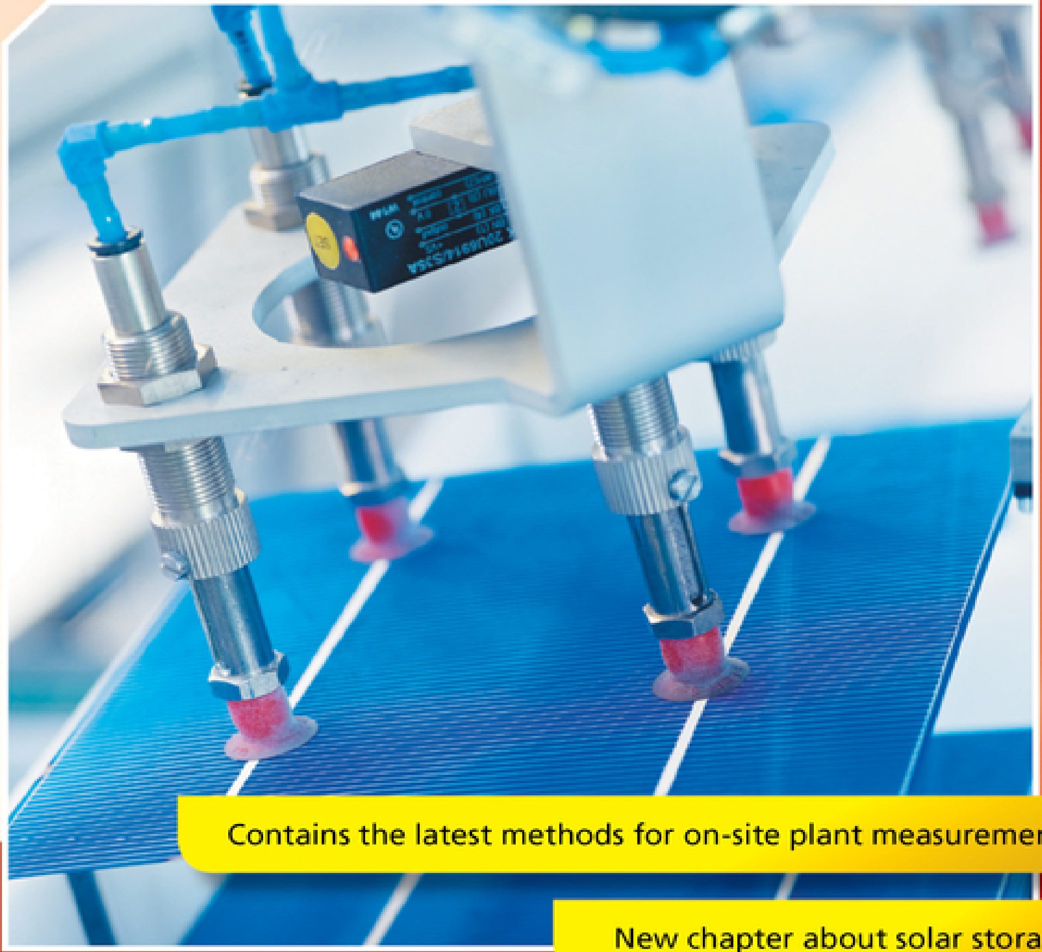
Konrad Mertens

Second Edition

Photovoltaics

Fundamentals, Technology, and Practice



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Photovoltaics – Fundamentals, Technology, and Practice

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Preface to the First International Edition

A steadily growing number of requests for an English version led to the decision to publish this international version of the Photovoltaics textbook. For this – besides the translation of the German text – several figures, tables, and solar radiation maps were extended with worldwide data and information. Moreover, as the photovoltaic market and technology have developed very quickly, numerous updates have found room in this first international version.

I would like to express my thanks to John Wiley & Sons, Ltd. for making this book possible. My special thanks to Gunther Roth for the translation, Richard Davies for managing the whole book project, and Laura Bell for taking care of all the small problems that arose.

A new English website has been created at *www.textbook-pv.org*.
Here the reader can find most of the figures of the book as a free download, supporting software and solutions to the exercises (and possibly corrections to the book).

I am very glad that the book is now accessible for a worldwide readership. We all know that the transformation of the current worldwide energy system into an environmentally friendly and sustainable one is a giant challenge. Photovoltaics can become an important part in the future energy supply. I hope that this book will help to deepen the understanding of the technology and the possibilities for photovoltaics, and can therefore support this development.

