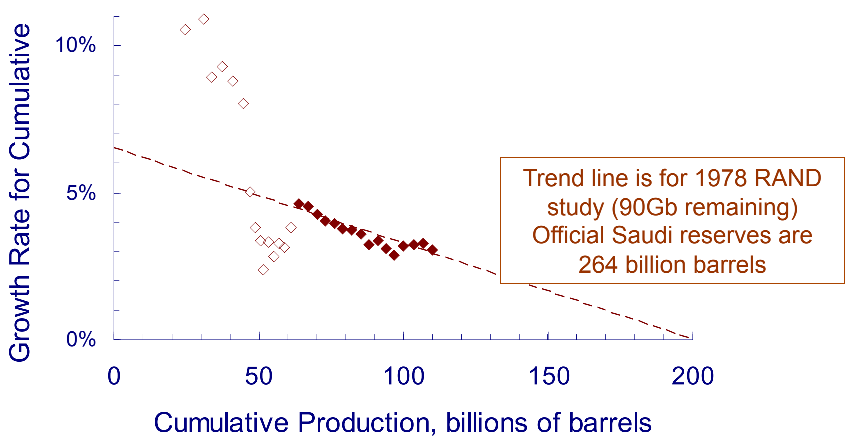
- 1864 reserves from Edward Hull of the Geological Survey
- Other data from the World Energy Council Surveys of Energy Resources
- Resources include seams of 2ft or more at depths of 4000ft or less

Fraction of Reserves Eventually Produced



- 1864 reserves from Edward Hull of the Geological Survey
- Other data from the World Energy Council Surveys of Energy Resources
- Will use trends if they exist, reserves otherwise

How Much Oil do the Saudis Have?



- EIA data (open 1975-1990, closed 1991-2006), 1975 cumulative from Richard Nehring
- Matt Simmons was the first to call attention to this anomalous situation in his book, *Twilight in the Desert*

(Dave Rutledge: Caltech 2007)

Excerpts from Table 2.2 in book (but in Gbbl/year instead of Mbbl/day)

Country	Prod (Gbbl/ year)	Reserves (Gbbl)	No. Prod. Wells	years left
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Countries with top oil reserves (World Oil Journal 2006)

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USA	21.7
China	16
Mexico	12.3
Canada	12
Brazil	11.9
Algeria	11.3
Angola	9
Norway	8
Sudan	6.1
Indonesia	5.0

Shouldn't we therefore discourage oil usage?

- In this country, so far no such thing!
- U.S. taxes on gasoline are 6.5 times lower than in most industrialized countries (about 32 cents per gallon in the U.S.)
- No meaningful increase in CAFE or efficiency standards
- Efforts on the part of the U.S. to keep oil prices low have lead to numerous questionable actions on the international scene

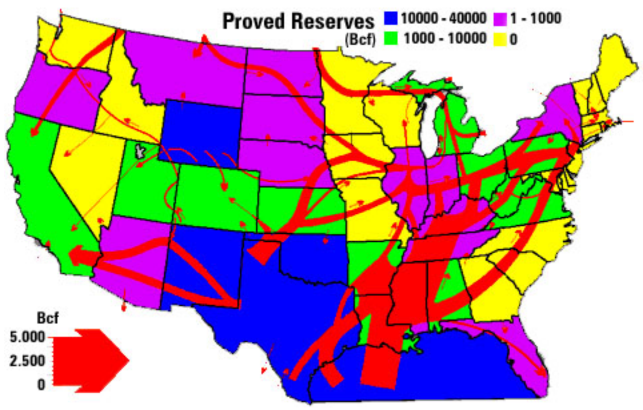
Q

Natural Gas

- Extracted as oil-drilling byproduct
  - was once burned off at well head as means of disposal
- Mostly methane, some ethane, and a little propane, butane
- 2 times cheaper than electricity per energy content, comparable to gasoline per joule
  - But getting more expensive; in 2004, nat gas was 3.5 times cheaper than electricity, now only 2.1 times cheaper than electricity (for same energy) (and 2.5 times cheaper than current gasoline)
- Well-suited to on-the-spot heat generation: water heaters, furnaces, stoves/ovens, clothes dryers
  - more efficient than using fossil-fuel-generated electricity
  - Less CO_2 than burning gasoline or coal

Distribution of natural gas

- Impractical to ship: must route by pipe
- 1.3 million miles of pipe (250,000 miles of mains)



How much do we use, and where do we get it?

