Part I

Introduction

1 Energy

As this book is on *Solar Energy*, it is good to start the discussion with some general thoughts on *Energy*. We will begin with a quote from *The Feynman Lectures on Physics*.

> There is a fact, or if you wish, a *law*, governing all natural phenomena that are known to date. There is no known exception to this law—it is exact so far as we know. The law is called the *conservation of energy*. It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same.
>
> ...
>
> Energy has a large number of *different forms*, and there is a formula for each one. These are: gravitational energy, kinetic energy, heat energy, elastic energy, electrical energy, chemical energy, radiant energy, nuclear energy, mass energy. If we total up the formulas for each of these contributions, it will not change except for energy going in and out.
>
> It is important to realise that in physics today, we have no knowledge of what energy is. We do not have a picture that energy comes in little blobs of a definite amount. It is not that way. However, there are formulas for calculating some numerical quantity,

and when we add it all together it gives ... always the same number. It is an abstract thing in that it does not tell us the mechanism or the reasons for the various formulas [1].

1.1 Some definitions

We will now state some basic physical connections between the three very important physical quantities of *energy, force, and power*. These connections are taken from classical mechanics but generally valid. We start with the *force* F, which is any influence on an object that changes its motion. According to Newton's *second law*, the force is related to the acceleration a of a body via

$$\mathbf{F} = m\mathbf{a}, \tag{1.1}$$

where m is the mass of the body. The bold characters denote that $\mathbf{F}$ and $\mathbf{a}$ are vectors. The unit of force is *Newton* (N), named after Isaac Newton (1642-1727). It is defined as the force required to accelerate the mass of 1 kg at an acceleration rate of 1 m/s^2, hence 1 N = 1 kg·m/s^2.

In mechanics, energy E, the central quantity of this book, is given as the product of force times distance,

$$E = \int F(s)\,\mathrm{d}s, \tag{1.2}$$

where s denotes distance. Energy is usually measured in the unit of *Joule* (J), named after the English physicist James Prescott Joule (1818-1889), which it defined as the amount of energy required applying the force of 1 Newton through the distance of 1 m, 1 J = 1 Nm.

Another important physical quantity is the *power* P, which tells us the rate of doing work, or, which is equivalent, the amount of energy consumed per time unit. It is related to energy via

$$E = \int P(t)\,\mathrm{d}t, \tag{1.3}$$

where t denotes the time. The power is usually measured in *Watt* (W), after the Scottish engineer James Watt (1736-1819). 1 W is defined as one Joule per second, 1 W = 1 J/s and 1 J = 1 Ws.

As we will see later on, 1 J is a very small amount of energy compared to the human energy consumption. Therefore, in the energy markets, such as the electricity market, often the unit *Kilowatt hour* (kWh) is used. It is given as

$$1\,\mathrm{kWh} = 1000\,\mathrm{Wh} \times 3600\,\frac{\mathrm{s}}{\mathrm{h}} = 3\,600\,000\,\mathrm{Ws}. \tag{1.4}$$

On the other hand, the amounts of energy in solid state physics, the branch of physics that we will use to explain how solar cells work, are very small. Therefore, we will use the unit of *electron volt*, which is the energy a body with a charge of one elementary charge ($e = 1.602 \times 10^{-19}$ C) gains or looses when it is moved across a electric potential difference of 1 Volt (V),

$$1\,\mathrm{eV} = e \times 1\,\mathrm{V} = 1.602 \times 10^{-19}\,\mathrm{J}. \tag{1.5}$$

1.2 Human and world energy consumption

After this somewhat abstract definitions we will look at the *human energy consumption*. The human body is at a constant temperature of about 37°C. It hence contains *thermal energy*. As the body is continuously cooled by the surroundings, thermal energy is lost to the outside. Further, blood is pumped through the blood vessels. As it travels through the vessels, its *kinetic energy* is reduced because of internal friction and friction at the walls of the blood vessels, *i.e.* the kinetic energy is converted into heat. To keep the blood moving, the heart consumes energy. Also, if we want our body to move this consumes energy. Further, the human brain consumes a lot of energy. All this energy has to be supplied to the body from the outside, in the form of food. A grown up average body requires about 10 000 Kilojoule every day.[1] We can easily show that this consumption corresponds to an average power of the human body of 115.7 W. We will come back to this value later.

In modern society, humans do not only require energy to keep their body running, but in fact we consume energy for many different purposes. We use energy for heating the water in our houses and for heating our houses. If water is heated, its thermal energy increases, and this energy must be supplied. Further, we use a lot of energy for transportation of people and products by cars, trains, trucks and planes. We use energy to produce our goods and also to produce food. At the moment, you are consuming energy if you read this book on a computer or tablet. But also if you read this book in a printed version, you implicitly consumed the energy that was required to print it and to transport it to you place.

As we mentioned already above, energy is never produced but always converted from one form to another. The form of energy may change in time, but the total amount does not change. If we want to utilise energy to work for us, we we usually convert it from one form to another more useable form. An example is the electric motor, in which we convert electrical energy to mechanical energy.

