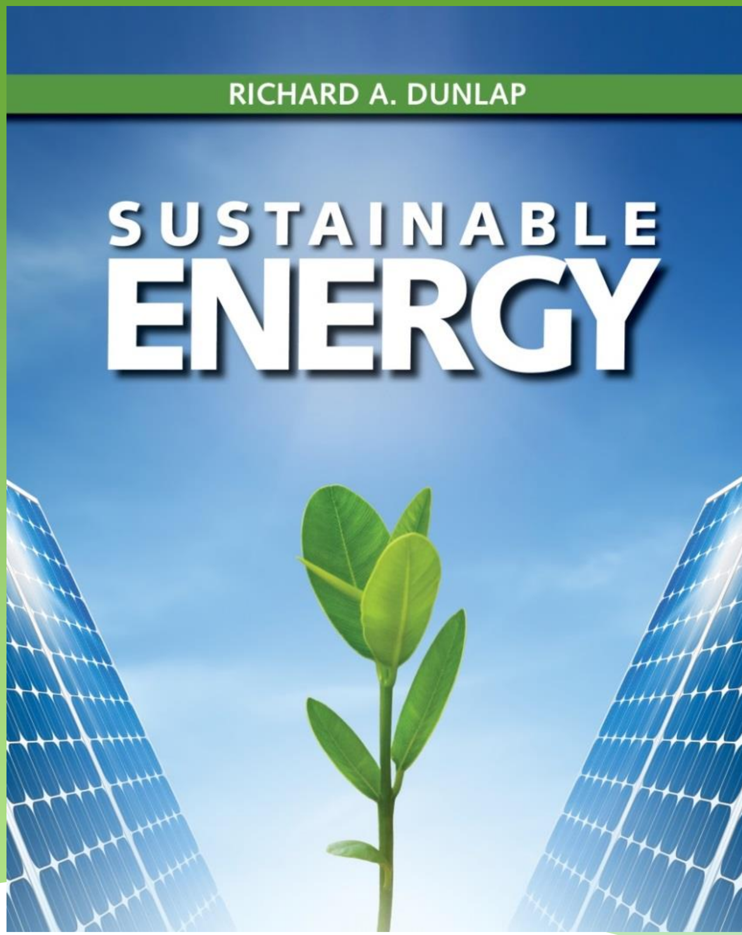
Sustainable Energy



Chapter 3

- Fossil Fuel Resources and Use

CENGAGE Learning

Learning Objectives

- The properties of fossil files and methods for obtaining and processing them.
- The availability of fossil fuels.
- The use of fossil fuels worldwide.
- The application of the Hubbert model to fossil fuel use.
- Enhanced fossil fuel recovery methods.
- The properties and availability of shale oil and tar sands.
- Methods for coal liquefaction and gasification.

Fossil fuels

Fossil fuels are categorized as

- Oil
- Natural gas
- Coal

Oil

Oil (as well as natural gas) is formed from decomposition of marine organisms that lived about 500 million years ago from extended periods of high temperature and pressure.

20 tonnes of organic matter produces about 1 liter of oil.

Location of oil deposits

Deposits are trapped under a layer of impermeable rock and may be under the ocean or (because of continental drift) under land

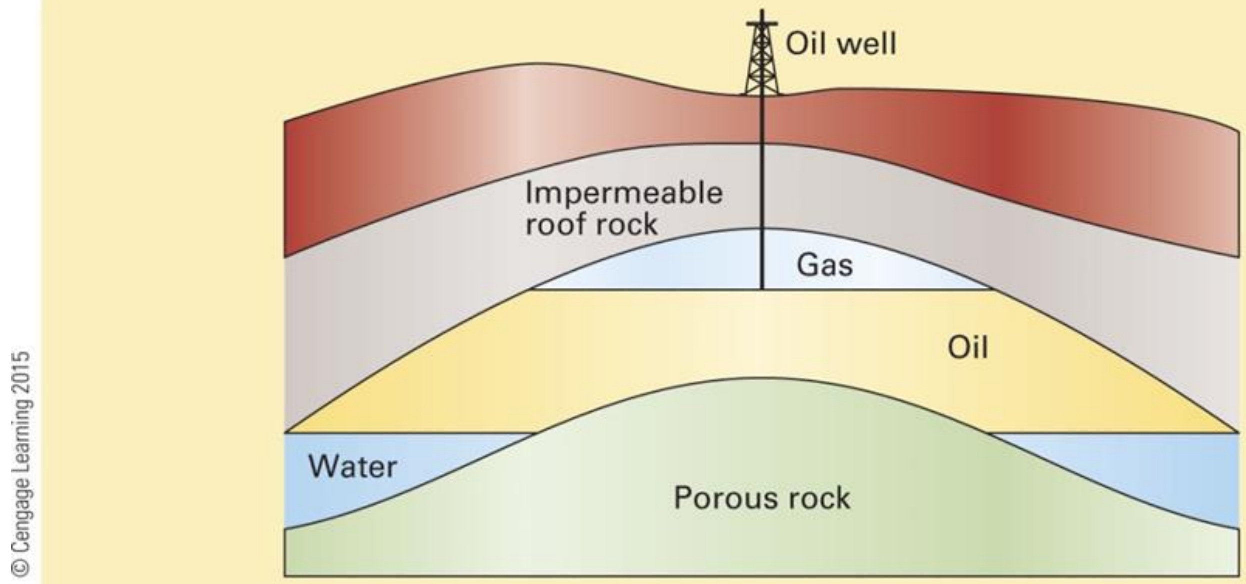


Figure 3.1: Geology of a typical oil deposit where the oil and gas are trapped in porous rock between layers of dense rock. The gas rises to the top, and the oil floats on any water in the deposit.