- In 2003, we used 21.8 Tcf (Tera-cubic feet, or $10^{12}ft^3$); about 23 QBtu (23% of total)
  - (Luckily 1QBtu ~ 1 Tcf nat gas)
- Out of the 21.8 tcf used, 88% was domestic
  - 11.8% from Canada
  - 0.08% from Algeria (shipped in liquefied form)
  - 0.03% from Mexico
- Total U.S. has used about 1,100 Tcf to date
- You pay about SDG&E about $1.10/therm (they pay about $0.56/therm; therm (=100,000Btu) is about 100cf of nat gas (electicity is about $0.14/kWh => 1 therm worth of electricity costs about $4.00

(1 therm worth of gasoline costs about:

($4.10/gal)(1 gal /125,000Btu)(100,000Btu/1 therm) = $3.28.

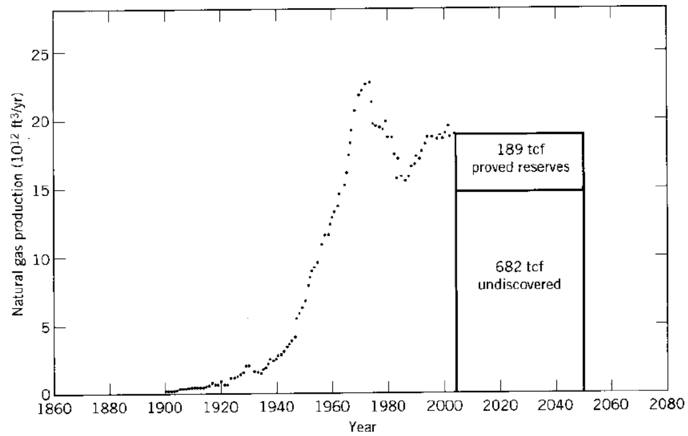
(nat gas that contains 1 gal gas worth of energy costs about:

($1.1/therm)(1 therm/100,000Btu)(125,000Btu/1gal gas) = $1.38/gal

So if your car ran off natural gas it would cost about $1.38 gal equivalent

Q

How much do we have left?



- Estimated recoverable amount: 871 tcf
- 40 years at current rate
- Estimates like this *do* account for future discoveries
  - present proven reserves provide only 8 years' worth
  - Are discoveries going to be made as predicted? (2006 numbers now show proved reserves at about 204 tcf, not 189)
  - And above assumes we don't increase usage of this cleaner and cheaper energy source

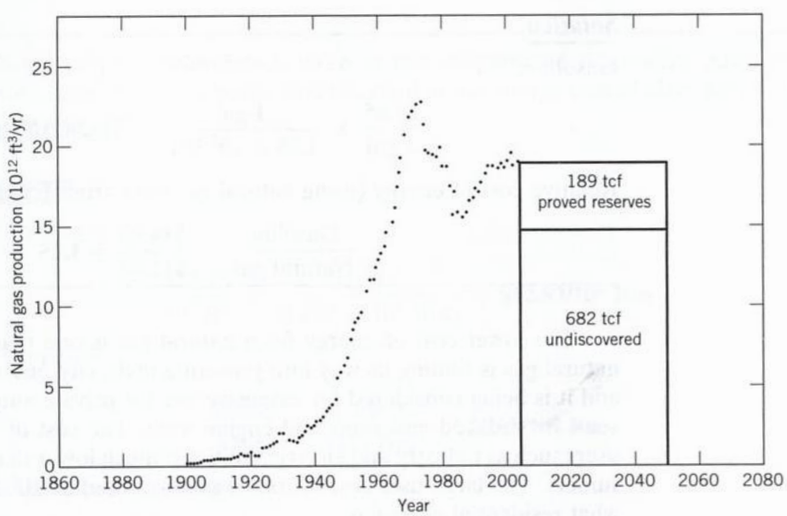


Figure 2.6 Annual rate of natural gas production in the United States. Data through 1996 are from the American Petroleum Institute. Data from 1997 through 2003 are from the U.S. Energy Information Administration. The rectangle at the right has an area representing the 871 tcf of natural gas estimated to be remaining for future production. The proved reserves are from Table 2.5. The undiscovered recoverable natural gas is from Table 2.1.

