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Introduction

The supply of our industrial community with electrical energy is indispensable on one hand but, on the other, is accompanied by various environmental and safety problems. In this first 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**. They permit an emission-free conversion of sunlight into electrical energy and, because of their great potential, **will be an important pillar in future energy systems**.

However, the changeover of our energy supply will be a **huge task** that will 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, First 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. But 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 this **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.

The **second chapter** 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.

In the **third chapter** we deal 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.

In **Chapter 4** we get 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. On the basis of 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.

The **structures and properties of solar generators** are the subjects of **Chapter 6**. 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**. 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. Off-grid systems are handled in their own section.

In **Chapter 8** we concentrate 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.

Design and operation of grid-coupled plants are both presented in **Chapter 9**. Besides the optimum planning and dimensioning of plants, methods of feasibility 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. Finally we will discuss the role that photovoltaics can play in the energy systems of the future.

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. Also 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 1.1(a)):

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

with

g: Earth's gravity, $g = 9.81\ \mathrm{m/s^2}$

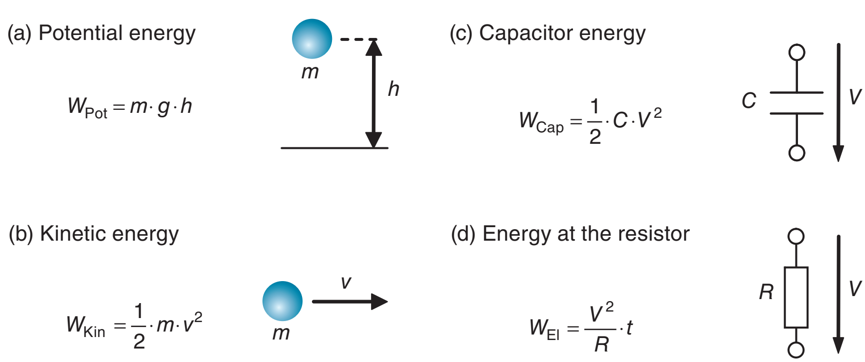

Figure 1.1 Depiction of different forms of energy

If a bowling partner drops his 3 kg bowling ball then the "one meter-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:

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** $\boldsymbol{W_{Kin}}$ (or movement energy, see Figure 1.1(b)) in being propelled forward:

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

with

v: velocity of the ball

A similar equation describes the electro-technics of the energy stored in a **capacitor** $\boldsymbol{W_{Cap}}$

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

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** $\boldsymbol{W_{El}}$ (Figure 1.1(d)):

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

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

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

1.2.2 Units of Energy

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

$$1\text{J(Joule)} = 1\ \text{Ws} = 1\ \text{Nm} = 1\ \text{kg} \cdot \text{m/s}^2 \tag{1.6}$$

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

$$W_{\text{Pot}} = m \cdot g \cdot h = 50\ \text{kg} \cdot 9.81\ \text{m/s}^2 \cdot 1\ \text{m} = 490.5\ \text{Nm} = 490.5\ \text{Ws} \tag{1.7}$$

■

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

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

$$1\ \text{kWh} = 1000\ \text{Wh} = 1000\ \text{W} \cdot 3600\ \text{s} = 3.6 \cdot 10^6\ \text{Ws} = 3.6\ \text{MWs} = 3.6\ \text{MJ} \qquad (1.8)$$

Due to the fact that in the energy industry very large quantities are often dealt with, a listing of unit 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

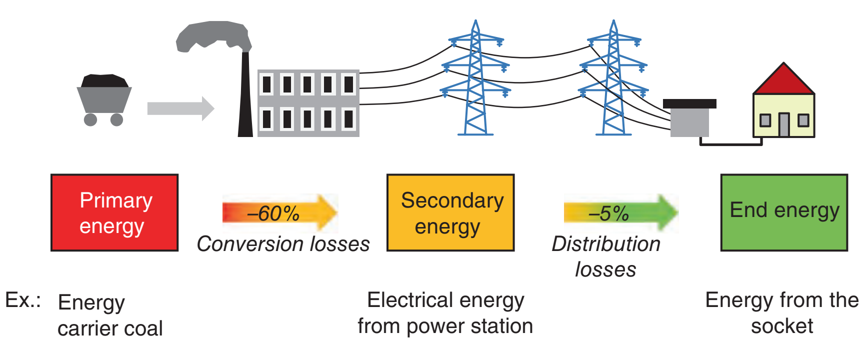

Figure 1.2 Depiction of the types of energy as an example of coal-fired power: Only about one third of the applied primary energy arrives at the socket by the end customer

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 power station with approximately 40% is relatively small, the **overall degree of efficiency** $\eta_{\mathbf{Over}}$ up to the socket of the end user is:

$$\eta_{\text{Over}} = \eta_{\text{Powerstation}} \cdot \eta_{\text{Distr}} \approx 0.4 \cdot 0.95 \approx 0.38 \tag{1.9}$$

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, etc.). 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 **tonnes oil equivalent** and refers to the conversion factor of 1 kg crude oil in Table 1.2. Thus, 1 toe is 1000 kg · 11.63 kWh/kg = 11.630 kWh. 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 m^3 natural gas ≈ 1 l oil ≈ 1 l petrol ≈ 1 kg coal ≈ 2 kg wood ≈ 10 kWh

Table 1.2 Conversion factors of various energy carriers [121, Wikipedia]