Oil production

Oil first used as a fuel in mid-1800s

Early production in Pennsylvania and Ontario

Reproduction, copyrighted in 1890, of a retouched photograph showing Edwin L. Drake, to the right, and the Drake Well in the background, in Titusville, Pennsylvania, where the first commercial well was drilled in 1859 to find oil.

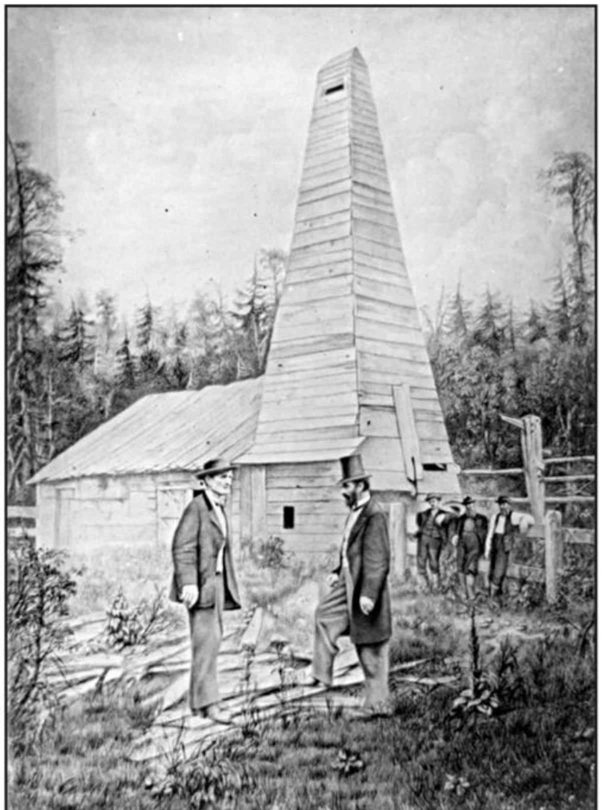


Figure 3.2: Oil well drilled in Titusville, Pennsylvania, in 1859 by Edwin Drake.

Courtesy of Martin Dillon

Figure 3.3: Oil well dug in Petrolia, Ontario, in 1858.

Current oil production

Small land based oil well

Figure 3.4: Small pump jack oil well.

Off-shore oil production

Figure 3.6: Off-shore oil platform.

Refining

Crude oil contains a variety of hydrocarbons that can be separated according to molecular weight by refining

Table 3.1: Properties of typical hydrocarbons extracted from oil during the refining process.

name	number of carbon atoms per molecule	state at room temperature	boiling temperature (°C)	uses
natural gas	1–5	gas	−165 to 25	gaseous fuel
petroleum ether	5–7	liquid	25 to 90	industrial solvent
gasoline	5–12	liquid	25 to 200	automobile fuel
kerosene	12–16	liquid	175 to 275	stove and jet fuel
fuel oil	15–18	liquid	< 375	diesel and home heating
lubricating oil	16–20	liquid	> 350	lubrication
grease	>17	semisolid	—	lubrication
paraffin	>19	solid	—	candles
tar	large	solid	—	roofing and paving

Alkanes

Some hydrocarbons are in the alkane series with compositions C_nH_{2n+2}

Table 3.2: Alkane series of hydrocarbons with the formula C_nH_{2n+2}. The heat of combustion is the HHV (Chapter 1).

					heat of combustion	
n	formula	name	boiling temperature (°C)	molecular mass (g/mol)	MJ/kg	eV per molecule
1	CH_4	methane	−164	16	55.5	9.20
2	C_2H_6	ethane	−89	30	51.9	16.1
3	C_3H_8	propane	−42	44	50.3	23.0
4	C_4H_{10}	butane	0	58	49.5	29.8
5	C_5H_{12}	pentane	36	72	48.7	36.3
6	C_6H_{14}	hexane	69	86	48.1	42.9
7	C_7H_{16}	heptane	98	100	48.1	49.9
8	C_8H_{18}	octane	125	114	46.8	55.3

Refinery process

Hydrocarbons with different molecular weights and different boiling points can be separated by allow crude oil to travel up a fractionating column with progressively lower temperature.