Countries with top nat gas reserves (World Oil Journal 2006)

Russia	1689 (Tcf)	290 Gboe
Iran	965	160
Quatar	906	150
Saudi Arabia	243	41
UAE	205	35
USA	204	35
Nigeria	182	31
Algeria	160	27
Venezuela	151	26
Australia	120	20
Indonesia	92	16
Iraq	84	14
Norway	83	14
Eygpt	67	11
Kazakhstan	65	11
Malaysia	58	10
Kuwait	57	10
China	56	10
Canada	54	9
Libya	52	9
Netherlands	51	9

Afghanistan and natural gas?

Check the article: by John Foster
http://www.policyalternatives.ca/documents/National_Office_Pubs/2008/
A_Pipeline_Through_a_Troubled_Land.pdf
TAPI backed by U.S. runs through Taliban Kandhar areas; U.S. opposes IPI which would help Iran (both cost around 7 billion $).

Map 1. Proposed Central Asian Gas Pipelines

World Natural gas

- Total proven reserves about 6200 Tcf ~ 1060Gboe ~ 6000 Qbtu, about same energy content as world's oil proven reserves
- U.S. only 3% of total
- Undiscovered amount quite uncertain
- Could also get methane from coal seams, fracking shale deposits, deep sea hydrates; potentially large amounts
- LNG: Transport at T=-260F makes 600 times smaller volume

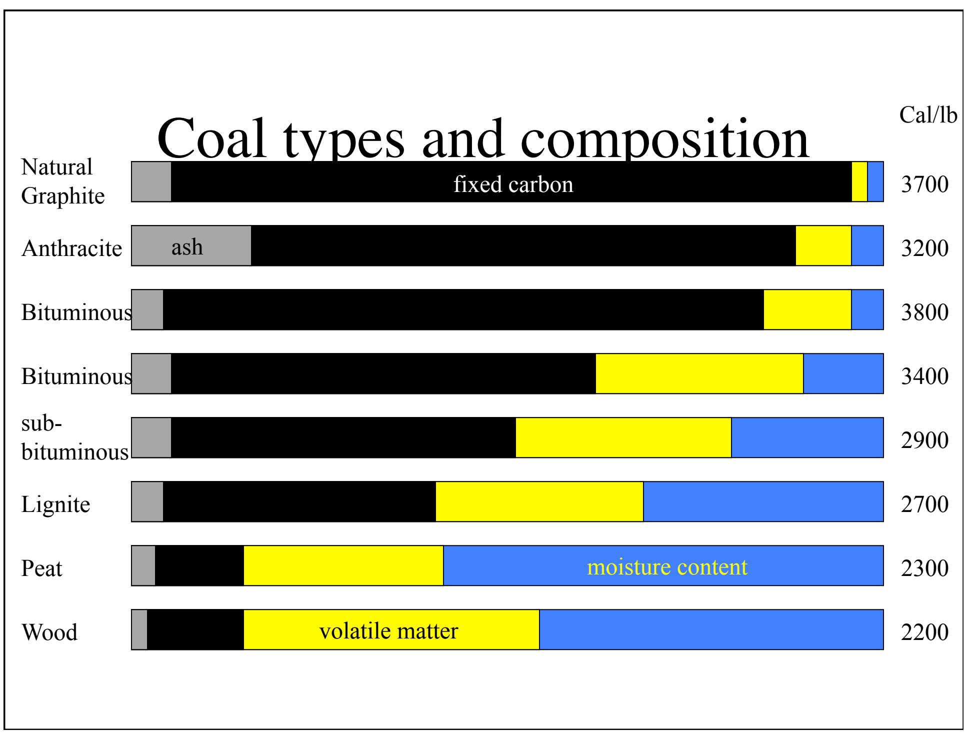
Coal

- Coal is a nasty fuel that we seem to have a lot of
- Primarily carbon, but some volatiles (CO, CH_4)
- Reaction is essentially $C + O_2 \rightarrow CO_2$ + energy
- Energy content varies depending on quality of coal, ranging from 5–8 Cal/g
- Highly polluting because of large amounts of ash, sulphur dioxide, arsenic, and other pollutants, plus must dig up ground over large areas