Energy carrier	Energy content (kWh)	Remarks
1 kg coal	8.14	–
1 kg crude oil	11.63	Petrol 8.7 kWh/liter, Diesel: 9.8 kWh/liter
1 m^3 natural gas	8.82	
1 kg wood	4.3	(at 15% moisture)

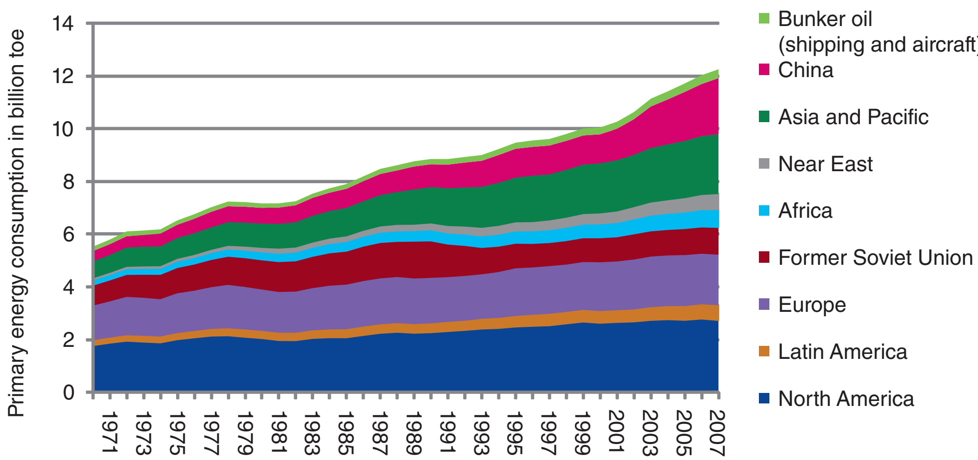

Figure 1.3 Development of worldwide primary energy requirements since 1971 [3]

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.

1.3.1 Growing Energy Requirements

Figure 1.3 shows the development of worldwide primary energy usage in the last 40 years. From 1971–2008 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 [2].

The second cause for this development is the **rising standards of living**. Thus, the requirement of **primary energy in Germany** is approximately **45 000 kWh/head**; in a weak industrialized country such as Bangladesh, on the other hand, it is only 1500 kWh/head. With growing standards of living in developing countries, the per-head consumption will increase substantially. In China, as a very dynamic emerging nation it is above 16 000 kWh/head [3]. 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% [4].

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.

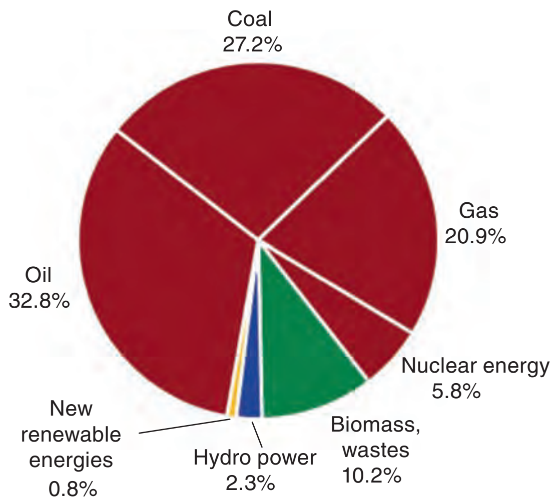

Figure 1.4 Distribution of worldwide primary energy consumption in 2008 according to energy carriers [4]

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%, whilst biomass, hydro and renewable energies (wind, photovoltaics, solar heat, etc.) up to now have only reached 10%.

Meanwhile, the strong usage of fossil sources has led to scarcity. Table 1.3 shows the individual extraction quantities in the years 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 USA. However, much engineering

Table 1.3 Extraction and reserves of fossil fuels [5]

	Oil		Nat. gas		Coal	
	2001	2008	2001	2008	2001	2008
Extraction EJ/a	147	163	80	121	91	151
Reserves EJ	6,351	6,682	5,105	7,136	19,620	21,127
Lasting for	43 a	41 a	64 a	59 a	215 a	140 a
Lasting with annual growth of 2.2%		**30 a**		**38 a**		**65 a**

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.

1.3.3 Climate Change

The decomposition of biomasses (wood, plants, etc.) causes **carbon dioxide (CO_2)** to be released into the atmosphere. At the same time plants grow due to photosynthesis and take up CO_2 from the air. In the course of the history of the Earth this has equalized itself and has led to a relatively constant CO_2 concentration in the atmosphere.

CO_2 is also created when wood, coal, natural gas or oil are burned and is released into the atmosphere. In the case of wood this is not tragic as long as felled trees are replanted. The newly growing wood binds CO_2 from the air and uses it for building up the existing biomasses.

In the case of energy carriers, however, this looks different. These were formed millions of years ago from biomass and have been burned up in one to two centuries. Figure 1.5 shows the course of CO_2 concentrations in the atmosphere in the last 20 000 years.

Apparently, in earlier times there were already fluctuations in these concentrations but really **disturbing** is the **steep rise since the start of industrialization**. In the year **2012** the concentration was approximately **400 ppm** (parts per million); a value that has not been reached for millions of years.

Why is the CO_2 concentration in the atmosphere so important for us? The reason is that CO_2, besides the other trace gases (e.g., methane, CH_4) affects the temperature of the Earth through the **greenhouse effect**. For clarity, consider Figure 1.6. The light from the **Sun** (visible and infrared radiation ①) arrives almost unhindered through the atmosphere and is absorbed by the ground ②. This causes the surface ③ to be warmed and emits heat radiation as a so-called **black body source** (see Chapter 2) ④. This radiation is again absorbed by the trace gases ⑤ and released to the environment as heat ⑥. The **heat energy** thus **remains** in the **atmosphere** to a large extent and only a small amount is returned back in to Space.

