Sustainable Energy

Lecture 7: Fossil Fuels and Fossil Energy

Introduction

- What are fossil fuels?
  - Fossil fuels are solid, liquid, or gaseous substances that contain organic or covalently bonded carbon and are produced by chemical and physical transformations of plant and animal remains over geological time periods.
- Fossil fuel types:
  - Coal
  - Natural gas
  - Petroleum
  - Oil shale (yields 10-30 gallons of liquid/ton)
  - Tar sands
  - See Table 7.1 for heating values.

Fossil Fuel heating values

Table 7.1. Hydrogen-to-Carbon Ratio and Heating (Calorific) Value of Selected Fossil and Process-Derived Fuels

Fuel Type	H/C, Atomic[a]	Gross Heating Value (kcal/g)[b,c]
Gaseous		
High-Btu		
Methane	4.0	13.3
Natural gas	3.5–4.0	11.7–11.9
Intermediate-Btu		
Hydrogen	∞	33.9
Coke oven gas	4.9	9.6
Water gas (H_2 - CO)	2.0	4.3
Low-Btu		
Producer gas (N_2-diluted; from bituminous coal)	1.2	1.2
Liquid		
Methanol	4.0	5.3
Gasoline	2.0–2.2	11.2–11.4
No. 2 fuel oil	1.7–1.9	10.7–11.0
No. 6 fuel oil	1.3–1.6	10.0–10.5
Crude shale oil	1.6	10.3–10.4
Bitumen (Athabasca tar sands)	1.4–1.5	9.8–10
Solid		
Kerogen (Green River oil shale)	1.5	10
Lignite	0.8	3.9–5.4
Subbituminous coal	0.8	5.5
Bituminous coal	0.5–0.9	6.7–8.8
Anthracite	0.3	8.4
Low-temperature coke	0.4	8.2
High-temperature coke	0.06	8.0

Fossil Fuel Resource Base

- How long will fossil fuels last?
  - Levels (proved reserves)
    - Oil: 1,119 to 1,317 billion[2005-2007
    - Gas: 6,183 - 6,381 trillion cubic feet[1 (2005)
  - Flows (daily production) during 2006
    - Oil: 84 million barrels per day[13]
    - Gas: 104,435[14]*0.182)= 19 million barrels oil equivalent per day {MBOED}
    - Coal: 10,230[15]*0.907186*4.879= 29 MBOED
  - Years of production left in the ground with the most optimistic proved reserve estimates (Oil & Gas Journal, World Oil)
    - Oil: 1,317,000 million barrel reserve/84 million barrels used per day/365 days per year= 43 years
    - Gas: 1,161,000 million barrels equivalent reserve/19 million barrel equivalent used per day/365 days per year= 167 years
    - Coal: 4,416,000 million barrels equivalent reserve/29 million barrel equivalent used per day/365 days per year= 417 years