Schematic of a fractionating column

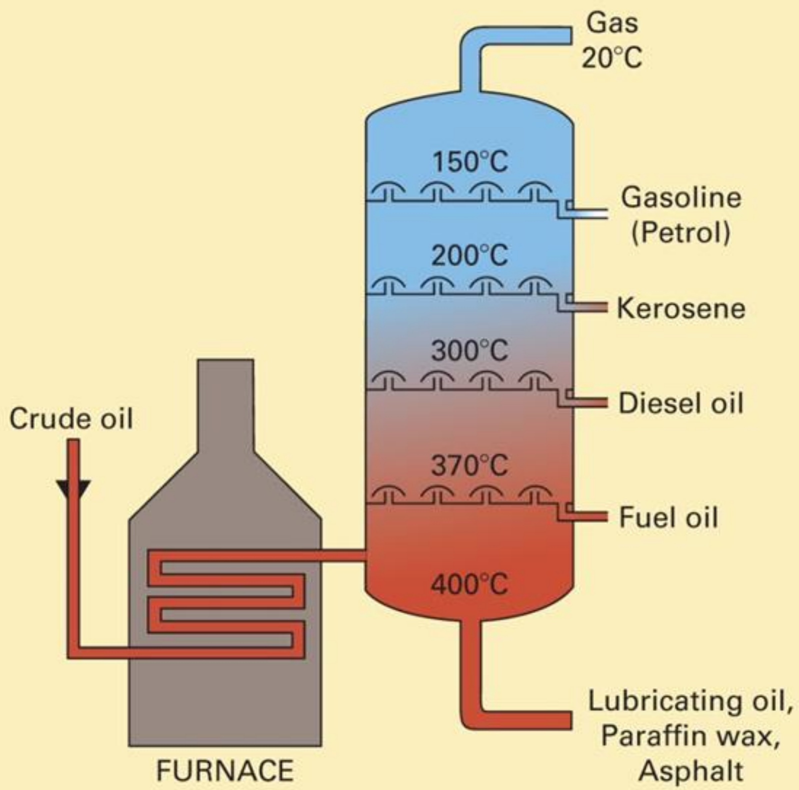


Figure 3.7: Schematic representation of a fractionating distillation column.

Based on U.S. Energy Information Administration, http://www.eia.gov/todayinenergy/detail.cfm?id=6970

Fractionating columns at an oil refinery

Figure 3.8: Fractionating columns at Dartmouth Refinery, Dartmouth, Nova Scotia.

Natural gas

Natural gas is often found mixed with oil deposits or in deposits of its own.

Typically a mixture of about 85% methane and 15% ethane.

Combustion is approximated by the combustion of methane as

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 55.5\ MJ/kg \qquad (3.1)$$

Coal

Coal is formed from terrestrial plant matter over many years of elevated temperature and pressure.

The oldest coal deposits are about 350 million years old.

About 0.8% of original carbon in the plant matter becomes coal.

Ranks of coal

Type (or rank) of coal depends on formation conditions and age

Common ranks of coal

Table 3.3: Types of coal and their properties. These are typical values; the actual values can be quite variable, and the ranges overlap. Most of the noncarbon content of coal is in the form of volatile compounds, with a significant fraction being water.

type	carbon (%)	moisture content (%)	energy content (MJ/kg)
anthracite	90	10	35
bituminous	55	20	31
sub-bituminous	45	30	23
lignite	25	45	14

Coal use in the United States

Most coal in the U.S. is used to generate electricity in thermal generating stations

Table 3.4: Current use of coal in the United States.

use	% of total
electricity generation	70
coke production	17
export	10
other (residential heating, industrial processes, etc.)	3

Comparison of U.S. and Saudi Arabian oil production

United States produces 2.45×10^9 bbl per year from about 600,000 oil wells.

Saudi Arabia produces 3.96×10^9 bbl per year from about 1000 oil wells.

Production rates per well

- United States 1.2 L/min
- Saudi Arabia 1200 L/min

Why such a discrepancy?
U.S. oil wells are much closer to depletion

Application of the Hubbert model to U.S. oil production

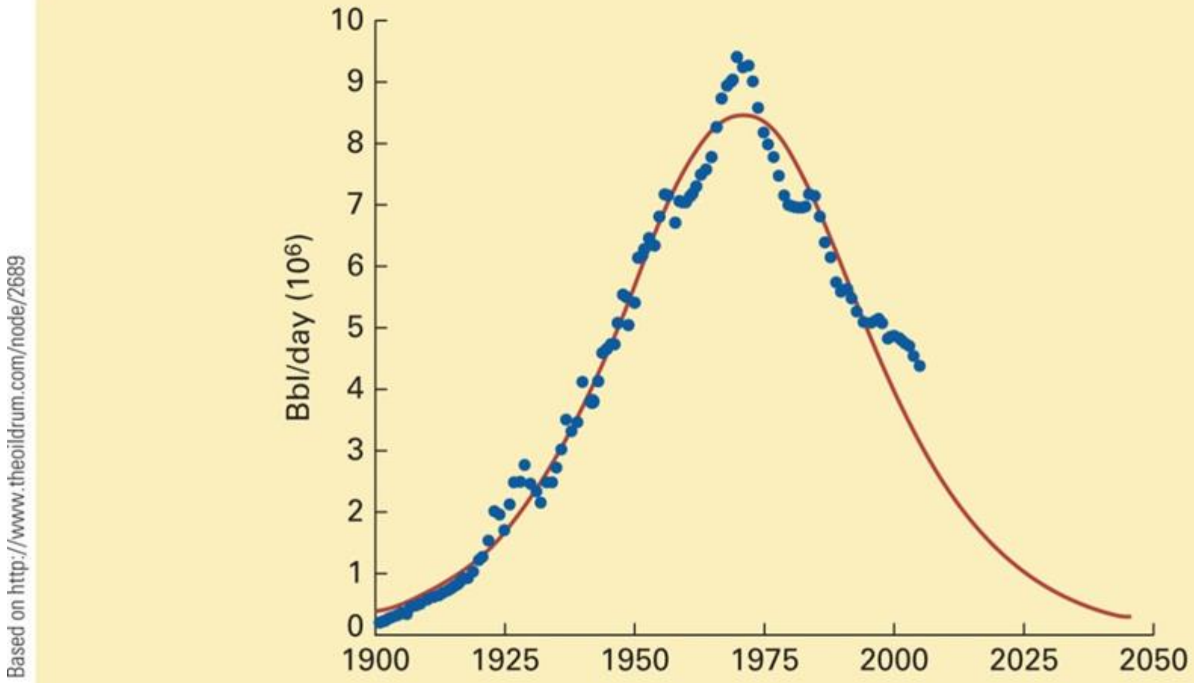


Figure 3.10: Hubbert model of oil production in the continental United States (10^6 bbl/day).

