1
Introduction

1.1
Global Energy Flow

The global demand for primary energy has grown enormously during the past decades. It is now about $5.0 \cdot 10^{20}$ J per year or 16 TW (Figure 1.1). Most of this energy is dissipated as waste heat. As the solar power reaching the Earth (insolation) is 170 000 TW, we recognize that, on a global scale, the heat dissipation caused by human activities is about 10 000 times smaller than the solar input. However, inside cities, the anthropogenic heat dissipation and the solar input can become comparable. This leads to a warmer microclimate.

1.2
Natural and Anthropogenic Greenhouse Effect

A much more severe and global problem associated with the flow of energy is the anthropogenic emission of greenhouse gases. Most important among these is carbon dioxide (CO_2) released by burning of fossil carbon (Table 1.1). The average dwell time of CO_2 in the atmosphere is about 120 years. CO_2 is a natural constituent of the atmosphere together with water vapor, the latter being the dominant greenhouse gas. These gases interact with a thermal radiation of $1.1 \cdot 10^{17}$ W or about 220 W/m^2 from the Earth (Figures 1.1 and 1.2). Their molecules either have a permanent electric dipole moment, as with H_2O, or are vibrationally excited, as in the case of CO_2 and CH_4, another greenhouse gas.

These gases thus reduce the radiative heat transfer from the Earth into space, raising the global mean temperature from -18 to $+15\,^\circ$C, a precondition for a habitable Earth. A stable mean temperature requires a balance between solar input and thermal output (Figure 1.3).

It is important to answer the question why the concentration of CO_2 is of any consequence. After all, the concentration of water vapor is about 100 times larger. Figure 1.4 shows that some of the absorption bands of CO_2 coincide with "windows" in the H_2O spectrum. Thus, a relatively small amount of CO_2 can reduce the thermal flow, that would otherwise escape into space through these windows. The effect of the other greenhouse gases on the thermal flow into space

Essentials of Energy Technology: Sources, Transport, Storage, and Conservation, First Edition.
Jochen Fricke and Walter L. Borst.

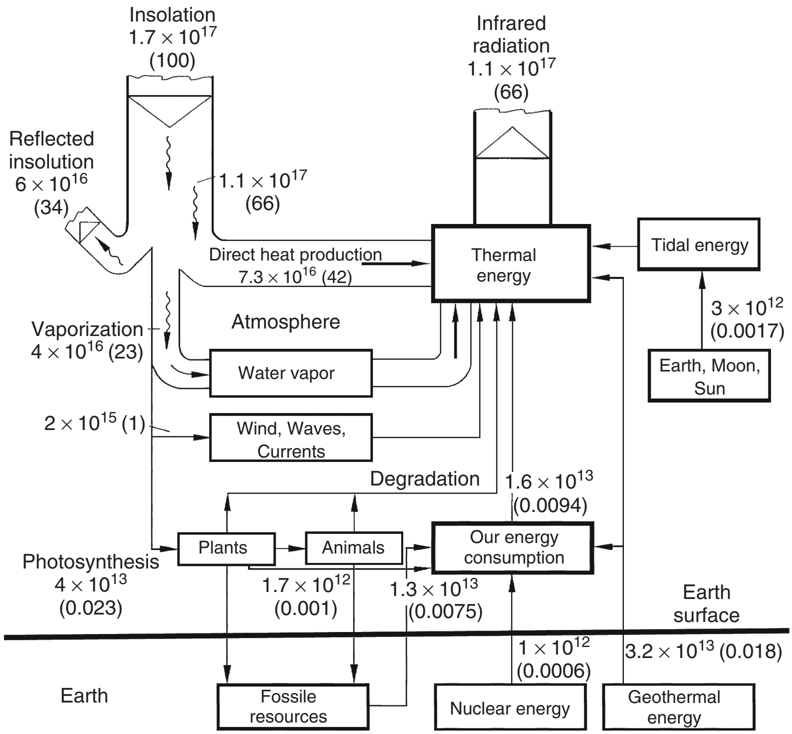

Figure 1.1 Present global energy flow in Watt. The numbers in parentheses are relative to the solar input. About 80% of our primary energy is provided by fossil fuels, about 10% by biomass, and 6% by nuclear reactors. The contributions from photovoltaics, solar thermal, wind, geothermal, and tides are not shown, as each of them still amount to <1% of the primary energy demand. (Source: Adapted from [1].)