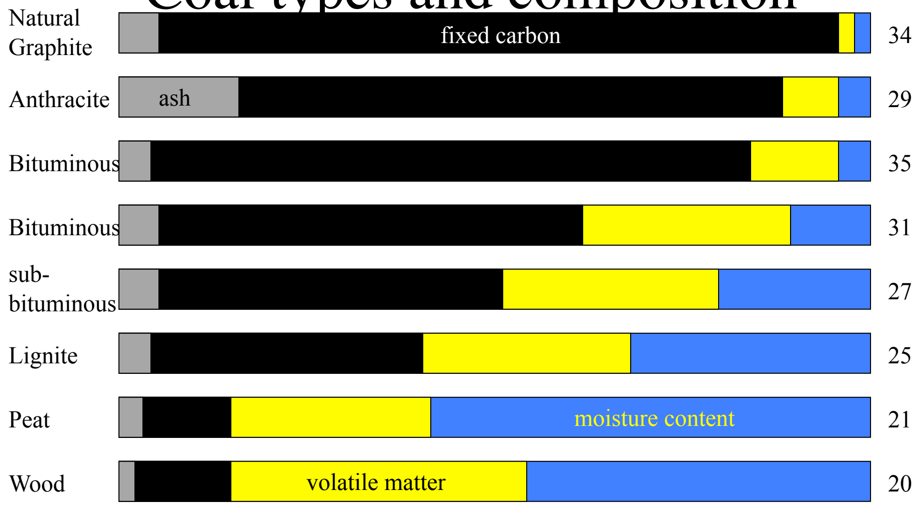
Coal

- Coal made differently from other fossil fuels and found differently
- Starting 300 million years ago, swamps
- Lies in strata called seams 2-8ft thick usually about 300 ft down
- In U.S. Rocky Mountain coal is cleanest, but not highest energy content.


Western Coal


Coal types and composition
Cal/lb
Natural Graphite
fixed carbon
3700
Anthracite
ash
3200
Bituminous
3800
Bituminous
3400
sub-bituminous
2900
Lignite
2700
Peat
moisture content
2300
Wood
volatile matter
2200

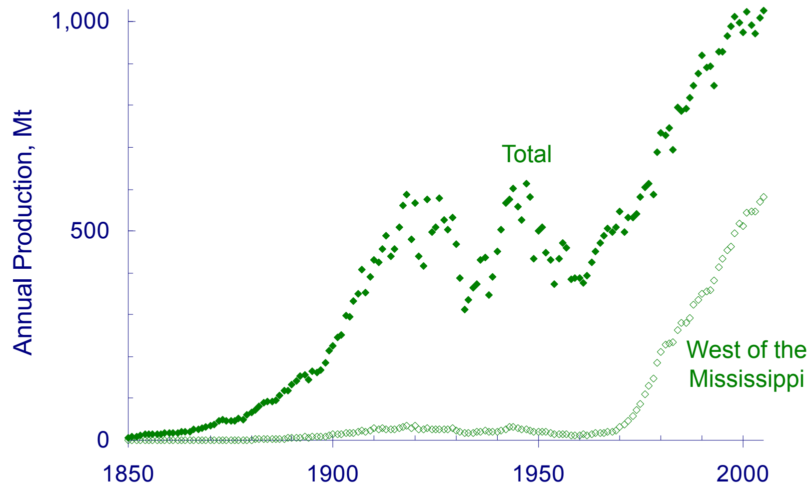
Coal types and composition



Use of Coal

- 88% of the coal used in the U.S. makes steam for electricity generation
- 7.7% is used for industry and transportation
- 3.5% used in steel production
- 0.6% used for residential and commercial purposes
- 0.00001% used on Halloween for trick-or-treaters

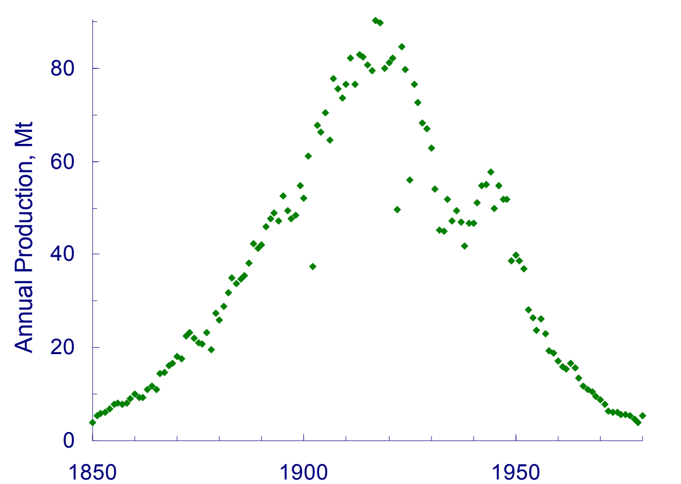
US Coal Production



- Data from the USGS (Robert Milici)
- Will consider the East and the West separately

