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Chapter 22

Control of Carbon Dioxide

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SWJTU

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Cause and Impact of Global Climate Change (GCC)

- human activities releasing gases that trap heat in the Earth's biosphere
- the most significant problem ever faced by humankind
- the potential to lead to massive human casualties:

  significant disruptions in weather, agriculture, economy, and society， human deaths…

22.1 Introduction

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Is global warming really happening?

Scientific and empirical evidences:

Rising Global Temperatures，Melting Glaciers，Sea Level Rise，Increased Frequency of Extreme Weather，Ocean Acidification，Scientific Climate models

1. The average global temperature anomaly (AGTA)

Figure 22.1： the past 130 years.
more accurate than the average temperatures.

Track the differences between temperatures in a given year and a baseline of past average temperatures (over a baseline period of years) at the various sites around the world and average them.

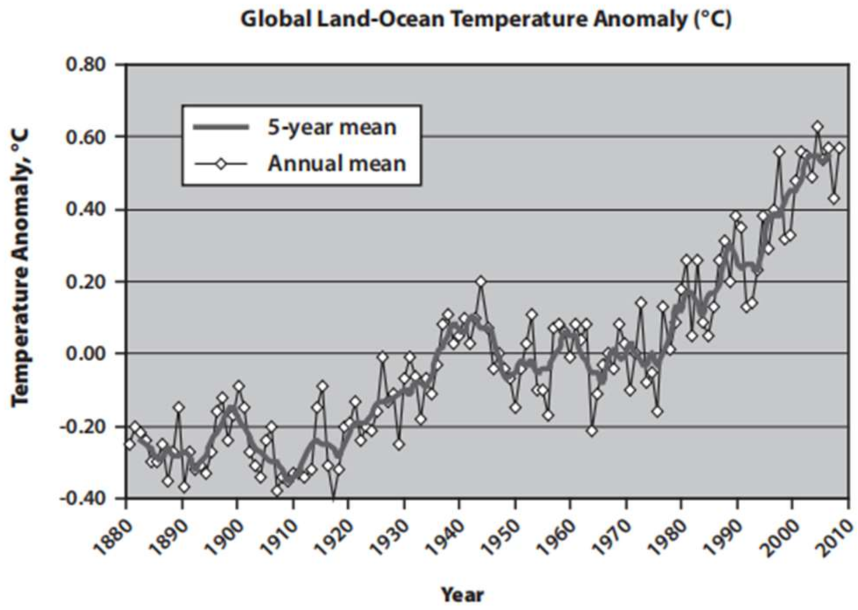

Figure 22.1
Global land and ocean temperature anomaly (°C).
(Source: http://data.giss.nasa.gov/gistemp/graphs/)

22.1 Introduction

Is global warming really happening?

2. Atmospheric CO2 concentrations

Figure 22.2: a rapid growth in the atmospheric CO2 concentration over the past 50 yrs

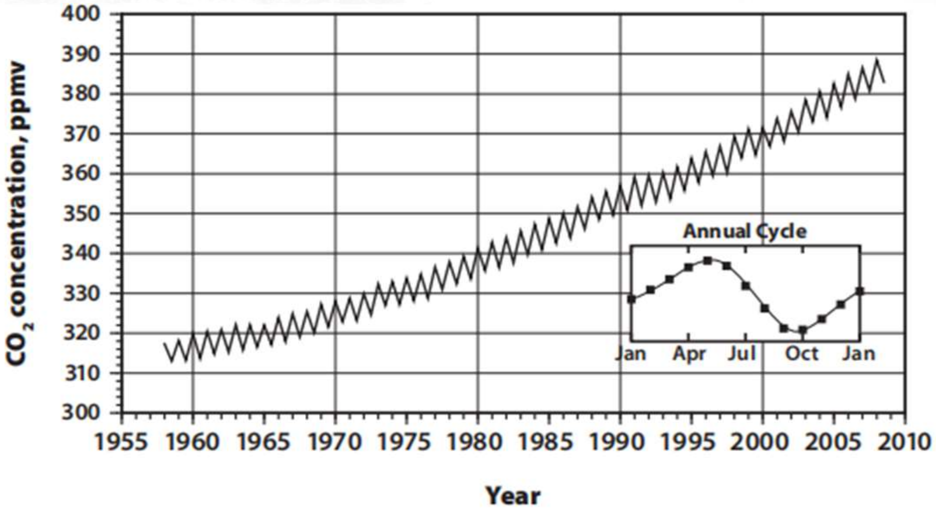

Figure 22.2
Details of the rise in atmospheric CO_2 over the past 50 years.
Note: Atmospheric concentrations of CO_2 are expressed in parts per million by volume (ppmv).
(Source: Adapted from Tans, P. "Trends in Atmospheric Carbon Dioxide." National Oceanic & Atmospheric Administration, Earth System Research Laboratory, n.d. Accessed March 2010 from http://www.esrl.noaa.gov/gmd/ccgg/trends)

22.1 Introduction

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Is global warming really happening?

(1) **a close correlation** between the

temperature anomaly

and

CO2 concentration

(2) a large and rapid change in the past century.

The existence of global warming

is widely accepted by the scientific community !