Table 1.1 The amount of CO_2 emitted per thermal kilowatt hour depends strongly on the atomic carbon/hydrogen ratio of the fossil fuel (1 kg of C is oxidized into 3.7 kg CO_2).

Carbon source	Lignite	Anthracite	Mineral oil	Methane
kg CO_2/kWh$_{thermal}$	0.40	0.33	0.29	0.19

is characterized by the global warming potential (GWP). For example, CH_4 has a GWP $\approx$ 25, indicating that one molecule of CH_4 is 25 times more effective than one molecule of CO_2.

CO_2 and other noncondensing greenhouse gases together account for about 25% of the terrestrial greenhouse effect. Atmospheric modeling [3] shows that these gases via feedback processes provide the necessary infrared absorption to sustain the present levels of water vapor and clouds, which make up the remaining 75% of the terrestrial greenhouse effect. (Without CO_2 and the other noncondensing

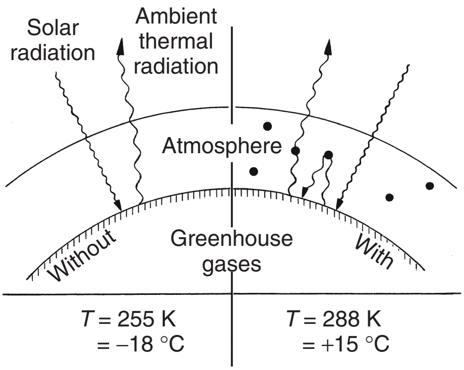

Figure 1.2 Hypothetical atmosphere of the Earth without infrared-active trace gases assumed in the left half of the figure. About two-thirds of the incoming solar radiation is absorbed at the surface of the Earth (with an albedo or reflectivity of 0.35), reemitted as thermal radiation, and completely given off into space. The resulting temperature would be about 18 °C below zero, preventing life as we know it. Greenhouse gases present in the real atmosphere are added in the right half of the figure. They absorb part of the outgoing thermal radiation and send it back to Earth. This greenhouse effect provides life-supporting temperatures of +15 °C. The most important greenhouse gas is H_2O with typically 1–2% by weight, followed by CO_2, CH_4, NO_x, and so on.

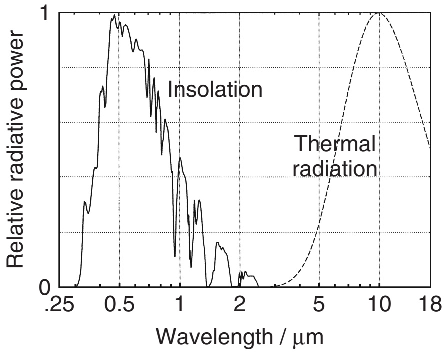

Figure 1.3 Normalized solar radiation input and thermal radiation at 300 K as a function of wavelength. The solar blackbody spectrum at 6000 K is modified by absorption in the Earth's atmosphere.

greenhouse gases, the atmospheric water vapor would condense. The terrestrial greenhouse would collapse within a few decades, sending Earth into an ice-bound state.)