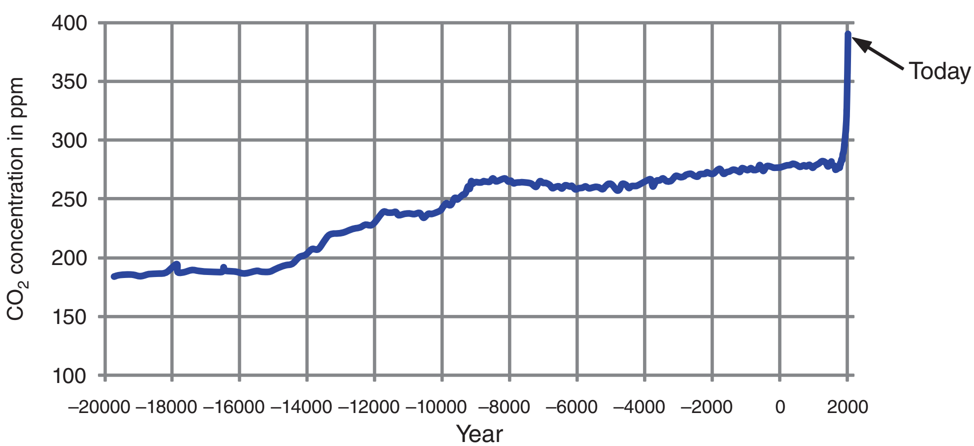

Figure 1.5 Development of the CO_2 content in the atmosphere in the last 22 000 years: noticeable is the steep rise since the start of industrialization [6,7,137]

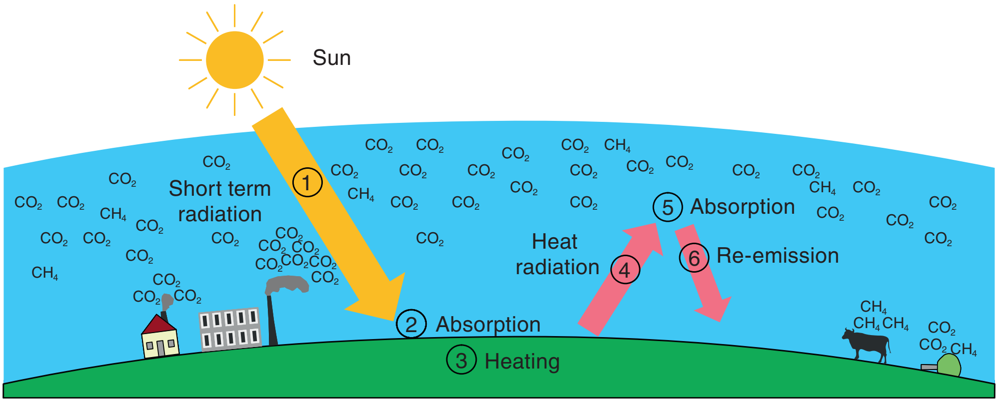

Figure 1.6 Depiction in principle of the greenhouse effect: the heat radiation reflected from the ground is held back by the greenhouse gases

The comparison to a greenhouse is thus fitting: the atmosphere with trace gases acts as the glass of a greenhouse that allows the Sun's rays to pass into the greenhouse but holds back the internally resulting heat radiation. The result is a heating up of the greenhouse.

Now we should be happy that this greenhouse effect even exists. **Without** it, the temperature on the earth would be **−18 °C** but because of the **natural greenhouse effect** the actual average temperature is approximately 15 °C. However, the additional emissions of CO_2, methane, and so on, caused by people as an **anthropogenic greenhouse effect**, leads to additional heating. Since the start of industrialization this **temperature rise** has been approximately 0.74 °C; it is expected in future this rise will accelerate by 0.2 °C per decade [8].

The results of the temperature increase can already be seen in the **reduction of glaciers** and melting of the ice in the North Polar Sea. Besides this, **extreme weather phenomena** (hurricanes, drought periods in some regions) are connected to the rise in temperatures. In the long term further rises in temperatures are expected with a significant **rise** in **water levels** and **displacement of weather zones**.

In order to slow down the climate change, the **Kyoto agreement** was promulgated in 1997 at the World Climate Conference in the Japanese city of Kyoto. There the industrial countries obligated themselves to lower their greenhouse emissions by 5.5% below the 1990 level by 2012. The declared aim was the limitation of the rise of temperature caused by people by 2 °C. Of its own will, Germany obligated itself to reduce emissions by 21%. After Germany had achieved its aim, in the year 2010 the Federal Government decided on a **reduction of 40% by 2020** (compared to 1990). Important elements to achieving this goal, besides the increase in **energy efficiency**, are the extensions of renewable energies. After the catastrophe in Fukushima it was also decided to **completely** change over to **renewable energies by 2050**.

1.3.4 Hazards and Disposal

An almost CO_2-free generation of electricity is presented by nuclear energy. However, it is associated with a number of other problems. The reactor catastrophe in Fukushima in 2011 showed that the risk of a **super catastrophe** (largest expected accident) can never be fully excluded. Even when no tsunami is expected in Germany there is still a great danger as the nuclear power stations here are only **insufficiently protected against terrorist attack**.