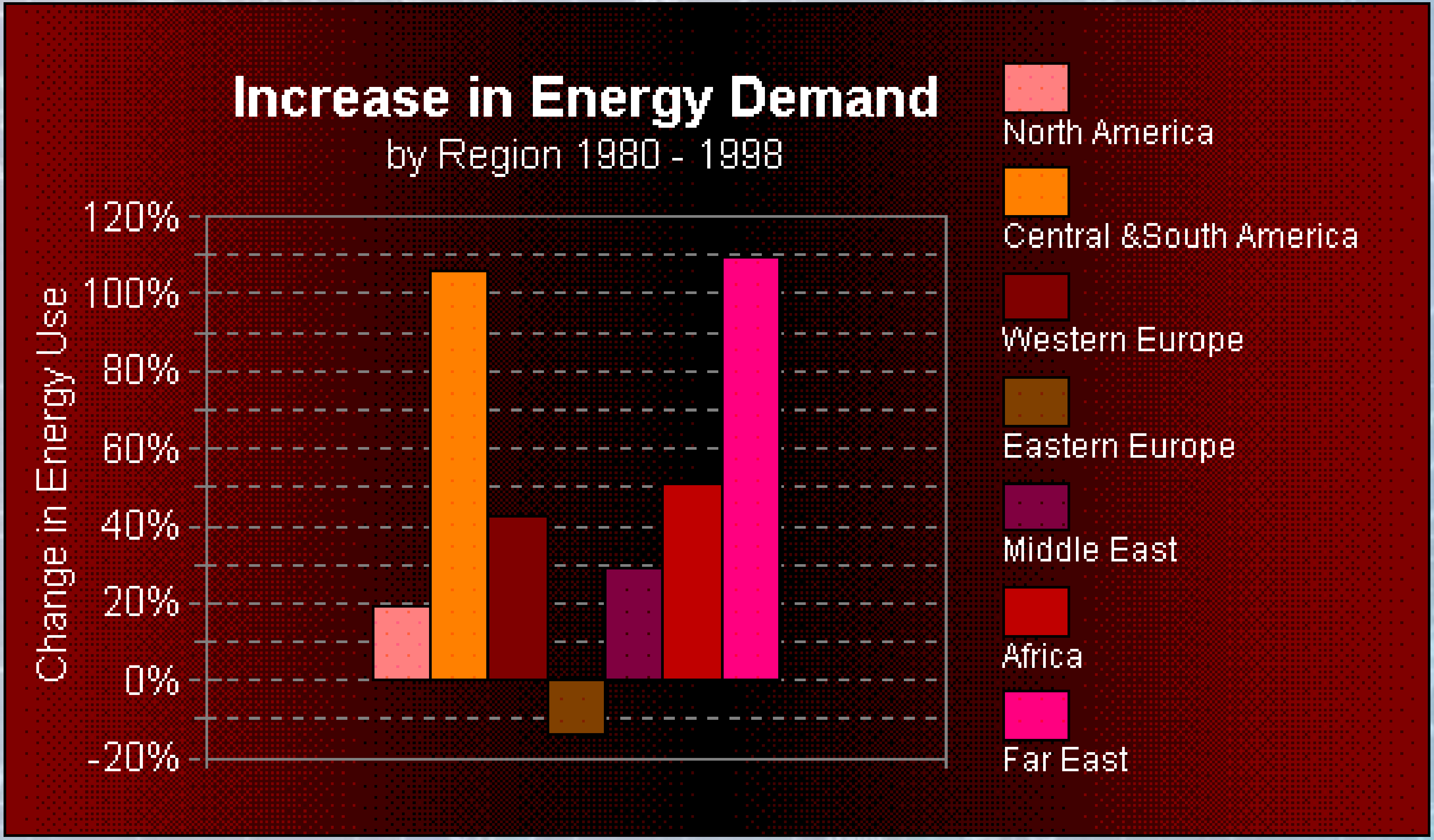
Estimates of Various Energy Resources

Table 7.2. Estimates of Various Energy Resources on Earth ca. 1999 (See also Sample Problem 7.1)

Fuel	10^{15} kJ*
Coal	290,000
Petroleum	2,600
Natural Gas	5,400
Tar Sands	5,700
Oil Shale	11,000
Peat	3,000
Uranium (^{235}U)	2,600

*1 kJ = 0.948 Btu

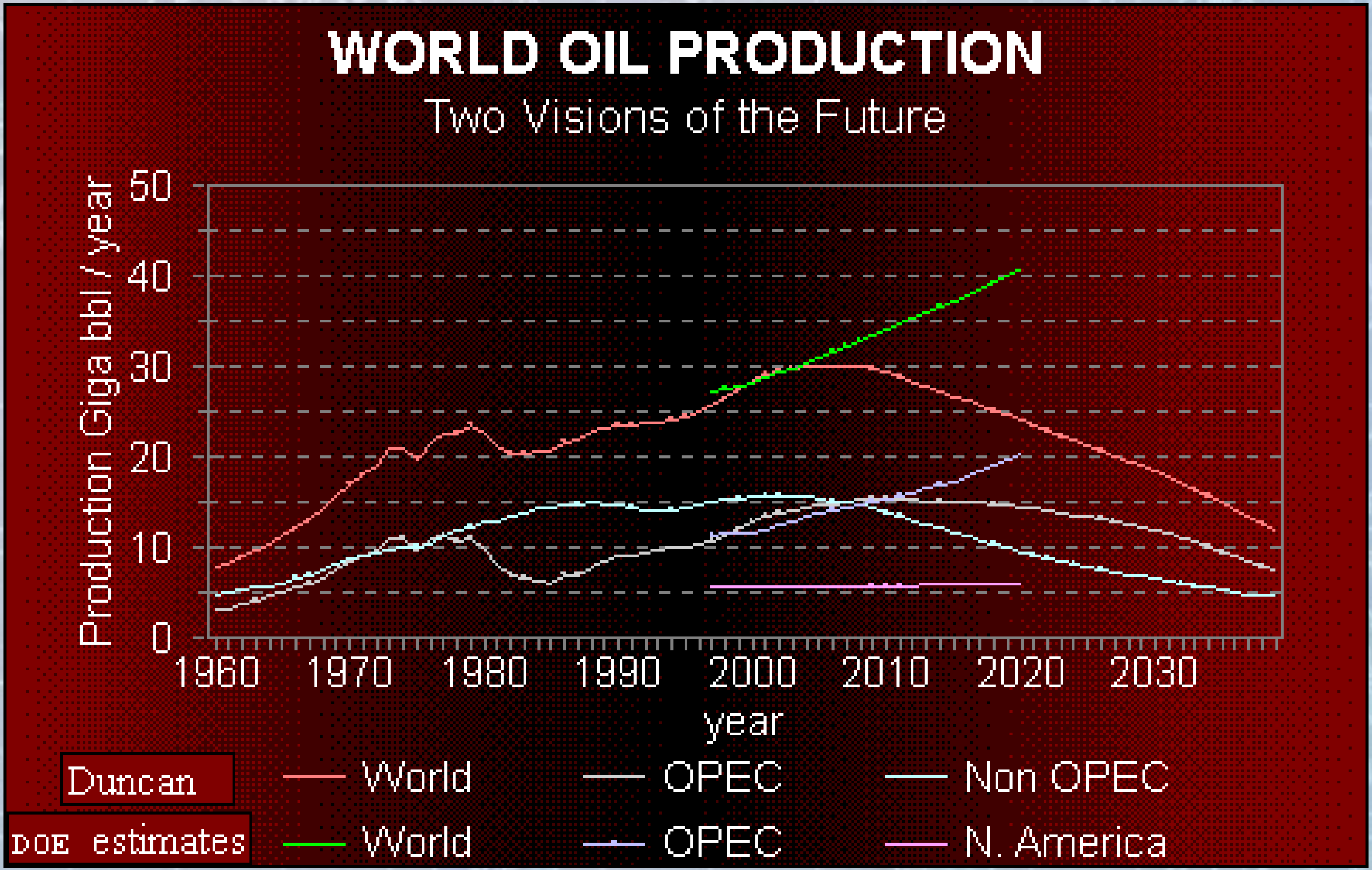
Energy Demand



National Average Emission Figures/MWe

	CO_2 lb/MWhe	NOx lb/MWhe	SO_2 lb/MWhe
Coal	2400	8.8	17
Fuel Oil	2000	4.2	12
Natural Gas	1300	4.6	0

