SOLAR ENERGY

THE PHYSICS AND ENGINEERING OF PHOTOVOLTAIC CONVERSION TECHNOLOGIES AND SYSTEMS

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Solar energy

The physics and engineering of photovoltaic conversion, technologies and systems

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Foreword

The implementation of a sustainable world-wide energy supply system is one of the most important measures to be taken to prevent further climate change. Solar energy can play an instrumental role in such a system. Solar energy is abundantly available and is a very versatile energy source.

Solar energy has been used for heating for centuries. Since the invention of the crystalline silicon solar cell by Gerald Pearson, Daryl Chapin and Calvin Fuller in 1954, solar cells have become a very important option for the large scale production of solar electricity. In 2015 photovoltaic electricity already contributes 1% to the global electricity production. The 2014 IEA Roadmaps for Solar Photovoltaic and Solar Thermal Electricity envisage a total share of 27% of the global electricity production by 2050.

Solar energy is used already for supplying small amounts of electricity and heat in rural areas, thereby contributing to the economic development of these areas. Millions of small photovoltaic systems are operational, providing energy, for example, for lighting and telecommunications. Solar energy systems can be integrated very well in the built environment and are contributing substantially to the impressive growth of the utilisation of solar energy that we see today. Solar energy can be used for large scale production of electricity in power plants by means of flat plate and concentrator photovoltaic (PV) systems, as well as by thermal concentrated solar power (CSP) systems.

The utilisation of solar energy is growing very fast. In addition, the goals for solar energy as laid down in government policies on national and European level are very ambitious. As a result many newcomers are entering the field, taking up the challenges. In order to do so, adequate training and education is required. The training needs to be focussed on each level, e.g. the academic level, the level of the system engineer, the level of installers, etc.

The solar-energy field and in particular photovoltaics is very broad. The field of photovoltaics ranges from optics, material and device physics for solar-cell development, to module and power electronics required for the design of complete stand alone and grid-connected systems. For the newcomer to the field, but also for the specialist, it is often difficult to obtain a good overview of the whole field. On one hand it is important that cell and module designers have enough basic knowledge of photovoltaic systems and applications. On the other hand system designers should have sufficient knowledge of the various solar-cell technologies to make the right selection, and once the selection is made, how to use the cells for optimum energy yield.

In this book, first a comprehensive and clear treatment of the fundamental aspects of photovoltaic energy conversion is given. Subsequently, both existing and emerging solar-cell technologies are discussed, and a number of new approaches for future efficiency improvements, like spectral conversion, are introduced. Next an introduction is given into both off-grid and grid-connected photovoltaic systems. This book is completed with an overview of other solar technologies such as flat plate solar collectors and CSP technologies, and solar fuels.

This is an excellent book for education and self-teaching at academic level, but it can also be used by those having a technical background. Though the emphasis is on photovoltaics, the book gives a very good overview of other solar-energy technologies as well.

June 2015

Ronald J. Ch. van Zolingen
Emeritus professor
Eindhoven University of Technology

Dean's message

Providing the world with energy in an environmentally sustainable and climate friendly way poses one of the greatest challenges to mankind. Solar energy will play a prominent role in the generation of electrical energy, whose global consumption is growing even faster than the total energy consumption. The rapid growth of the use of electrical energy is driven by the pervasive digitization of our society, rapid urbanization and the growth of public and private electrical transportation. Annually, the global production of energy is close to a Zetta joule (10^{21} J), of which about 20% of this is electrical energy. In turn today about 1% of this electrical energy is generated by solar systems.

By coincidence the world population generates a Zettabyte of information per year. One byte of information per joule consumed. Fortunately, the information generation is growing a lot faster than our energy consumption, which is hopefully indicative of our potential to find smart solutions for the generation, transport and use of energy. For the increased use of solar electricity, such smart solutions are inevitable. Smart grids are essential for the transport and efficient use of electricity generated by distributed and variable sources. Smart integration of solar power generation in urban environments is another enabler of its increased use.

The solar energy research program at Delft University of Technology is one of the leading programs of our faculty. Its researchers hold key positions in the global solar energy community and their innovative solutions are applied in our society, both by large corporations, start-up companies and in the public domain. In addition, the research team plays a significant role in sustainable energy education at our university and large groups of students follow their courses. Sustainable energy attracts many Dutch students as well international students of master programs such as Sustainable Energy Technology.

The pervasive presence of digitization, as mentioned earlier, has had a significant effect on our educational opportunities as well. This is illustrated by TU Delft's leading position in Massive Open and Online Courses (MOOCs) and other forms of online education. One of our first MOOCs was about solar energy. This course, provided through the edX-platform, was hugely successful and attracted close to 60 thousand participants in its first edition. Now, in its third run the total number of enrolments will be well over a hundred thousand.

In addition to the English language version, this MOOC runs in Arabic and will be presented in Chinese too with the support of our partner organisations. The enormous size and enthusiasm of course participants investing seriously in solar energy knowledge and competencies has inspired the teachers to make this (e-)BOOK with the MOOC. The widespread knowledge and enthusiasm about solar electricity production is certainly indicative of the forthcoming rapid increase of the solar energy fraction of our energy consumption. We are very happy to see that our courses aroused the interest of so many learners in the science and application of solar energy. Several of them were inspired to create a solar energy solution for their local community and decided to go for it.

August 2015

Professor Dr Rob Fastenau
Dean of the Faculty Electrical Engineering, Mathematics and Computer Science
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Preface

At Delft University of Technology we believe that the energy system of the future will be completely different from the system we know today. All the energy we use in the future will come from the Sun; directly via solar photovoltaic modules and thermal collectors, or indirectly in the form of wind and biomass. In this future energy system the conversion and utilization of energy will be highly efficient. These two components, renewable energy sources and energy efficiency, are the key components of sustainable energy. The transition towards a sustainable energy system is a major societal challenge needed to preserve Earth for future generations.

