Part One

Introduction to Photovoltaics

1.1

Introduction

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1.1.1 Introduction to Photovoltaic Solar Energy

At present, photovoltaic (PV) systems have become an established part of the electrical energy mix in Europe, the United States, Japan, China, Australia and many more countries all around the globe. So far, no single other energy technology has shown such a distributed set-up and modularity as PV systems. Stand-alone and grid-connected applications provide power in an extended range, from tenths of watts up to hundreds of megawatts. At the end of 2015, the total global cumulative capacity of installed PV systems exceeded 227 gigawatts, and this capacity is equivalent to about 280 coal-fired plants. For instance, in 2014, in Germany, Italy and Greece, 6 to 11% of the annual electricity generated originated from PV systems, while across Europe PV systems account for 3.5% of the electricity need (IEA-PVPS, 2015). According to the IEA (2016), electricity generated by PV systems contributed 0.8% of the total electricity production in the USA, in Japan 3.9%, and in China 1.0%.

Originally the development of PV technology was driven by the need for reliable and durable electricity systems for space applications, such as satellites. Nowadays, the implementation of PV systems in our society is driven by the need to reduce CO_2 emissions. Since PV systems have an extremely low CO_2 emission per kWh of electricity generated, namely below 30 g/kWh, see Figure 1.1.1 and Louwen *et al.* (2015), they are considered by policy-makers an important technology to slow down global warming due to the increased greenhouse effect (IPCC, 2013). This should be compared with the amount of more than 800 g CO_2/kWh emitted by coal-fired plants, see Figure 1.1.1. At present, all the major economies have policy targets to reduce greenhouse gas emissions, for instance, a 20% reduction of CO_2 emission is set by 2020 for Europe, 40% by 2030 and a 80–95% cut in greenhouse gases by 2050 compared to 1990
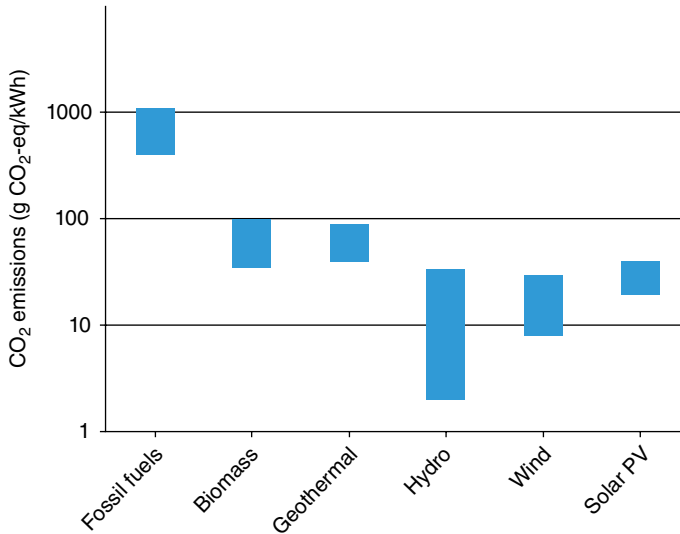
Figure 1.1.1 Comparison of CO_2-equivalent emissions of various energy technologies. Note the logarithmic *y*-scale. Courtesy of A. Reinders, University of Twente

levels (European Commission, 2011). To achieve these targets solar photovoltaic technologies will be unavoidable, as well as other sustainable energy technologies in combination with an increased energy efficiency of society. Therefore, we can expect further growth of the volume of PV systems in our electrical energy mix and in off-grid applications. According to Greenpeace's (2015) updated *Energy Revolution* scenario, we can even expect a 100% sustainable energy supply, which will end global CO_2 emissions, by 2050, which will be achieved by 20% of our electricity demand being produced by PV systems.