World Oil Production



Harvesting Energy from Fossil Fuels

- Exploration, discovery and extraction of fuels
  - Modern technologies are allowing more reserves to be exploited.
- Fuel storage and transportation
  - Storage and transfer of fossil fuels pose considerable safety and environmental risks.
- Fuel Conversion
  - Petroleum refining
  - Coal gasification – production of alternative fuels (synthetic fuels)
  - Conversion Steps:
    - Compartmentalization – separation into components/fractional distillation
    - Conversion – modification of the chemical composition (catalytic cracking of oil distillates into gasoline)
    - Cleaning – removal of pollutants from the fuel (removing sulfur, nitrogen and metals)
- Fuel Combustion
  - Rankine cycle coal combustion
  - Gas turbine-steam combined cycle
  - Pressurized fluid bed combined cycle

Coal Pyrolysis/gasification

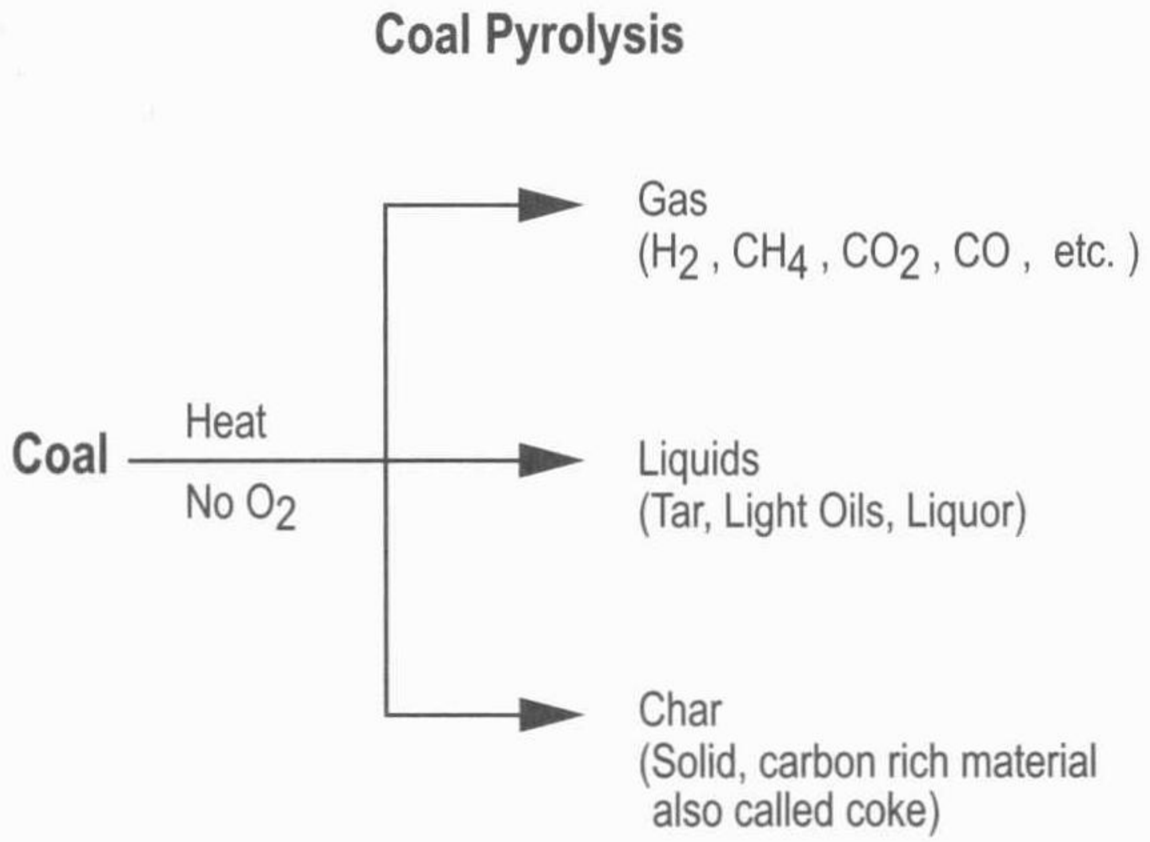


Figure 7.2. Schematic of coal pyrolysis showing three major product categories.