Modern society is very much based on the capability

[1] The energy content of food usually is given in the old-fashioned unit of kilocalories (kcal). The conversion factor is 1 kcal = 4.184 kJ. An average male human requires about 2500 kcal a day.

Table 1.1: Total primary energy consumption per capita and average power used per capita of some countries in 2011 [2].

Country	Energy consumption (kWh/capita)	Average power use (W/capita)
U.S.A.	81 642	9 319
Netherlands	53 963	6 160
Germany	44 310	5 058
China	23 608	2 695
India	6 987	797

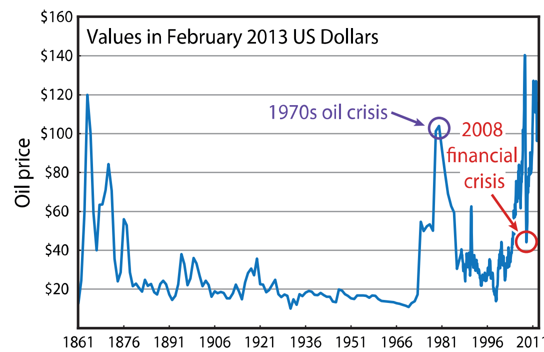

Figure 1.1: The history of the oil price normalised to the February 2013 value of the U.S. Dollar [3].

of us humans to covert energy from one form to another form. The most prosperous and technologically developed nations are also the ones which have access to and are consuming the most energy per inhabitant. Table 1.1 shows the primary energy consumption per capita and the average power consumed per capita for several countries. We see that the average U.S. citizen uses an average power of 9 319 W, which is about 80 times what his body needs. In contract, an average citizen from India only uses about 800 W, which is less then a tenths of the U.S. consumption.

Many people believe that tackling the *energy problem* is amongst the biggest challenges for human kind in the 21st century. It is a challenge because of several problems: The first challenge the human kind is facing is a supply-demand problem. The demand is continuously growing. The world population is still rapidly growing, and some studies predict a world population of 9 billion around 2040 in contrast to the 7 billion people living on the planet today. All these people will need energy, which increases the global energy demand. Further, in many countries the living standard is rapidly increasing like China and India, where approximately 2.5 billion people are living, which represents more than a third of the World's population. Also the increasing living standards lead to an increased energy demand.

According to the IEA World Energy Outlook 2013, the

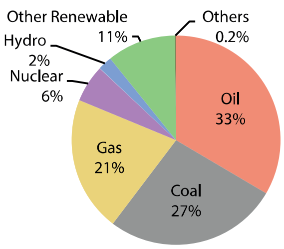

Figure 1.2: The primary energy consumption of the world by source in 2008. The total supply was 143 851 TWh [5].

global energy demand will grow about one third from 2011 to 2013 [4]. The increasing demand in energy has economic impact, as well. If there is more demand for a product, while supply does not change much, the product will get more expensive. This basic market mechanism is also true for Energy. As an example we show a plot of the annual averaged price for an oil barrel, normalised to the value of the 2008 US Dollar in Fig. 1.1. We see that prices went up during the oil crisis in the 1970s, when some countries stopped producing and trading oil for a while. The second era of higher oil prices started at the beginning of this millennium. Due to the increasing demand from new growing economies, the oil prices have been significantly increased.

A second challenge that we are facing is related to the fact that our energy infrastructure heavily depends on fossil fuels like oil, coal and gas. Fossil fuels are nothing but millions and millions of years of solar energy stored in the form of chemical energy. The problem is that humans deplete these fossil fuels much faster than they are generated through the photosynthetic process in nature. Therefore fossil fuels are not a sustainable energy source. The more fossil fuels we consume, the less easily available gas and oil resources will be available. Already now we see that more and more oil and gas is produced with *unconventional* methods, such as extracting oil from tar sands in Alberta, Canada and producing gas with fracturing such as in large parts of the United States. This new methods use much more energy to get the fossil fuels out of the ground. Further, off-shore drilling is put regions with ever larger water depths, which leads to new technological risks as we have seen in the Deepwater Horizon oil spill in the Gulf of Mexico in 2010.

A third challenge is that by burning fossil fuels we produce the so-called greenhouse gases like carbon dioxide (CO_2). The additional carbon dioxide created by human activities is stored in our oceans and atmosphere. Figure 1.3 shows the increase in carbon dioxide concentration in the Earth's atmosphere up to 2000. According to the International Panel on Climate Change (IPCC) Fifth Assessment Report (AR5),

> The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Car-

> bon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification [7].

Further, in the AR5 it is stated that

> Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system [7].

and

> Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. This evidence for human influence has grown since AR4. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century [7].

