1
Problems of the Energy Economy

The energy economy of nearly all and, in particular, of the industrialized countries is based on the use of stored energy, mainly fossil energy in the form of coal, oil, and natural gas, as well as nuclear energy in the form of the uranium isotope ^{235}U. Two problems arise when we use our reserves to satisfy our energy needs. A source of energy can continue only until it is depleted. Well before this time, that is, right now at the latest, we have to consider how life will continue after this source of energy is gone and we must begin to develop alternatives. Furthermore, unpleasant side effects accompany the consumption of the energy source. Materials long buried under the surface of the Earth are released and find their way into air, water, and into our food. Up to now, the disadvantages are hardly perceptible, but they will lead to difficulties for future generations. In this chapter, we estimate the size of the fossil energy resources, which, to be precise, are composed not only of fossil energy carriers but also of the oxygen in the air that burns with them. In addition, we examine the cause of the greenhouse effect, which is a practically unavoidable consequence of burning fossil fuels.

1.1
Energy Economy

The amount of chemical energy stored in fossil energy carriers is measured in energy units, some more and some less practical. The most fundamental unit is the joule, abbreviated J, which is, however, a rather small unit representing the amount of energy needed to heat 1 g of water by a quarter of a degree or the amount of energy that a hair drier with a power of 1 kW consumes in 1 ms. A more practical unit is the **k**ilo **W**att **h**our (kWh), which is 3.6×10^6 J. 1 kWh is the energy contained in 100 g of chocolate. The only problem with this unit is that it is derived from the watt, the unit for power, which is energy per time. This makes energy equal to power times time. This awkwardness leads to a lot of mistakes in the nonscience press such as kilowatt per hour for power, because most people

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mistake kilowatt to be the unit for energy, which they perceive as the more basic quantity. The energy of fossil fuels is often given in barrels of oil equivalents or in (metric) tons of coal equivalents (t coal equiv.).

The following relations apply:

$$1\,\text{kWh} = 3.6 \times 10^6\,\text{J} = 1\,\text{kWh}$$
$$1\text{ t coal equiv.} = 29 \times 10^9\,\text{J} = 8200\,\text{kWh}$$
$$1\text{ kg oil} = 1.4\,\text{kg coal equiv.} = 12.0\,\text{kWh}$$
$$1\,\text{m}^3\text{ gas} = 1.1\,\text{kg coal equiv.} = 9.0\,\text{kWh}$$
$$1\text{ barrel oil} = 195\,\text{kg coal equiv.} = 1670\,\text{kWh}$$

The consumption of chemical energy per time is an energy current (power) taken from the energy reserves. Thus, the consumption of one ton of coal per year, averaged over one year amounts to an energy current of

$$1\text{ t coal equiv./a} = 8200\text{ kWh/a} = 0.94\text{ kW}$$

We look at Germany as an example of a densely populated industrialized country. Table 1.1 shows the consumption of primary energy in Germany in the year 2002, with a population of 82.5×10^6. These figures contain a consumption of electrical energy per year of

$$570\text{ TWh/a} = 65\text{ GW} \Longrightarrow 0.79\text{ kW/person}$$

The energy consumption per capita in Germany of 5.98 kW is very high compared with the energy current of 2000 kcal/d = 100 W = 0.1 kW taken up by human beings in the form of food, representing the minimum requirement for sustaining life.

Table 1.2 shows the consumption of primary energy in the world in 2002, with a population of 6×10^9. This energy consumption is supplied from the available reserves of energy with the exception of hydro, wind, and biomass. The current remaining reserves of energy are shown in Table 1.3. This is the amount of energy that is estimated to be recoverable economically with present-day techniques at current prices. The actual reserves may be up to 10 times as large, about 10×10^{12} t coal equiv.

Table 1.1 Primary Energy Consumption in Germany in 2002.

Type	Consumption (10^6 t coal equiv./a)	Per capita consumption (kW/person)
Oil	185	2.24
Gas	107	1.30
Coal	122	1.48
Nuclear energy	62	0.75
Others	17	0.21
Total	494	5.98

Table 1.2 World Primary Energy Consumption in 2002.

Type	Consumption (10^9 t coal equiv./a)	Per capita consumption (kW/person)
Oil	4.93	0.82
Gas	3.19	0.53
Coal	3.36	0.56
Nuclear energy	0.86	0.14
Others	0.86	0.14
Total	13.2	2.19

Table 1.3 The World's Remaining Energy Reserves.