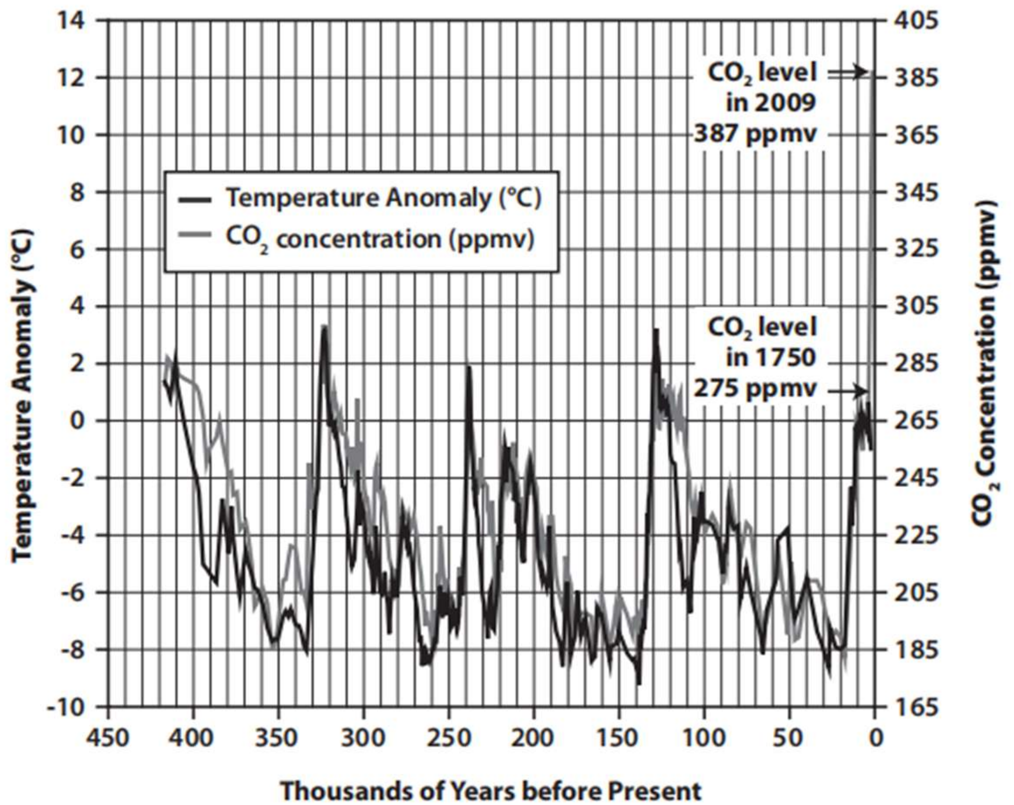

Figure 22.3
Temperature and carbon dioxide behavior from Vostok ice core data.

22.1 Introduction

Open Important questions about cause and effect of CO_2 and global temperatures

- Do increasing CO_2 concentrations follow temperatures or precede them?

  If the former, to what degree does it amplify the change?

  If atmospheric CO_2 is causing temperatures to rise, what is the lag time?
- Will temperature crashes similar to that which occurred in the past repeat in the near future?
- Will global temperatures continue to rise to unprecedented levels?

Key contributors

CO_2: most responsible for the current warming trend due to its higher emissions; **the primary concern**

CH_4, N_2O, CFCs : higher GCC potential gases (better IR absorbers)

e.g.CH_4 25 times the GCC potential than CO_2 over a 100-year time horizon

(25 tons of carbon dioxide equivalents, CO_2e)

22.1 Introduction

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Table 22.1 Atmospheric Gases that Affect Global Climate Change

Gas	Pre-industrial concentration	Current concentration	% increase in last 300 years	% contribution to the increase in warming
Carbon dioxide	280 ppm	390 ppm	37	66
Methane	700 ppb	1745 ppb	149	21
Nitrous oxide	270 ppb	314 ppb	19	6
CFCs	0	533 ppt	Infinite	7

Source: Denman et al., Intergovernmental Panel on Climate Change, 2007.

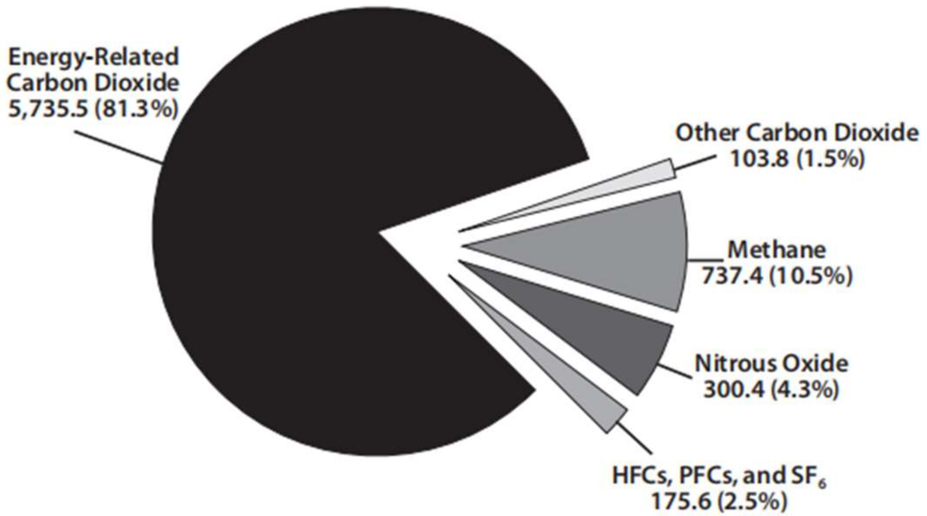

Figure 22.4
U.S. anthropogenic greenhouse gas emissions by gas, 2008 (million metric tons of carbon dioxide equivalent).
(Energy Information Administration, 2009a)