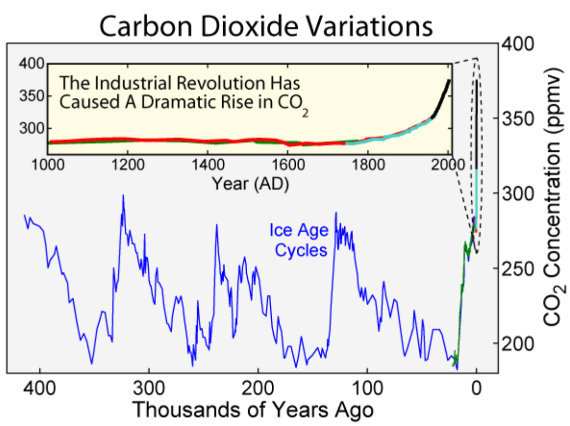

Figure 1.3: The atmospheric CO_2 content in the last 400 000 years [6].

Hence, it seems very clear that the increase in carbon dioxide is responsible for the global warming and climate change, which can have drastic consequences of the habitats of many people.

Since the beginning of the industrial revolution, mankind is heavily dependent on fossil fuels. Within a few centuries, we are using solar energy that was incident on Earth for hundreds of millions of years, converted in to chemical energy by the photosynthetic process and stored in the form of gas, coal and oil.

Before the industrial revolution, the main source of energy was wood and biomass, which is a secondary form of solar energy. The energy source was replenished in the same characteristic time as the energy being consumed. In the pre-industrial era, mankind was basically living on a secondary form of solar energy. However, also back then the way we consumed energy was not fully sustainable. For example, deforestation due to increasing population density was already playing a role at the end of the first millennium.

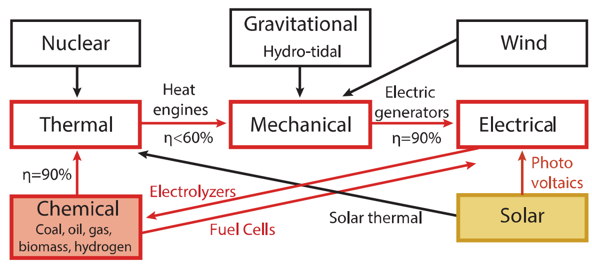

Figure 1.4: The different energy carriers and how we utilise them [8].

1.3 Methods of Energy Conversion

Figure 1.4 shows different energy sources and the ways we utilise them. We see that usually the chemical energy stored in fossil fuels is converted to usable forms of energy via heat by burning, with an efficiency of about 90%. Using heat engines, thermal energy can be converted in to mechanical energy. Heat engines have a conversion efficiency of up to 60%. Their efficiency is ultimately limited by the Carnot efficiency limit that we will discuss in Chapter 10. The far majority of the current cars and trucks works on this principle. Mechanical energy can be converted in to electricity using electric generators with an efficiency of up to 99%. Most of the World's electricity is generated with an *turbo generator* that is connected to a steam turbine, where the coal is the major energy source. This process is explained in more detail in our discussion on solar thermal electric power in Chapter 20. Along all the process steps of making electricity out of fossil fuels, at least 50% of the initial available chemical energy is lost in the various conversion steps.

Chemical energy can be directly converted into electricity using a fuel cell. The most common fuel used in fuel cell technology is hydrogen. Typical conversion efficiencies of fuel cells are 60%. A regenerative fuel cell can operate in both directions and also convert electrical energy into chemical energy. Such an operation is called *electrolysis*; typical conversion efficiencies of hydrogen electrolysers of 50-80% have been reported. We will discuss electrolysis in more detail in Chapter 21.

In *nuclear power plants*, energy is released as heat during *nuclear fission* reactions. With the heat steam is generated that drives a steam turbine and subsequently an electric generator just as in most fossil fuel power plants.

1.3.1 Renewable energy carriers

All the energy carriers discussed above are either fossil or nuclear fuels. They are not renewable because they are not "refilled" by nature, at least not in a useful amount of time. In contrast, *renewable energy carriers* are energy carriers that are replenished by natural processes at a rate comparable or faster than its rate of consumption by humans. Consequently, hydro-, wind- and solar energy are renewable energy sources.

Hydroelectricity is an example of an energy conversion technology that is not based on heat generated by fossil or nuclear fuels. The potential energy of rain falling in mountainous areas or elevated plateaus is converted into electrical energy via a *water turbine*. With *tidal pools* the potential energy stored in the tides can also be converted to mechanical energy and subsequently electricity. The kinetic energy of *wind* can be converted into mechanical energy using wind mills.

Finally, the energy contained in sunlight, called *solar energy*, can be converted into electricity as well. If this energy is converted into electricity directly using devices based on semiconductor materials, we call it *photovoltaics* (PV). The term *photovoltaic* consists of the greek word $\phi\omega\varsigma$ (phos), which means light, and -volt, which refers to electricity and is a reverence to the Italian physicist Alessandro Volta (1745-1827) who invented the battery. As we will discuss in great detail in this book, typical efficiencies of the most commercial *solar modules* are in the range of 15-20%.