In summary, the natural greenhouse effect determined the climate on the Earth in the past and supported the development of life. About 150 years of anthropogenic activities, however, accompanied by the burning of coal, oil, and natural gas, have led to a drastic increase in the concentration of greenhouse gases in the atmosphere. This is causing an additional, human-related reduction in the thermal radiation transfer to space. The imbalance, also called *radiative forcing*, is about $1\,W/m^2$

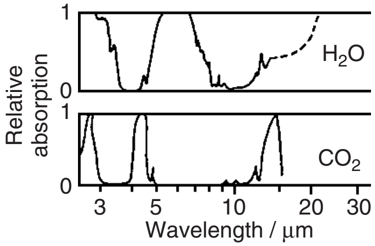

Figure 1.4 Relative spectral absorption of water vapor and carbon dioxide in the atmosphere. A value of 1 means a saturated absorption or complete opaqueness, 0 indicates a "window" for radiative escape. One sees, for example, that CO_2 drastically reduces the escape of thermal radiation in the H_2O-window of 4–5 µm. Note that the three CO_2-absorption bands shown are saturated only in their center but not in the flanks. Therefore, a further increase in CO_2 in the atmosphere can definitely enhance the greenhouse effect. (Source: Adapted from [2].)

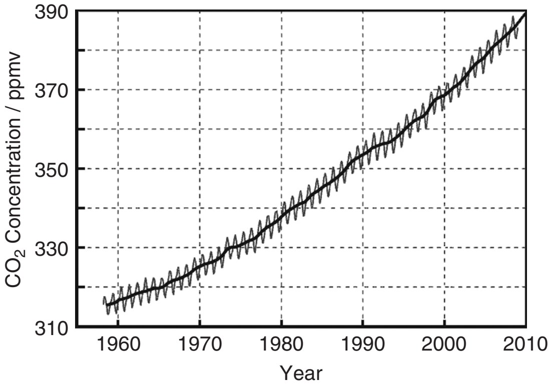

Figure 1.5 The concentration of CO_2 in the atmosphere at present is increasing by nearly two parts per million by volume per year (ppmv) and was about 390 ppmv in 2010. The oscillations on the continuous rise are about 6.5 ppmv peak-to-peak and are caused by annual variations in bioactivity and oxidation of biomass. Photosynthesis in summer causes a relative minimum in September/October, while oxidation of biomass in winter leads to a relative maximum in May. The preindustrial value was 280 ppmv. (Source: Adapted from Mauna Loa, Hawaii.)

today [4]. This is only a 0.5% contribution to the total radiative heat transfer from the Earth. Furthermore, the large thermal mass of the oceans has stored large amounts of heat. Nonetheless, a global warming of about 0.8 K since 1870 and 0.6 K since about 1960 is observed.

The main culprit for the warming of the Earth is anthropogenic CO_2. Its concentration in the atmosphere rose from a preindustrial value of 280 to about 390 ppm in the year 2010 (Figure 1.5).

In order to put the anthropogenic influence on our climate in perspective, we have to look at the history of CO_2. The CO_2 concentration during the past 400 000 years fluctuated between about 180 and 280 ppm, and never exceeded 300 ppm. A higher

CO_2 concentration was always accompanied by warmer temperatures and vice versa. The increase to 390 ppm thus is rather dramatic. The retreat of mountain glaciers and the north polar ice sheet appear to be manifestations of the problem.

Problem 1.1

A warmer atmosphere can hold more moisture [5] and thus more torrential rains can be expected. Calculate the relative increase in water vapor pressure for an atmosphere at 20 °C, assuming a temperature increase of 1 K. The exponential dependence of vapor pressure on temperature is $p(T) = p_0 \cdot \exp[-\Delta E/(k_B \cdot T)]$. (In order to find ΔE, start with the mass specific heat of vaporization, then find the molar mass of water and the number of water molecules per mole.)

We should mention here that aerosols in the atmosphere are responsible for a negative radiative forcing. Combustion caused by humans has increased the amount of atmospheric aerosols substantially. The interaction between these aerosols and solar radiation leads to a direct cooling of the atmosphere. In addition, aerosols enhance the condensation of moisture and modify the optical properties of clouds. The sign of this indirect aerosol effect – whether positive or negative – is still uncertain. A third indirect aerosol effect involves the change of biochemical cycles [6]. All three effects may have reduced global warming substantially. Anticipating future worldwide installations of scrubbing devices, much higher CO_2 mitigation costs could result than previously thought.