22.2 Magnitude of the CO_2 Problem

Estimation of CO_2 emission

Example 22.2

In 2008, the coal burned for electricity in the U.S. was about 1.0 billion tons. In that same year, the gasoline and diesel fuel burned in motor vehicles were 9.2 and 3.9 million barrels/day (1 barrel = 42 gal), respectively. Compare the CO_2 emitted in the United States from coal combustion for electricity with the amount emitted from motor vehicles.

Give your answers in units of Gt of carbon dioxide and Gt of carbon. For this problem, assume that coal has an average carbon content of 65%. Also, the average density of gasoline is 6.2 lbs/gal and that of diesel fuel is 7.1 lbs/gal. Furthermore, the carbon content of each of these fuels is roughly 86%.

Example 22.3

Calculate the coal burned and the CO_2 emitted today just from the new power plants that were built in China in 2007. Assume that Chinese coal has an average heat content of 7000 kcal

22.2 Magnitude of the CO2 Problem

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An overview of the magnitude of the CO2 problem in U.S

1. **GHG total emissions**
   6,343 million metric tons of CO2e in 2022， a 3.0 % decrease since 1990.

2. **Electric Power Sector**
   Used to be the largest source in the U.S
   In 2023, >80% reductions in U.S. energy-related CO2 emissions in this sector （largely due to a decrease in coal-fired electricity generation） .

3. **Transportation Sector:**
   a major contributor, 28% of total U.S. GHG emissions in 2022
   Cars, trucks, commercial aircraft, and railroads.

4. **Industrial Processes:**
   a significant source
   burning fossil fuels for energy and chemical reactions necessary for production.

5. **Residential and Commercial Sectors:**
   burning of fossil fuels for heat, use of gases for refrigeration and cooling, …

6. **Agriculture:**
   Agricultural activities, including livestock and rice production,
   contribute to methane and nitrous oxide emissions .

7. **Land Use, Land-Use Change, and Forestry**
   as a net sink for CO2 and offsetting 13% of total U.S. GHG emissions .

22.2 Magnitude of the CO2 Problem

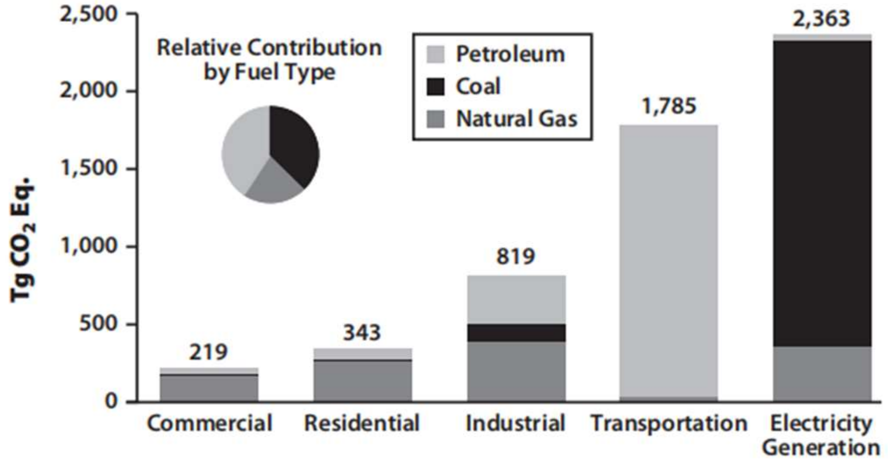


Figure 22.7
U.S. emissions of CO_2 in 2008 by energy consuming sector and fuel type.
Note: 1 teragram = 1 million metric tons.
(U.S. EPA 2010).

Table 22.3 World's Largest CO_2 Emitters (2008)

Country or Region	CO_2 Emissions, Gt/year
China	6.5
United States	5.8
European Union	4.2
Russia	1.7
India	1.5
Japan	1.2
Rest of the world	9.5
Total world	30.4

Source: EIA, "Independent Statistics and Analysis," n.d.

The U.S. has a significant historical responsibility for emissions, when considering cumulative CO2 emissions since 1751.

China's commitment and action?

China’s Dual Carbon plan

A national strategic decision: **Aiming for carbon peak by 2030 and carbon neutrality by 2060**

China‘s commitment to sustainable development and global climate action climate change

Energy Sector: reduce reliance on fossil fuels and increase the share of non-fossil energy sources, like wind and solar power.

Transportation: reduce energy consumption and emissions, promoting electric vehicles, and improving public transportation systems.

Urban and Rural Development: emphasis on green building standards , development of energy-efficient infrastructure in both urban and rural areas.

Industrial Adjustment: adopt greener production processes

Economic Transformation: economic structures, energy structures, and transportation systems to align with green, low-carbon, and circular development models.