Synthesis Gas

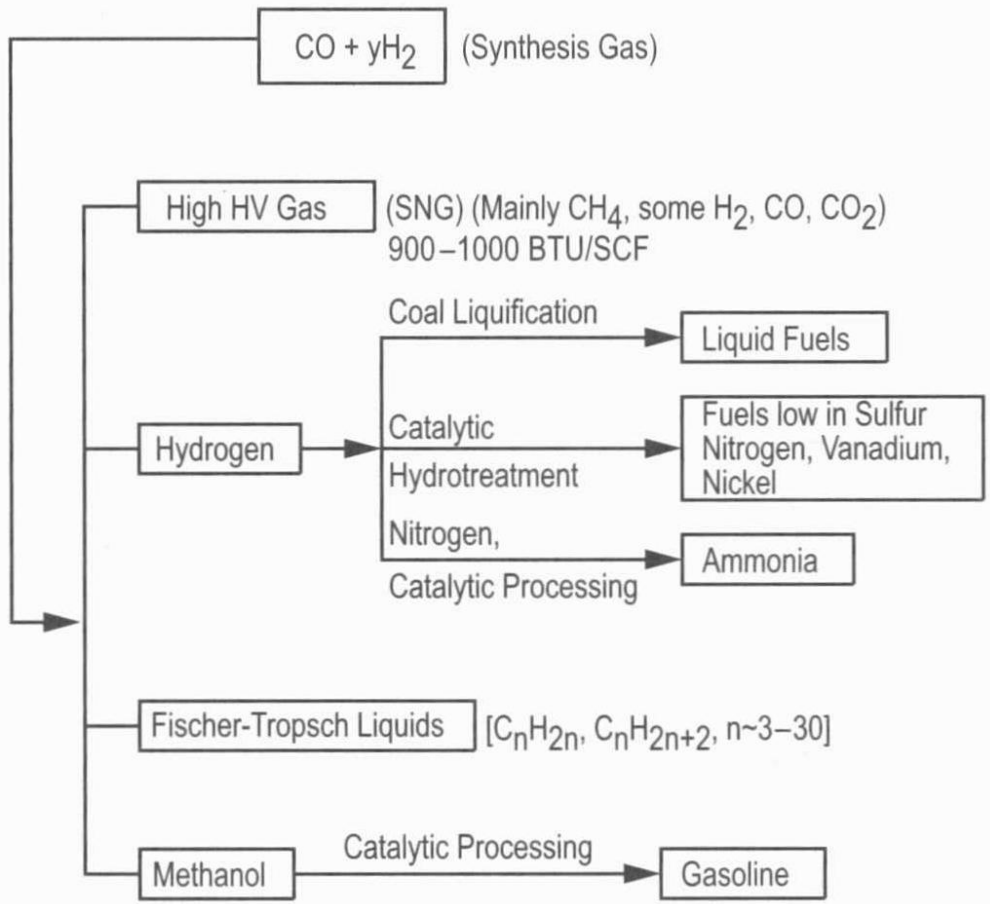


Figure 7.4. Examples of the wide variety of fuels and chemicals obtainable from synthesis gas.

Coal Power Generation

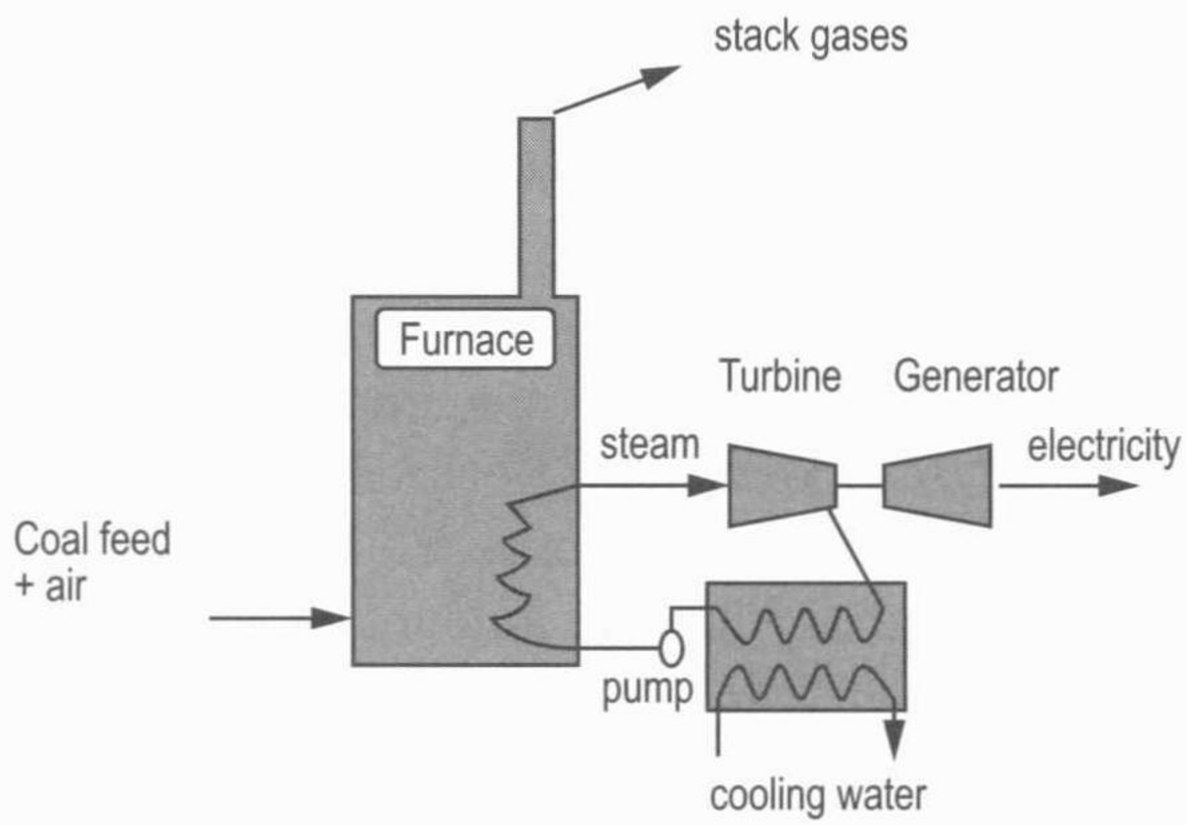


Figure 7.9. Typical coal plant.