Hubbert peak was passed about 40 years ago

Hubbert model for world oil production

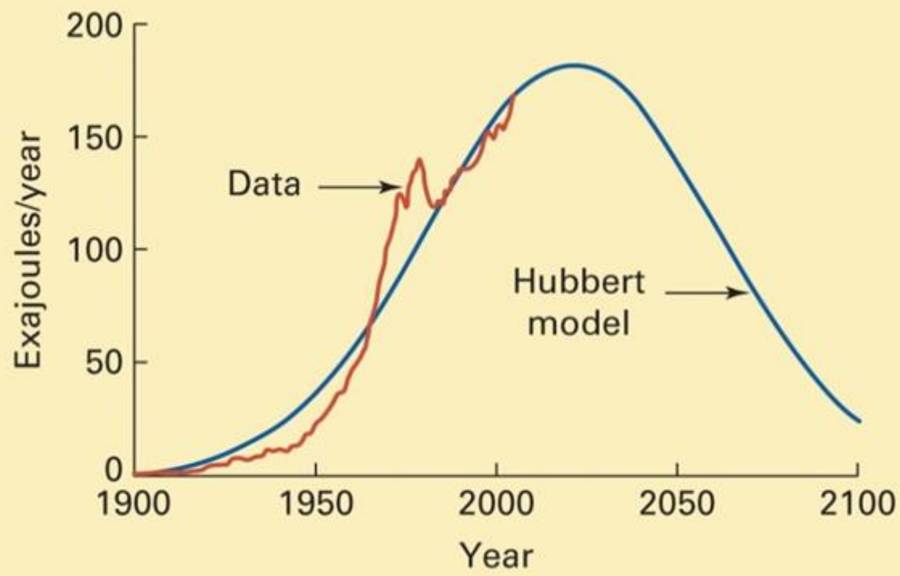


Figure 3.11: Hubbert model of oil use worldwide.

Based on E. L. McFarland, J. L. Hunt and J. L. Campbell. Energy, Physics and the Environment. Cengage Learning, 2007.