Carbon Market: regulate and reduce GHG emissions through market mechanisms.

Public Participation: calls for public awareness and participation in low carbon life

(greener lifestyles and consumption patterns).

International Cooperation: China is committed to international cooperation on climate change

How to address the CO_2 problem?

A multi-faceted approach:

- transitioning to cleaner energy sources
- improving energy efficiency
- implementing carbon capture and storage technologies.

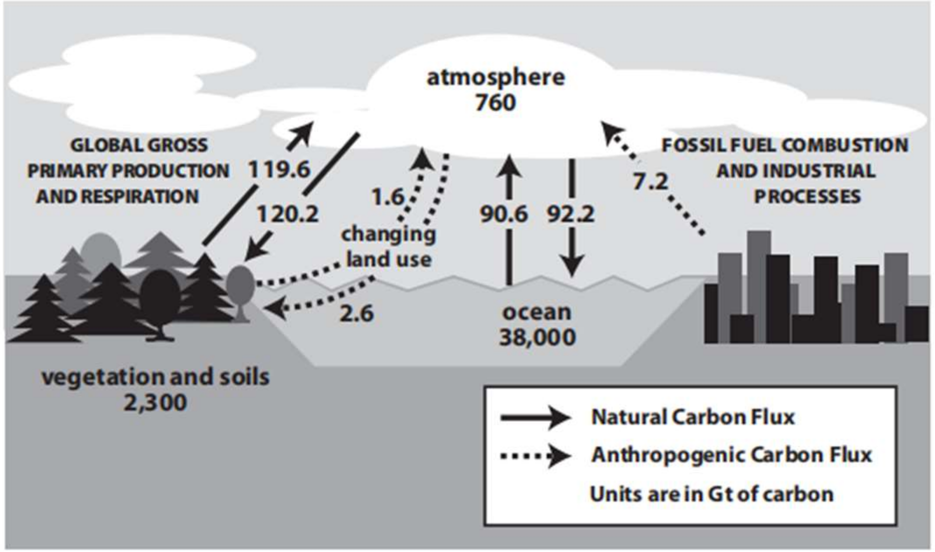


Figure 22.6
Global carbon cycle.
(Adapted from Energy Information Administration, 2008a)

Two Key concepts: Sources v.s. Sinks

Sources:

The points or activities that release GHGs into the atmosphere.

Examples:

burning fossil fuels for energy,

deforestation,

industrial processes.

Sinks:

Natural or artificial systems that absorb and store CO2 or other GHGs from the atmosphere.

Examples:

forests, oceans,

technologies like carbon capture and storage (CCS).

Sinks help to mitigate the effects of climate change by reducing the amount of GHGs in the atmosphere.

22.3 CO_2 Prevention 733

An overview of strategies for preventing CO_2 emissions:

1. **Conservation:**
2. **Alternative Fuels / Renewable Energy**:

   Shift from fossil fuels to renewable energy sources

   like solar, wind, hydro, and geothermal power to generate electricity without CO_2 emissions.
3. **Energy Efficiency Improvements**:

   Reduce the amount of energy needed in buildings, transportation, and industrial processes to use alternative energy sources.

Table 22.4 World Energy Consumption by Source, Quadrillion Btu

Energy source	2000	2002	2004	2006	2008	% of total in 2008
Oil	142.0	144.2	152.4	153.8	157.1	31.7%
Natural Gas	84.7	91.4	96.9	102.6	109.0	22.0%
Coal	93.5	96.2	110.6	121.7	132.2	26.7%
Nuclear	23.4	24.4	25.0	25.4	24.8	5.0%
Hydroelectric	24.0	23.9	25.4	27.4	28.7	5.8%
Renewables	24.8	26.4	27.2	31.2	44.0	8.9%
Total	392.5	406.5	437.6	462.0	495.8	

Sources: BP, 2009; EIA, 2009b; and others.

fossil fuels are the dominant source of the world's energy

alternative fuels (renewables) 9%.（In U.S., a smaller %）.

if hydroelectric as a conventional source,

the alternative energy sources：

wind, solar, biomass (including landfill gas), and geothermal.

the largest share：biomass—about 82% in 2007 (EIA 2007).

carbon based, puts that same amount of carbon back into the air when combusted.

but it removes carbon from the atmosphere as it grows

it essentially adds no net carbon to the atmosphere.

22.3 Efficiency Improvements 736

The overall average thermal efficiency of all the existing coal-fired power plants in the world：30– 35%.