Steinfurt, January 2014 *Konrad Mertens*

Preface to the Second International Edition

The large demand makes it possible that the second edition of this textbook can be published already. Explicitly, I thank the readers for the positive comments on the first edition. Many thanks to John Wiley & Sons, Ltd. who made it possible that this edition is now published in full color.

As the development of photovoltaics advances quickly, this new edition shows a considerable increase in volume. Besides the usual actualizations, it contains a completely new chapter about “Storage of Solar Power.” Moreover, the chapter dealing with photovoltaic metrology was amended by the description of up-to-date on-site measurement technologies such as outdoor-electroluminescence and detection of potential induced degradation (PID) of solar modules.

The chapter “Future Development” now also looks on the cooperation of the different renewable energies in the present and in the future.

Particularly, I want to recommend the accompanying website *www.textbook-pv.org*.

Here you can find the figures of the book as a free download, supporting software, the solutions to the exercises, and corrections to the book.

I wish much joy and success to all the readers through learning the fascinating technology of photovoltaics.

Steinfurt, May 2018 *Konrad Mertens*

Abbreviations

AC	alternating current
ALB	Albedo
AM	air mass
a-Si	amorphous silicon
CAES	compressed air energy storage
CCCV	constant current, constant voltage
CdTe	cadmium telluride
CET	Central European Time
CID	current interrupt device
CIGS	copper indium gallium sulfide
CIGSe	copper indium gallium selenide
CIS	copper indium sulfide
CISe	copper indium selenide
c-Si	crystalline silicon
DC	direct current
DOD	depth of discharge
DSM	demand side management
EEG	Renewable Energy Law (Erneuerbare-Energien-Gesetz)
EMC	electromagnetic compatibility
EVA	ethyl-vinyl-acetate
FF	fill factor
GaAs	gallium arsenide
GaN	gallium nitride
GCB	generator connection box
HIT	heterojunction with intrinsic thin layer
IBC	interdigitated back contact
ITO	indium tin oxide
LST	local solar time
MPP	maximum power point
NAS	sodium sulfur
NOCT	nominal operating cell temperature
PECVD	plasma enhanced chemical vapor deposition
PERC	passivated emitter and rear cell
PERL	passivated emitter rear locally diffused
PID	potential induced degradation

PR	performance ratio
PWM	pulse width modulation
RCD	residual current device
SiC	silicon carbide
SOC	state of charge
SR	sizing ratio
STC	standard test conditions
TC	temperature coefficient
tce	tons of coal equivalent
TCO	transparent conducting oxide
toe	tons of oil equivalent
UTC	coordinated universal time
VRF	vanadium redox flow

1

Introduction

The supply of our industrial community with electrical energy is indispensable on the one hand, but, on the other hand, it is accompanied by various environmental and safety problems. In this chapter, therefore, we will look at the present energy supply and will familiarize ourselves with renewable energies as feasible future alternatives. At the same time, photovoltaics will be presented in brief and its short but successful history will be considered.

1.1 Introduction

In the introduction, we will explain why we are occupying ourselves with photovoltaics and who should read this book.

1.1.1 Why Photovoltaics?

In past years, it has become increasingly clear that the present method of generating energy has no future. Thus, finiteness of resources is noticeably reflected in the rising prices of oil and gas. At the same time, we are noticing the first effects of burning fossil fuels. The melting of the glaciers, the rise of the ocean levels, and the increase in weather extremes, as well as the nuclear catastrophe in Fukushima, all show that nuclear energy is not the path to follow in the future. Besides the unsolved final storage question, fewer and fewer people are willing to take the risk of large parts of their country being radioactive.

Fortunately, there is a solution with which a sustainable energy supply can be assured: Renewable energy sources. These use infinite sources as a basis for energy supplies and can ensure a full supply with a suitable combination of different technologies such as biomasses, photovoltaics, wind power, and so on. A particular role in the number of renewable energies is played by photovoltaics. It permits an emission-free conversion of sunlight into electrical energy and, because of its great potential, will be an important pillar in future energy systems.

However, the changeover of our energy supply will be a huge task that can only be mastered with the imagination and knowledge of engineers and technicians. The object of this book is to increase this technical knowledge in the field of photovoltaics. For this purpose, it will deal with the fundamentals, technologies, practical uses, and commercial framework conditions of photovoltaics.

Photovoltaics – Fundamentals, Technology, and Practice, Second Edition. Konrad Mertens.