This transition means that electricity will gain a more dominant role in energy demand. We expect electricity to become a universal energy carrier and the backbone of energy supply in the future. By writing a book on solar energy with focus on the direct conversion of solar energy into electricity, so-called photovoltaics (PV), we aim to make more people familiar with this fascinating energy conversion technology. We believe that this book is our contribution to facilitating and accelerating the energy transition towards sustainable energy.

We hope that our book Solar Energy Conversion: Fundamentals, Technologies and Systems will be a useful source for readers studying the different topics on solar energy. These topics are discussed in three courses on photovoltaics at Delft University of Technology: PV Basics, PV Technologies, and PV Systems. In addition, this book also covers other aspects of solar energy, in particular solar thermal applications and solar fuels. Hopefully this book inspires students and professionals around the world to contribute to the realization of a sustainable energy infrastructure, for example by building their own PV system. This book is an excellent supplement to the Massive Open Online Course (MOOC) on Solar Energy (DelftX, ET.3034TU) that is presented by Arno Smets on the edX and edraak platforms.

We received a lot of support and help during the preparation of the book. We are very grateful to Ronald van Zolingen, professor at Eindhoven University of Technology, for reviewing this book. He carried out this task very thoroughly and provided us with many comments and suggestions that resulted in a better and more compact work. We are happy that he also wrote the foreword.

We want to express our special thanks to Gireesh Ganesan Nair for supporting us with figures, exercises, and text editing. We thank Mathew Alani and Adwait Apte for text editing. Giorgos Papakonstantinou together with Dimitris Deligiannis are acknowledged for providing some of the text and figures for Chapter 14. We thank Arianna Tozzi for text and visual material regarding the model estimating the effect of wind speed and irradiance on the module temperature that is presented in Section 20.3. We are grateful for the information on real-life PV systems provided by Stephan van Berkel. Ravi Vasudevan and

Do Yun Kim are acknowledged for many discussions on PV systems, Mirjam Theelen for giving feedback on CIGS and CdTe technologies, and Andrea Ingenito for his insights on the fabrication of crystalline silicon solar cells. We want to thank Wilson Smith and Paula Perez Rodriguez for their support on the chapter on solar fuels, Christiane Becker from Helmholtz-Zentrum Berlin for her remarks on thin-film c-Si solar cells, Rowan MacQueen from the University of New South Wales for his review on third-generation concepts, and Nishant Narayan for his assistance in developing exercises and for contributing to the PV Systems part. Further, we thank all students who followed the lectures at Delft University of Technology or the MOOC Solar Energy, and who provided us with feedback and helped us to reduce the number of typing errors and mistakes.

Enjoy the book!

The AUTHORS

Delft, the Netherlands and Berlin, Germany
September 2015

About this book

This book aims to cover all the topics that are relevant for obtaining a broad overview on the different aspects of *Solar Energy*, with a focus on *photovoltaics*, which is the technology that allows energy carried by light to be converted directly into electrical energy.

The organization of this book is roughly linked to the three lecture series on photovoltaics (PV) that are given at the *Faculty for Electrical Engineering, Mathematics and Computer Science* of *Delft University of Technology* throughout the academic year: PV Basics, which roughly covers the topics covered in Part II on PV Fundamentals; PV Technologies, which covers the topics treated in Part III; and PV Systems, which are treated in Part IV.

In total, this book contains *five parts*. In the introductory Part I we provide the reader with some general facts on energy in Chapter 1, summarize the current status of PV in the world in Chapter 2, and give a first short explanation on how solar cells work in Chapter 3.

Part II aims to cover all the physical fundamentals that are required for understanding solar cells in general and the different technologies in particular. After discussing some basics of electrodynamics in Chapter 4 and solar radiation in Chapter 5, we spend several chapters explaining the most important concepts of semiconductor physics. Following the discussion on the basics in Chapter 6, we elaborate on the different generation and recombination mechanisms in Chapter 7 and introduce different types of semiconductor junctions in Chapter 8. After introducing the most important parameters for characterizing solar cells in Chapter 9, we conclude Part II with a discussion on the efficiency limits of photovoltaic devices in Chapter 10, from which we distil some general design rules that are very important in Part III.

The different PV technologies are discussed in Part III. After summarizing the history of solar cells in Chapter 11, we discuss crystalline silicon technology, which is by far the most important PV technology, in Chapter 12. We continue the discussion by taking a look at the different thin-film technologies in Chapter 13. After that, we take a closer look at some processing technologies in Chapter 14 and discuss how to fabricate PV modules from solar cells in Chapter 15. Part III is concluded with a discussion on several third-generation concepts that aim to combine high efficiencies with low cost in Chapter 16.

Part IV is dedicated to the planning of real PV systems. After a short introduction on PV systems in Chapter 17, we discuss the position of the Sun and its implications in great detail in Chapter 18. The different components of a PV system, starting from the modules, but also including all the balance-of-system components, are introduced in Chapter 19. With all this knowledge we elaborate on designing PV systems – for both off-grid and grid-connected situations in Chapter 20. This part concludes with a discussion on the ecological and economical aspects of PV systems in Chapter 21.

In Part V two alternative solar energy conversion technologies are discussed: we introduce different concepts related to solar thermal energy in Chapter 22. In Chapter 23, which is the last chapter of the regular text, we discuss solar fuels, which allow long-term storage of solar energy in the form of chemical energy.

Most chapters contain exercises in the last section, which allow the reader to assess the studied topics. The book is an extensive source of information that allows students to teach themselves all relevant topics on solar energy. The book concludes with an Appendix, where some derivations are shown that are too lengthy for the book.