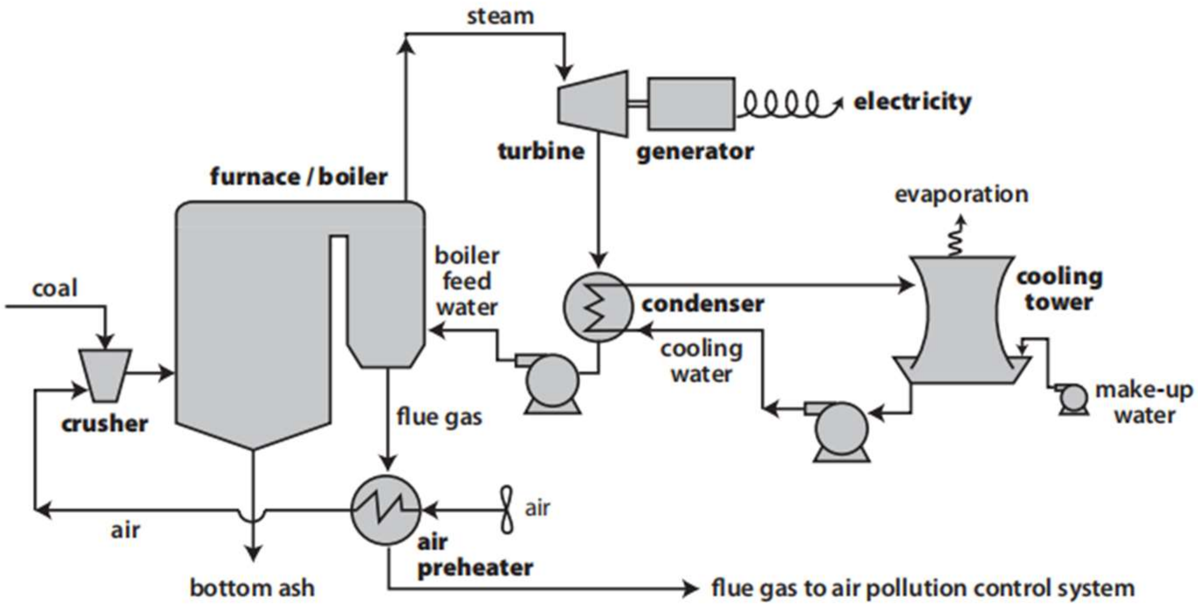


Figure 22.8
Simplified process flow diagram for a coal-fired power plant.

22.3 Efficiency Improvements 736

Example 22.4.

If the average thermal efficiency of fossil-fuel-fired power plants worldwide could be raised from about 32% to 45%, how much would that reduce CO2 emissions?

Table 22.5 Typical Operating Conditions for Three Types of Modern Coal-Fired Plants

Type of Plant	Steam Temperature °F	Steam Pressure psia	Thermal Efficiency %
Conventional	950–1,100	2,000–2,400	32–37
Supercritical (SC)	1,200–1,350	3,000–4,500	38–43
Ultra-supercritical (USC)	1,350–1,500	4,500–6,000	44–49

The real question is what kind of technology is needed to make new power plants significantly more efficient?

---A brief overview of Supercritical PC Power Plants

utilize steam at P and T beyond the critical point of water (22.12 MPa and 647.14 K),

operating at pressures typically above 22.12 MPa and temperatures above 374°C,

Higher Efficiency:

thermal efficiency : 38% to 42% v.s. subcritical plants, 33% to 38%.

Environmental Considerations:

easily incorporate advanced pollution control technologies .

reduced CO_2 emissions per unit of power;

absolute emissions still significant, CCS still necessary.

Economic Factors:

Material Challenges: the use of specialized, more expensive materials that can withstand high operating temperatures and pressures conditions,.

The higher initial investment.

Global Status:

widely adopted in many countries, China, the US, Russia.

Future Developments:

To develop advanced plants with steam temperatures of 700°C or more, which could achieve efficiencies of over 47% .

To integrate with Renewables energy

22.3 Efficiency Improvements
--A brief overview of IGCC Plants

Integrated Gasification Combined Cycle (IGCC) technology：

a type of coal-fired power generation technology,

higher efficiency； lower environmental impact than traditional ones

Process:

Coal gasified at high pressure and temperature,

producing a synthesis gas (syngas: H2 + CO), which is cleaned of impurities such as sulfur and particulates before being burned to drive a gas turbine.

The exhaust heat from the gas turbine is then used to generate steam, which drives a steam turbine to produce additional power .

22.3 Efficiency Improvements 736

Efficiency: higher, rivaling the most advanced pulverized coal plants.

Current designs, around 43%–45%

Environmental Benefits: easier CO_2 capture

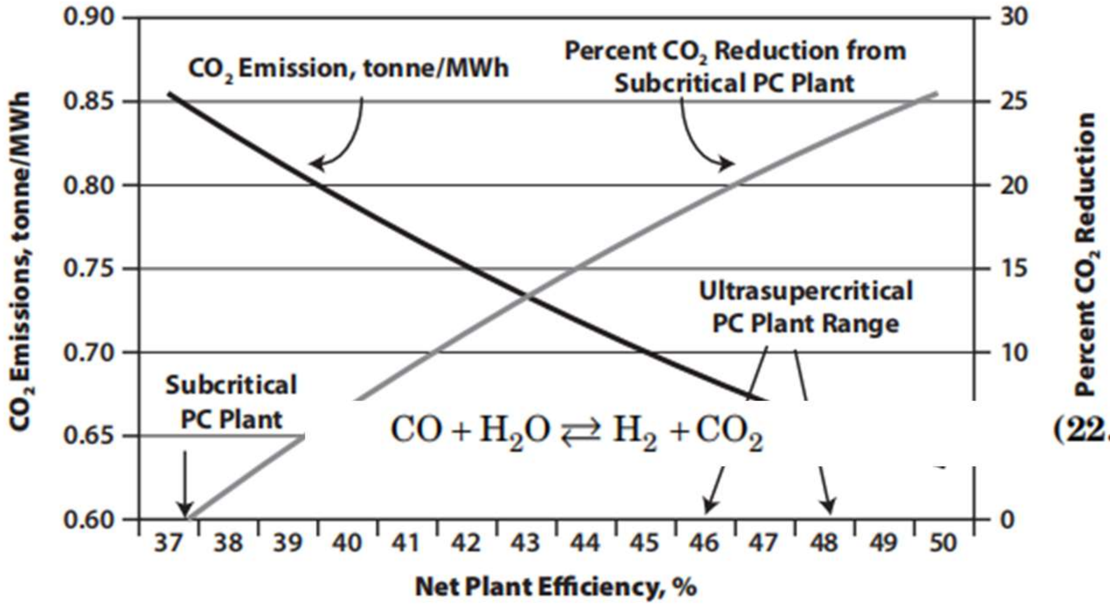
Due to a higher concentration and pressure than in a dilute exhaust stream