Added to this is the **unsolved problem** of final storage of radioactive waste. At present there is no final **storage for highly radioactive waste in the world**. This must be safely stored for thousands of years. There is also the question as to whether it is **ethically correct** to saddle future generations with such a burdensome legacy.

Here, too the **availability** should be taken into account. The known reserves of uranium including estimated stores are approximately 4.6 million tons. Included in these are the ones with relatively poor concentrations of uranium that are difficult to extract. If we accept the current annual requirements of 68 000 t/a as a basis, then the stocks will last for 67 years [9]. Assuming the increase of energy from Table 1.3, then the **reserves** will last for approximately **40 years**. If the whole of today's energy requirement were changed over to nuclear energy, then the stocks of uranium would last for just **4 years**.

1.4 Renewable Energies

1.4.1 The Family of Renewable Energies

Before we turn to photovoltaics in more detail we should allocate them into the family of renewable energies. The term **renewable** (or **regenerative**) means that the supply of energy is not used up. The wind blows every year again and again, the Sun rises every day and plants grow again after the harvest. In the case of geothermic energy, the Earth is cooling off but this will only be noticeable thousands of years in the future.

As Figure 1.7 shows, the actual **primary energies** of the renewable energies are the **movements of the planets**, the **heat of the Earth** and **solar radiation**. Whereas movements of

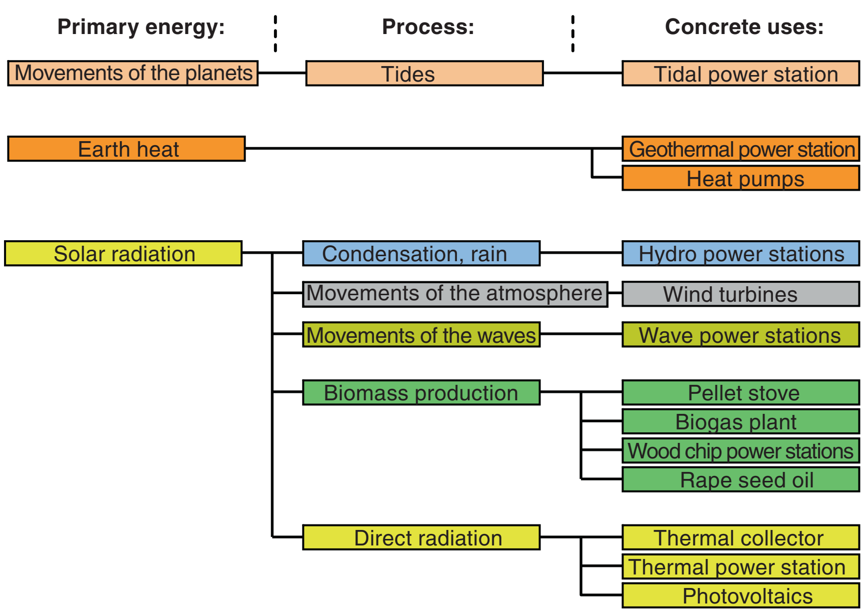

Figure 1.7 Various possibilities for the use of renewable energies

the planets are used only in the somewhat exotic tidal power plants, the heating of the Earth as well as the heating of buildings can be achieved with the aid of a heat pump as well as for generating electrical energy in a geothermal power station.

Solar radiation is the basis for a surprising range of energies. Thus, the use of **hydro power** is only possible by the **condensation of water** and subsequent precipitation onto land. **Atmospheric movement** originates mostly due to solar radiation, which is also the basis for the **use of wind power**. In the case of biomass products it is again sunlight that causes **photosynthesis**, and thus the growth of biomass is conditioned by it.

Solar radiation can also be used directly for the generation of heat, for instance in a **thermal collector** for domestic water or domestic space heating. **Thermal solar power stations** generate process heat from concentrated sunlight in order to drive generators for production of electricity. Last but not least, with **photovoltaics**, solar radiation is directly converted into electrical energy.

Thus we can consider **photovoltaics** as the **young daughter of the large family** of renewable energies. However, they have a very special attraction: they are the only one able to convert sunlight directly into electrical energy without complicated intermediate processes and without using mechanical converters that can wear out.

1.4.2 Advantages and Disadvantages of Renewable Energies

Renewable energies have certain common characteristics. Their greatest advantage is that in contrast to all other energy carriers they are **practically inexhaustible**. Added to this they are almost **free of any emissions** and with only **few environment effects** and **hazards**.

A further important advantage is in the fact that there are practically **no fuel costs**. The Sun shines for free, the wind blows irrespectively and the heat of the Earth is an almost inexhaustible reservoir. On the other hand, the **energy densities** in which the renewable energies are available **are small**. Large areas are needed (solar module area for photovoltaics, rotor area for wind turbines, etc.) in order to "collect" sufficient energy. This means that typically **large investment costs** are incurred as the large surfaces require the **use of a lot of material**.

A further large disadvantage is the **varying energy supply**. **Photovoltaics** and **wind power** are especially affected by this. As a result, further power stations **(backup power stations)** must be kept on reserve in order to ensure a constant supply. **Geothermal power** is not affected by this; it can provide energy practically **independently of time of day or year**. A special case is **biomass** which is the only renewable energy that is **easy to store** (branches in the woods, biogas in the tank, etc.).

In many **developing countries** there is no power grid. There, a further advantage of renewable energies can be used: their **decentralized availability and utility**. Thus autarchic village power supplies can be installed far from large towns without an overland grid being necessary.