The growth of the market for PV technologies brings economies of scales. In the past decade, economies of scales together with technological progress in solar cell efficiencies, standardization of technologies, improved manufacturing and lower costs of production of feedstock materials, such as silicon, have brought down the cost of, for example, silicon PV modules from \$4/Wattpeak to less than \$1/Wattpeak (see Chapter 13.1). Present record efficiencies of 21% for commercial PV modules will reduce these costs even more in the forthcoming years. Due to these low investment costs and low O&M costs, the price of PV electricity is able to compete with consumer electricity prices in many countries, thus realizing grid parity on the customer side of the meter (Hurtado Muñoz *et al*., 2014). Though incentives still remain necessary to overcome the hurdle of upfront investment costs at present, in the long run it seems feasible that PV technology will become an affordable self-sustained energy technology within the reach of many consumers, in particular in urbanized areas where the technology's silent operation with zero emissions during use will perfectly fit into a built environment. Additionally, a market for PV systems exists in developing countries, where more than one billion people do not have access to electricity. There, solar electricity can make a difference by being a means to access information, for instance, with the internet on laptops or through television, to communicate, by internet and by phone, to pump water, to cool food and medication, and to generate income.

All the rapid developments in the field, described above, have happened in the past five years. The global PV market is still growing rapidly at about 20–40% per annum, as of 2014. Most PV technologies are still relatively young and going through various innovations. Triggered by serious interest from "newcomers" in the field of solar energy, the PV scientific community faces a great educational challenge to change the educational message from a "physicist-only" audience to an audience with more diverse backgrounds in engineering, economics, and business. To keep the solar PV field growing and to prepare a successful future for photovoltaics, it is our sincere ambition to address a large part of these interested audiences and spread knowledge, enthusiasm, and inspiration about photovoltaic energy.

1.1.2   Properties of Irradiance

Readers of this book will often come across photons and other matters related to irradiance. Therefore, to make sure that we all have the same starting point, in this section we will briefly address a few basic topics related to irradiance.

1.1.2.1   Photons

German physicists Max Planck and Albert Einstein proposed in 1900 and 1905, respectively, that light, or more correctly, irradiance is composed of discrete particles. However, both Max Planck and Albert Einstein never used a specific term for these particles. It took some time, until the late 1920s, until the word "photon" became a synonym for the light quantum. The name photon is derived from the Greek word $\varphi\acute{\omega}\tau o$ (= photo), which means light. The suffix "-on" at the end of the word indicates that the photon is an elementary particle belonging to the same class as the proton, the electron, and the neutron.

The energy contained by a photon, E, is given by Equation (1.1.1):

$$E = \frac{hc}{\lambda} \qquad\qquad (1.1.1)$$

where λ is the wavelength (in m), h is Planck's constant ($6.626 \cdot 10^{-34}$ J$\cdot$s) and c is the speed of light in vacuum ($2.998 \cdot 10^8$ m/s). The energy contained in a photon is rather small and can therefore be better expressed by the unit electron-volt (indicated by eV) than the more common SI unit for energy, which is the joule (J). An electron-volt is the energy gained by one electron when accelerated through 1 volt of electric potential difference. Since the electric charge of one electron is given by the elementary charge, $q = 1.602 \cdot 10^{-19}$ C, in this situation 1 eV is equivalent to $1.602 \cdot 10^{-19}$ J. In practice, this results in the following simplified relationship for daily use: E (in eV) $= 1.24/\lambda$ (in µm). From Equation (1.1.1), it follows that photons with a short wavelength, such as ultra-violet and blue light, have a high energy and those with a long wavelength, such as red and infrared light, have a low energy. Figure 1.1.2 shows the colors of light, visible to human eye, with the corresponding wavelengths (nm) and energy (eV).

