1 Introduction

Physical science is a fascinating subject. Mechanics, quantum physics, electrodynamics, to name a few, present a coherent picture of physical reality. The present book aims at inspiring students with the enthusiasm the authors experienced while working in the field.

The work of the physical scientist always takes place in a social context. Ultimately, the scientist has to contribute to society, sometimes by increasing our knowledge of fundamental processes, more often by employing his or her skills in industry, a hospital, a consultancy firm or teaching. In the majority of cases the scientist contributes by tackling societal problems with a physics aspect or by educating students in understanding the strengths and limitations of the physics approach.

The text *Environmental Physics* focuses on two problems where physical scientists can contribute to make them manageable. The first is the need for a safe and clean supply of energy now and in the future, the second is the way to deal with the forecasted climate change. The major part of the text deals particularly with the physics aspects of these two problems. A brief discussion of the social context is given below with a section on the contribution of science. Science can point out the physical consequences of political choices, or of not making choices, but the decisions themselves should be taken through the political process. A more comprehensive discussion of the societal context is given in the last chapter of this book.

1.1 A Sustainable Energy Supply

The concept 'sustainable development' became well known by the work of the World Commission on Environment and Development, acting by order of the General Assembly of the United Nations. In 1987 it defined sustainable development as ([1], p. 8):

> Meeting the needs of the present generations without compromising the ability of future generations to meet their own needs.

Environmental Physics: Sustainable Energy and Climate Change, Third Edition. Egbert Boeker and Rienk van Grondelle.

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This is not a physics definition, as the meaning of 'needs' is rather vague. Does it imply an expensive car, a motorboat and a private plane for everybody? The definition leaves this open. In the political arena the precise meaning of 'needs' is still to be decided. Still, the concept forces one to take into account the needs of future generations and rejects squandering our resources. Indeed, sustainable development, the World Commission emphasized, implies that we should be careful with natural resources and protect the natural environment.

Since 1987 many governments have put the goal of a 'sustainable society' in their policy statements. Besides protection of the environment and a safe energy supply it then comprises objectives like good governance, social coherence, a reasonable standard of living. In this book we focus on a sustainable energy supply and adapt the 1987 definition as follows:

> A sustainable energy supply will meet the energy needs of the present generations without compromising the ability of future generations to meet their own energy needs. The environmental consequences of energy conversion should be such that present and future generations are able to cope.

Like with the previous definition the precise meaning of this statement is the subject of political debate. From a physics point of view one may make the following comments:

1. An energy supply based on fossil fuels is not sustainable. The resources of coal, oil and gas are limited, as will be illustrated in Chapter 9. So in time other energy sources will be required. In the meantime the environmental consequences of fossil fuel combustion should be controlled.
2. Renewable energy sources like solar energy, wind energy or bio fuels may be sustainable. Their ultimate source, solar irradiation, is inexhaustible on a human time scale. To be sure of the sustainability of renewable energy sources, one has to perform a life-cycle analysis: analyse the use of energy and materials of the equipment and their environmental consequences from cradle to grave. This book will provide building blocks for such an analysis.
3. It is under debate whether nuclear fission power is sustainable. The resources of ^{235}U, the main nuclear fuel, are large, but limited. Also, during the fission process many radioactive materials are produced. Proponents of nuclear power argue that most of these 'waste' materials may be used again as fuel and the remainder may be stored; in practice, it is claimed, nuclear fission power would be 'virtually sustainable'. Power from nuclear fusion may be sustainable, but its commercial exploitation is still far off.

Governments all over the world are stimulating renewable energies. Not only because of their sustainability. Another strong reason is the security of energy supply. This requires diversification of energy sources. Fossil fuels, especially oil and gas, are unevenly distributed over the world. Industrial countries do not want to be too much dependent on the willingness of other countries to supply them with oil and gas. One may put forward that solar irradiation is unevenly distributed as well, but even at moderate latitudes the irradiation is substantial and the wind blows everywhere.

Apart from these considerations, the combustion of fossil fuels produces CO_2, which has climatic consequences, to be discussed in the next section.

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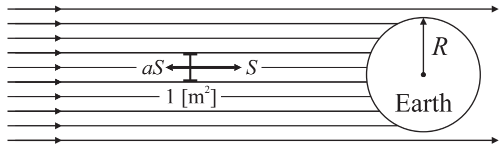

Figure 1.1 *Solar radiation is entering the atmosphere from the left, S [Wm^{-2}]. A fraction a, called the albedo, is reflected back.*

1.2 The Greenhouse Effect and Climate Change

In the simplest calculation the temperature of the earth is determined by the solar radiation coming in and the infrared (IR) radiation leaving the earth, or

$$\textit{energy in} = \textit{energy out} \tag{1.1}$$

The amount of radiation entering the atmosphere per [m^2] perpendicular to the radiation is called S, the *total solar irradiance* or *solar constant* in units [Wm^{-2}] = [J s^{-1} m^{-2}]. Looking at the earth from outer space it appears that a fraction a, called the *albedo*, is reflected back. As illustrated in Figure 1.1, an amount $(1-a)S$ penetrates down to the surface. With earth radius R the left of Eq. (1.1) reads $(1-a)S\pi R^2$.