1.5 Photovoltaic – The Most Important in Brief

In the following chapters we will work through some fundamentals in which some may perhaps question their necessity. For this reason, in order to increase motivation and for the sake of clarity, we will briefly consider the most important aspects of photovoltaics.

1.5.1 What Does "Photovoltaic" Mean?

The **term photovoltaic** is a combination of the Greek word *phós*, *phōtós* (light, of the light) and the name of the Italian physicist Alessandro Volta (1745–1825). He discovered the first functional electro-chemical battery and the unit of electricity, **Volt**, is named after him. Thus, a translation of the word photovoltaic could be **light battery** or also **light source**. More generally we understand the word **photovoltaics** as the direct conversion of sunlight into electric energy.

1.5.2 What are Solar Cells and Solar Modules?

The basic component of every photovoltaic plant is the solar cell (see Figure 1.8). This consists in most cases of **silicon**, a semiconductor that is also used for diodes, transistors and computer chips. With the introduction of foreign atoms **(doping)** a **p-n junction** is generated in the cell that "installs" an **electrical field** in the crystal. If light falls on the solar cell then charge carriers are dissolved out of the crystal bindings and moved by the electrical field to the outer contacts. The result at the contacts of the solar cells is the creation of a **voltage of** approximately **0.5 V**. The released **current** varies depending on radiation and cell area, and lies between **0 and 10 A**.

In order to achieve a usable voltage in the region of 20–50 V, many cells are switched together in series in a **solar module** (Figure 1.8). Besides this, the solar cells in the modules are mechanically protected and sealed against environmental influences (e.g., entrance of moisture).

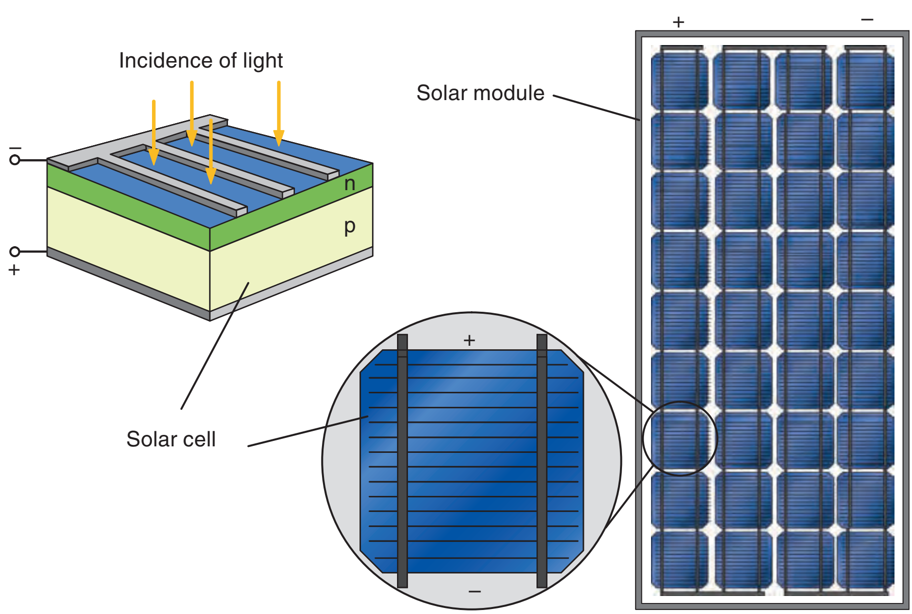

Figure 1.8 The solar cell and solar module as basic components of photovoltaics

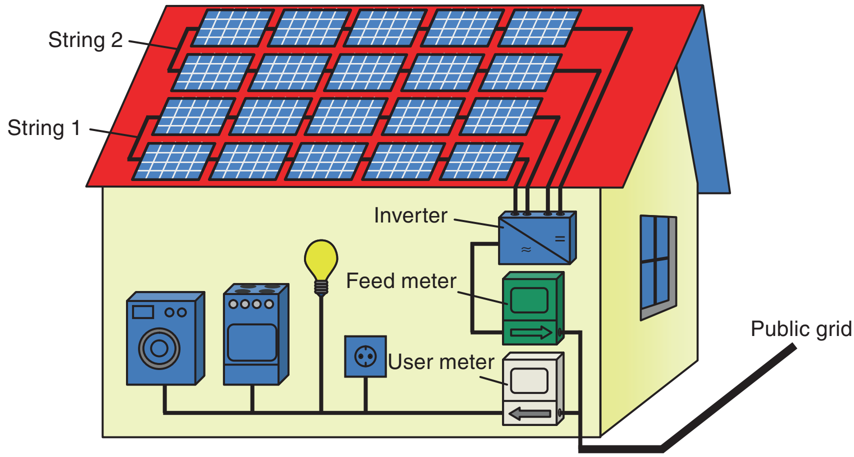

Figure 1.9 Structure of a grid-coupled photovoltaic plant. An inverter converts the direct current supplied by the solar modules into alternating current and feeds it into the public grid

1.5.3 How is a Typical Photovoltaic Plant Structured?

Figure 1.9 shows the structure of a grid-coupled plant typical for Germany. Several solar modules are switched in series into a **string** and connected to an **inverter**. The inverter converts the direct current delivered by the modules into alternating current and feeds it into the public grid. A **feed meter** measures the generated electricity in order to collect payment for the energy generated. The **user meter** counts the current consumption of the household separately.

The plant is financed on the basis of the **Renewable Energy Law (EEG)**. This guarantees that the fed-in **electric energy** is **paid** for by the energy supply company for **20 years** at a guaranteed price. To a certain extent, the owner of the plant becomes a power station operator.