Gas turbine-steam combined cycle power generation

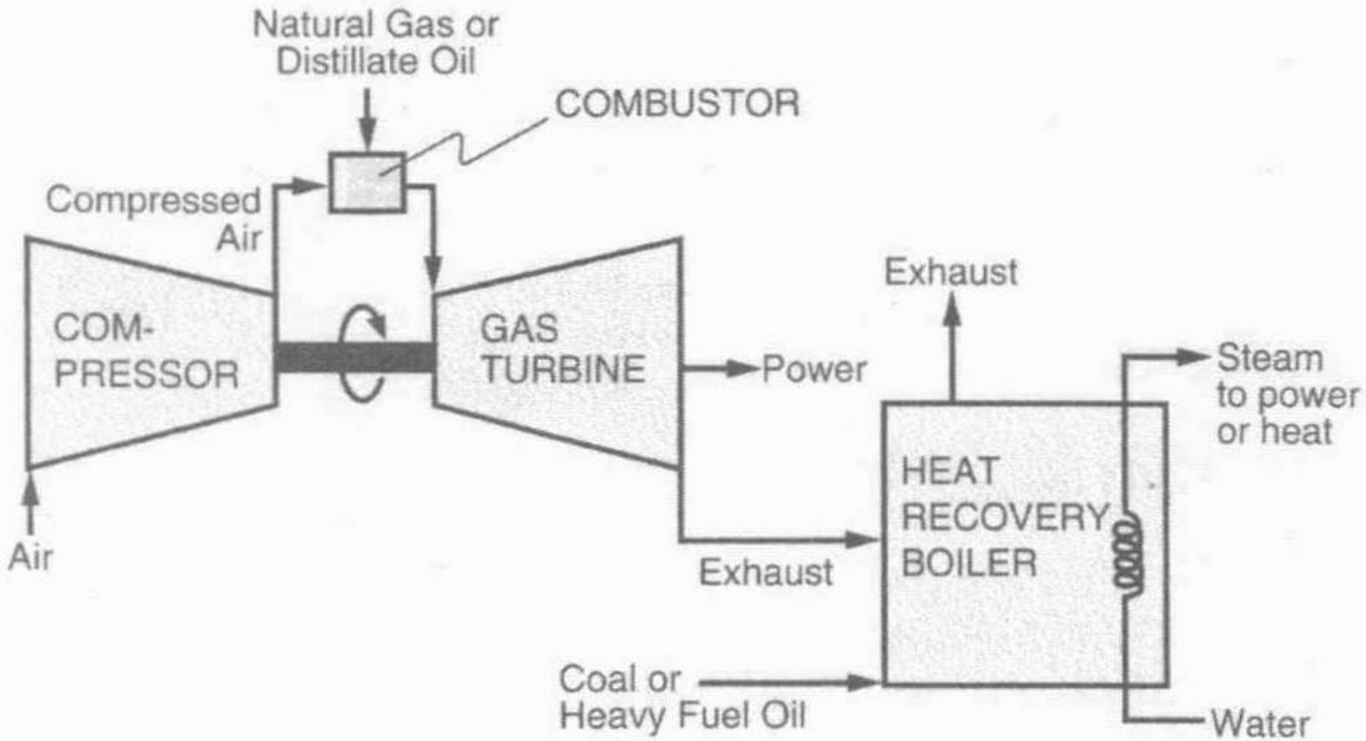


Figure 7.8. A schematic of a gas turbine-steam turbine combined cycle. Source: Beér (2000). Reprinted with author's permission.

Pressurized Fluid Bed Combined Cycle Coal Plant

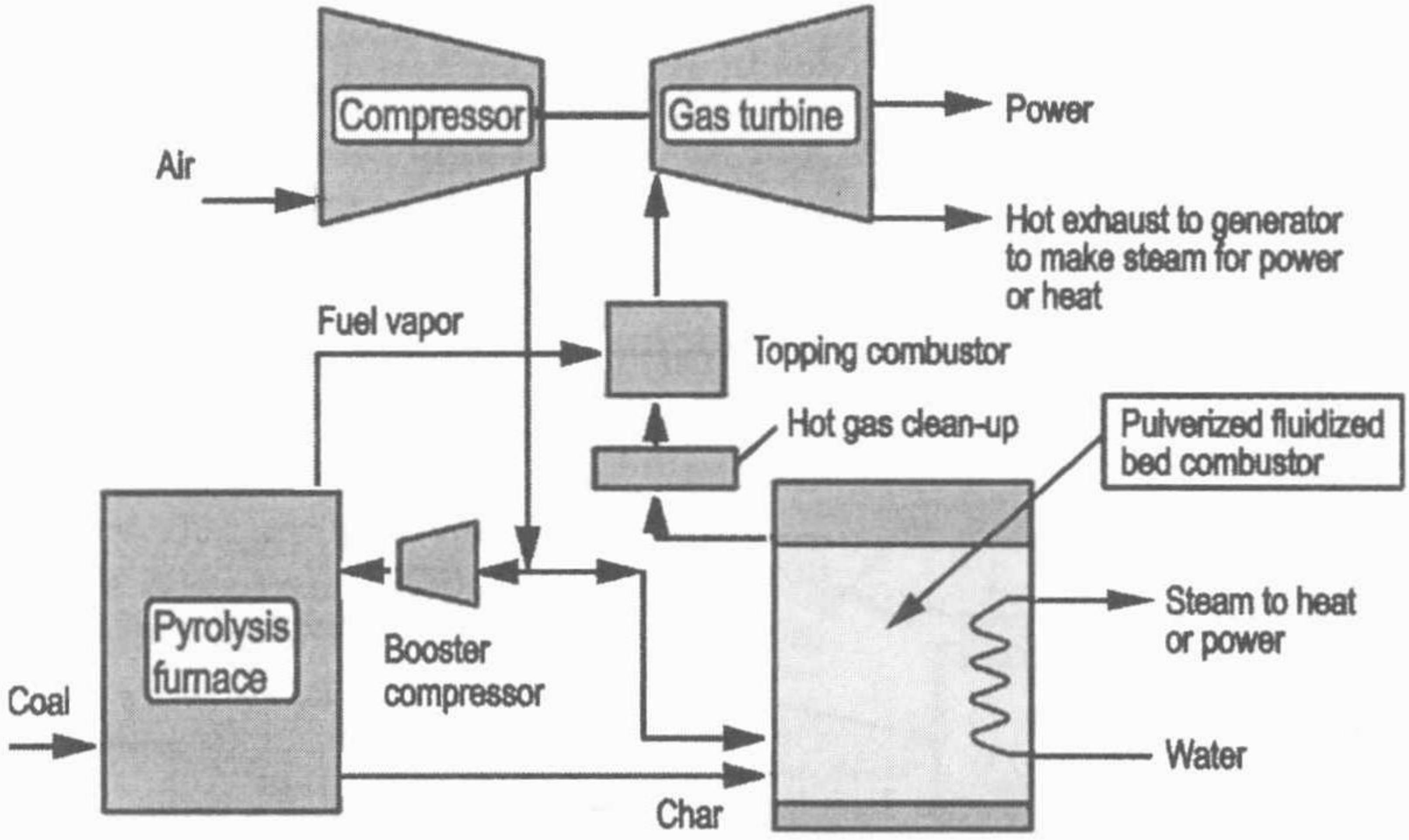


Figure 7.10. Typical pressurized fluid bed combined cycle.