In order to make an estimate of the right-hand side of Eq. (1.1) we approximate the earth as a *black body* with temperature T. A black body is a hypothetical body, which absorbs all incoming radiation, acquires a certain temperature T and emits its radiation according to simple laws, to be discussed in Chapter 2. At present the student should accept that according to Stefan–Boltzmann's law a black body produces outgoing radiation with intensity σT^4 [Wm^{-2}]. The total outgoing radiation from the earth then becomes $\sigma T^4 \times 4\pi R^2$. Substitution in Eq. (1.1) gives:

$$(1-a)S \times \pi R^2 = \sigma T^4 \times 4\pi R^2 \tag{1.2}$$

or

$$(1-a)\frac{S}{4} = \sigma T^4 \tag{1.3}$$

Numerical values of σ, R and S are given in Appendix A. For albedo a one finds from experiments $a = 0.30$. Substitution gives $T = 255$ [K], which is way below the true average earth surface temperature of 15 [°C] = 288 [K]. The difference of 33 [°C] is due to the *greenhouse effect*, for which the earth's atmosphere is responsible.

As will be shown later, the emission spectrum of the sun peaks at a wavelength of 0.5 [μm], whereas the earth's emission spectrum peaks at 10 [μm], the far IR. Several gases in our atmosphere, the so-called greenhouse gases, absorb strongly in the IR. In that way a large part of the solar radiation reaches the surface, but the emitted IR radiation has difficulty in escaping. The same effect happens in a greenhouse, hence the name.

It will be discussed later how human activities contribute to the greenhouse effect by increasing the concentration of greenhouse gases like CO_2, tropospheric O_3, N_2O, CH_4 and many HFCs. The increase of their concentrations necessarily leads to an increase in the surface temperature of the earth and consequently to climate change. It will be a challenge

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to science, technology and policy to find ways to slow down the increase in greenhouse gas concentration.

Example 1.1: Geothermal Heat Flow

As an illustration of the physics of this section, consider the heat flow F from the interior of the earth reaching the earth's surface. This flow originates from decay of radioactive elements in the earth interior and the friction between the tectonic plates caused by their 'tidal motion'. The flow is estimated[1] as $F \approx 42 \times 10^{12}$ [W]. What is the flow per [m^2]? Assume the solar influx would not be present. Calculate the equilibrium surface temperature of the earth arising from the internal heat flow only.

Answer

The heat flow per [m^2] is found with $F/(4\pi R^2)$, where R is the radius of the earth. With the data from Appendix A we find that this becomes 0.082 [Wm^{-2}]. If there is no solar input the internal flow is the only source. In a steady-state situation the inflow from the interior equals the outflow at temperature T: *energy in* = *energy out*. Following Stefan–Boltzmann's law we have $F/(4\pi R^2) = \sigma T^4$, which gives $T = 35$ [K]. So, without the influx of solar energy the temperature of the earth's surface would be down to a value about 35 [K]. Therefore, as we know well, the present, pleasant temperature on earth is due to the sun.

1.3 Light Absorption in Nature as a Source of Energy

The sun also provides energy for plants, algae and so-called cyanobacteria by photosynthesis, a mechanism, which will be discussed extensively in Sections 5.4 to 5.7. Figure 1.2 shows the solar absorption by the important pigments of several photosynthetic organisms. All the light energy absorbed by the pigments can be used for photosynthesis. For comparison the solar spectrum as it enters the top of the atmosphere is shown. At the earth's surface it is more structured (as we will find in Figure 2.2), but the message remains that the pigments shown absorb in important parts of the spectrum.

Chlorophyll-*a*, the major pigment of higher plants, algae and cyanobacteria, absorbs red and blue light. In combination with carotenoids such as β-carotene they provide plants with their typical green colour.

The major photosynthetic organisms of the world oceans, the cyanobacteria (often called blue-green algae), absorb sunlight by a specialized protein which is called phycobilisome and contains as major pigments phycoerythrin (absorbing around 580 [nm]), phycocyanin (absorbing around 620 [nm]) and allophycocyanin (absorbing around 650 [nm]).