Nomenclature

Abbreviations

AM	air mass, –
AOI	angle of incidence, –
BOS	balance of system
DoD	depth of discharge, –
DHI	diffuse horizontal irradiance, Wm^{-2}
DNI	direct normal irradiance, Wm^{-2}
EQE	external quantum efficiency, –
GHI	global horizontal irradiance, Wm^{-2}
IQE	internal quantum efficiency, –
ppm	parts per million
SoC	state of charge, –
SRH	Shockley-Read-Hall (recombination)
SVF	sky view factor, –
TCO	transparent conducting oxide

Latin letters

A	absorption profile, $cm^{-3}s^{-1}$
A	surface, m^2
a, $\mathbf{a}$	acceleration, ms^{-2}
D	diffusion coefficient, m^2s^{-1}
E	energy, J
f	Fermi-Dirac distribution, –
F, $\mathbf{F}$	force, N
FF	fill factor, –
G	generation rate, $m^{-3}s^{-1}$
g	density of states function, $m^{-3}J^{-1}$

G_M	irradiance on a PV module, Wm^{-2}
I	current, A
I_e	irradiance, Wm^{-2}
J, $\mathbf{J}$	current density, Am^{-2}
k	wave number, m^{-1}
ℓ_n, ℓ_p	width of space charge region, m
L	diffusion length, m
L_e	radiance, $\mathrm{Wm}^{-2}\mathrm{sr}^{-1}$
m	mass, kg
m^*	effective mass, kg
M_e	radiant emittance, $\mathrm{Wm}^{-2}\mathrm{sr}^{-1}$
N	particle density, m^{-3}
n	electron concentration, m^{-3}
n	refractive index (real part), –
P	power, W
p	hole concentration, m^{-3}
Q	heat, J
R	recombination rate, $\mathrm{m}^{-3}\mathrm{s}^{-1}$
R	reflectivity, –
S_r	surface recombination velocity, ms^{-1}
T	temperature, K
T	transmittance, –
U	heat exchange coefficient, WK^{-1}
V	electric potential, V
$\mathbf{v}$, v	velocity, ms^{-1}
W	work, J
z	height (function), m

Greek letters

α	absorption coefficient, –
α	albedo, –
γ	angle of incidence, –
ϵ	electric permittivity, –
ϵ	emissivity, –

$\boldsymbol{\zeta}$	magnetic field, $\mathrm{Am^{-1}}$
η	efficiency, –
θ	polar angle, generic angle, –
κ	refractive index (imaginary part), –
λ	wavelength, m
μ	mobility, $\mathrm{m^2V^{-1}s^{-1}}$
ν	frequency, $\mathrm{s^{-1}}$
$\boldsymbol{\xi}$	electric field, $\mathrm{Vm^{-1}}$
ρ	charge density, $\mathrm{A{\cdot}s{\cdot}m^{-3}}$
σ	capture cross section, $\mathrm{m^2}$
σ_r	rms roughness, m
τ	lifetime, relaxation time, s
Υ	volume, $\mathrm{m^3}$
ϕ	azimuth angle, –
ϕ	work function, V
Φ_{ph}	photon flux, $\mathrm{m^{-2}s^{-1}}$
χ	dielectric susceptibility, –
χ	electron affinity, V
Ψ_{ph}	photon flow, $\mathrm{s^{-1}}$
Ω	solid angle, –
ω	angular frequency $(\omega = 2\pi\nu)$, $\mathrm{s^{-1}}$

Subscripts

0	*in vacuo*
A	acceptor
C	conduction band
D	donor
d	drift
F	Fermi
G	bandgap
i	intrinsic, incident
λ	spectral property parameterized by wavelength
L	light
mpp	maximum power point

ν	spectral property parameterized by frequency
oc	open circuit
p	plasma
ph	photon
r	reflected
sc	short circuit
t	transmitted
th	thermal
V	valence band

Constants

c_0	speed of light *in vacuo* ($299\,792\,458\ \mathrm{ms}^{-1}$)
ϵ_0	vacuum permittivity ($8.854\,187 \times 10^{-12}\ \mathrm{AsV}^{-1}\mathrm{m}^{-1}$)
F	Faraday constant ($96\,485.3365\ \mathrm{As\,mol}^{-1}$)
h	Planck constant ($6.626\,069 \times 10^{-34}\ \mathrm{Js}$)
k_B	Boltzmann constant ($1.380\,649 \times 10^{-23}\ \mathrm{JK}^{-1}$)
μ_0	vacuum permeability ($4\pi \times 10^{-7}\ \mathrm{VsA}^{-1}\mathrm{m}^{-1}$)
q	elementary charge ($1.602 \times 10^{-19}\ \mathrm{C}$)
σ	Stefan-Boltzmann constant ($5.670\,373 \times 10^{-8}\ \mathrm{Wm}^{-2}\mathrm{K}^{-4}$)
Z_0	impedance of free space ($367.7\ \Omega$)

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 begin with a quote from *The Feynman Lectures on Physics* [1].

> 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 realize 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 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 are 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 Sir Isaac Newton (1642–1727). It is defined as the force required to accelerate the mass of 1 kg at an acceleration rate of 1 $\mathrm{m\,s^{-2}}$, hence 1 N = 1 $\mathrm{kg\,m\,s^{-2}}$.

Energy E, *the* central quantity of this book, is given as the product of F times the distance s,

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

Energy is usually measured in the unit of *joule* (J), named after the English physicist James Prescott Joule (1818–1889). It is defined as the amount of energy required to apply the force of 1 newton through the distance of 1 m, 1 J = 1 Nm.

Another important physical quantity is *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. P is usually measured in the unit of *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 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

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

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 ($q = 1.602 \times 10^{-19}$ C)[1] gains or loses when it is moved across an electric potential difference of 1 volt (V),

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

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[1] Often, the symbol e is used for the elementary charge. However, in order not to confuse the elementary charge with the Euler number, we use q, just as many others in the solar cell and semiconductor device communities.