Not quite yet at the peak

U.S. dependence on imported oil

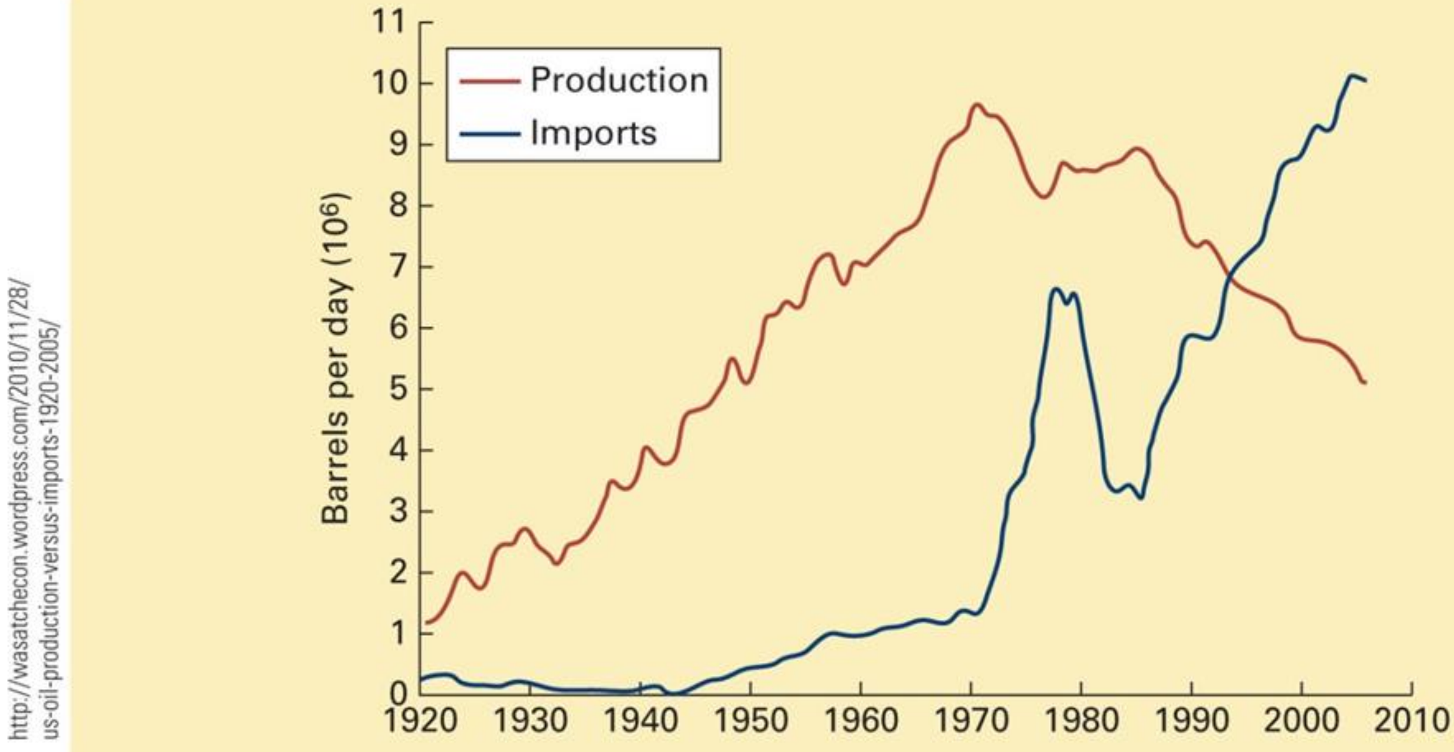


Figure 3.9: Percent of oil used in the United States that is imported from other countries.

Lifetime of oil resources

Longevity of oil resources in the U.S., Canada and worldwide

Depends critically on growth rate

Table 3.7: Lifetime of traditional oil resources for different annual growth rates.

region	0% annual growth (y)	2% annual growth (y)	5% annual growth (y)	actual growth rate 1995–2005 (%)
United States	45	33	24	−2.1
Canada	200	80	48	2.6
world	75	45	31	1.7

Based on data from E. L. McFarland, J. L. Hunt and J. L. Campbell. Energy, Physics and the Environment. Cengage Learning, 2007.

Lifetime of natural gas resources

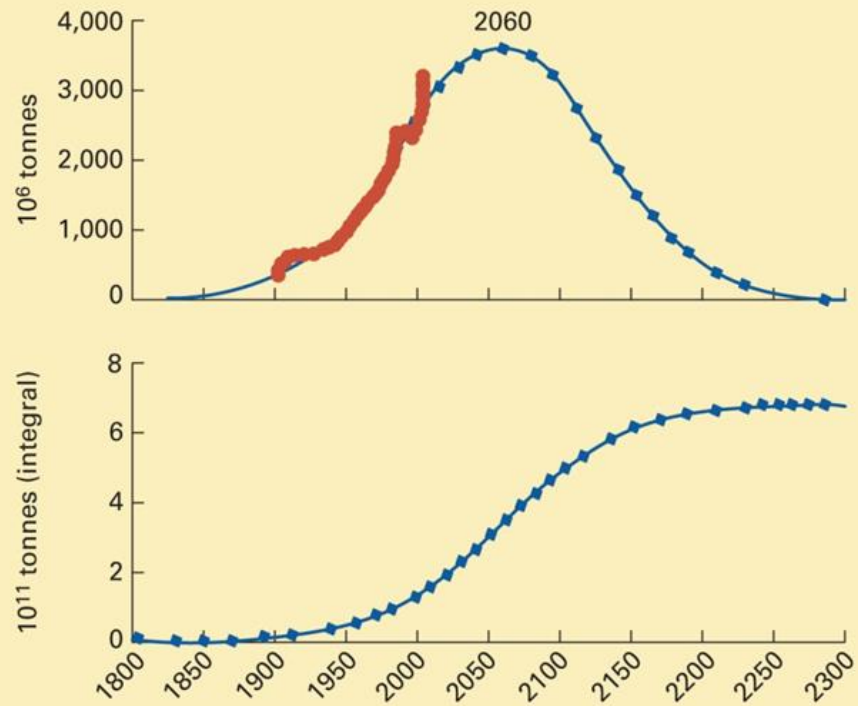
Longevity of natural gas resources in the U.S., Canada and worldwide

Based on data from E. L. McFarland, J. L. Hunt and J. L. Campbell. Energy, Physics and the Environment. Cengage Learning, 2007.

Table 3.9: Lifetime of traditional natural gas resources for different annual growth rates.

region	0% annual growth (y)	2% annual growth (y)	5% annual growth (y)	actual growth rate 1995–2005
United States	35	27	20	−0.2%
Canada	55	38	27	1.6%
world	75	46	32	2.6%

Application of the Hubbert model to coal production



Based on A. Valero and A. Valero "Physical geonomics: Combining the exergy and Hubbert peak analysis for predicting mineral resources depletion," Resources, Conservation and Recycling 54 (2010) 1074–1083.

Figure 3.13: Application of the Hubbert model to the world utilization of coal. Data are plotted as the mass of oil with equivalent energy content.

Note that the peak occurs around 2060 and that the curve is much wider than for oil

Lifetime of coal resources

Longevity of natural gas resources in the U.S., Canada and worldwide

Based on data from E. L. McFarland, J. L. Hunt and J. L. Campbell. Energy, Physics and the Environment. Cengage Learning, 2007.