1.1.2 Who Should Read This Book?

This book is meant mostly for students of the engineering sciences who wish to deepen their knowledge of photovoltaics. Nevertheless, it is written in such a way that it is also suitable for technicians, electricians, and the technically interested layman. Furthermore, it can be of use to engineers in the profession to help them to gain knowledge of the current technical and commercial position of photovoltaics.

1.1.3 Structure of the Book

In the introduction, we will first deal with the subject of energy: What is energy and into what categories can it be divided? From this base, we will then consider the present energy supply and the problems associated with it. A solution to these problems is renewable energies and will be presented next in a brief overview. As we are primarily interested in photovoltaics in this book, we will finish with the relatively young but stormy history of photovoltaics.

Chapter 2 deals with the availability of solar radiation. We become familiar with the features of sunlight and investigate how solar radiation can be used as efficiently as possible. Then in the Sahara Miracle, we will consider what areas would be necessary to cover the whole of the world's energy requirements with photovoltaics.

Chapter 3 deals with the basics of semiconductor physics. Here we will concentrate on the structure of semiconductors and an understanding of the p–n junction. Besides this, the phenomenon of light absorption will be explained, without which no solar cell can function. Those familiar with semiconductors can safely skip this chapter.

Chapter 4 gets to the details: We learn of the structure, method of operation, and characteristics of silicon solar cells. Besides this, we will view in detail the parameters and degree of efficiency on which a solar cell depends. Based on world records of cells, we will then see how this knowledge can be successfully put to use.

Chapter 5 deals with cell technologies: What is the path from sand, via silicon solar cell, to the solar module? What other materials are there and what does the cell structure look like in this case? Besides these questions, we will also look at the ecological effects of the production of solar cells.

Chapter 6 deals with the structures and properties of solar generators. Here we will deal with the optimum interconnection of solar modules in order to minimize the effects of shading. Besides this, we will present various types of plants such as pitched roof and ground-mounted plants.

Chapter 7 deals with system technology of grid-connected plants. At the start, there is the question of how to convert direct current efficiently into alternating current. Then we will become familiar with the various types of inverters and their advantages and disadvantages.

Chapter 8 deals with the storage of solar power, the very hot topic of the chapter. We learn to know different battery types together with their operating modes. Moreover, it is about systems who can enhance the self-consumption of solar power in domestic households or commercial enterprises. In an own subchapter off-grid systems are considered.

Chapter 8 concentrates on photovoltaic metrology. Besides the acquisition of solar radiation, we deal especially with the determination of the real power of solar modules.

Furthermore, we become familiar with modern methods of quality analysis such as thermography and electroluminescence metrology.

Chapter 9 presents design and operation of grid-coupled plants. Besides the optimum planning and dimensioning of plants, methods of profitability calculation are also discussed. In addition, methods for monitoring plants are shown and the operating results of particular plants are presented.

Chapter 10 provides a view of the future of photovoltaics. First, we will estimate power generation potential in Germany. This is followed by a consideration of price development and the coaction of the different energies in the current electrical power system. Finally, we will reflect on how the future energy system will look like and what role photovoltaics will thereby play.

Each chapter has exercises associated with it, which will assist in repeating the material and deepening the knowledge of it. Besides, they provide a control of the students' own knowledge. The solutions to the exercises can be found in the Internet under *www.textbook-pv.org*.

1.2 What Is Energy?

We take the use of energy in our daily lives as a matter of course, whether we are operating the coffee machine in the morning, using the car during the day, or returning to a warm home in the evening. In addition, the functionality of our whole modern industrial community is based on the availability of energy: Production and transport of goods, computer-aided management, and worldwide communication are inconceivable without a sufficient supply of energy.

At the same time, the recognition is growing that the present type of energy supply is partly uncertain, environmentally damaging, and available only to a limited extent.

1.2.1 Definition of Energy

What exactly do we understand about the term *energy*? Maybe a definition of energy from a famous mouth will help us. Max Planck (founder of quantum physics: 1858–1947) answered the question as follows:

> Energy is the ability of a system to bring outside effects (e.g. heat, light) to bear.

For instance, in the field of mechanics, we know the potential energy (or stored energy) of a mass m that is situated at a height h (Figure 1.1a):

$$W_{\text{Pot}} = m \cdot g \cdot h \tag{1.1}$$

with g: Earth's gravity, $g = 9.81\ \text{m s}^{-2}$.

If a bowling partner drops his 3 kg bowling ball, then the "1-m-high ball" system can have a distinct effect on his foot.