1.2 Human energy consumption

After these somewhat abstract definitions we will look at the *human energy consumption*. The human body is at a constant temperature of about 37 °C. It therefore contains *thermal energy*. As the body is continuously cooled by its 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 of this energy has to be supplied to the body from the outside in the form of food. An average body of a human adult male requires about 10,000 kJ every day.[2] 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 not only require energy to keep their body running but in fact 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 from the outside. 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 when you are reading this book on a computer or tablet. But also if you are reading it in a printed version, you implicitly consume the energy that was required to print it and to transport it to your place.

As mentioned 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 utilize energy to work for us, 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.

To measure the amount of energy humankind consumes, we refer to two concepts: first, *primary energy*, which 'is the energy embodied in natural resources prior to undergoing any human-made conversions or transformations. Examples of primary energy resources include coal, crude oil, sunlight, wind, running rivers, vegetation[3], and uranium [2]. Humans do not directly use carriers of primary energy, but converted forms of energy, which are called *secondary energy* or *final energy*. Examples of secondary energy carriers are electricity, refined fuels such as gasoline or diesel, and heat which is transported to consumers via district heating.

Modern society is very much based on the capability of humankind to convert energy from one form to another. 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 US citizen uses an average power of 9,319 W, which is about 80 times what his body needs. In contrast, an average citizen from India only uses about 800 W, which is less then a tenth of the US consumption.

Many people believe that tackling the *energy problem* is among the biggest challenges

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[2] 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 adult male human requires about 2500 kcal a day.

[3] Or biomass *authors note*.

Table 1.1: Total primary energy consumption per capita and average power used per capita of some countries in 2011 [3].

Country	Energy consumption (kWh/capita)	Average power use (W/capita)
USA	81,642	9,319
Netherlands	53,963	6,160
China	23,608	2,695
Colombia	7,792	890
India	6,987	797
Kenya	5,582	637

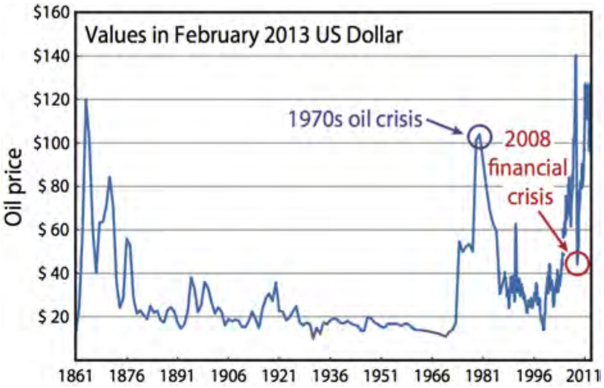

Figure 1.1: The history of the oil price per barrel normalized to the February 2013 value of the US dollar [4].

for humankind in the 21st century. This challenge consists of several problems: First, humankind is facing a supply–demand problem. The demand is continuously growing as the world population is rapidly increasing – some studies predict a world population of 9 billion around 2040, in contrast to the 7 billion people living on the planet in 2014. 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 BP Energy Outlook 2035 the global energy consumption is expected to rise by 37% between 2013 and 2035, where virtually all (96%) of the projected growth is in non-OECD countries [5]. The increasing demand in energy has economic impact, as well. If there is more demand for a product, while supply does not change that 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 average price for a barrel of oil in Figure 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

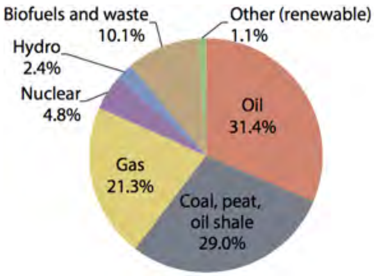

Figure 1.2: The primary energy consumption of the world by source in 2012. The total supply was 155,505 TWh (data from [6]).

economies, the oil prices increased significantly.

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, as shown in Figure 1.2. 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 extractable 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 hydraulic fracturing [7], such as in large parts of the United States. These new methods use much more energy to get the fossil fuels out of the ground. Further, offshore drilling is put in 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 such 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 2015. 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. Carbon 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 [11].

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 [11].

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

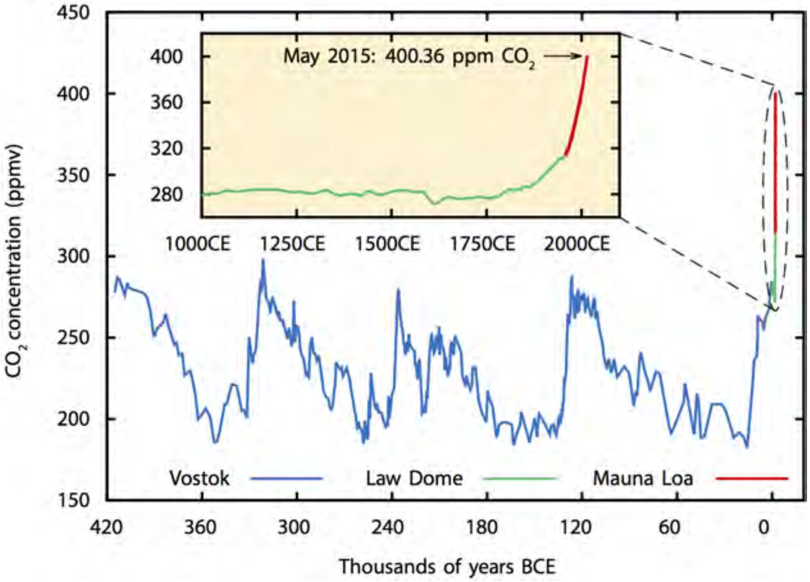

Figure 1.3: Atmospheric CO_2 concentration in the last 420,000 years (detailed view since the year 1000 shown in the inset). The drastic rise of the CO_2 concentration since the onset of the industrial revolution (ca. 1750) is clearly visible. The figure combines data from the Antarctic Vostok [8] and Law Dome [9] ice cores and updated data from the Mauna Loa Observatory in Hawaii [10].