Table 3.11: Lifetime of traditional coal resources for different annual growth rates.

region	0% annual growth (y)	2% annual growth (y)	5% annual growth (y)	actual growth rate 1995–2005
United States	1500	170	88	0.3%
Canada	1800	180	92	−1.5%
World	1200	160	84	2.5%

Enhanced fossil fuel recovery methods

Oil recovery from traditional oil wells can be enhanced by several techniques

- Primary oil recovery - oil flows from well under its own pressure (about 10 - 15% of oil recovered)
- Secondary oil recovery - water or gas pumped into reservoir to pressurize it (additional 25% of oil recovered)
- Tertiary oil recovery - Various techniques include
  - Surfactant injection
  - Steam injection
  - Fireflooding

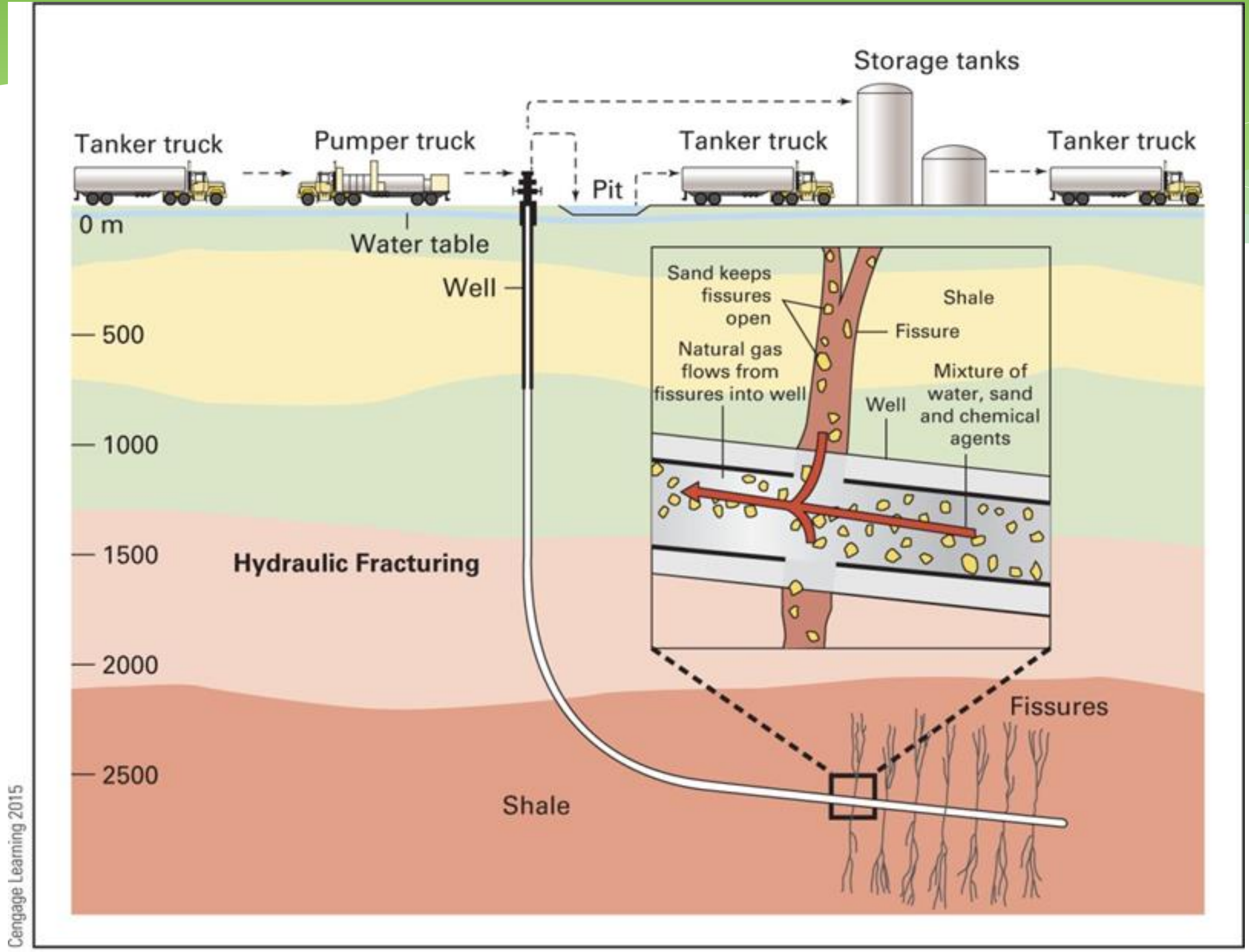
Fracking

Fracking (hydraulic fracturing) is often used to enhance natural gas recovery.

Water (with chemicals added for various reasons) is injected into the well under pressure to fracture the rock and allow gas to enter the well.

This technique is controversial because of potential contamination of water supply with fracking liquids or natural gas.

Diagram of the fracking process



The fracking process

Shale oil

Oil shale is a sedimentary rock that contains complex hydrocarbons called *kerogens.*

Heating kerogens breaks them down into petroleum-like materials that can be used in place of traditional oil.

Estimated shale oil resources

Table 3.12: Estimated in-ground shale oil resources.

location	resources (10^9 bbl)
Congo	100
Morocco	53
United States	3707
Brazil	82
Italy	73
Russia	248
Jordan	34
Australia	32
rest of world	457
total	**4786**

The U.S. has the largest know resources and these exceed estimates of the world total oil resources from traditional sources

Energy content of oil shale

Good quality oil shale produces the equivalent of about 100 L oil per tonne of shale.

This is about 12% the energy content of one tonne of bituminous coal.