Economic Considerations:
higher initial capital costs,
offset by the efficiency gains and potential for CO_2 capture and utilization .

Global Status:
setbacks with closures of several plants in Europe and the US;
Interest in China and India, where coal remains a significant part of the energy mix .

Future Prospects:
closely tied to the development of gas turbine technology, advances in integration, and supporting processes

22.3 Efficiency Improvements 736



$$CO + H_2O \rightleftarrows H_2 + CO_2 \quad (22.1)$$

Figure 22.9
Effect of pulverized coal plant efficiency on CO_2 emissions.
(Booras & Holt 2004; used with permission of the Electric Power Research Institute.)

$$CO + H_2O \rightleftarrows H_2 + CO_2 \quad (22.1)$$

22.3 Oxy-fuel Combustion 741

A technology that employs pure oxygen instead of air for combustion

Principle:
separation of oxygen from air
fuel burned in nearly pure oxygen-rich environment.
Flue gas primarily composed of CO2 and water vapor,
combined with a substantial amount of recycled flue gas, high CO2 concentration.

Advantages:
Clean exhaust gas
enhancing the concentration of CO2 for easier capture and sequestration .
significantly reducing nitrogen in the flue gas

Challenges:
high energy demand of air separation units,
reduce the overall efficiency of the power plant by about 10%–12%

Research and Development:
laboratory and pilot-scale experiments worldwide.

Future Outlook:
promising for coal-fired power plants
a potential solution for carbon capture and storage in a carbon-constrained world .

22.4 CO2 Capture 742

Wet Scrubbing of CO2 742

$$2\,RNH_2 + CO_2 + H_2O \leftrightarrow (RNH_3)_2CO_3 \quad (22.2)$$

$$(RNH_3)_2CO_3 + CO_2 + H_2O \leftrightarrow 2\,RNH_3HCO_3 \quad (22.3)$$

$$2\,RNH_2 + CO_2 \leftrightarrow RNHCOONH_3R \quad (22.4)$$

Process:

spraying a liquid absorbent into the industrial exhaust gas stream.

Absorbents:

various chemicals that can selectively react with CO2, e.g. amines

The choice of absorbent affect the efficiency of CO2 capture and the ease of subsequent CO2 release for storage or use

Table 22.6 Various Amines Used for Capturing CO_2

Name of Amine	Abbreviation	Molecular formula	Molecular Weight
Monoethanolamine	MEA	$H_2NC_2H_4OH$	61.1
Diethanolamine	DEA	$HN(C_2H_4OH)_2$	105.1
Methyldiethanolamine	MDEA	$CH_3N(C_2H_4OH)_2$	119.2
Diglycolamine	DGA	$HN(C_2H_4OH)_2$	105.1
Diisopropanolamine	DIPA	$HN[(CH_3)(CH_2)CHOH]_2$	133.2

Wet Scrubbing of CO_2

Advantages:
high CO_2 capture rates .
A mature technology: relatively simple ; a variety of industrial sources.
Disadvantages:
energy-intensive ;
complex and costly in handling and disposal of absorbent and the waste streams.
Economic Considerations: significant
due to the need for large absorbent volumes and the energy required for CO_2 release and absorbent regeneration .
Future Directions:
more efficient and environmentally friendly wet scrubbing systems,
including the use of novel absorbents and integrated systems that minimize waste and energy use .

22.4 CO2 Capture 742

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Biogenic Capture by biological processes.

Bio-Integrated Carbon Capture and Utilization (BICCU),

a novel approach that integrates biological processes with chemical carbon capture methods to improve efficiency and reduce the energy required for CO_2 capture .