> 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 [11].

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

Since the beginning of the industrial revolution, humankind has been heavily dependent on fossil fuels. Within a few centuries, we are exhausting solar energy that was incident on Earth for hundreds of millions of years, converted into chemical energy by photosynthetic processes and stored in the form of gas, coal and oil.

Before the industrial revolution, the main source of energy was wood and other biomasses, 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, humankind 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.

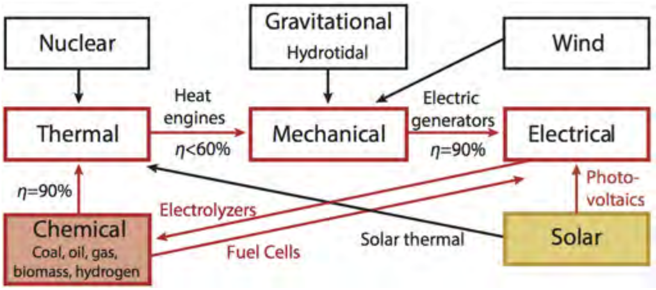

Figure 1.4: The different energy carriers and how we utilise them (adapted from L Freris and D Infield, Renewable Energy in Power Systems (copyright John Wiley & Sons Inc, Chichester, United Kingdom, 2008)) [12].

1.3 Methods of energy conversion

Figure 1.4 shows different energy sources and the ways we utilize 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 into 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 vast majority of the current cars and trucks works on this principle. Mechanical energy can be converted into electricity using electric generators with an efficiency of 90% or even higher. Most of the world's electricity is generated using *turbogenerators* that are connected to a steam turbine, where coal is the major energy source. This process is explained in more detail in our discussion on solar thermal electric power in Chapter 22. 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 for hydrogen electrolysis of 50-80% have been reported. We will discuss electrolysis in more detail in Chapter 23.

In *nuclear power plants*, energy is released as heat during *nuclear fission* reactions. The heat generates steam which 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 their 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 windmills.

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* is derived from 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 see in this book, typical efficiencies of the most commercial *solar modules* are in the range of 15-20%.

The energy carried with sunlight can also be converted into heat. This application is called *solar thermal energy* and is discussed in detail in Chapter 22. 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 used, temperatures of several hundreds of degrees are achieved; this 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 into 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 23.

We just have seen that solar energy can be converted into electricity, heat and chemical energy. The Sun is the energy source for almost all the processes happening 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 sunlight. As the Sun is the only real energy source we have, we need to move to an era in which we start to utilize the energy provided by the sun directly for satisfying our energy needs. The aim of this book is to teach the reader how solar energy can be utilized directly.

1.3.2 Electricity

As we see in Figure 1.5 (a), 17% of all the world's final energy is used as electricity, which is a form of energy that can be easily and cheaply transported with relatively small losses through an electric grid. It is important to realize 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, wash, do the laundry, illuminate buildings and streets, and for countless other applications. The access to electricity strongly determines 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 Figure 1.5 (b), about 67% of the electricity is generated using fossil fuels, where coal is the dominant contributor. As coal emits about twice as much CO_2 per gen-

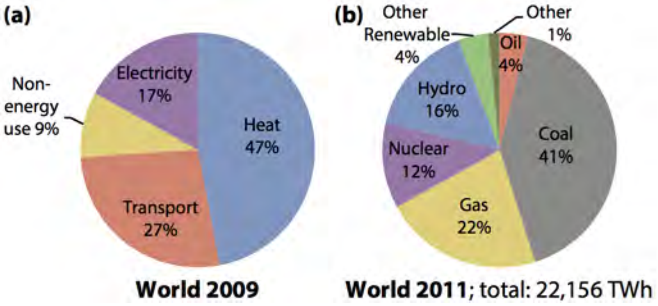

Figure 1.5: (a) The final energy consumption by energy service [13] and (b) the energy carriers used for electricity generation [14] (©OECD/IEA 2012, Insights Series 2012: Policies for renewable heat, IEA Publishing. Licence: www.iea.org/t&c/termsandconditions).

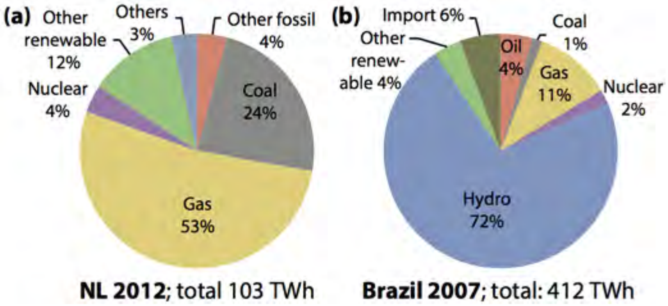

Figure 1.6: The energy mix used for electricity production in (a) the Netherlands [15] and (b) Brazil [16] (Data from Centraal Bureau voor de Statistiek (CBS; Statistics Netherlands) and used according to Creative Commons license: https://creativecommons.org/licenses/by/3.0/nl).

erated kWh as natural gas, coal power plants are a major contributor to global warming. Nuclear is responsible for 12% of the World's electricity generation. With 16%, hydroelectricity is by far the largest contributor among the renewable energy sources.

Of all the generated electricity, about 40% is used for residential purposes and 47% is used by industry. 13% is lost in transmission. In 2007, transport did not play a significant role in the electricity consumption. However, this is expected to change as electric cars become 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.