If, on the other hand, he propels the ball as planned forward, then he performs work on the ball. With this work, energy is imparted to the ball system. Thus, we can say in general:

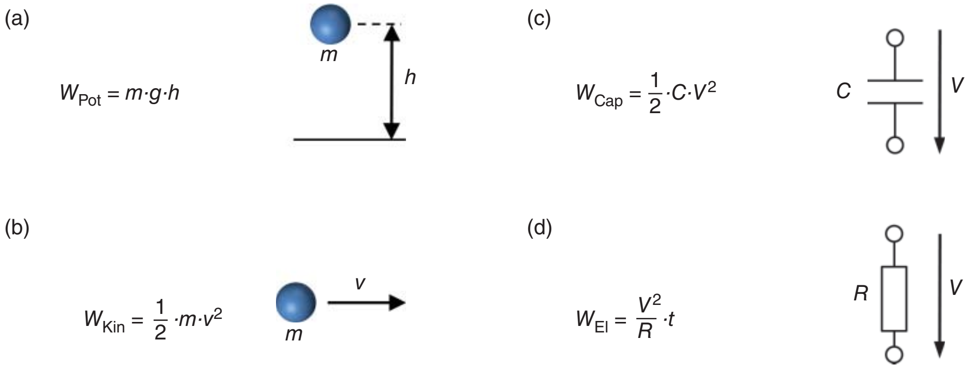

Figure 1.1 Depiction of different forms of energy. (a) Potential energy. (b) Kinetic energy. (c) Capacitor energy. (d) Energy at resistor.

> The energy of a system can be changed with the addition or transfer of work. To put it another way, energy is stored work.

In the case of the bowling partner, the ball obtains kinetic energy W_{Kin} (or movement energy, see Figure 1.1b) in being propelled forward:

$$W_{\mathrm{Kin}} = \frac{1}{2} \cdot m \cdot v^2 \tag{1.2}$$

with v: velocity of the ball.

A similar equation describes the electrotechnics of the energy stored in a capacitor W_{Cap} (see Figure 1.1c)

$$W_{\mathrm{Cap}} = \frac{1}{2} \cdot C \cdot V^2 \tag{1.3}$$

with C: capacity of the capacitor; V: voltage of the capacitor.

If, again, there is a voltage V at an ohmic resistor R, then in the time t it will be converted into electrical work W_{El} (Figure 1.1d):

$$W_{\mathrm{El}} = P \cdot t = \frac{V^2}{R} \cdot t. \tag{1.4}$$

The power P shows what work is performed in the time t:

$$P = \frac{\text{Work}}{\text{Time}} = \frac{W}{t}. \tag{1.5}$$

1.2.2 Units of Energy

Unfortunately, many different units are in use to describe energy. The most important relationship is

$$1\ \mathrm{J(Joule)} = 1\ \mathrm{W\,s} = 1\ \mathrm{N\,m} = 1\ \mathrm{kg\ m\ s^{-2}}. \tag{1.6}$$

Table 1.1 Prefixes and prefix symbols.

Prefix	Prefix symbol	Factor	Number
Kilo	k	10^3	Thousand
Mega	M	10^6	Million
Giga	G	10^9	Billion
Tera	T	10^{12}	Trillion
Peta	P	10^{15}	Quadrillion
Exa	E	10^{18}	Quintillion

Example 1.1 ***Lifting a sack of potatoes***

If a sack of 50 kg of potatoes is lifted by 1 m, then this provides it with stored energy of

$$W_{\text{Pot}} = m \cdot g \cdot h = 50\text{ kg} \cdot 9.81\text{ m s}^{-2} \cdot 1\text{ m} = 490.5\text{ N m} = 490.5\text{ W s}. \qquad \blacksquare$$

In electrical engineering, the unit of the kilowatt hour (kW h) is very useful and results in

$$1\text{ kW h} = 1000\text{ W h} = 1000\text{ W} \cdot 3600\text{ s} = 3.6 \times 10^6\text{ W s} = 3.6\text{ MW s} = 3.6\text{ MJ}. \tag{1.7}$$

Due to the fact that in the energy industry, very large quantities are often dealt with, a listing of units that prefixes into factors of 10 is useful; see Table 1.1.

1.2.3 Primary, Secondary, and End Energy

Energy is typically stored in the form of energy carriers (coal, gas, wood, etc.). This form of energy is typically called primary energy. In order to use it for practical purposes, it needs to be converted. If one wishes to generate electricity, then for instance, coal is burned in a coal-fired power station in order to generate hot steam. The pressure of the steam is again used to drive a generator that makes electrical energy available at the exit of the power station (Figure 1.2). This energy is called secondary energy. This process chain is associated with relatively high conversion losses. If the energy is transported on to a household, then further losses are incurred from the cables and transformer stations. These are added together under distribution losses. The end energy finally arrives at the end customer.