Energy continued

- Fuel Cells
  - Fuels cells are electrochemical combustors.
    - The fuel cell converts chemical potential energy to usual electrical energy in the form of moving electrons without direct combustion.
    - In a fuel cell the fuel and the oxidant react separately in different regions that are connected to each other by two different conduits for charged particles.
    - Fuel cells do not produce greenhouse gases in their operation or other pollutants associated with typical combustion technologies.
    - Many common fuels theoretically can be used to power fuel cells:
      - Hydrogen, methane, diesel, methanol, gasoline
      - Current fuel cell technology uses hydrogen, methanol or methane.
    - Fuel cells have now been used in commercial power generation, back-up power applications, automobiles and residential homes.

Fuel Cell Operation

Figure 7.11 shows a schematic of a fuel cell in which hydrogen (H_2) is converted to electricity using oxygen (O_2) as the oxidant and an acidic electrolyte. The essential chemical and physical processes for this cell to operate are:

1. Oxidation of gaseous $H_{2(g)}$, the fuel, at a region of the anode in interfacial contact with the electrolyte:

$$H_{2(g)} \rightarrow 2H^+ + 2\,e^- \qquad (7\text{-}15)$$

2. Physical transport of the hydrogen ion from the anode through the electrolyte to the cathode:

$$2H^+ \text{ (anode-electrolyte interface)} \rightarrow 2H^+ \text{ (electrolyte-cathode interface)} \qquad (7\text{-}16)$$

3. Reduction of gaseous O_2, the oxidant, at a region of the cathode in interfacial contact with the electrolyte:

$$\tfrac{1}{2}O_{2(g)} + 2\,e^- + 2H^+ \rightarrow H_2O \qquad (7\text{-}17)$$

4. Physical transport of electrons from the anode to the cathode through the external circuit:

$$2\,e^- \text{ (anode-electrolyte interface)} \rightarrow 2\,e^- \text{ (cathode-electrolyte interface)} \qquad (7\text{-}18)$$

Fuel Cell Technologies

Table 7.4. Summary of Common Fuel Cell Technologies

Fuel Cell	Anode Reaction	Electrolyte	Transfer Ion[a]	Cathode Reaction	Operating Conditions: Temp, °C	Operating Conditions: Pressure, atm	H_2-to-Electricity Efficiency,%
Proton Exchange Membrane (PEM)[b]	$H_2 \rightarrow 2H^+ + 2e^-$	Solid Polymer	H^+	$2H^+ + 1/2O_2 + 2e^- \rightarrow H_2O$	80–100	1–8[c]	36–38
Phosphoric Acid (PAFC)	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$	Phosphoric Acid	H+	$2H^+ + 1/2O_2 + 2e^- \rightarrow H_2O$	150–250	1–8[c]	40
Alkaline (AFC)	$H_2 \rightarrow 2H^+ + 2e^-$	Aqueous Base	OH-	$H_2O + 1/2O_2 + 2e^- \rightarrow 2OH^-$	80–250	1–10[c]	50–60+
Molten Carbonate (MCFC)	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	Molten Salt (Metal Carbonate)	CO_3^{2-}	$CO_2 + 1/2O_2 + 2e^- \rightarrow CO_3^{2-}$	600–700	1–10	50–55
Solid Oxide (SOFC)	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	Solid Ceramic Oxide	O2-	$2H^+ + 1/2O_2 + 2e^- \rightarrow H_2O$	800–1,000	1	50–55

Source: Adapted from O'Sullivan (1999).

[a]Positively charged ions (cations) travel through the electrolyte from the anode to the cathode; negatively charged ions (anions) traverse the electrolyte in the opposite direction.

[b]Also called Polymer Electrolyte Fuel Cell

[c]Pressure must be sufficiently high to prevent boiling of water in PEM or aqueous electrolytes in PAFC and AFC.