1.4 Exercises

1.1 How many mega joules (MJ) are equivalent to 2.5 kWh?

1.2 To get a feeling of the concepts of power and energy, let us look at the power and energy generated by the human body. In 1994, the Spanish cyclist Miguel Indurain set a world hour record of 53,040 metres in 1 hour. Spanish scientists measured an average power of 509.5 watts produced by him during that hour. What is the energy generated by him in that hour expressed in kWh?

1.3 By using fossil fuels, what is the maximum efficiency that you can achieve from converting chemical energy to electrical energy?

(a) 34%
(b) 49%
(c) 75%
(d) 90%

1.4 Below different energy conversion processes are described.

Person An active person consumes 2,500 kcal of energy in one day.

Lightning A bolt of lightning strikes the ground. It has a voltage of 100 MV and carries a current of 100 kA for 30 μs.

BBQ During a barbeque 1 kg of coal (consisting mostly of carbon) is burned in 1 hour. Assume the following combustion reaction:

$$C + O_2 \rightarrow CO_2 + 4\,\text{eV}.$$

Tea To make tea an electric heater is used to boil (i.e. heat from 20 °C to 100 °C) 1 kg of water in three minutes.

House The flat roof of a house (6 x 8 m^2) absorbs sunlight for a year. Assume the house is in the Netherlands where the annual irradiation is about 1,000 kWh/m^2 year.

Battery A 1.5 V battery with a capacity of 2,300 mAh is charged in 3 hours.

Humankind The whole world population (7 billion people) consuming on average 1,500 watts per person for one year.

Solar energy Solar energy reaching planet Earth in one hour. Assume a solar constant of 1,361 W/m^2.

(a) For each of the processes above, answer the following questions.
    i. In what form is the energy before and after the process?
    ii. How much energy (in joules) is converted?
    iii. What is the average conversion power (in watts)?
(b) Order the processes from low to high energy.
(c) Order the processes from low to high power.

Hint: Make simplifying assumptions if needed and use the following background information.
Elementary charge: $q = 1.6022 \times 10^{-19}$ C
Avogadro constant: N = 6.0022×10^{23} mol^{-1} [number of atoms in 12 g of carbon]
Specific heat of water: c = 4.184 J/g °C
Radius of Earth: r = 6,378 km
1 kcal: the amount of energy it takes to heat 1 kg of water by 1 °C.

2

Status and prospects of PV technology

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

Figure 2.1 shows the worldwide cumulative installed PV power, which is exponentially increasing in time. The vertical axis represents the cumulative installed power capacity expressed in GW_p. The letter p denotes *peak power*, which is the maximum power a PV module can deliver if it is illuminated with the standardized AM1.5 solar spectrum that we introduce in Section 5.5. 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 [17]. By the end of 2013, already almost 140 GW_p was installed around the globe [18]. Of all the installed PV power at the end of 2013, almost one third was installed in 2013 alone!

In Figure 2.2 the annually installed capacity of PV modules in recent years is shown. We see that the number of installed PV systems between 2000 and 2011 has grown almost exponentially, with an average growth of 60%. The strongest growth was between 2007 and 2008 with a growth of 143%. In these years, by far the most PV systems were installed in Europe. However, since 2011 the number of installed systems in Europe has been going down rapidly, while it strongly increases in the other regions of the world. While in 2011 74% of all PV systems were installed in Europe, in 2013, this was only 29%. It will be interesting to see how this development continues in the coming years.

In Figure 2.3 the installed PV power in several countries at the end of 2013 is shown. About 26% 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 [19].[1] Considering that Germany lies within an area with a relatively low radiation level that is comparable

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[1] We will discuss the *feed-in tariff* scheme in Chapter 21.

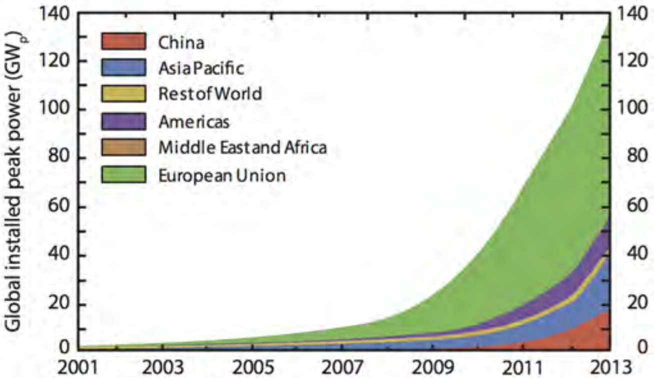

Figure 2.1: The globally installed PV capacity (data from [18] and reproduced with kind permission from the European Photovoltaic Industry Association EPIA).

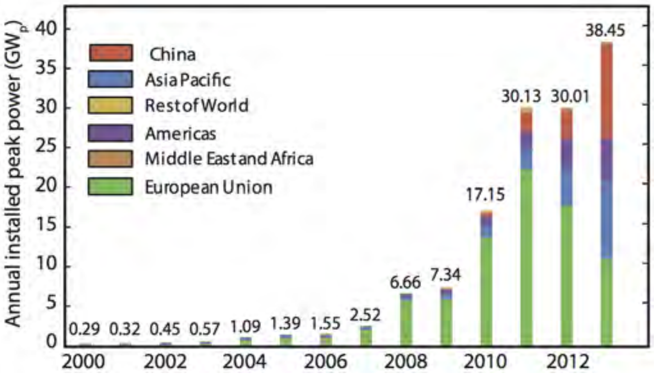

Figure 2.2: The annual installed PV capacity in recent years (data from [18] and reproduced with kind permission from the European Photovoltaic Industry Association EPIA).