Type	Reserves in 10^9 t coal equiv.
Oil	210
Gas	170
Coal	660
Total	1040

The global energy consumption of 13.2×10^9 t coal equiv. per year appears to be very small when compared with the continuous energy current from the Sun of

$$1.7 \times 10^{17}\ \mathrm{W} = 1.5 \times 10^{18}\ \mathrm{kWh/a} = 1.8 \times 10^{14}\ \mathrm{t\ coal\ equiv./a}$$

that radiates toward the Earth.

In densely populated regions such as Germany, however, the balance is not so favorable if we restrict ourselves to the natural processes of photosynthesis for the conversion of solar energy into other useful forms of energy. The mean annual energy current that the Sun radiates onto Germany, with an area of 0.36×10^6 km^2, is about 3.6×10^{14} kWh/a = 4.3×10^{10} t coal equiv./a. Photosynthesis, when averaged over all plants, has an efficiency of about 1% and produces around 400×10^6 t coal equiv./a from the energy of the Sun. This is insufficient to cover the requirements of primary energy of 494×10^6 t coal equiv./a for Germany. What is even more important is that it also shows that over the entire area of Germany plants are not able to reproduce, by photosynthesis, the oxygen that is consumed in the combustion of gas, oil and coal. And this does not even take into consideration that the biomass produced in the process is not stored but decays, which again consumes the oxygen produced by photosynthesis. This estimate also shows that solar energy can cover the energy requirements of Germany over its area only if a substantially higher efficiency for the conversion process than that of photosynthesis can be achieved. The fact that no shortage in the supply of oxygen will result in the foreseeable future is owed to the wind, which brings oxygen from areas with lower consumption. Nevertheless, well before we run out of oxygen we will be made aware of an increase in the combustion product CO_2.

1.2
Estimate of the Maximum Reserves of Fossil Energy

For this estimate [1] we assume that neither free carbon nor free oxygen was present on the Earth before the beginning of organic life. The fact that carbon and oxygen react quickly at the high temperatures prevailing during this stage of the Earth's history, both with each other to form CO_2 and also with a number of other elements to form carbides and oxides, is a strong argument in support of this assumption. Since there are elementary metals on the surface of the Earth even today, although only in small amounts, it must be assumed that neither free carbon nor free oxygen was available to react.

The free oxygen found in the atmosphere today can therefore only be the result of photosynthesis occurring at a later time. The present-day amount of oxygen in the atmosphere thus allows us to estimate a lower limit to the size of the carbon reserves stored in the products of photosynthesis under the assumption that all oxygen produced by photosythesis is still present as free oxygen.

During photosynthesis, water and carbon dioxide combine to form carbohydrates, which build up according to the reaction

$$n \times (\mathrm{H_2O} + \mathrm{CO_2}) \Longrightarrow n \times \mathrm{CH_2O} + n \times \mathrm{O_2}$$

A typical product of photosynthesis is glucose: $C_6H_{12}O_6 \equiv 6 \times CH_2O$. For this compound and also for most other carbohydrates, the ratio of free oxygen produced by photosynthesis to carbon stored in the carbohydrates is

$$1\ \mathrm{mol\ O_2} \Longrightarrow 1\ \mathrm{mol\ C} \quad \text{or}$$

$$32\ \mathrm{g\ O_2} \Longrightarrow 12\ \mathrm{g\ \ C}$$

The mass of the stored carbon m_C can therefore be found from the mass of free oxygen m_{O_2}:

$$m_C = \frac{12}{32}\, m_{O_2}$$

The greatest proportion of the oxygen resulting from photosynthesis is found in the atmosphere and, to a lesser extent, dissolved in the water of the oceans. The fraction in the atmosphere is sufficiently large to be taken as the basis for an estimate.

From the pressure $p_E = 1\ \mathrm{bar} = 10\ \mathrm{N\,cm^{-2}}$ on the surface of the Earth resulting from the air surrounding our planet, we can calculate the mass of air from the relationship $m_{air} \times \mathrm{g} = p_E \times \text{area}$:

$$m_{air}/\text{area} = p_E/\mathrm{g} = \frac{10\ \mathrm{N\,cm^{-2}}}{10\ \mathrm{m\,s^{-2}}} = 1\ \mathrm{kg\,cm^{-2}}$$

Multiplying by the surface of the Earth gives the total mass of air

$$m_{air} = 1\ \text{kg cm}^{-2} \times 4\pi R^2_{Earth} = 5 \times 10^{15}\ \text{tons of air}$$

Since air consists of 80% N_2 and 20% O_2 (making no distinction between volume percent and weight percent), the mass of oxygen is: $m_{O_2} = 10^{15}$ t O_2. The amount of carbon produced by photosynthesis and now present in deposits on the Earth corresponding to the amount of oxygen in the atmosphere is therefore:

$$m_C = \frac{12}{32} m_{O_2} = 375 \times 10^{12}\ \text{tons of carbon}$$

There may be even more. The large deposits of iron oxide in Australia are probably the result of the reaction of iron ions with oxygen produced in the early ages of photosynthesis in shallow sea water.