1.3
Limit to Atmospheric CO_2 Concentration

In order to prevent catastrophic climate changes in the future, causing, for example, a rise in sea level of several meters, the CO_2 concentration in the atmosphere will have to be limited. The actual limit is the subject of much discussion at present.

As an example, let us consider a maximum tolerable CO_2 concentration of 560 ppm, that is, twice the preindustrial value. From the known global annual use of fossil fuels and the measured CO_2 increase in the atmosphere, one can obtain the following estimate [7]: For each 4 Gt of burned carbon, the CO_2 concentration in the atmosphere increases by 1 ppm. (If about one-half of the emitted CO_2 were not absorbed in the ocean and by forests, the parts per million increase would be about twice as high). This amount of carbon corresponds to $4 \cdot (12 + 32)/12\ \text{Gt} = 14.7\ \text{Gt}$ of CO_2.

A limit of 560 ppm would "allow" an increase in CO_2 concentration of $(560 - 390)\ \text{ppm} = 170\ \text{ppm}$. This corresponds to a maximum total CO_2 emission of $170\ \text{ppm} \cdot 14.7\ \text{Gt/ppm} = 2500\ \text{Gt}$. If we assume the present annual global CO_2 emission of 35 Gt to be constant in the future, we find a time span of about 70 years for "allowed" CO_2 emissions. After that, any CO_2 emission would have to stop. If we limit the CO_2 concentration to 450 ppm, as many scientists suggest, the time span would shrink dramatically.

Problem 1.2
Calculate the remaining time span for a maximal CO_2 concentration of 450 ppm. Assume that the global CO_2 output due to human activities is kept at 35 Gt per year.

This type of estimate suggests how strongly the CO_2 emission has to be reduced in the near future. As a reduction of the anthropogenic CO_2 emission remains rather elusive, some concerned scientists have proposed geoengineering, the intentional large-scale alteration of the climate system [8]. The proposals include light shades positioned in space, ocean fertilization, aerosol injection into the stratosphere, and cloud brightening with saltwater droplets.

Considering the CO_2 problem, we find that the discussion about "peak oil production or consumption" can be misleading. The carbon limit resulting from the above CO_2 emission limit is $2500 \cdot (12/44)$ Gt $\approx$ 680 Gt. Releasing this amount would severely worsen the greenhouse problem, but this amount is small compared to the still available fossil carbon resources. It seems that we will not be able to consume these resources.

On the other hand, we note that there are no energy or electricity sources that are entirely CO_2-free. Even if a power plant emits no CO_2 during operation, this greenhouse gas is emitted during construction of the plant. Thus electricity and thermal energy even from nuclear reactors and renewable sources are not CO_2-free, but they have a low CO_2 "footprint." Perhaps in the far future, nonfossil energy systems will provide the energy needed for constructing power plants without a CO_2 footprint.

Problem 1.3
Which reactions generate heat in a coal-fired power plant and in a nuclear reactor?

1.4 Potential Remedies

A compulsory lower CO_2 production will be extremely difficult to accomplish in the next few decades if we keep in mind the magnitude of 13 TW of power produced from fossil fuels. In the following, we discuss some possible measures for reducing the emission of CO_2 in the near term:

- Energy conservation
- Rational energy production and use
- Carbon capture and storage (CCS)
- Nuclear energy
- Renewable energies.

1.4.1 Energy Conservation

A most efficient way to conserve energy is the thermal insulation of buildings. This especially applies to heating in cold climates and cooling in hot climates. Here, consumption could be reduced by a factor of 3 or more if existing houses were converted into low or ultra-low-energy houses. Many new houses in Germany are "passive houses," where the demand for heating is below 30 kWh per m^2 of living space and year. In Germany, 20 cm thick conventional fiber or foam insulation is the insulation standard for walls at the present time. In the United States, similar measures could be applied to a greater extent. Quite independent of this, much energy could be saved with more efficient and smaller cars.