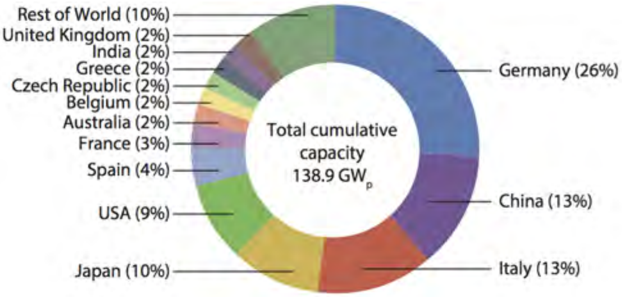

Figure 2.3: Fraction of PV installations for different countries by the end of 2013 (data from [18] and reproduced with kind permission from the European Photovoltaic Industry Association EPIA).

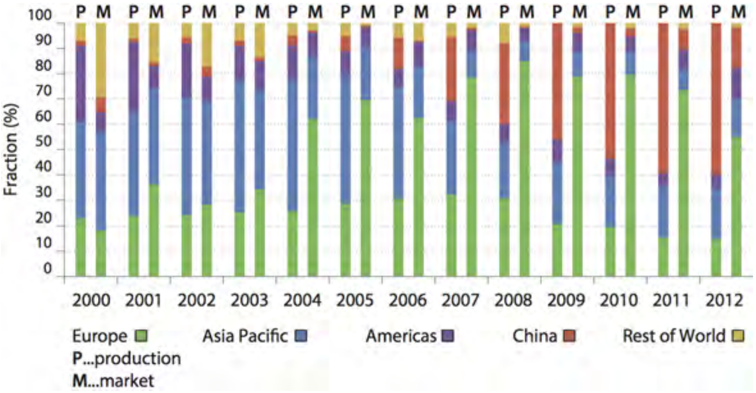

Figure 2.4: Development of the market and production shares of different PV markets since 2000 (data from [17] and reproduced with kind permission from the European Photovoltaic Indusctry Association (EPIA)).

to that of Alaska [20], 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 is also observed in Italy, which accounts for 13% of the world wide PV capacity. China, with a contribution of 13%, is the fastest growing market at the moment. In 2010, China only contributed 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 9% (USA). Also Japan shows a strong growth in PV installations. 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.

While PV was mainly a local affair at the beginning of this century, the situation changed strongly around 2009, which is illustrated in Figure 2.4. This figure shows 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 US) and Asia Pacific (mainly Japan) have increased very rapidly and are 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 has changed drastically! The Chinese production share has increased very strongly to an amount of about 60% in 2012, which can be explained with huge investments by the Chinese government in order to scale up PV module manufacturing in China.

In 2000, the PV markets were 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. More recently, the market has become a global market. As a

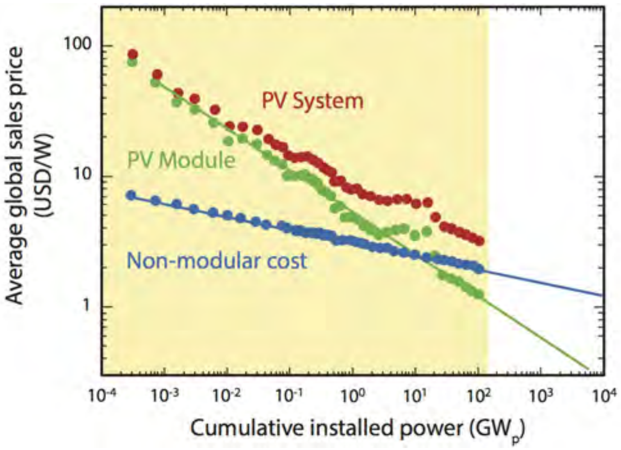

Figure 2.5: The learning curve for PV modules and PV systems (data from [21]).

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 is also strongly stimulated by the decreasing cost price of PV technology. Figure 2.5 shows the *learning curve* of PV technology. The learning curve 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 betterr 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 manpower 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 upscaling reduces the cost. Learning curves usually show an exponentially decreasing cost price, until the technology or product is fully developed.

In Figure 2.5, the average global sales price 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 the white area are extrapolations 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, the 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 PV technology, the system price was dominated by the module price, currently, the cost of the *balance of system*, i.e. the *non-modular components* of PV systems, are getting more and more dominant. By non-modular components, we refer to components such as the racking, wiring, inverter, batteries for stand-alone systems, and also the maintenance costs. All these components are discussed in detail in Chapter 19. The difference between the red and green lines corresponds to the non-modular costs, which are dropping more slowly than that of the PV modules.

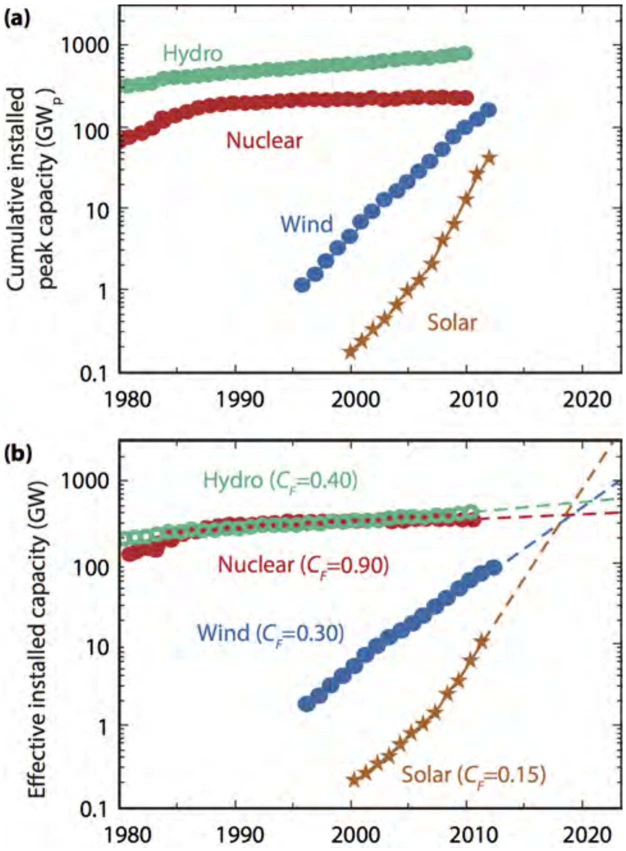

Figure 2.6: (a) Development of the installed capacity (in GW) of several non-fossil electricity generation technologies since 1980. (b) The same graph corrected by the capacity factor C_F and extrapolated until 2020.