World use of shale oil

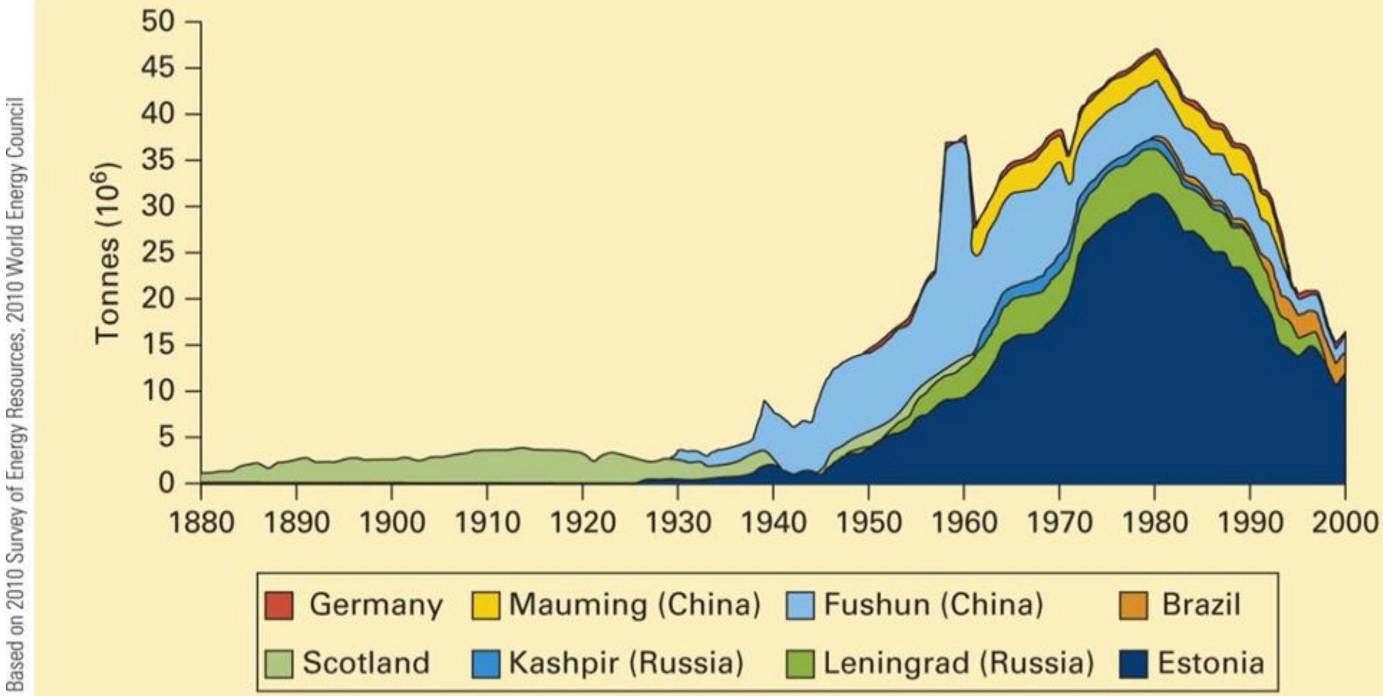


Figure 3.14: Annual processing of oil shale in different countries.

Estonia is the only major shale oil user and extracts the majority of its energy from this source

Use of U.S. shale oil resources

Despite the extensive resources available in the U.S., there is virtually no utilization of shale oil.

The reasons for this result, at least in part, from the location of the resources and the methods of extracting shale oil from the rock.