With a petrol-driven car, the oil is the primary energy carrier. It is converted to petrol by means of refining (secondary energy) and then brought to the petrol station. As soon as the petrol is in the tank, it becomes end energy. This must again be differentiated from useful energy, and in the case of the car, it is the mechanical movement of the vehicle. As a car engine has an efficiency of less than 30%, only a small fraction of the applied primary energy arrives on the road. In the case of electrical energy, the useful energy would be light (lamp) or heat (stove plates).

In order that end energy is available at the socket, the conversion and distribution chain shown in Figure 1.2 must be passed through. As the efficiency of a conventional

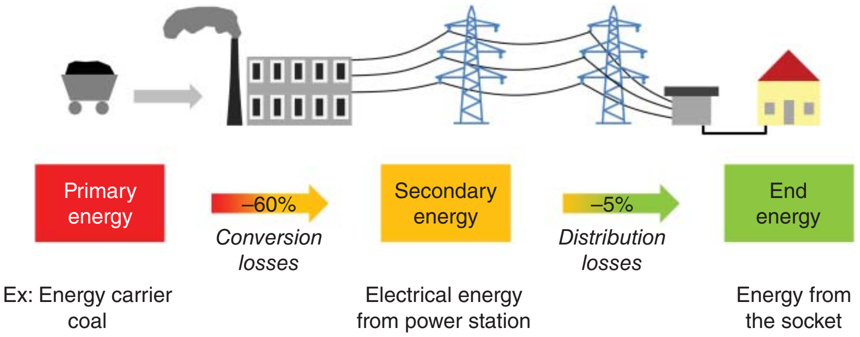

Figure 1.2 Depiction of the types of energy as an example of coal-fired power: Only about one-third of the applied primary energy arrives at the socket by the end customer.

power station with approximately 40% is relatively small, the overall degree of efficiency η_{Over} up to the socket of the end user is

$$\eta_{\text{Over}} = \eta_{\text{Powerstation}} \cdot \eta_{\text{Distr}} \approx 0.4 \cdot 0.95 \approx 0.38. \tag{1.8}$$

> Thus, we can state that in the case of conventional electrical energy, only about one third of the applied primary energy arrives at the socket.

And yet electrical energy is used in many fields as it is easy to transport and permits the use of applications that could hardly be realized with other forms of energy (e.g. computers, motors). At the same time, however, there are uses for which the valuable electricity should not be used. Thus, for the case of electric space heating, only a third of the applied primary energy is used, whereas with modern gas energy, it is more than 90%.

1.2.4 Energy Content of Various Substances

The conversion factors in Table 1.2 are presented in order to estimate the energy content of various energy carriers.

In the energy industry, the unit toe is often used. This means tons of oil equivalent and refers to the conversion factor of 1 kg crude oil in Table 1.2. Thus, 1 toe is

Table 1.2 Conversion factors of various energy carriers [1, Wikipedia].

Energy carrier	Energy content (kW h)	Remarks
1 kg coal	8.14	—
1 kg crude oil	11.63	Petrol: 8.7 kW h l^{-1}, diesel: 9.8 kW h l^{-1}
1 m^3 natural gas	8.82	—
1 kg wood	4.3	(at 15% moisture)

$1000\,\text{kg} \cdot 11.63\,(\text{kW h})\,\text{kg}^{-1} = 11.630\,\text{kW h}$. Correspondingly, there is the conversion of tons of coal equivalent (tce) with the factor for coal in Table 1.2.

We can remember the very approximate rule:

$$1\ \text{m}^3\ \text{natural gas} \approx 1\ 1\ \text{oil} \approx 1\ 1\ \text{petrol} \approx 1\ \text{kg coal} \approx 1\ \text{kg wood} \approx 10\ \text{kWh}.$$

1.3 Problems with Today's Energy Supply

The present worldwide energy supply is associated with a series of problems; the most important aspects will be presented in the following sections.

1.3.1 Growing Energy Requirements

Figure 1.3 shows the development of worldwide primary energy usage in the last 40 years. In the period considered this more than doubled, the average annual growth being 2.2%. While at first mainly Western industrial countries made up the greatest part, emerging countries, especially China, caught up rapidly.