Hydrogen Fuel Cell

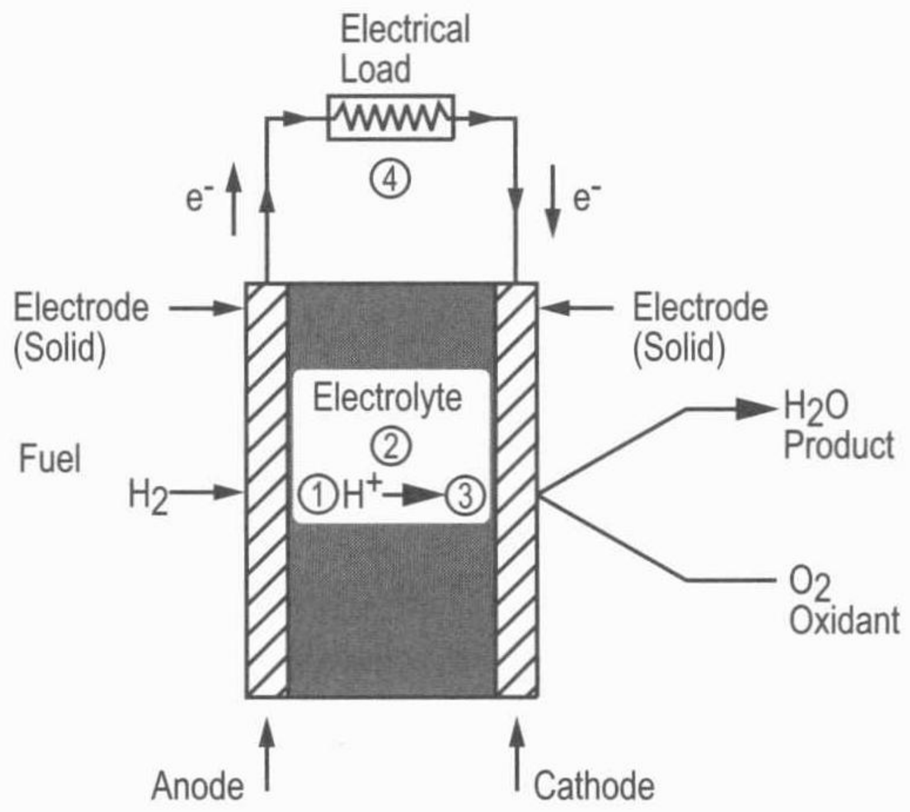


Figure 7.11. Schematic of a hydrogen-oxygen fuel cell with an acidic electrolyte and H^+ as the transfer ion. Personal communication, Sadoway; 1999.

Environmental Impacts

- Pollutant Sources
  - Products of incomplete combustion (PICs)
    - Fuel itself
    - Fuel components unchanged or modified by combustion
      - Carbon monoxide
      - Polycyclic aromatic hydrocarbons (PAHs) – naphthalene, anthracene, chrysene
      - Sulfur dioxide and nitrous oxide
      - Particulates/soot
      - Heavy metals – lead and mercury
  - Products of combustion
    - Carbon dioxide
- Carbon Management
  - Efficiency
  - Fuel switching
  - Carbon sequestration
  - Ocean fertilization

Carbon Dioxide Mitigation

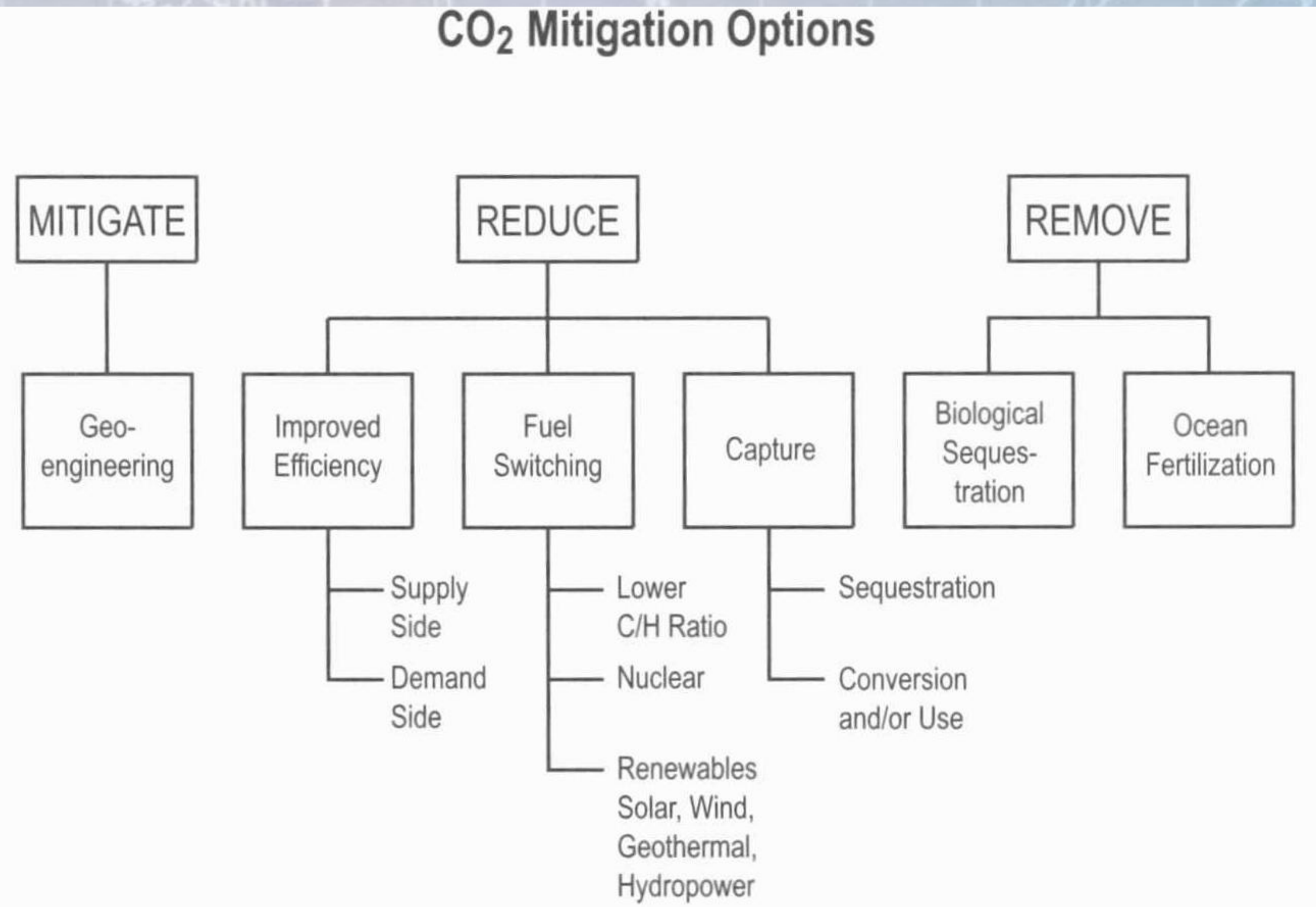


Figure 7.16. Options for mitigation of the release of fossil fuel-derived carbon dioxide to the earth's atmosphere. Source: Herzog et al., 2000.