Up to now 10.4×10^{12} t coal equiv. has been found.

Thus, there is reason to hope that the reserves of fossil energy will continue to grow as a result of continued exploration. In fact, in recent years the known reserves have grown continuously because more has been found than was consumed. There are rumors that very large reserves of methane hydrate can be found in moderate depths on the ocean floor. This compound dissociates into methane and water when it is heated or taken out of the ocean. The prospects of possibly large reserves, however, must not distract our attention from the urgency of restricting the mining of these reserves. If we actually use up the entire reserves of carbon for our energy requirements, we will in fact reverse the photosynthesis of millions of years and in doing so eliminate all our oxygen. Even if more than the estimated 375×10^{12} tons of carbon should exist, we cannot burn more than 375×10^{12} tons of carbon because of the limited amount of oxygen.

If we examine oil and gas consumption as an example for the consumption of fossil energy reserves over a long period of time, for example, since the birth of Christ, we obtain a frightening picture (Figure 1.1). Up to the beginning of the twentieth century, the consumption of reserves was practically negligible. From then, it has been rising exponentially and will reach a maximum value in one or two decades. Consumption will then fall off again as the reserves are gradually

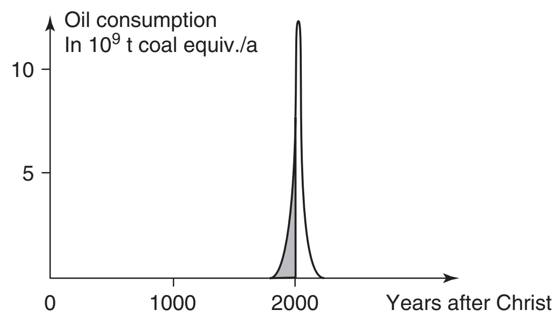

Figure 1.1 Annual consumption of oil. The area under the curve gives the estimated total oil reserves.

used up. The maximum consumption is expected when the reserves have fallen off to one half of their original levels. The reserves that have accumulated over millions of years will then literally go up in smoke over a period of only about 100 years. Here, the elimination of energy reserves is the lesser problem. Much worse will be the alteration of the atmosphere as a result of the products of combustion. These effects will last for a long time. Even if later generations change over to supplying energy from regenerative sources, they will still suffer from the heritage that we have left them.

1.3
The Greenhouse Effect

CO_2 is produced in the combustion of fossil energy carriers. The increase in the concentration of carbon dioxide in our atmosphere will have serious consequences on our climate. Currently, the atmosphere contains a fraction of 0.04% of CO_2. This corresponds to 3.5×10^{12} t of CO_2.

1.3.1
Combustion

Pure carbon is consumed according to the reaction $C + O_2 \Rightarrow CO_2$. Accordingly $12\,g\,C + 32\,g\,O_2 \Rightarrow 44\,g\,CO_2$. The mass of CO_2 produced by combustion is given by the mass of carbon consumed according to $m_{CO_2} = 44/12 m_C$. The combustion of 1 t of carbon thus results in 3.7 t of CO_2.

For different compounds of carbon other relationships apply:

- Carbohydrates:

$$30\,g\,CH_2O + 32\,g\,O_2 \Longrightarrow 18\,g\,H_2O + 44\,g\,CO_2 \tag{1.1}$$

  resulting in $m_{CO_2} = 1.47\,m_{CH_2O}$. This is the chemical reaction for the combustion of food in the human body.
- Methane (main component of natural gas):

$$16\,g\,CH_4 + 64\,g\,O_2 \Longrightarrow 36\,g\,H_2O + 44\,g\,CO_2$$

  resulting in $m_{CO_2} = 2.75\,m_{CH_4}$.

The present global consumption of the 10^{10} t coal equiv./a produces globally $\Rightarrow 2.2 \times 10^{10}$ t of CO_2 per year. Half of this is dissolved in the water of the oceans and half remains in the atmosphere. If the annual energy consumption does *not* continue to rise, the amount of CO_2 in the atmosphere will double only after about 200 years. However, it is necessary to take into account that energy consumption continues to increase. Currently the growth of 1% per year is relatively low. In the developing countries, energy consumption even decreased in 1999, because of the inability of these countries to pay for more energy. If global energy consumption continues to increase at about 1% per year the CO_2 concentration in the atmosphere will have doubled after about 100 years. This increase is less the result of a per capita increase in energy consumption than that of the increasing global population. The increasing CO_2 concentration in the atmosphere will have consequences on the temperature of the Earth.