(Dave Rutledge: Caltech 2007)

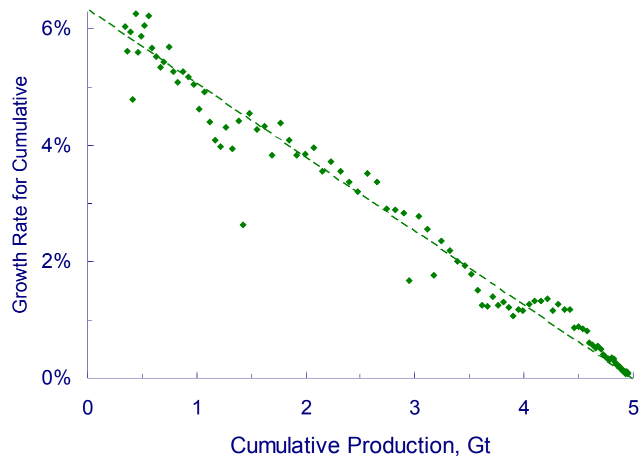
Anthracite in Pennsylvania



- Data from the USGS (Robert Milici)
- Anthracite is a grade of coal used for home heating that burns with little smoke

(Dave Rutledge: Caltech 2007)

Growth-Rate Plot for PA Anthracite



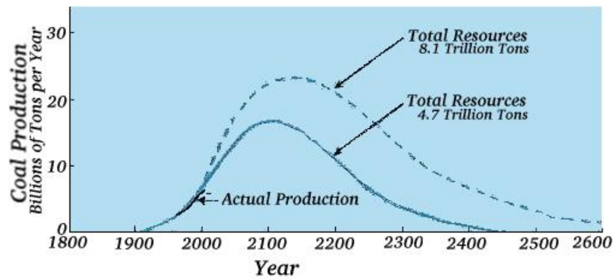
- Data from the USGS (Robert Milici) cumulative from 1800, symbols 1875-1995
- 16% of the 1913 reserves were eventually produced

(Dave Rutledge: Caltech 2007)

Estimated Worldwide Coal Reserves

Country	Amount (G tonne/Gboe)	Percentage of Total
United States	250 Gtonne / 1400 Gboe	25
Russia	230 / 1290	23
Europe	138 / 770	14
China	115 / 640	12
Australia	82 / 460	8.3
Africa	55 / 300	5.6
South America	22 / 120	2.2
Mex/Canada	7.7 / 40	0.8
Total	**984 Gtonne / 5300 Gboe**	**100**

When will coal run out?



Note numbers are much larger than current estimates; the estimates changed recently!

- We use 10^9 tonnes of coal per year, so the U.S. supply alone could last as long as 250 years at current rate
- Using variable rate model, more like 75-100 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

Shale Oil

- Possibly 600–2000 billion barrels of oil in U.S. shale deposits
  - compare to total U.S. oil supply of max 230 billion bbl
- Economically viable portion may only be 80 billion bbl
- 8 times less energy density than coal
  - lots of waste rock: large-scale disposal problem
  - takes lots of water
- Maximum rate of extraction may be only 5% of our current rate of oil consumption
  - limited by water availability