Solar light can also be converted into heat. This application is called *solar thermal energy* and is discussed in detail in Chapter 20. Examples are the heating of water flowing through a black absorber material that is heated in the sunlight. This heat can be used for water heating, heating of buildings or even cooling. If concentrated solar power systems are temperatures of several hundreds of degrees are achieved, which is sufficient to generate steam and hence drive a steam turbine and a generator to produce electricity.

Next to generating heat and electricity, solar energy can be converted in to chemical energy as well. This is what we refer to as *solar fuels*. For producing solar fuels, photovoltaics and regenerative fuel cells can be combined. In addition, sunlight can also be directly converted into fuels using photoelectrochemical devices. We will discuss solar fuels in Chapter 21.

We thus see that solar energy can be converted into electricity, heat and chemical energy. The sun has is energy source for almost all the processes that happen on the surface of our planet. Wind is a result of temperature difference in the atmosphere induced by solar irradiation, waves are generated by the wind, clouds and rain are initially formed by the evaporation of water due to sun light. As the sun is the only real energy source we have, we need to move to an era in which we start to utilise the energy provided by the sun directly to satisfy our energy needs. The aim of this book is to teach the reader how solar energy can be utilised directly.

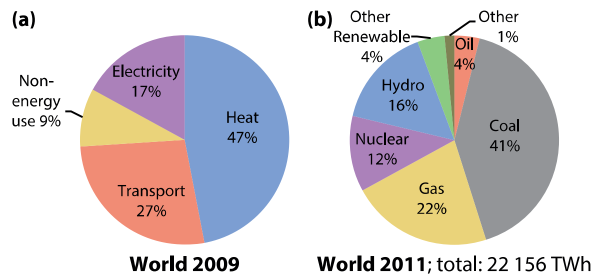

Figure 1.5: (a) The final energy consumption by energy service [9] and (b) the energy carriers used for electricity generation [10].

1.3.2 Electricity

As we see in Fig. 1.5 (a), 17% of all the World's secondary energy is used as electricity, which is a form of energy that can be easily and cheaply transported with relative small losses through an electric grid. It is important to realise that without electricity modern society as we know it would not be possible. Electricity has been practically used for more than 100 years now. It provides us the energy to cook food, to wash, to do the laundry, illuminate the house and streets, and countless other applications. The access to electricity to electricity strongly determines the our living standard. Despite this importance of electricity, in 2009 still about 1.3 billion people had no access to electricity.

As we see in 1.5 (b), about 65% of the electricity is generated using fossil fuels, where coal is the dominant contributor. As coal emits about twice as much CO_2 per generated kWh as natural gas, coal power plants are a major contributor to global warming. Nuclear is responsible for 16% of the World's electricity generation. With 19%, hydroelectricity is by far the largest contributor among the renewable energy sources.

Of all the generated electricity, about 40% of the electric energy is used for residential purposes and 47% is used by industry. 13% is lost in transmission. As you can see, in 2007, transport did not play a significant role in

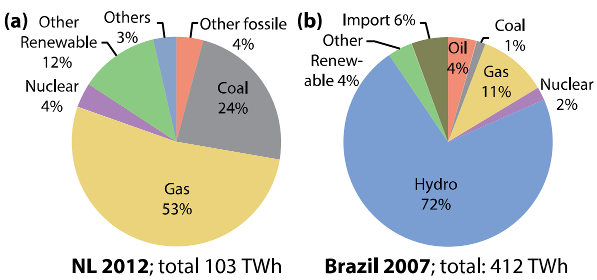

Figure 1.6: The energy mix used for electricity production in (a) the Netherlands [11] and (b) Brazil [12].

the electricity consumption. However, this is expected to change as electric cars are becoming more and more important.

Figure 1.6 shows which energy carriers are mainly used for electricity generation in the Netherlands and Brazil. We see that in the Netherlands, electricity generation heavily depends on the local gas resources, whereas in Brazil hydroelectricity is the most important resource.

2

Status and prospects of PV technology

In this Chapter we will give a brief overview on the current status of the PV technology and discuss its prospects.

In Fig. 2.1 the global production of PV modules in recent years is shown. The vertical axis represents the annual production expressed in the total produced power capacity in MW_p. The letter p denotes *peak power*, this means the maximum power a PV module can deliver if it is illuminated with the standardised AM1.5 solar spectrum, which we introduce in Section 5.5. On the horizontal axis the time is shown. We see that the solar cell production is increasing more than 40% every year, which is exponential growth.

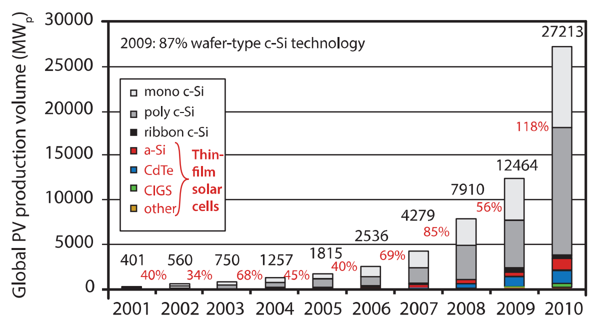

Figure 2.1: The global PV production volume in recent years REFERENCE.