1.3.2 The Temperature of the Earth

The temperature of the Earth is stationary, i.e. constant in time if the energy current absorbed from the Sun and the energy current emitted by the Earth are in balance. We want to estimate the temperature of the Earth in this steady state condition. For this purpose we make use of radiation laws, not derived until the following chapter.

The energy current density from the Sun at the position of the Earth (but outside the Earth's atmosphere) is

$$j_{E,\mathrm{Sun}} = 1.3\,\mathrm{kW\,m^{-2}}$$

For the case of complete absorption, the energy current absorbed by the entire Earth is the energy current incident on the projected area of the Earth:

$$I_{E,\mathrm{abs}} = \pi R_\mathrm{e}^2 j_{E,\mathrm{Sun}} \quad \text{with} \quad R_\mathrm{e} = 6370\,\mathrm{km} \quad \text{(radius of the Earth)}$$

According to the Stefan–Boltzmann radiation law, the energy current density emitted by the Earth into space is given by

$$j_{E,\,\mathrm{Earth}} = \sigma T_\mathrm{e}^4 \quad \text{where} \quad \sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}K^{-4}}$$

is the Stefan-Boltzmann constant. The energy current emitted by the entire Earth is

$$I_{E,\mathrm{emit}} = 4\pi R_\mathrm{e}^2 \sigma T_\mathrm{e}^4$$

From the steady state condition $I_{E,\,\mathrm{abs}} = I_{E,\,\mathrm{emit}}$, it follows that the estimated mean temperature of the Earth is $T_\mathrm{e} = 275\,\mathrm{K}$.

The mean temperature of the Earth is in fact around 288 K. The approximate agreement is, however, only coincidental. Taking into account that about 30% of the incident solar radiation is reflected back into space by the atmosphere of the Earth and thus only about 70% ($1\,\mathrm{kW\,m^{-2}}$) reaches the surface of the Earth, a temperature of 258 K then results. The actual temperature of the Earth is in fact greater, because the radiation emitted by the Earth is partly absorbed in the atmosphere. The atmosphere then becomes warmer and emits heat back to the Earth. The same effect occurs in greenhouses, where the glass covering absorbs the thermal radiation emitted from within the greenhouse and emits some of it back into the greenhouse.

We can understand the greenhouse effect of the atmosphere using a simple model. Owing to a temperature of 6000 K of the Sun, the solar radiation spectrum (expressed as energy current per wavelength) has a maximum at a wavelength of about 0.5 μm, at which the atmosphere is transparent. As a result of the lower temperature of the Earth, the emission from the Earth has its maximum at a wavelength of about 10 μm (in the infrared region). All triatomic molecules, including CO_2, are good absorbers in the infrared region. Consequently, while most of the incident solar radiation reaches the surface of the Earth, a great part of the energy emitted from the surface is absorbed in the atmosphere. This causes warming of the atmosphere, which in turn leads to heat emission back to the Earth. The temperature of the Earth is at maximum when the radiation from the surface of the Earth is completely absorbed by the atmosphere, a situation that will be faced if the atmospheric concentration of CO_2 continues to rise.

In our model, we assume that the Earth's surface absorbs all radiation incident upon it from the Sun and the atmosphere. In the steady state, it must also emit the same energy current. All energy emitted in the infrared region is assumed to be absorbed by the atmosphere. This leads to the condition of Figure 1.2:

$$I_{E,\,\mathrm{Earth}} = I_{E,\,\mathrm{Sun}} + \tfrac{1}{2} I_{E,\,\mathrm{atm}}$$

Since radiation emitted by the Earth's surface is fully absorbed by the atmosphere, the solar energy current incident on the surface of the Earth can only be emitted into space by emission from the atmosphere. This leads to the following conditions:

$$\tfrac{1}{2} I_{E,\,\mathrm{atm}} = I_{E,\,\mathrm{Sun}} \quad \text{and} \quad I_{E,\,\mathrm{Earth}} = 2 I_{E,\,\mathrm{Sun}}$$

It then follows that

$$I_{E,\,\mathrm{Earth}} = 4\pi R_\mathrm{e}^2 \sigma T^4_{\mathrm{e,\,greenhouse}} = 2\pi R_\mathrm{e}^2 \times 1.3\ \mathrm{kW\ m^{-2}}$$

This yields a temperature of

$$T_{\mathrm{e,\,greenhouse}} = \sqrt[4]{2}\ T_\mathrm{e} = 1.19 \times 275\ \mathrm{K} = 327\ \mathrm{K} = 54\ ^\circ\mathrm{C}$$

With this mean temperature, the Earth would be virtually uninhabitable.