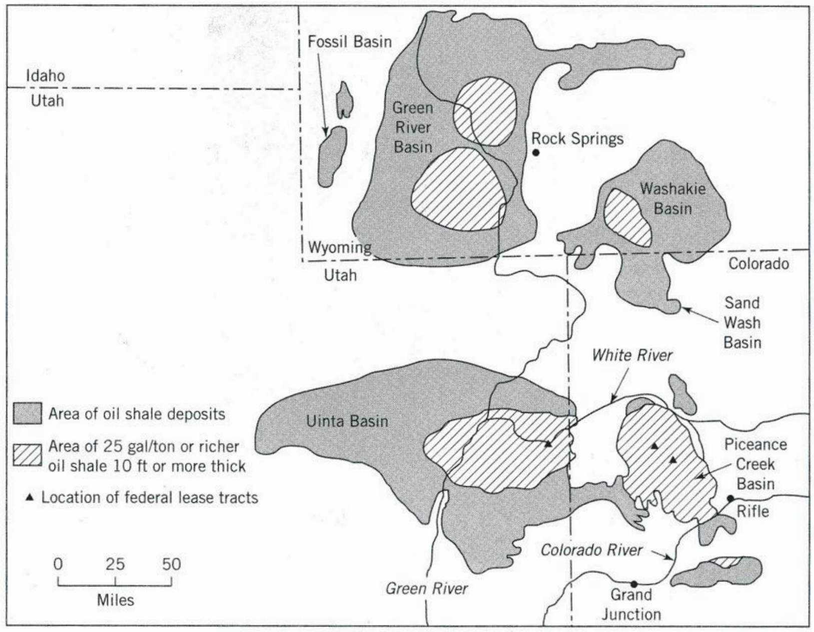


Figure 2.8 Oil shale deposits in the Green River Formation of the western United States.

Fort McMurray, Alberta Oil Sands

Tar Sands

- Sand impregnated with viscous tar-like sludge
- Huge deposit in Alberta, Canada
  - 300 billion bbl possibly economically recoverable
  - Perhaps 1/3 of world total
- It takes two tons of sands to create one barrel of oil
  - energy density similar to that of shale oil, much less than coal
  - Needs to be heated => Canada nuclear plant just for that!
  - Takes lots of water
- In 2003, 1 million bbl/day produced
- 2002 production cost was $20 per barrel, so economically competitive;

Canadian Oil Sands

- 1.0 Mb per day in 2005, increasing 8% per year
- 35Gb reserves for mining (comparable to one year of world oil production)
- 140Gb reserves for wells
  - Production with a steam process
  - Production and upgrading to synthetic crude oil use 25% of the oil energy equivalent in natural gas
  - Canadian gas reserves are 10Gboe (end of 2005)
  - Annual gas production is 12% of reserves per year
  - Challenges in meeting obligations under the Kyoto agreement

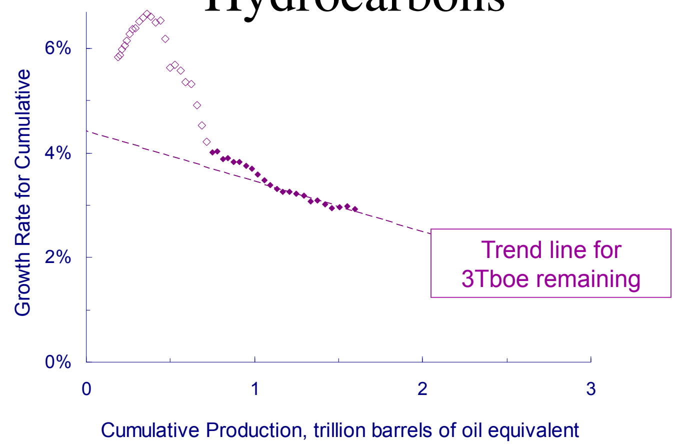
Question

1. List the current useful reserves of fossil fuels from largest to smallest
   a. oil, nat gas, coal, tar sands, shale oil
   b. Coal, oil, nat gas, tar sands, shale oil
   c. Natural gas, coal, oil, tar sands, shale oil
   d. Tar sands, shale oil, coal, natural gas, oil
   e. None of the above s correct