Problem 1.4

A rather heavy car of mass $m = 2000$ kg stops every 0.5 km in city traffic and then accelerates again to $v = 50$ km/h. Calculate the extra number N of liters of diesel fuel (volume specific enthalpy $h = 40$ MJ/l) needed for this over a distance $\ell = 100$ km. Assume an engine efficiency of $\eta = 0.35$. If the fuel mileage of the car is 7 l per 100 km or about 34 miles per gallon (mpg) during steady highway driving, what is it during city driving? Comment on alternatives to obtain a better fuel mileage.

1.4.2
Rational Energy Production and Use

Gas-fired, combined-cycle power plants employing gas and steam turbines in combination can achieve efficiencies of 60% for the generation of electricity. Fossil energy can be converted into electricity plus useful heat with efficiencies of over 80% if the power plant is connected to a district heating system. In the near future, coal-fired power plants with steam temperatures of 700 °C and efficiencies around 50% are feasible.

Another area with a large potential for higher energy efficiency is refrigeration. Refrigerators manufactured with an innovative insulation technology, using VIPs (vacuum insulation panels) with a nearly 10-fold improved insulation capability, consume 40–60% less electricity than conventionally insulated systems.

Replacing incandescent light bulbs by compact fluorescent lamps (CFL) and light-emitting diodes (LEDs) reduces the electricity demand for lighting by about a factor of 5.

1.4.3
Carbon Capture and Storage (CCS)

The extraction of CO_2 from flue gases is being tested worldwide in pilot plants [9, 10]. The CO_2 is absorbed at low temperatures in an amine solution and desorbed at higher temperatures for compression and storage, for example, in saline aquifers. Another technique, the oxifuel process, uses oxygen for combustion instead of air. This renders an extraction unnecessary but requires the separation of nitrogen and oxygen. The attitude of "not in my backyard" characterizes the difficulties of finding suitable underground storage sites for CO_2. However, as 80% of our primary energy supply is still provided by fossil resources, carbon capture and storage (CCSs) seems a must.

1.4.4 Nuclear Energy

Worldwide, 437 nuclear reactors with a total installed power of about 390 GW were operating in 31 countries as of December 2011 [11]. They provide roughly 2600 TWh per year of base-load electricity. This corresponds to about 12% of the global annual electricity production of 22 000 TWh [12]. At present, 63 nuclear reactors with a total electric power output of 65 GW are under construction in 15 countries.

The reactors under development, so-called generation IV reactors, have improved safety features and higher efficiencies and they produce less radioactive waste than conventional reactors. For example, the European Union had been supporting a $400-million-a-year international effort to develop such reactors before the Fukushima reactor disaster [13]. The thorium high-temperature reactor (THTR) in Germany, operated in the 1980s and decommissioned in 1989, already had characteristics of a Gen IV reactor. The molten salt reactor (MSR) developed and operated in the 1960s at Oak Ridge National Laboratory in Tennessee used thorium fuel and had improved safety features compared to light water reactors, that is, a low pressure and a core that cools down and solidifies by itself.

After Fukushima, several countries have decided to phase out nuclear reactors, while others adhere to their commitment for more nuclear power. The German government announced in May 2011 that it would shut down all 17 German reactors. Italian voters opted for a non-nuclear future. On the other hand, South Korea announced plans in November 2012 to add 17 reactors to its 20 existing reactors by 2030 and to begin research and development on next-generation reactors. South Korean companies are preparing to build four reactors in the United Arab Emirates. China has 14 operating reactors and 27 reactors under construction. However, after Fukushima, it suspended approvals for new reactor construction. Vietnam, Turkey, Bangladesh, and Belarus are planning their first nuclear reactors with imports from abraod, primarily Russia. In the United States, the Nuclear Regulatory Commission granted the first construction permits for new reactors since 1978. The price tag for a new reactor is about $10 billion today compared to about $2 billion then and may pose an impediment [13].