Figure 2.2 shows the worldwide cumulative installed

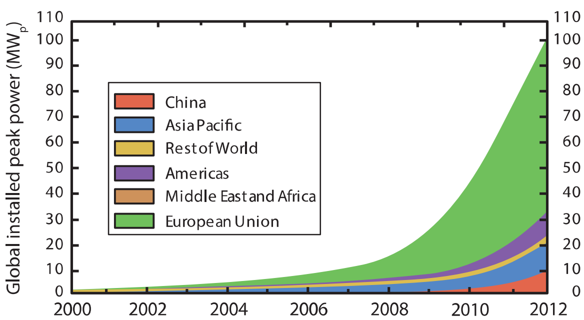

Figure 2.2: The global installed PV capacity (Data from [13]).

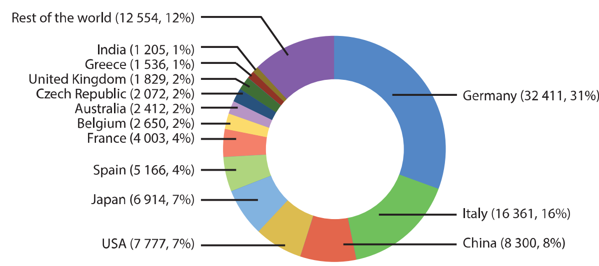

Figure 2.3: Fraction of PV installations for different countries by the end of 2012 (Data from [13]).

PV power, which is exponentially increasing in time as well. By far the largest share is installed in Europe. It is followed by the Asia Pacific Region, where most of the PV power is installed in Japan. For China we observe a very strong increase in installed PV power since 2010. By the end of 2012 the 100 GW_p threshold was passed for the first time [13]. By the end of 2013, already almost 140 GW_p was installed around the globe [14]. Of all the installed PV power at the end of 2013, almost one third was installed in 2013 alone!

In Fig. the installed PV power in several countries at the end of 2012 is shown. About 31% of the total PV capacity is installed in Germany. This is a result of the German government's progressive feed-in-tariff policy that was introduced in 2000 [15].[1] Considering that Germany lies within an area with a relatively low radiation level that is comparable to that of Alaska [16], the large contribution of solar electricity to Germany's electricity production indicates the promising potential of solar energy for the sunnier parts of the world.

A very strong increase also is observed in Italy, which accounts for 16% of the world wide PV capacity. China with a contribution of 8% is the fastest growing market at the moment, in 2010, China only contributed with 2% to the global PV capacity. Within the top six, we also find the United States, Japan and Spain. Their PV capacity contributes between 4% (Spain) and 7% (U.S.A.). Also Japan shows a strong growth in PV installations.

[1] We will discuss the *feed-in tariff* scheme in Chapter 19.

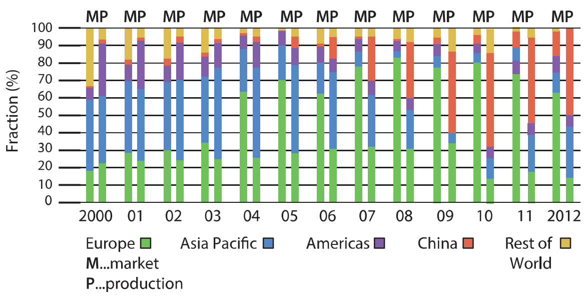

Figure 2.4: Development of the market and production shares of different PV markets since 2000 (Data from [13]).

After the *Fukushima Daiichi nuclear disaster* on 11 March 2011 the Japanese government introduced some progressive feed-in tariffs to promote and accelerate the introduction of renewable energy conversion technologies.

It is interesting to see that PV technology is not only a European affair. The local demand and supply has been changing rapidly in the last 13 years, which is illustrated in Fig. 2.4. This figure illustrates the evolution of the world-wide supply and demand of PV modules in the various regions around the world. We see that in 2000 the biggest market was Japan with a total share of 40%. In 2000, Germany introduced the *Erneuerbare Energie Gesetz* (Renewable Energy act) which induced a strong growth of the German and hence the European PV market. By 2008, Europe had a market share of more than 80%. Back then, PV was mainly a European industry. Starting from 2009, the domestic PV markets in China, the Americas (mainly U.S.) and Asia Pacific (mainly Japan) are increasing very rapidly and catching up quickly with Europe.

Figure 2.4 also shows the supply side. Up to 2005 we see that the Asia Pacific and the Europe production shares were slowly increasing, as their growth was faster than that of the other regions. Since then the picture changed drastically! Since then the Chinese production share was increasing very strongly. This can be explained by the fact that the Chinese government made huge investments in order to scale up PV module manufacturing in China. In 2012, around 60% of all PV modules were produced in China.

In 2000, the PV markets was an essentially local, meaning the European companies produced for the European market *etc*. The local demands and supplies in Asia, the Americas and Europe were in balance. In the last years, the market has become a global market. As a result, in 2012 no local balance between supply and demand existed anymore. While the majority of the demand is in Europe, the majority of the production is in China.