One reason for the growth in energy requirements is the growth of the world population. This has almost doubled in the past 40 years from 3.7 billion to the present 7 billion people. By the year 2030, a further rise to more than 8 billion people is expected [3].

The second cause for this development is the rising standards of living. Thus, the requirement of primary energy in Germany is approximately 45 000 kW h per head; in a weak industrialized country such as Bangladesh, on the other hand, it is only 1500 kW h per head. With the growing standards of living in the developing countries, the per-head consumption will increase substantially. In China, as a very dynamic emerging nation, it is above 26 000 kW h per head. The International Energy Agency (IEA) assumes that China will increase its energy requirement in the next 25 years by 75% and India by even 100%.

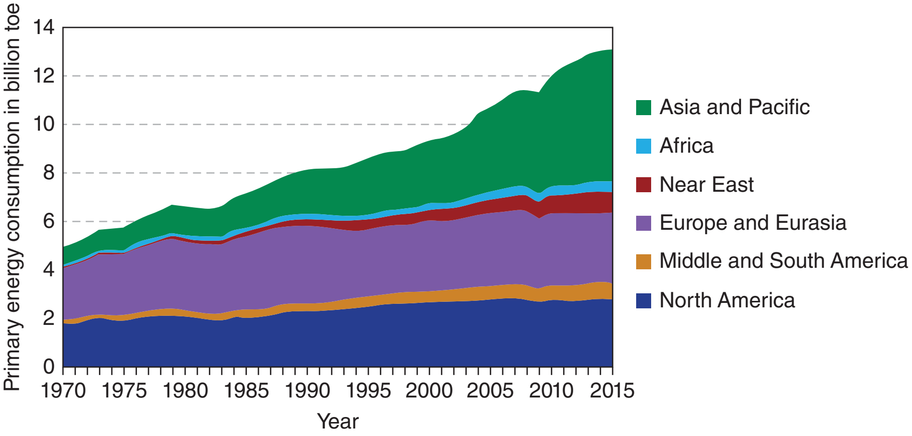

Figure 1.3 Development of worldwide primary energy requirements since 1971 [2].

The growing energy requirement would not be so grave if this did not cause a series of problems:

1. Tightening of resources
2. Climate change
3. Hazards/disposals

These will now be looked at in more detail.

1.3.2 Tightening of Resources

The worldwide requirement for energy is covered today mainly by the fossil fuels: oil, natural gas, and coal. From Figure 1.4, it can be seen that they make up a portion of more than 80%, while biomass, hydro, and renewable energies (wind, photovoltaics, solar heat, etc.) up to now have only reached 14%.

Meanwhile, the strong usage of fossil sources has led to scarcity. Table 1.3 shows the individual extraction quantities in 2001 and 2008. Already, in 2001, the estimated reserves of oil were estimated to last 43 years and natural gas 64 years. Only coal reserves were estimated to last for a relatively long period of 215 years. By 2008, more oil reserves were found but by then the annual consumption had increased substantially. Thus, the reserves have reduced from 140 to 41 years.

If one assumes that the world energy consumption continues to grow as previously, then reserves will be reduced drastically in 30–65 years (see also Exercise 1.3). The scarcity of fuels will lead to strongly rising prices and distribution wars.

In the past, a start has also been made with the extraction of oil from oil sands and oil shales. This has been carried out particularly in Canada and the United States. However, much engineering effort is required for the generation of synthetic oil. Extraction in open-cast mining leads to the destruction of previously intact ecosystems. Therefore, the use of these additional fossil sources is no real future option.

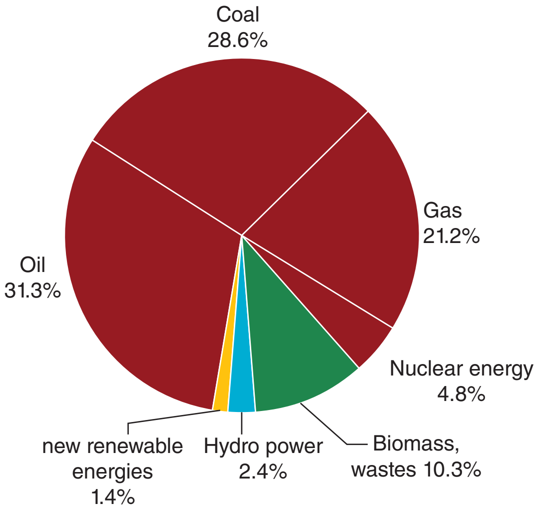

Figure 1.4 Distribution of worldwide primary energy consumption in 2014 according to energy carriers [4].