Summary of world fossil fuel sources

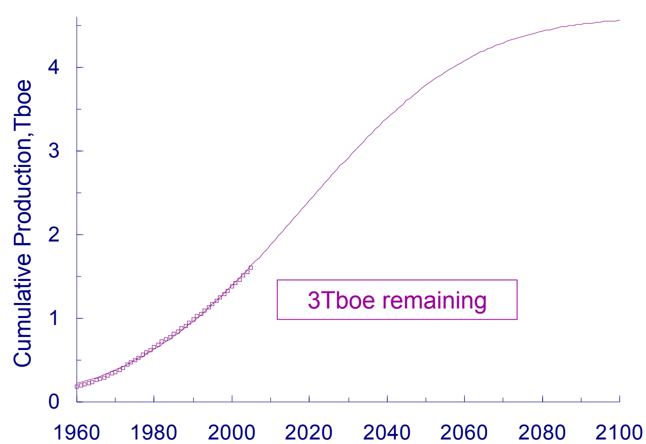
- Oil: 1000 Gbbl (trend) - 1500 Gbbl
- Nat gas: ~1000 Gboe (proved) -? (exploration not as complete as oil)
- Tar sands: ~500 Gboe (quite uncertain how much economically recoverable)
- Rutledge uses Hubbert trend analysis to estimate total liquid/gas hydrocarbons to be 3000Gboe; German govt. says 2700Gboe
- Coal: World Energy Council (used by DoE) says ~5000 Gboe, but Hubbert type trend analysis says only 3200 Gboe; IPCC uses old numbers of 18000 Gboe (important since burning this gives predictions of climate change, sea level rise, etc.)
- Shale oil: 80Gboe - 800Gboe or more depending on price, etc.
- Deep sea clathrate (methane hydrates): could be more energy in these than all of the above combined! (but no one has figured out how to get at them and to turn it in to useful energy)

Growth-Rate Plot for World Hydrocarbons



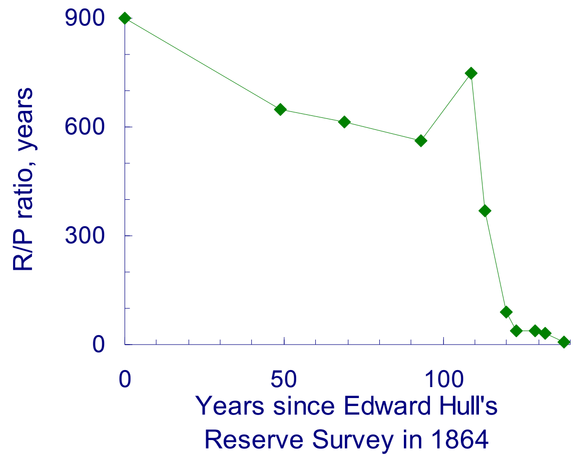
- Oil + natural gas + natural gas liquids like propane and butane
- Data 1965, 1972, 1981, 2006 *BP Statistical Review* (open 1960-1982, closed 1983-2005)
- The German resources agency BGR gives hydrocarbon reserves as 2.7Tboe
  - Expectation of future discoveries and future OPEC oil reserve reductions
  - Includes 500Gboe for non-conventional sources like Canadian oil sands

World Hydrocarbon Production



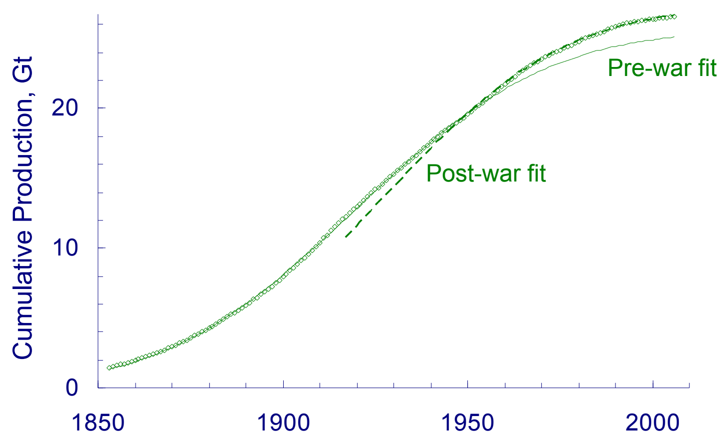
- Cumulative normal (ultimate 4.6Tboe, lms fit for mean 2018, sd 35 years)
- IPCC scenarios assume that 11 to 15Tboe is available

Reserves-to-Production Ratio for UK Coal



- 1864 reserves from Edward Hull of the Geological Survey
- Other data from the World Energy Council Surveys
- Current R/P ratio is 7 years

Cumulative British Coal Production



- Pre-war lms fit (1854-1945, ultimate 25.6Gt, mean 1920, sd 41 years)
- Post-war lms fit (1946-2006, ultimate 27.2Gt, mean 1927, sd 39 years)