The demand also is strongly stimulated by the decreasing cost price of PV technology. Figure 2.5 shows the *learning curve* of PV technology. The learning curve

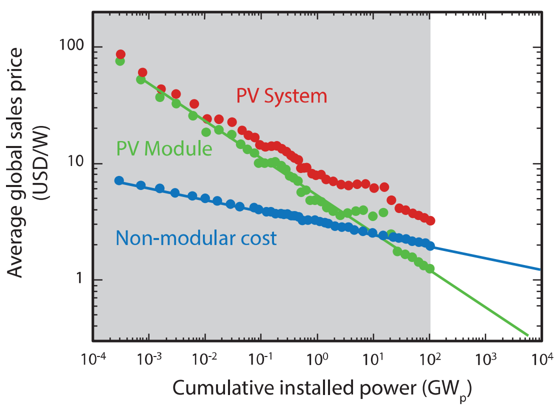

Figure 2.5: The learning curve for PV modules and PV systems (Data from [17]).

shows in a graphical way, how the cost price develops with increasing experience, where the experience is expressed by the cumulatively installed PV capacity. With more PV produced — and hence also with time — the PV industry gets more experienced. On the one hand, the industry learns to increase the *energy conversion efficiency* without increasing the cost via better and better understanding the production process and hence increasing the *production yield*. On the other hand, industry also learns to produce more efficiently, which means that the man power required per production unit can be reduced. Also, the materials and energy required for producing the PV modules becomes less and less per production unit. In addition, also up-scaling reduces the cost. Learning curves usually show an exponentially decreasing cost price, until the technology or product is fully developed.

In Fig. 2.5, the averaged global sales prices of a PV module versus the cumulative installed power up to 20 GW is shown. Note, that the points up to 20 GW (up to 2009) in the grey area are real data points, while the points in white area are extrapolation of the general trend. It is important to note that the sales prices, except for some fluctuations, follow a largely exponential decay. Currently, the average retail price of PV modules is below 1 US Dollar per Watt-peak. However, cost price of a PV system is not only determined by the module. The red dots show the decrease in the cost price of complete PV systems. While in the early days of the PV technology, the system price was dominated by the module price, currently, the cost of the *non-modular components* of PV systems are getting more and more dominant. With non-modular components, we refer to components such as the the racking, wiring, inverter, batteries for stand-alone systems, and also the maintenance costs. All these components are discussed in detail in Chapter 17. The difference between the red and green line corresponds to the non-modular costs, which is dropping much slower than that of the PV modules.

As a consequence, PV technologies with higher energy conversion efficiencies have an advantage, as with higher efficiency less area is required to install the same PV power. As the area is directly linked to the non-modular costs, technologies with higher efficiencies require less modular costs which has an positive effect on the cost price of the complete PV system. Consequently, the c-Si PV technology, with module efficiencies ranging from 14% up to 20% has an advantage with respect to thin-film technologies, that have lower efficiencies.

In Chapter **??** we have seen that hydropower is responsible for 17% of the total worldwide electricity production while 12% of the electricity is generated in nuclear power plants. Howe do these numbers compare to solar electricity? This question is answered in Fig. 2.6 (a), where the installed capacity (in GW) of several electricity generation technologies is shown on a logarithmic scale. The figure only considers electricity generation technologies that are not dependent on fossil fuels. We see that the installed nuclear power capacity is hardly growing anymore, while the installed hydropower is still slightly growing in time. Wind is growing at a much faster rate of 20% per year. Solar has by far the largest growth rate with an annual increase of installed capacity exceeding 40% since 2008.

However, it is not fair to compare the installed power between technologies like this, because the numbers shown in the graph represent the maximum (peak) power the different technologies can generate instead of the average power they have delivered in reality. The relationship between the totally installed power and the power generated on average is called the *capacity factor* C_F. Of the technologies shown in Fig. 2.6 (a) nuclear has by far the highest capacity factor with $C_F(\text{nuclear}) = 90\%$ followed by hydropower with $C_F(\text{hydro}) = 40\%$. For wind electricity we assume $C_F(\text{wind}) = 30\%$ and for solar electricity $C_F(\text{solar}) = 15\%$. The low capacity factor for PV systems can be explained by the fact that for most geographical locations, almost half of the solar day is devoid of solar radiation at night time.