As is shown in the picture bacteriochlorophyll-*a* and bacteriochlorophyll-*b* are the major pigments of two classes of photosynthetic bacteria absorbing in the near IR part of the solar spectrum.

[1] In this book data without a reference are taken from refs. [2] and [3], in this case from [2], p. 92.

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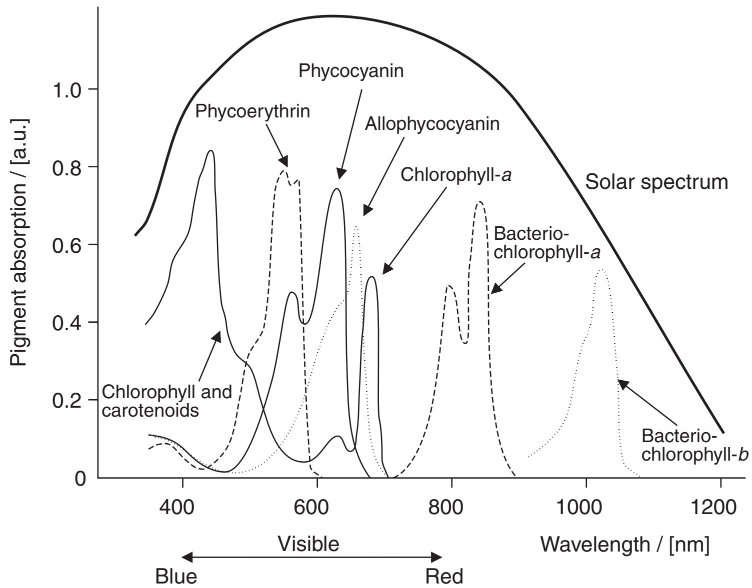

Figure 1.2 *Light absorption by important pigments of a variety of photosynthetic organisms in arbitrary units (a.u.) as a function of wavelength. For comparison the solar spectrum is sketched, adapted to the same scale.*

1.4 The Contribution of Science: Understanding, Modelling and Monitoring

The first question for a physical scientist is always, 'Why are things as they are?' For example, why is the surface temperature on earth 33 [K] higher than calculated by means of Eq. (1.3). Understanding starts in this case by indicating the role of the earth's atmosphere and the greenhouse effect. Then one has to proceed and understand the 33 [K] quantitatively. In Chapter 3 we show that an analysis of the composition of the atmosphere and the radiative properties of the atmosphere and the surface allow us to give a quantitative explanation.

A second question would be how the greenhouse effect is influenced by human activities. Here one needs a model to project these activities into the future, calculate emission of gases and other factors influencing climate, and finally calculate the future greenhouse effect. One has to check how the greenhouse gases behave over time and therefore one has to monitor their concentrations continuously. Comparisons of predictions with reality will increase our understanding of climate and climate change.

One will find this continuous loop of understanding, modelling, monitoring and increased understanding in many parts of science, if not all. In order to increase the production of bio fuels from crops or algae, for example, one needs to increase the efficiency of photosynthesis. Again the first step is to understand the process (Sections 5.4 and 5.5). The next step is to construct a model which reproduces the real situation with parameters that may be changed by human interference. The third step is to make a pilot with parameters which are supposed to increase the bio-yield of the crop, monitor all external influences and check the results against the model. This, in fact, is the way in which technology works.

A realistic model needs to take into account many variables in a consistent and coherent way. That is the subject of computer science, a field which is outside the scope of this book. The present text does provide the student with the building blocks of modelling in the realm of climate and sustainable energy and makes it possible to judge a model as to its applicability in certain situations. Because of the importance of monitoring as part of the scientific process, Chapter 8 is devoted to this subject.

Exercises

1.1 Check the units to the left and right of Eq. (1.3) using Appendix A. Check the calculation which produces a temperature of 255 [K] for the earth.

1.2 Repeat the calculation following Eq. (1.3) for the planets venus and mars.
  (a) Calculate the solar 'constants' S_V and S_M for these planets, using that the distance from venus to the sun averages 0.72 times the distance from earth to the sun. For mars the corresponding number becomes 1.52.
  (b) Ref. [3], Sect 14 gives the albedo of venus as 0.65 and that of mars as 0.15. Find their radiation temperatures, that is, the temperatures following from Eq. (1.3). Compare with the surface temperatures of 730 [K] and 218 [K] and explain.

1.3 Calculate the temperature of the solar surface, using the total solar irradiance S, the solar radius $R_s = 6.96 \times 10^8$ [m] and the sun–earth distance $R_{se} = 1.50 \times 10^{11}$ [m]. Use the assumption that in this regard the sun behaves as a black body.

References

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[3] Haynes, W.M. (1996) *Handbook of Chemistry and Physics*, 77th edn, CRC Press.