1.5.4 What Does a Photovoltaic Plant "Bring?"

For the owner of a solar power plant the power of his plant is of interest and so is the quantity of energy fed into the grid during the course of a year.

The power of a solar module is measured according to the **Standard-Test-Conditions (STC)** and defined by three limiting conditions:

1. Full Sun radiation (radiation strength $E = E_{STC} = 1000\,W/m^2$)
2. Temperature of the solar module: $\vartheta_{Module} = 25\,°C$
3. Standard light spectrum AM 1.5 (for more details see Chapter 2)

The capacity of the solar module under these conditions is the **rated power** (or **nominal power**) **of the module**. It is given in **Watt-Peak (Wp)** as it actually describes the peak power of the module under optimal conditions.

The **degree of efficiency η_{Module}** of a solar module is the relationship of delivered electric rated power P_{STC} referenced to incidental **optical power P_{Opt}**:

$$\eta_{\text{Module}} = \frac{P_{\text{STC}}}{P_{\text{Opt}}} = \frac{P_{\text{STC}}}{E_{\text{STC}} \cdot A} \tag{1.10}$$

with

A: module surface

The **efficiency** of **silicon solar modules** is in the range of **13–20%**. Besides silicon there are also **other materials** such as cadmium telluride or copper-indium-selenide, which go under the name of **thin film technologies**. These reach module efficiencies of 7–13%.

Example 1.2 Power and yield of a roof plant

Assume that the house owner has a roof area of $40\,\text{m}^2$ available. He buys modules with an efficiency of 15%. The rated power of the plant is:

$$P_{\text{STC}} = P_{\text{Opt}} \cdot \eta_{\text{Module}} = E_{\text{STC}} \cdot A \cdot \eta_{\text{Module}} = 1000 \frac{\text{W}}{\text{m}^2} \cdot 40\,\text{m}^2 \cdot 0.15 = 6\,\text{kWp}$$

In Germany with a South facing rooftop plant the result is typically a **specific yield w_{Year} of approximately 900 kWh/kWp** (kilowatt hours per kilowatt peak) per year. This brings our house owner the following annual yield W_{year}:

$$W_{\text{Year}} = \text{P}_{\text{STC}} \cdot w_{\text{Year}} = 6\,\text{kWp} \cdot 900 \frac{\text{kWh}}{\text{kWp} \cdot \text{a}} = 5400\,\text{kWh/a}$$

In comparison to the **typical electric power consumption of a household** of **3000–4000 kWh per year** the energy quantity is not bad.

■

After this quick course on the subject of photovoltaics we will now consider the quite recent history of solar power generation.

1.6 History of Photovoltaics

1.6.1 How it all Began

In the year **1839** the French scientist **Alexandre Edmond Becquerel** (the father of Antoine Henri Becquerel, after whom the unit of the activity of radioactive material is named) discovered the **photo-electric effect** while carrying out electro-chemical experiments. He placed two coated platinum electrodes in a container with an electrolyte and determined the current flowing between them (see Figure 1.10(a)) . Becquerel found that the strength of the current changed when exposed to light [10]. In this case it was a matter of the outside photo-effect in which electrons move out of a fixed body when exposed to light.

In **1873** the British engineer **Willoughby Smith** and his assistant **Joseph May** discovered that the semiconductor selenium changed its resistance when exposed to light. They thus saw

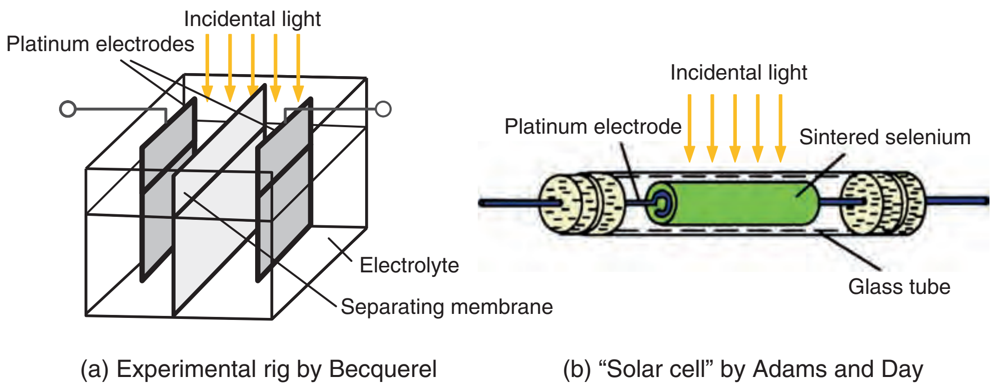

Figure 1.10 The beginnings of photovoltaics: Electrochemical experiment of A.E. Becquerel and the first solar cell by Adams and Day [16,17]

for the first time the internal photo-effect relevant for photovoltaics in which electrons in the semiconductor are torn from their bindings by light and are thus available as free charge carriers in the solid-state body.

Three years later the Englishmen **William Adams** and **Richard Day** found out that a **selenium rod** provided with platinum electrodes can **produce electrical energy** when it is exposed to light (see Figure 1.10(b)) With this it was proven for the first time that a solid body can directly convert light energy into electrical energy.