Figure 2.6 (b) shows the effective installed power corrected with the capacity factors. Currently solar energy generates about an order of magnitude less electricity than wind energy and more than two orders of mag-

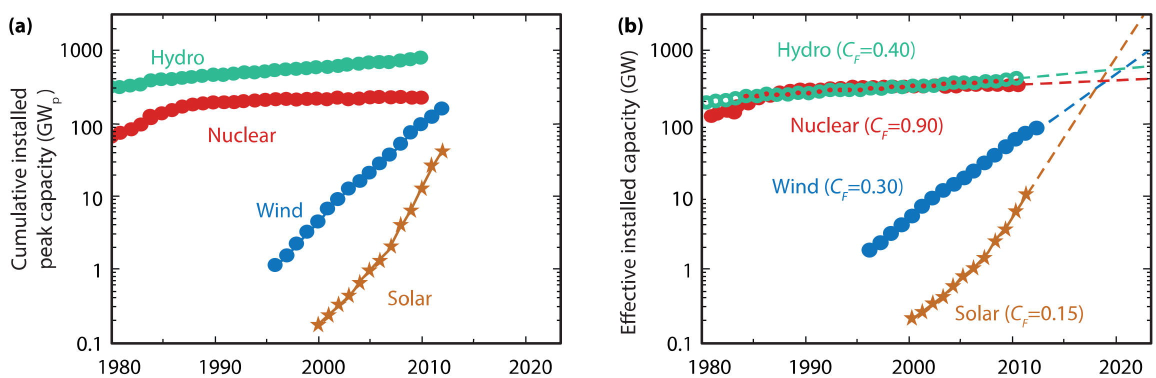

Figure 2.6: (a) Development of the installed capacity (in GW) of several electricity generation technologies since 1980. (b) The same graph corrected by the capacity factor C_F and extrapolated until 2020.

nitude less than hydro and nuclear electricity. Seen the development in recent years we however can claim that the trend in the growth of solar energy will continue the coming years. If we therefore extrapolate the trends of the last decade until 2020 we see that the installed power of solar energy will exceed nuclear, wind and hydropower by then. It is just a matter of time until solar electricity will be the most important electricity generation technology that is not based on combustion of fossil fuels.

Of course, we have to justify why solar electricity can grow much faster than the other technologies shown in Fig. 2.6. First, solar radiation is available everywhere on Earth and it is available in great abundance. The amount of solar energy incident on Earth is about 10 000 time larger than the *total* energy[2] consumption of mankind. As hydroelectricity is powered by water that is evaporated by the sun and falls on the ground as rain, it is a secondary form of solar energy. Also wind arises from temperature and pressure differences of the atmosphere and hence also is a secondary form of solar energy. As a consequence, solar energy is by far the largest available form of renewable energy.

Secondly, hydro- and nuclear electricity are *centralised* electricity generation technologies. For hydro power plants, big dams are needed. Also nuclear power plants have large power rates at about 1 GW. Building new hydro and nuclear power plants requires large public or private investments. While solar electricity can be generated in large PV parks or solarthermal power plants (see Chapter 20) as well, it has an unique advantage: PV systems can be installed decentralised on every roof. Electricity consumers can generate a least a part of their required electricity in their own homes, which makes them partially independent of the electricity market. In addition, the cost price of PV systems has dropped below grid parity in large parts of the world [18]. This means, that averaged during the lifetime of the PV system PV generated electricity is cheaper than electricity from the grid.

We believe that the installation of decentralised PV systems will be the big force behind the solar revolution in the coming years. It will change the energy landscape much faster than most people think, which is justified in Fig. 2.6 (b). As more and more people become aware of these facts, it is more likely that the growth will be further enhanced than it will be slowed down.

[2] We really mean the *total* human energy consumption and not only electricity!

3 The Working Principle of a Solar Cell

In this chapter we present a very simple model of a solar cell. Many notions presented in this chapter will be new but nonetheless the great lines of how a solar cell works should be clear. All the aspects presented in this chapter will be discussed in larger detail in the following chapters.

The working principle of solar cells is based on the *photovoltaic effect*, *i.e.* the generation of a potential difference at the junction of two different materials in response to electromagnetic radiation. The photovoltaic effect is closely related to the photoelectric effect, where electrons are emitted from a material that has absorbed light with a frequency above a material-dependent threshold frequency. In 1905, Albert Einstein understood that this effect can be explained by assuming that the light consists of well defined energy quanta, called *photons*. The energy of such a photon is given by

$$E = h\nu, \tag{3.1}$$

where h is Planck's constant and ν is the frequency of the light. For his explanation of the photoelectric effect Einstein received the Nobel Prize in Physics in 1921 [19].

The photovoltaic effect can be divided into three basic processes:

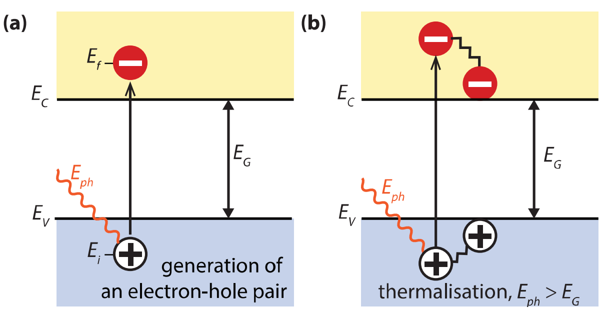

Figure 3.1: (a) Illustrating the absorption of a photon in a semiconductor with bandgap E_g. The photon with energy $E_{\text{ph}} = h\nu$ excites an electron from E_i to E_f. At E_i a hole is created. (b) If $E_{\text{ph}} > E_g$, a part of the energy is thermalised.