As a consequence, PV technologies with higher energy conversion efficiencies have an advantage, because they require less area to deliver 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 a 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 1 we have seen that hydropower is responsible for 16% of the total worldwide electricity production while 12% of the electricity is generated in nuclear power plants. How do these numbers compare to solar electricity? This question is answered in Figure 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 any more, while the installed hydropower is still slightly growing with 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 Figure 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 magnitude less than hydro and nuclear electricity. Seeing the development in recent years, nonetheless we can claim that the trend in the growth of solar energy will continue in 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 before solar electricity will be the most important electricity generation technology that is not based on the combustion of fossil fuels.

Of course, we have to justify why solar electricity can grow much faster than the other technologies shown in Figure 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 times 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 in the atmosphere and hence 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 *centralized* electricity generation technologies. For hydropower plants, big dams are needed. Also nuclear power plants have large power rates of 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 22), it also has a unique advantage: PV systems can be installed decentralized on every roof. Electricity consumers can generate at least a part of their required electricity on 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 many parts of the world [22]. 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 decentralized 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 Figure 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 be slowed down.

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

Exercises

For all the exercises below, assume that the worldwide total amount of electricity generated is 20,200 TWh per year.

2.1 In 2010, the worldwide installed hydroelectricity power was 1,010 GW. Assume a capacity factor for hydropower of 40%. What percentage of the total electricity generation worldwide was covered by hydropower in 2010?

2.2 In 2010, the worldwide installed nuclear power was 380 GW. Assume a capacity factor for nuclear power of 90%. What percentage of the total electricity generation worldwide was covered by nuclear power in 2010?

2.3 In 2012, the worldwide installed wind power was 280 GW. Assume a capacity factor for wind power of 30%. What percentage of the total electricity generation worldwide was covered by wind energy in 2012?

2.4 In 2013, the worldwide installed solar power was 140 GW. Assume a capacity factor for solar power of 15%. What percentage of the total electricity generation worldwide was covered by solar energy in 2013?

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 general idea of how a solar cell works should be clear. All the aspects presented in this chapter will be discussed in greater 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 [23].

The photovoltaic effect can be divided into three basic processes:

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 Figure 3.1 (a). Photons can only be absorbed if electron energy levels E_i and E_f are present so that their difference equals 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

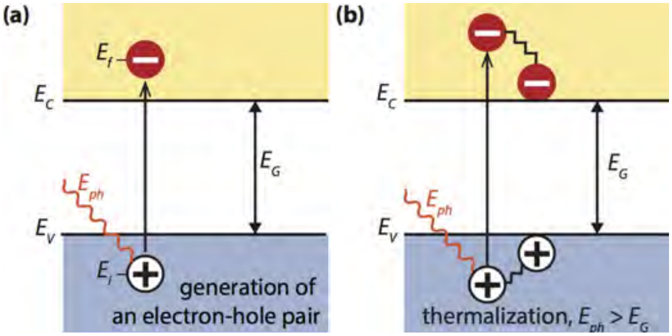

Figure 3.1: (a) Illustrating the absorption of a photon in a semiconductor with bandgap E_G. The photon with energy $E_{\mathrm{ph}} = h\nu$ excites an electron from E_i to E_f. At E_i a hole is created. (b) If $E_{\mathrm{ph}} > E_G$, a part of the energy is thermalized.

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 momentum of an electron in the semiconductor. This means that the energy of an electron is dependent on its momentum because of the periodic structure of the semiconductor crystal. 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 momentum. Such a semiconductor is called a *direct bandgap* material. If the electron cannot be excited without changing its momentum, we refer to it as an *indirect bandgap* material. The electron can only change its momentum by momentum exchange with the crystal, i.e. by receiving momentum from or giving momentum to vibrations of the crystal lattice. The absorption coefficient in a direct bandgap material is much higher than in an indirect bandgap material, thus the absorbing semiconductor, often just called the *absorber*, can be much thinner [24].

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 Figure 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 between 67% for non-concentrated sunlight and 86% for fully concentrated sunlight [25].

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

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-

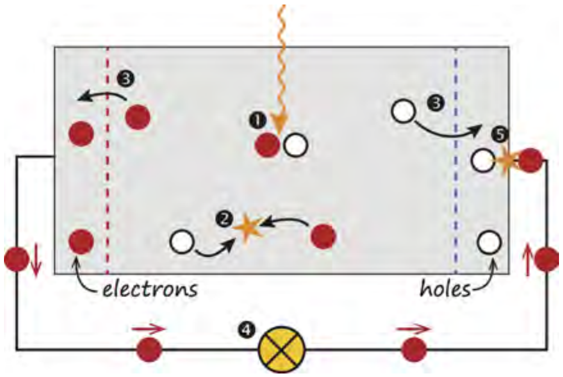

Figure 3.2: A very simple solar cell model. ❶ Absorption of a photon leads to the generation of an electron-hole pair. ❷ Usually, the electrons and holes will recombine. ❸ With semipermeable membranes the electrons and the holes can be separated. ❹ The separated electrons can be used to drive an electric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

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 can only flow out through one membrane and holes can only flow out through the other membrane [25], as illustrated in Figure 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 have passed through the circuit, they will recombine with holes at a metal-absorber interface, as illustrated in Figure 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 thermalization of photon energies exceeding the bandgap, as illustrated in Figure 3.1 (b). These two mechanisms alone amount to the loss of about half the incident solar energy in the conversion process [26]. 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 [27].

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