Location of U.S. Oil shale resources

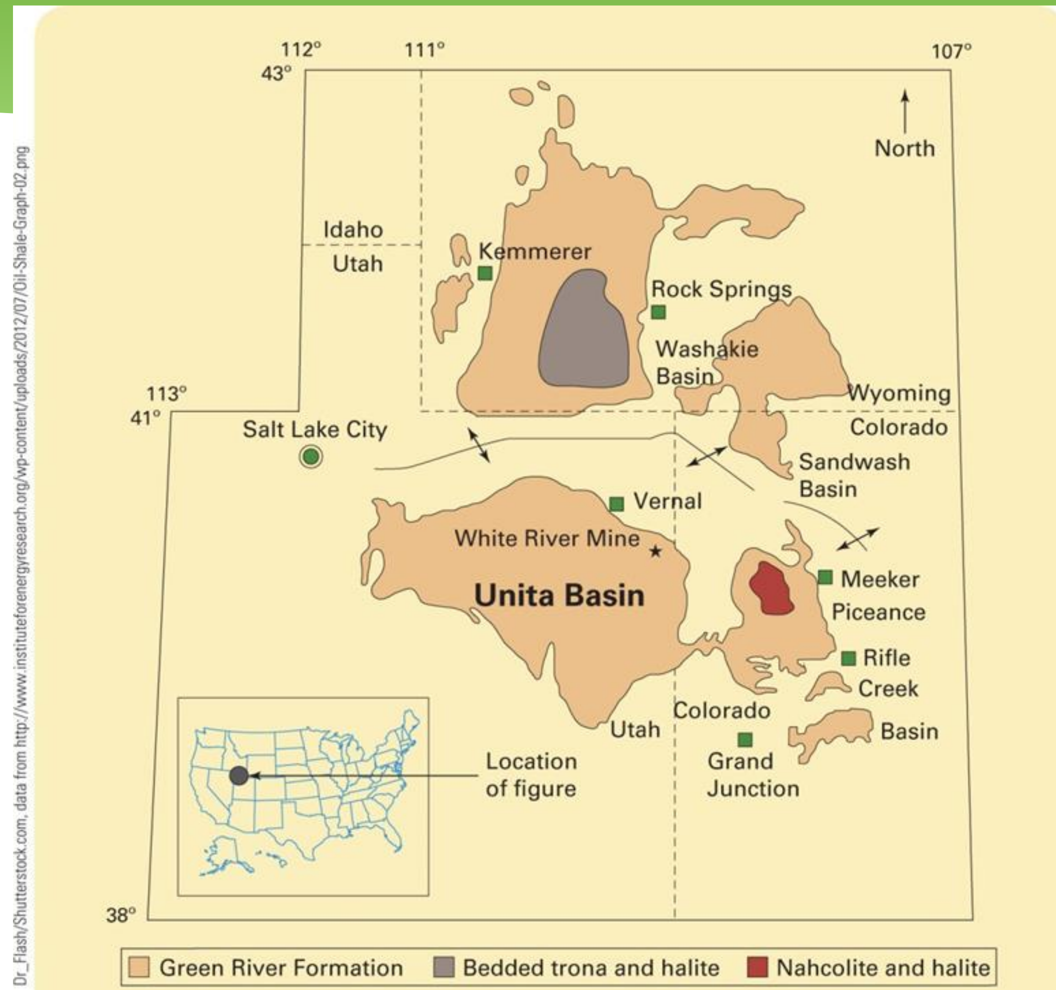


Figure 3.15: Location of most significant oil shale deposits in the United States.

Extraction of shale oil

Oil is extracted from oil shale by

- heating the shale oil to about 500°C to extract the kerogens
- refining the resulting hydrocarbons as for crude oil

Concerns for shale oil production

The following points of concern must be addressed for U.S. shale oil resources

Water supply

- The area of the oil shale deposits have generally little rainfall and water from rivers is a valuable resource for agriculture

Disposal of spent shale

- Because of the low energy density (compared to coal) large quantities of shale need to be processed and disposed of

Further factors against U.S. shale oil production

Environmental consequences

- Shale oil production releases significant pollution and greenhouse gases, 97% of Estonia's air pollution comes from the shale oil industry

Cost

- Some studies have suggested that shale oil would cost about twice the price of conventional crude oil

Extra heavy oil

Extra heavy oil has a very high viscosity and, as a result, is more difficult to extract

Virtually all extra heavy oil is located in Venezuela

Table 3.13: Estimated extra-heavy oil resources.

location	10^9 bbl
Venezuela	2012
rest of world	38
total	**2050**

Extra heavy oil production

Estimated extra heavy oil resources are close to the estimates for total conventional oil resources.

Commercial extra heavy oil production has been ongoing in Venezuela since 2001 and has been at a rate of about 4×10^{7} L/day.

Tar sands

Tar sands represents deposits of oil that are mixed with sand.

The majority of tar sands resources are located in Alberta, Canada and are estimated to be a substantial fraction of world resources of conventional oil.

World tar sands resources

Table 3.14: Estimated oil resources from natural bitumen (tar sands).

location	10^9 bbl
Nigeria	425
Canada	1625
Kazakhstan	250
Russia	200
rest of world	56
total	**2256**

Location of Canadian tar sands resources

Figure 3.18: Location of tar sands oil deposits in Alberta, Canada.

Production of oil from tar sands

Production of oil from tar sands in Canada began in 1967.

Production of about 5×10^8 L/day is anticipated.

Coal liquefaction and gasification

Liquid or gaseous fuels suitable for transportation use can be produced from coal.

Coal (mostly carbon) can be heated in the presence of oxygen or water to yield the following reactions

$$2C + O_2 \rightarrow 2CO \qquad (3.3)$$

$$C + H_2O \rightarrow H_2 + CO \qquad (3.4)$$

Combustion of coal gas

Coal gas can be burned to yield energy by the reactions

$$2CO + O_2 \rightarrow 2CO_2 \quad (3.6)$$

$$2H_2 + O_2 \rightarrow 2H_2O \quad (3.7)$$

Use of coal gas and related fuels

During gasoline shortages in World War II, gaseous fuels were produced from solid hydrocarbons for vehicle use

Figure 3.19: Automobile manufactured by Adler with wood gas generator attached to the back (Adler Diplomat equipped with Imbert Holzgas Generator, 1941).

Coal liquefaction

Liquid hydrocarbons similar to gasoline or diesel fuel can be produced from coal by various chemical reactions and polymerization.

Coal gas and liquid fuels produced from coal have not been shown to be economically viable and produce more greenhouse gas emissions than conventional petroleum products.

Summary

- Fossil fuels are categorized as oil, natural gas and coal
- All fossil fuels are produced under extreme pressure by the decomposition of ancient organic matter
- Crude oil can be refined to yield a variety of products
- Natural gas is about 85% methane and 15% ethane
- Coal has different ranks depending on formation conditions
- Worldwide oil production is approaching the peak in the Hubbert model, in the U.S. it has passed the peak
- Coal has a greater longevity than other fossil fuels
- Enhanced recovery technologies may extend the lifetime of oil
- Shale oil is a plentiful resource but is not viable at this time
- Extra heavy oil and tar sands have been utilized for a number of years
- Coal may be gasified or liquefied to produce a transportation fuel