Carbon Sequestration

Table 7.5. Estimates of the CO_2 Capacity of Various Sequestration Options

Sequestration Option	Worldwide Capacity (Order of Magnitude)
Ocean	100,000 Gt
Aquifers	10,000 Gt
Depleted Oil and Gas	1,000 Gt
Active Oil	1 Gt/yr
Utilization	0.1 Gt/yr
Coal Seams	?

Notes:
Total CO_2 emissions worldwide = 22 Gt/yr
CO_2 emissions from US power plants = 1.7 Gt/yr
Source: Herzog (2000).

Geopolitical and Social Factors

- Complex relationships have evolved between exporting and importing nations.
- Imports make up about one half of US petroleum consumption.
- Wars and international conflicts over oil is now a reality and we can expect more of the same in the future.
- Fossil fuel energy sales are a tremendous boon for governments.

Government earnings from fossil fuels

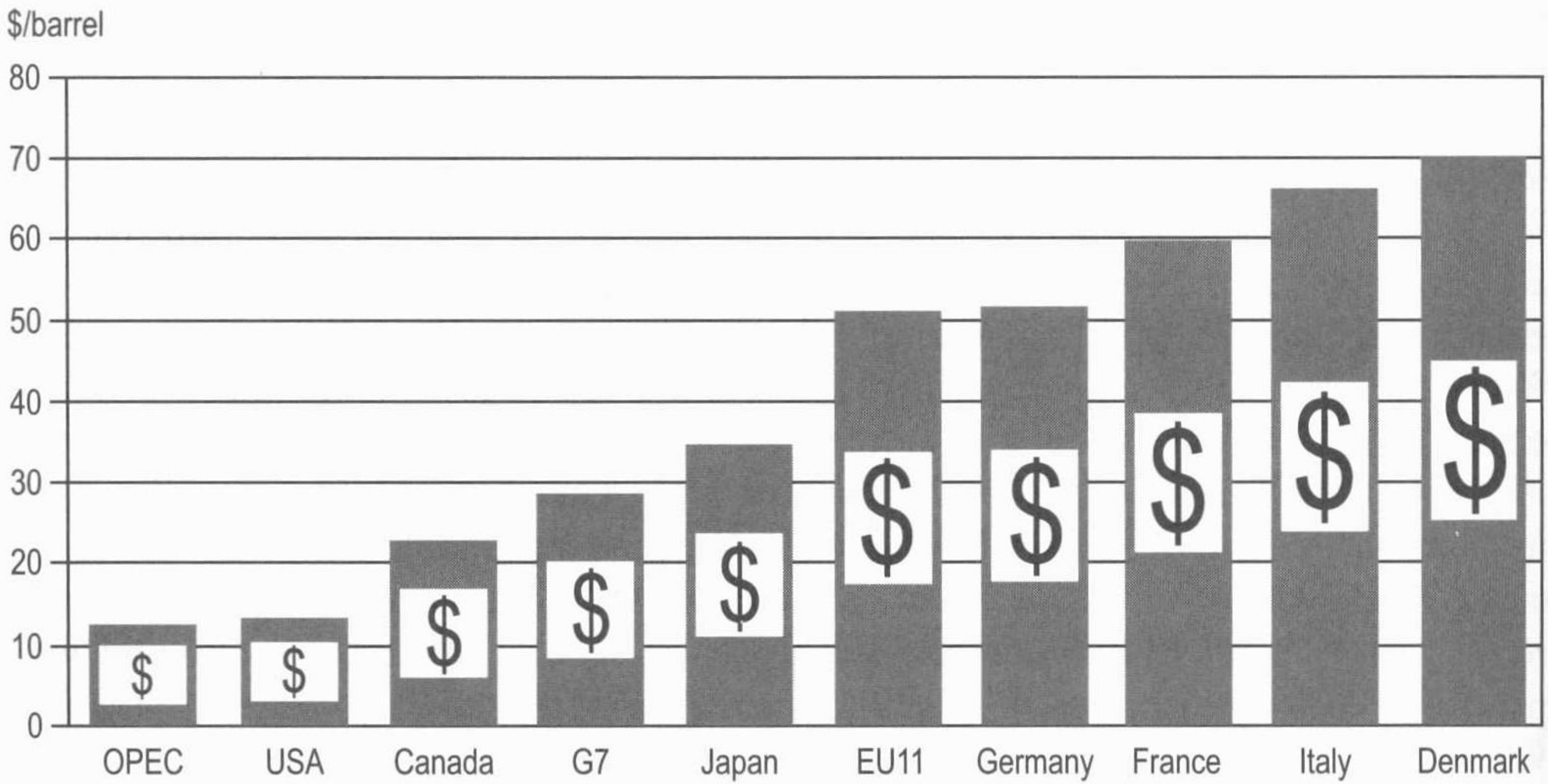


Figure 7.17. Net earning per barrel of crude oil in 1993 by OPEC and by various governments by means of fuel taxes. Source: Okogu, 1995. Reprinted with permission of OPEC.

Why are fossil fuels important to sustainable energy?

- Fossil fuels are needed to sustain economic progress now and for the foreseeable future.
- Fossil fuels must be used to enable the transition to non-fossil alternatives.
- Developing countries with fossil fuel reserves will wish to use these sources for their own development and as a source of revenue for development.
- The development of non-fossil alternatives must continue along with the improvement of existing fossil energy technologies.