In 1883 the New York inventor Charles Fritts built a small "**Module**" of selenium cells with a surface area of approximately 30 cm^2 that had an **efficiency of almost 1%**. For this purpose he coated the selenium cells with a very thin electrode of gold. He sent a module to **Werner von Siemens** (German inventor and entrepreneur, 1816–1892) for assessment. Siemens recognized the importance of the discovery and declared to the Royal Academy of Prussia that with this "The direct conversion of light into electricity has been shown for the first time." [11]. As a result Siemens developed a lighting measuring instrument based on selenium.

In the following years the physical background of the photo-effect became better explained. In part this was particularly due to **Albert Einstein** (1879–1955) who presented his **light quantum theory** in 1905, for which he was awarded the Nobel Prize 16 years later. At the same time there were technological advances: in 1916 the Polish chemist **Jan Czochralski** at the AEG Company discovered the **crystal growth process** named after him. With the Czochralski process it became possible to produce semiconductor crystals as single crystals of high quality.

1.6.2 The First Real Solar Cells

In 1950, the co-inventor of the transistor, the American Nobel laureate **William B. Shockley** (1910–1989) presented an explanation of the method of **functioning of the p-n junction** and thus laid the theoretical foundations of the solar cells used today. On this basis, **Daryl Chapin**, **Calvin Fuller and Gerald Pearson** in the Bell Labs developed the **first silicon solar cell** with an area of 2 cm^2 and an **efficiency of up to 6%** and presented it to the public on **25 April 1954** (Figure 1.11) [12]. The *New York Times* published this on its front page the next day and promised its readers "The fulfilment of one of the greatest desires of mankind – the use of the almost limitless energy of the sun."

Figure 1.11 The inventors of the first "real" solar cell: Chapin, Fuller and Pearson. The right hand figure shows the first "solar module" in the world, a mini module of 8 solar cells (Courtesy of AT&T Archives and History Center)

The Bell cell **combined** for the first time the concept of the **p-n junction with the internal photo effect**. In this, the p-n junction serves as conveyor that removes the released electrons. Thus this effect can be more accurately described as the **depletion layer photo-effect** or also as the ***photovoltaic effect***.

In the following years the efficiency was raised to 10%. Because of the high prices of the solar modules (the price per Watt was around 1000 times more than today's price) they were only used for special applications. On the March 17, 1958 the first **satellite with solar cells** on board was launched: the American satellite **Vanguard 1** with two transmitters on board (Figure 1.12). Transmitter 1 was operated by mercury batteries and ceased operation after 20 days. Transmitter No 2 drew its energy from six solar cells attached to the outer skin of the satellite and operated till 1964.

Figure 1.12 View of the *Vanguard I* satellite: Because of the diameter of 16 cm it was also called "Grapefruit" (photo: NASA)

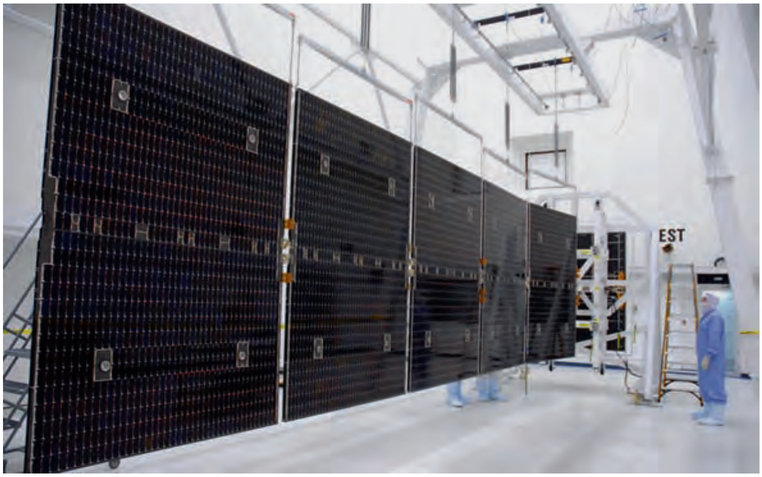

Figure 1.13 Modern solar array of the space probe *Dawn* with a power of 5 kW (photo: NASA)

The success of this project led to **photovoltaics** being used as the **energy source for satellites**. The developments in the 1960s were thus advanced by space flight. Besides the silicon cells the first solar cells of gallium arsenide (GaAs) and other alternative materials were presented.

As a comparison to **Vanguard I**, the Figure 1.13 shows one of the two solar arrays of the 2007 **spacecraft Dawn**. The probe is meant to reach the dwarf planet Ceres in February 2015. The array of 5 kW power is built up of high capacity three-layer stacked cells of InGaP/InGaAs/Ge (see Chapter 5) that achieve an **efficiency of 27.5%** in space [13].

1.6.3 From Space to Earth

The terrestrial use of photovoltaics limited itself first to applications in which the nearest electrical grid was very far away: transmitter stations, signal systems, remote mountain huts, and so on (Figure 1.14). However, a change in thinking was brought about with the oil crisis in 1973. Suddenly alternative sources of energy became the center of interest. In 1977 in the Sandia Laboratories in New Mexico, a **solar module** was developed with the aim of producing a standard product for **economical mass production**.

The accident in the nuclear power plant in Harrisburg (1979) and especially the reactor catastrophe in **Tschernobyl** (1986) increased the pressure on governments to find new solutions in energy supply.

1.6.4 From Toy to Energy Source

From the end of the 1980s research in the field of photovoltaics intensified especially in the USA, Japan and Germany. In addition, research programs were started in the construction of grid-coupled photovoltaic plants that could be installed on single-family homes. In Germany this was first the **1000-roof program** of 1990–1995 that provided valuable knowledge on the reliability of modules and inverters as well as on questions of grid-feeding [14].