In many countries, the commitment to nuclear power is strong. Largely unresolved is the storage or burial of the spent fuel in many parts of the world. Positive exceptions are Switzerland, Sweden, and Finland.

1.4.5 Renewable Energies

Hydroelectricity with 1000 GW installed power delivers about 3500 TWh per year or 16% of base-load electricity [12]. It has risen since 1965 at a rate of about

50 TWh/a, and has potential for further growth. In many countries, however, the growth is being slowed by environmental concerns. Base-load electricity from biomass amounts to about 400 TWh (2%). Wind energy with 240 GW installed power in 2011 provides a comparable but fluctuating output [12]. Geothermal sources with an output of 11 GW deliver 70 TWh (0.3%) of base load. Nearly 70 GW (fluctuating) from photovoltaics provided an amount of 70 TWh (0.3%) in 2011 [12]. Investments especially in wind turbines and photovoltaic and solar–thermal power plants are rising steeply today. With increasing installed power, the fluctuating electricity output of wind turbines and photovoltaic installations will pose problems for the stability of the electrical grid. Supply and demand have to be balanced on time scales ranging from seconds to months.

Energy storage facilities such as pumped water storage and electrochemical batteries are scarce. Highly dynamic power plants will have to cover the required loads in times of calm wind or overcast sky. Related to this is the search for suitable "smart grids." These are intended to switch on and off electricity-consuming devices such as refrigerators and batteries of electric cars, depending on the availability from the grid.

If one considers the long times necessary for changes to our energy system and the yet very low worldwide electricity production from renewable sources, it is difficult to assess the impact of these in the future. In the very long term, that is, a century and beyond, solar, wind, and nuclear energy are likely to dominate our electricity supply.

Problem 1.5

The delivery of electricity from hydroelectric and photovoltaic installations differs fundamentally. Please state the difference.

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Solutions

Solution 1.1 $dp/dT = p_0 \cdot \exp[-\Delta E/(k_B \cdot T)](+\Delta E/k_B \cdot T^2) = p(T) \cdot (+\Delta E/k_B \cdot T^2)$; $dp/p_0 = dT \cdot \Delta E/(k_B \cdot {T_0}^2)$. With $k_B = 1.38 \cdot 10^{-23}$ J/K, heat of vaporization of one molecule $\Delta E = 7 \cdot 10^{-20}$ J, $\Delta T = 1$ K and $T_0 = 293$ K, we obtain $dp/p_0 \approx 0.06$ or 6% for the increase in water vapor pressure.

Solution 1.2 $t(450) = (450 - 390)$ ppm $\cdot$ (14.7 Gt/ppm)/(35 Gt/a) $\approx$ 25 years.

Solution 1.3 The two heat-generating reactions are, respectively, $C + O_2 \rightarrow CO_2$ and $U_{235} + n(\text{thermal}) \rightarrow$ fission products $+ 2.3\,n(\text{fast})$.

Solution 1.4 The extra number N of liters of fuel needed in the stop-and-go traffic of city driving is $N = 2 \cdot \ell \cdot (\mathrm{m} \cdot \mathrm{v}^2/2)/(\eta \cdot h) = 2 \cdot 100 \cdot 2000 \cdot (50^2/3.6^2)/(2 \cdot 0.35 \cdot 40 \cdot 10^6)\ \mathrm{l} \approx 2.8\,\mathrm{l}$. This means a fuel consumption of 9.8 l per 100 km or 24 mpg in the city for this heavy car compared to 7 l per 100 km or 34 mpg on the highway. Comment: Driving a smaller car would save energy. Regenerative breaking with an electric motor/generator combination would save even more energy.

Solution 1.5 Hydroelectricity is base-load electricity; photovoltaics provides fluctuating electricity with capacity factors between 10 and 20%, depending on the number of sunshine hours.