What makes the problem of the increased absorption of infrared radiation in the atmosphere due to human influences even worse is that only one half of the present greenhouse effect is caused by the increasing CO_2 concentration. The other half results from methane, fluorinated hydrocarbons, and nitrogen oxides.

To estimate the greenhouse effect, we have treated the atmosphere as a fire screen, allowing the solar radiation to pass through but absorbing the radiation from the Earth. In view of the fact that the temperature of the atmosphere is not

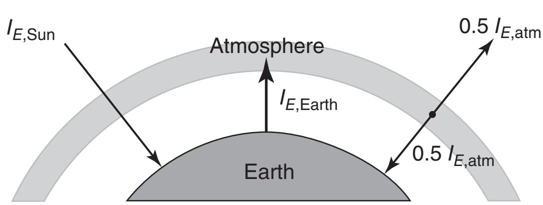

Figure 1.2 Balance of the absorbed and emitted energy currents on the surface of the Earth.

uniform, a better description would be in the form of several fire screens placed behind each other. Extending the fire-screen model to n fire screens, the temperature of the Earth's surface becomes

$$T_{\text{e, greenhouse}} = T_{\text{e}}\sqrt[4]{n+1}$$

For large values of n, the temperature of the Earth could become arbitrarily large and, in particular, even greater than the temperature of the Sun. This result is of course not correct, because at such high temperatures an essential condition of the model is no longer satisfied. If the temperature of the Earth were equal to that of the Sun, the spectrum emitted from the Earth would be identical with the solar spectrum. It would then no longer be possible for the solar radiation to pass through the atmosphere, while the radiation emitted from the Earth would be absorbed, as assumed for the fire-screen model.

As long as the requirements are satisfied, with more than one fire screen a higher temperature results. The conditions prevailing on Venus clearly show this. The distance of Venus from the Sun is 0.723 times the distance of the Earth from the Sun. The energy current density of the solar radiation at the position of Venus is therefore twice that reaching the Earth. The atmosphere of Venus is composed almost entirely of CO_2. Treating the atmosphere of Venus as a single fire screen yields a temperature of 116 °C for Venus, a factor of $\sqrt[4]{2}$ greater than that of the Earth. The actual temperature of Venus is, however, 475 °C.

The number of fire screens required to describe the atmosphere depends on the mean free path of the emitted radiation after which it is absorbed in the atmosphere. This determines the spacing of the fire screens in the model. Because of the high density of Venus' atmosphere, with a pressure of 90 bar, this mean free path is much shorter on Venus than on Earth.

Fortunately, we do not have to worry about temperatures on the Earth reaching those found on Venus. Even if the entire supply of oxygen on the Earth were consumed, resulting in a CO_2 pressure of about 0.2 bar, the temperature of the Earth could never reach the temperature of Venus. Nevertheless, serious alterations are already occurring even with much lower temperature increases, which are not only possible but in fact very probable on Earth. We also have to consider that there are numerous feedback effects. The most dangerous would be the release of large quantities of methane, an even more effective greenhouse gas than CO_2, when methane hydrate melts in a warmer ocean.

1.4 Problems

1.1 Describe in a few sentences the greenhouse effect
- **(a)** in a greenhouse for crops
- **(b)** in the Earth's atmosphere.

1.2 Why does burning methane lead to a higher greenhouse activity than burning (the same mass of) carbohydrates?

1.3 How long may a computer (50 W) be operated with an amount of energy of 1 kg of coal equiv.?

1.4 Assume the global human energy consumption to be 15×10^9 t coal equiv./a by now and the Earth's remaining consumable energy reserves to be 2×10^{12} t coal equiv. How long will these reserves last with the energy consumption

(a) increasing linearly, doubling in 35 years?

(b) increasing exponentially, doubling in 40 years?

1.5 Calculate the amount of methane present on Earth if all the oxygen in the atmosphere would have resulted from the production of methane from CO_2. Consider a total mass of oxygen of $m_{O_2} = 10^{15}$ t.

1.6 Why has Venus such a high surface temperature? Venus is the brightest object in the sky (except for the Sun and Moon) due to its high reflectance. This so-called albedo of Venus is $r_V = 0.7$. Calculate the intensity reaching the surface of Venus. Knowing the intensity and the surface temperature (475 °C), determine the number of fire screens according to the model in Section 1.3.2.