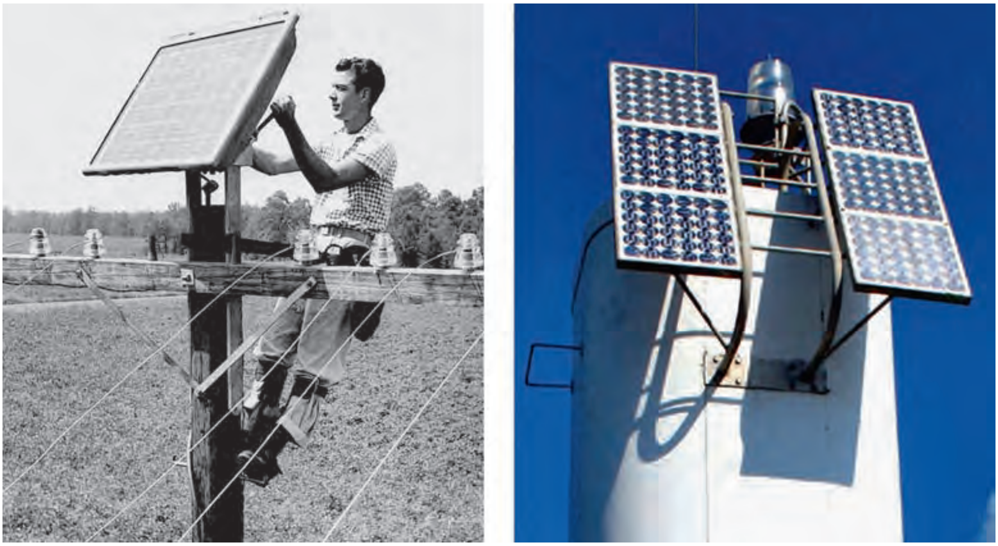

Figure 1.14 Examples of photovoltaic island plants: Telephone booster of 1955 with the legendary Bell Solar Battery and modern solar-driven lighting tower in Australia (photos: Courtesy of AT&T Archives and History Center, Erika Johnson)

The **Energy Feed-in Law** of 1991 obligated energy suppliers to accept power from small renewable power stations (wind, photovoltaics, etc.). Whereas the wind industry developed in a storm of activity, the subsidy of 17 Pfennigs per kWh was not nearly enough for an economical operation of photovoltaic plants. For this reason, environmentalists demanded a higher subsidy for solar power. A key role in this was played by the **Aachen Association for the Promotion of Solar Power (SFV)**. This association achieved that in 1995 the **cost-covering subsidy** at a rate of 2 DM per kWh for power from photovoltaic was introduced, which throughout the Federal Republic became known as the **Aachen Model**.

The 2000 promulgated **Renewable Energy Law** was introduced on the basis of this model. This successor law of the Energy Feed Law defined cost-covering subsidies for various renewable energy sources and led to an unexpected boom in photovoltaics (see Figure 1.15).

Figure 1.15 shows the photovoltaic capacities installed in the various countries over the years. In Germany the total installed photovoltaic capacity increased from 76 MWp in 2000 to approximately 32 GWp in 2012. Thus, up to now, around a third of all worldwide produced modules have been installed in Germany. In second place is Italy with a PV capacity of 16 GWp, which, as in Germany, has been achieved by energy subsidies for solar energy. The USA has installed more than 3 GWp in 2012 resulting in a total installed power of 7.2 GWp. Just behind is Japan with 7 GWp which enforced its PV program after the catastrophe in Fukushima. Spain had relatively high feed-in tariffs some years ago, that led to a short PV boom. This was suddenly stopped by cutting the subsidies; therefore the total installed power of 5 GWp has remained almost the same in the past years. The strongest growth is shown by China, which increased its installed PV capacity in a single year from 3.3 to 7 GWp.

All the other countries not shown individually in Figure 1.15 (Rest of World – ROW) have a total PV capacity of 15 GWp.

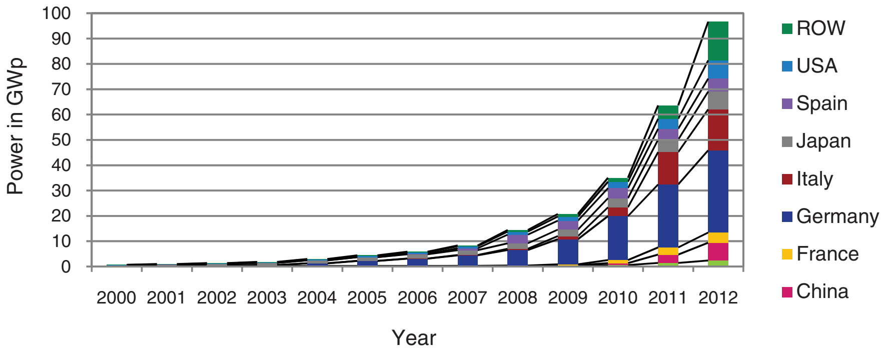

Figure 1.15 Development of the world-wide photovoltaic market (cumulative installed capacity) [15]

Independently of the view of the individual countries, Figure 1.15 emphasizes the **fast growth of photovoltaics in the past years**. The annual installed PV capacity has grown from 217 MWp in 2000 to 25 GWp in 2012, which corresponds to an average annual growth of about 48%!

The possible future development in photovoltaics and its contribution to electric energy consumption is dealt with in Chapter 10.