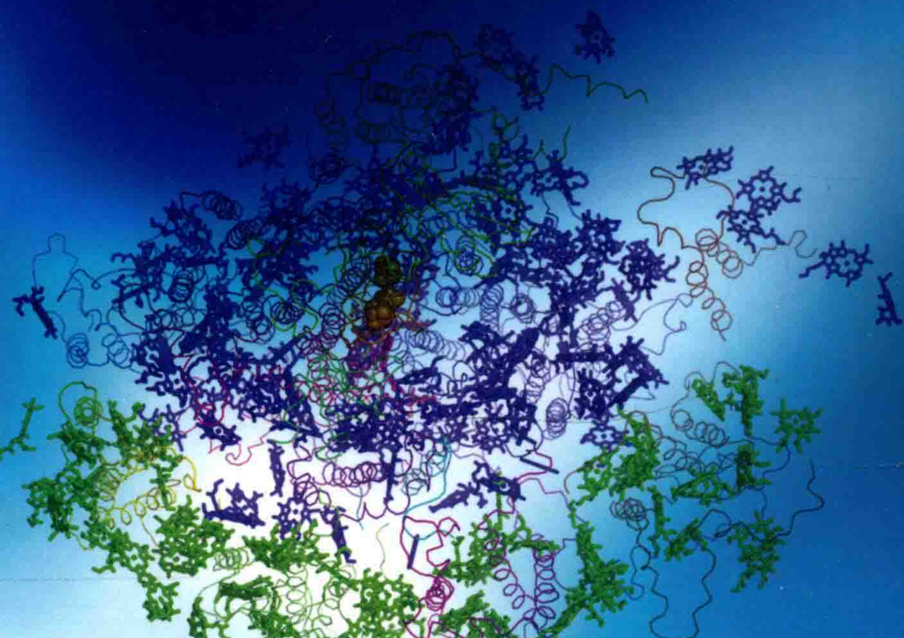
Egbert Boeker and Rienk van Grondelle

Environmental PHYSICS

Sustainable Energy and Climate Change



Third Edition

WILEY

Environmental Physics

Sustainable Energy and Climate Change

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Environmental Physics

Preface

This third edition of the textbook 'Environmental Physics' has been thoroughly revised to give more focus on sustainable energy and climate change. As fossil fuels and nuclear power will be with us for many years to come, the physical and environmental aspects of these ways of energy conversion are given ample attention as well.

The textbook is suitable for second year students in physics and related subjects as physical chemistry and geophysics. It assumes a basic knowledge in physics and mathematics, but all equations are derived from first principles and explained in a physical way. Therefore the book may serve as an introduction to physics in the context of societal problems like energy supply, pollution, climate change and finite resources of fossil fuels and uranium. Even where parts of the text will be familiar from other courses it is advisable to read those parts in order to grasp the way the material is presented here.

At some places we included parts that may be too 'heavy' for most second year students, but will not easily be found in the literature. They will be suitable for the final undergraduate year or for a Master course. They are indicated by ↓ at the beginning and with ↑ at the end. Usually we will indicate them in the introductory lines of each section as well.

As in any text, later chapters refer to concepts and properties discussed in earlier chapters. But the book is written such that the reader may read any chapter on its own. Therefore the teacher may select a few chapters as a module or for background reading.

A distinguishing feature of the text is the discussion of spectroscopy and spectroscopic methods, again from basic concepts, as a crucial means to quantitatively analyze and monitor the condition of the environment, the factors determining climate change and all aspects of energy conversion.

The emphasis in the book is on physics, on the concepts and principles that help in understanding the ways to produce energy efficiently or to mitigate climate change. Extra attention is given to photosynthesis, not only because of its importance in the field of renewable energy, but also because a comprehensive physics approach is lacking in the literature.

With regard to international treaties and conventions, we discuss the most important one for the subject matter of this book: the climate convention (Chapter 9) and more briefly the non-proliferation treaty (Chapter 6). The actual political situation is heavily influenced by the internal situation in major actors like the United States, Russia and China. That may change rapidly. As the need for a guaranteed energy supply is a constant in international relations, this book should give the reader enough background to judge the policy which his or her country is putting forward.

The structure of the book follows its emphasis. After an introduction, solar radiation is discussed as the input for most of the renewable energies (Chapter 2), next the factors influencing climate change (Chapter 3), then energy from fossil fuels with an excursion to the private car (Chapter 4) and renewable energy (Chapter 5). Because of its importance and the ongoing discussion of safety we have devoted a separate chapter to nuclear power (Chapter 6). Most if not all ways of energy conversion produce pollution as an inevitable side effect; therefore we discuss transport of pollutants in Chapter 7, albeit less detailed than in the second edition of this book. Monitoring is the subject of Chapter 8 and, finally, in Chapter 9 the social aspects are discussed. In the Appendices some helpful information is compiled.

The changed emphasis of this third edition results in many new sections and paragraphs and the omission or condensing of several sections of the earlier editions. For the interested reader these parts of the second edition may be downloaded free of charge from the website http://www.few.vu.nl/environmentalphysics. From this website also a description of environmental experiments for a student's lab may be downloaded, described briefly in Appendix D. The site also contains a few computer codes that will illuminate some points made in the text. Finally, any mistakes or omissions we discover will be put on the site as well.

Almost all equations in this book will be derived from first principles. After a, perhaps lengthy, derivation we often analyze the resulting formula by looking at the units on both sides of the equality sign (=). This provides more physical insight than comparing dimensions length, mass and time only. This same procedure was followed in the authors' book 'Environmental Science, Physical Principles and Applications' which is meant for a general science readership; there it worked very well. For clarity, units are given between square brackets [ ]; also dimensions are given between these brackets. In practice no confusion will arise.

Finally we mention some practical points. References are given between square brackets [ ] and printed at the end of each chapter. Also exercises are put there and for teachers the publisher has a teachers' manual available with the worked out solutions. In the final chapter 'social questions' ask for a considered opinion of the student. The student of course is entitled to have his or her own opinion, so there is no 'right' answer. But the arguments should be physically sound. In the teacher's manual some arguments on a certain statement will be given, without the pretention to present the ultimate truth.

Amsterdam, 20 January 2011

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Contents

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.

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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.

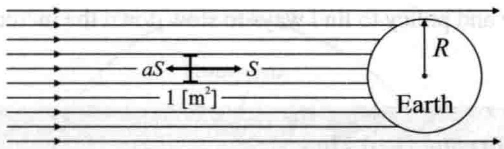

Figure 1.1 Solar radiation is entering the atmosphere from the left, S [Wm^{-2}]. A fraction a, called the albedo, is reflected back.

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