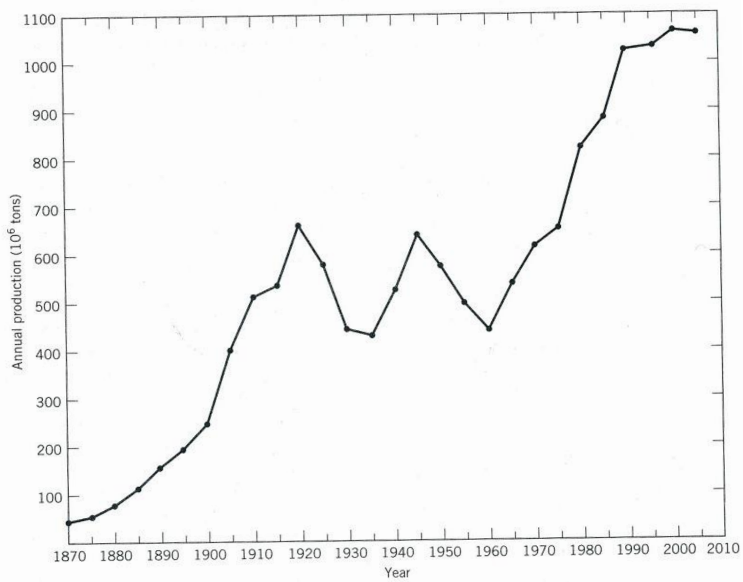
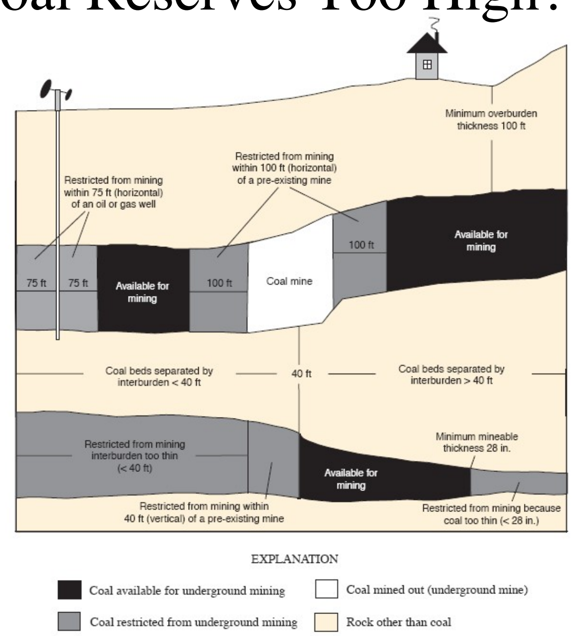


Figure 2.7 Annual production of coal in the United States since 1870. (*Sources: Historical Statistics of the United States: Colonial Times to 1970*, Washington D.C.: U.S. Department of Commerce, Bureau of the Census, 1975; and U.S. Energy Information Administration, *Annual Energy Review*, 1989, 1996, 2003.)

Why Are Coal Reserves Too High?

- It seems likely that there are many social, environmental, and technical hindrances that are not fully taken into account in the reserve estimates
- The German Energy Watch Group was early in pointing out that there is a problem with reserves worldwide
- Here are some technical restrictions from the USGS 2000 National Coal Assessment for the Illinois basin



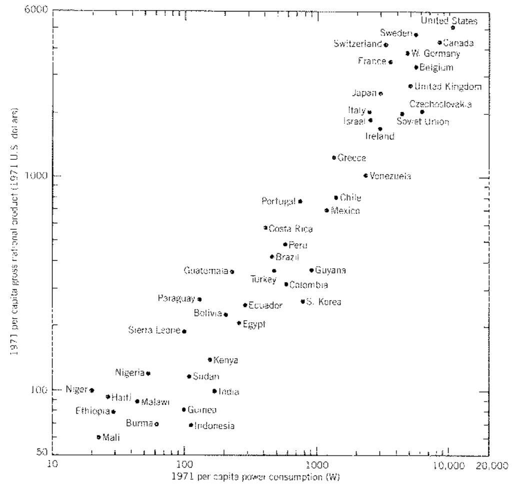


Figure 1–14.
Per capita gross national product and average per capita power consumption for various countries of the world in 1971. This does not include the energy in the food that is consumed.