1. Generation of charge carriers due to the absorption of photons in the materials that form a junction.

Absorption of a photon in a material means that its energy is used to excite an electron from an initial energy level E_i to a higher energy level E_f, as shown in Fig. 3.1 (a). Photons can only be absorbed if electron energy levels E_i and E_f are present so that their difference equals to the photon energy, $h\nu = E_f - E_i$. In an ideal semiconductor electrons can populate energy levels below the so-called *valence band* edge, E_V, and above the so called *conduction band* edge, E_C. Between those two bands no allowed energy states exist, which could be populated by electrons. Hence, this energy difference is called the *bandgap*, $E_g = E_C - E_V$. If a photon with an energy smaller than E_g reaches an ideal semiconductor, it will not be absorbed but will traverse the material without interaction.

In a real semiconductor, the valence and conduction bands are not flat, but vary depending on the so-called k-vector that describes the crystal momentum of the semiconductor. If the maximum of the valence band and the minimum of the conduction band occur at the same k-vector, an electron can be excited from the valence to the conduction band without a change in the crystal momentum. Such a semiconductor is called a *direct bandgap* material. If the electron cannot be excited without changing the crystal momentum, we speak of an *indirect bandgap* material. The absorption coefficient in an direct bandgap material is much higher than in an indirect bandgap material, thus the absorber can be much thinner [20].

If an electron is excited from E_i to E_f, a void is created at E_i. This void behaves like a particle with a positive elementary charge and is called a *hole*. The absorption of a photon therefore leads to the creation of an electron-hole pair, as illustrated in Fig. 3.2 ❶. The *radiative energy* of the photon is *converted* to the *chemical energy* of the electron-hole pair. The maximal conversion efficiency from radiative energy to chemical energy is limited by thermodynamics. This *thermodynamic limit* lies in between 67% for non-concentrated sunlight and 86% for fully concentrated sunlight [21].

The basic physics required for describing semiconductors is presented in chapter 6.

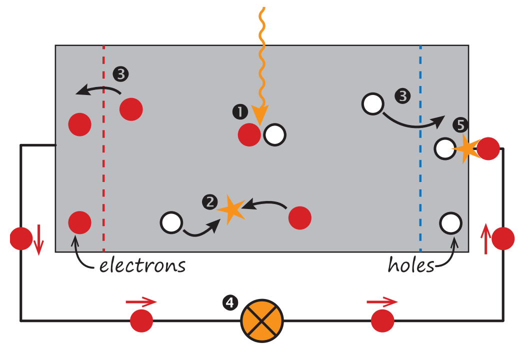

Figure 3.2: A very simple solar cell model. ❶ Absorption of a photon leads to the generation of an electron-hole pair. ❷ Usually, the electrons and holes will combine. ❸ With semi-permeable membranes the electrons and the holes can be separated. ❹ The separated electrons can be used to drive an electric circuit. ❺ After the electrons passed through the circuit, they will recombine with holes.

2. Subsequent separation of the photo-generated charge carriers in the junction.

Usually, the electron-hole pair will recombine, *i.e.* the electron will fall back to the initial energy level E_i, as illustrated in Fig. 3.2 ❷. The energy will then be released either as photon (*radiative recombination*) or transferred to other electrons or holes or lattice vibrations (*non-radiative recombination*). If one wants to use the energy stored in the electron-hole pair for performing work in an external circuit, *semipermeable membranes* must be present on both sides of the absorber, such that electrons only can flow out through one membrane and holes only can flow out through the other membrane [21], as illustrated in Fig. 3.2 ❸. In most solar cells, these membranes are formed by *n*- and *p*-type materials.

A solar cell has to be designed such that the electrons and holes can reach the membranes before they recombine, *i.e.* the time it requires the charge carriers to reach the membranes must be shorter than their lifetime. This requirement limits the thickness of the absorber.

We will discuss generation and recombination of electrons and holes in detail in chapter 7.

3. Collection of the photo-generated charge carriers at the terminals of the junction.

Finally, the charge carriers are extracted from the solar cells with electrical contacts so that they can perform work in an external circuit (Fig. 3.2 ❹). The *chemical energy* of the electron-hole pairs is finally converted to *electric energy*. After the electrons passed through the circuit, they will recombine with holes at a metal-absorber interface, as illustrated in Fig. 3.2 ❺.

Loss mechanisms

The two most important *loss mechanisms* in single bandgap solar cells are the inability to convert photons with energies below the bandgap to electricity and thermalisation of photon energies exceeding the bandgap, as illustrated in Fig. 3.1 (b). These two mechanisms alone amount to the loss of about half the incident solar energy in the conversion process [22]. Thus, the maximal energy conversion efficiency of a single-junction solar cell is considerably below the thermodynamic limit. This *single bandgap limit* was first calculated by Shockley and Queisser in 1961 [23].

A detailed overview of loss mechanisms and the resulting efficiency limits is discussed in Chapter 10.