Research and Development:
lab-scale, early stages

Future Outlook:
a promising technology for achieving carbon neutrality, If successful

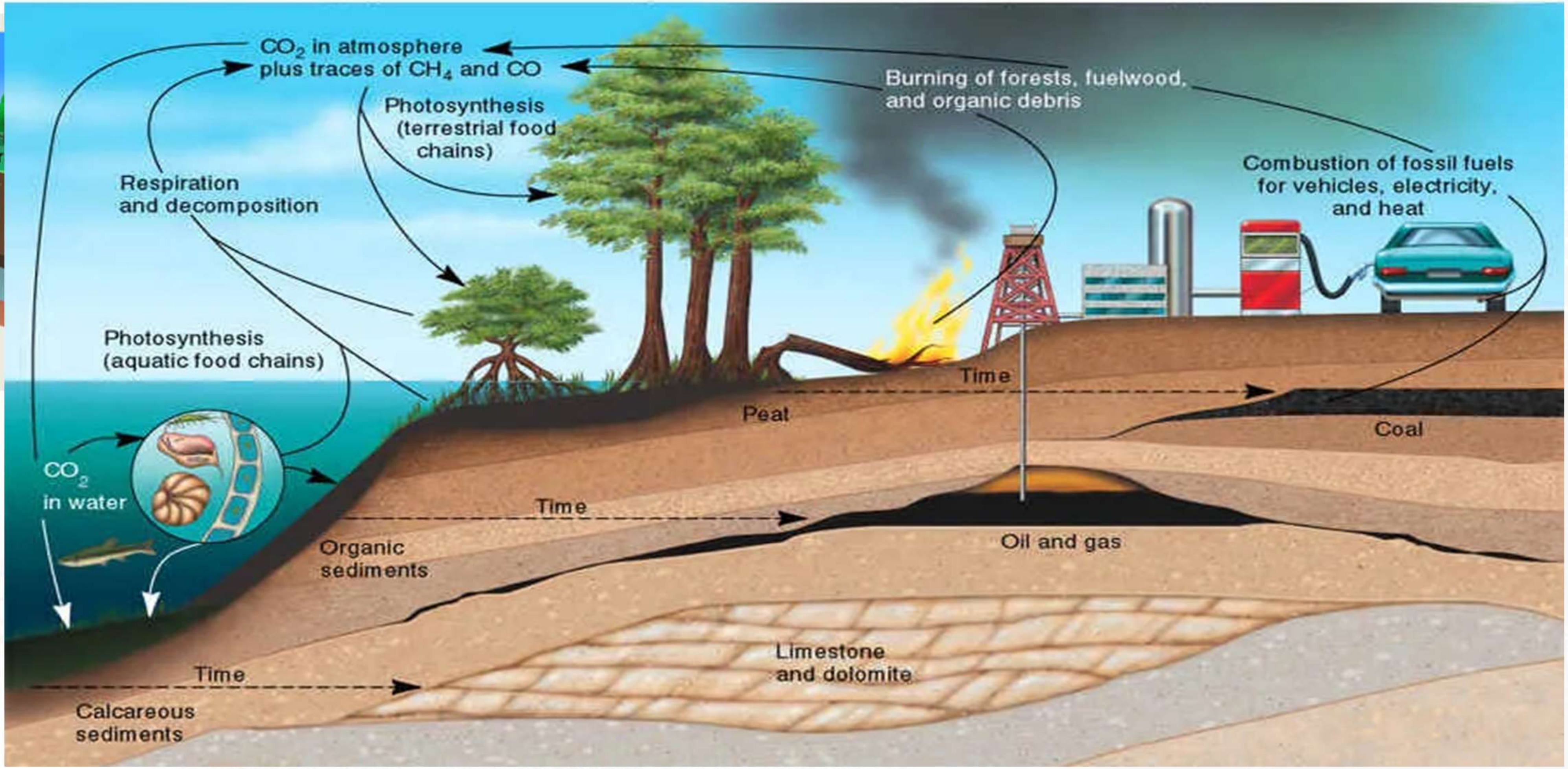
Research need to optimize the process,
To identify suitable microorganisms,
To develop biocompatible capture agents.

Table 22.7 Yields of Various Energy Crops

Energy crop	Biofuel produced	Yield of biofuel, kg/hectare-yr
Corn	Ethanol	145
Soybeans	Biodiesel	375
Rapeseed	Biodiesel	800
Palm Oil	Biodiesel	5000
Microalgae	Biodiesel	50,000–100,000*

*Note that claims of the potential yield from microalgae vary widely by source.

Source: Developed from data in Skjånes, Lindblad, and Muller, 2007, and others.


CO_2 in atmosphere
plus traces of CH_4 and CO
Photosynthesis
(terrestrial food
chains)
Burning of forests, fuelwood,
and organic debris
Respiration
and decomposition
Combustion of fossil fuels
for vehicles, electricity,
and heat
Photosynthesis
(aquatic food chains)
Time
Peat
Coal
CO_2
in water
Time
Organic
sediments
Oil and gas
Limestone
and dolomite
Time
Calcareous
sediments

22.4 Other Methods for Capturing CO_2 751

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1. **Enhanced Oil Recovery (EOR)**:
   CO_2 can be injected into depleted oil wells to enhance oil recovery.
   The CO_2 helps to extract more oil and is also stored underground.
2. **Physical Adsorption**:
   Solid sorbents like activated carbon, zeolites, and metal-organic frameworks (MOFs) ;
   CO_2 released by changing the temperature or pressure .
3. **Membrane Separation**
   semipermeable membranes.
   The efficiency depends on the membrane material and the operating conditions .
4. **Cryogenic Separation**
   by cooling the gas mixture to very low temperatures where CO_2 liquefies while other gases do not.
5. **Direct Air Capture (DAC)**:
   captures CO_2 directly from ambient air.
   an effective way to reduce atmospheric CO_2 levels, but energy-intensive due to the low concentration of CO_2 in the air
6. **Mineral Carbonation**:
   CO_2 reacting with metal oxides to form stable carbonates.
   a form of permanent CO_2 storage
   not yet widely used commercially
7. **Reforestation and Afforestation**:
   Plant more trees and protect existing forests.

Pre-knowledge: Supercritical state

CO2 transported in a supercritical state

by compressing the gas to pressures above 7.38 MPa and temperatures above 31.1°C.

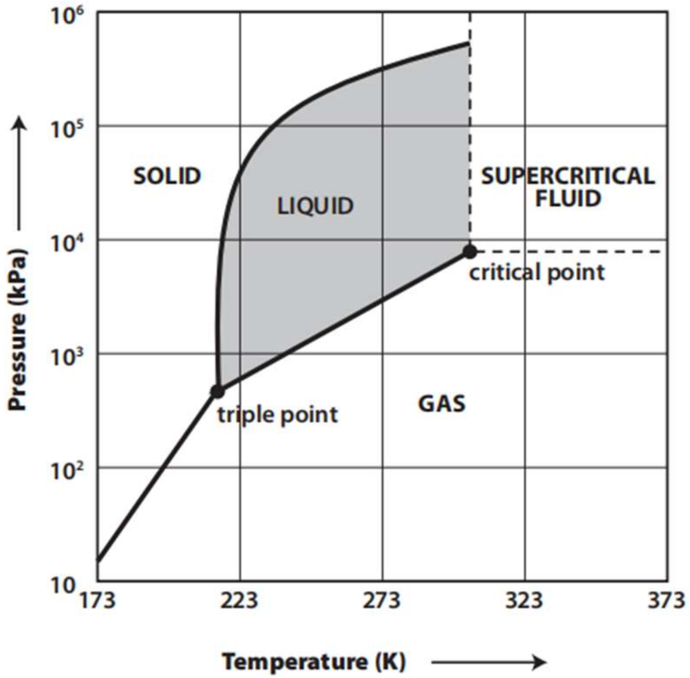

Figure 22.13
Phase diagram for CO_2.

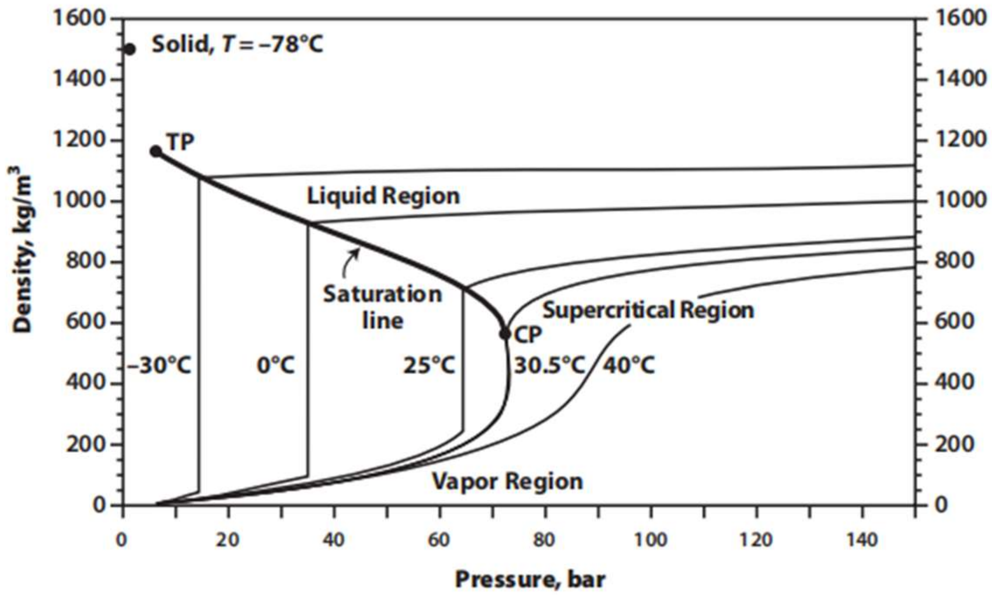

Figure 22.14
Pressure-density phase diagram for CO_2.
(Adapted from Aspelund et al. 2006)

Transportation of CO_2

After capture， 3 ways to be transported to storage sites

Ship Transport

Suitable for offshore transport, especially for distances too great for pipelines or where pipelines are not feasible.

Stored in specialized tanks designed to handle cryogenic liquids by pressurizing and cooling.

Pipeline Transport

The most common method

for long distances, especially for onshore locations.

Typically used for Enhanced Oil Recovery (EOR) .

Rail and Road Transport

not common

CO_2 in pressurized or cryogenic tanks by rail or truck.

typically used for shorter distances or to connect with other transport methods

Sequestration of CO_2

Sequestration in Geological Formations

Injecting CO_2 deep underground into geological formations such as depleted oil and gas reservoirs, saline aquifers, or unmineable coal seams.

The CO_2 is stored in these formations where it is trapped by the porous rock and sealed by an impermeable cap rock .

Sequestration in Oceans

Injecting CO_2 into the deep sea， at depths of 3000 meters or more,

Where it is expected to remain permanently sequestered .