Since the frequency ν (in Hz), wavelength λ, and speed of light c, are related by $\lambda \cdot \nu = c$, Equation (1.1.1), also called the Planck-Einstein relation, can be represented by:

$$E = h \cdot \nu \qquad\qquad (1.1.2)$$
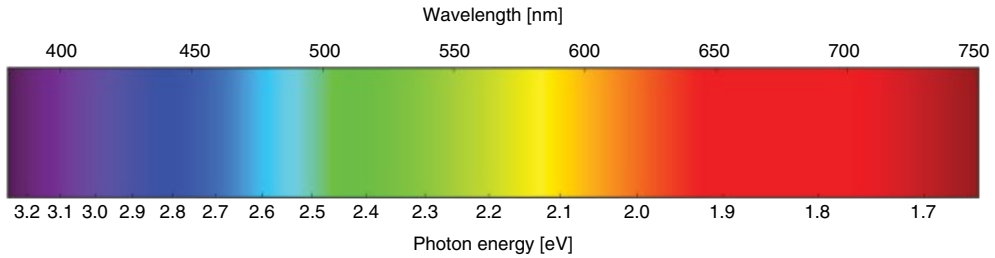
Figure 1.1.2 Relation between color of (visible) light, wavelength and its energy. Courtesy of A. Louwen, Utrecht University. (*See insert for color representation of the figure*)

In 1905, Einstein concluded that "the wave theory of light (Maxwell, 1865) has worked well in the representation of purely optical phenomena," however,

> observations associated with blackbody radiation, fluorescence, the production of cathode rays by ultraviolet light, and other related phenomena connected with the emission or transformation of light are more readily understood if one assumes that the *energy of light is discontinuously distributed in space*. In accordance with the assumption to be considered here, the energy of a light ray spreading out from a point source is not continuously distributed over an increasing space but *consists of a finite number of energy quanta* which are *localized at points in space*, which move without dividing, and *which can only be produced and absorbed as complete units*. (Einstein, 1905)

These assumptions are essential for the understanding of the photovoltaic effect and therefore the functioning of most of the photovoltaic materials applied nowadays in photovoltaic solar cells. In this sense, the classic wave theory of light in which light is represented as a form of electromagnetic radiation did not appear to be sufficient for an understanding of certain phenomena which are relevant to this field of research, though the wave theory is indispensable to the explanation and quantification of transmission, reflection and refraction of irradiance in various media.

Albert Einstein used the principle of discrete energy packages, light quanta, to explain the photoelectric effect in metal surfaces. The photovoltaic effect is the creation of voltage or electric current in a material upon exposure to irradiance. It was observed for the first time in 1839 by the French physicist Alexandre Edmond Becquerel, in a solution that contained two metal electrodes. In due course, despite the widespread occurrence of the photovoltaic effect in liquid and solid state systems, the term became predominantly associated with the functioning of layers of semiconductor materials applied in photovoltaic (PV) devices such as PV solar cells.

Einstein's theories on the photovoltaic effect in metal surfaces were experimentally validated by the American physicist Robert Millikan, who was able to confirm that the energy contained by photons varied according to the frequency – or the reciprocal of the wavelength – of the incident irradiance, and not according to the intensity of the irradiance. For these significant discoveries related to the properties of irradiance, Max Planck received the Nobel Prize in 1918, Albert Einstein received it in 1921 for his discovery of the law of the photoelectric effect, and later Robert Millikan also received it in 1923 for his work on the elementary charge of electricity and on the photoelectric effect. These discoveries were

essential for the development of PV solar cells, and in the early 1950s, Daryl Chapin, Calvin Fuller, and Gerald Pearson of Bell Laboratories observed the PV effect in doped silicon layers, by chance. In 1954, they presented the first silicon solar cell, which was reported to have a conversion efficiency of 6% (Chapin *et al.*, 1954). This is considered the start of the modern PV era that has led to a multi-billion market today.

1.1.2.2   *Solar Irradiance*

Solar irradiance is the name for the spectrum of light originating from the sun. For the purpose of photovoltaic applications, we can distinguish between extraterrestrial solar irradiance, which is available in space, and terrestrial solar irradiance, which is received on Earth. Solar irradiance in space is usually measured at the interface of space and the Earth's atmosphere, for the purpose of space applications of photovoltaics, such as satellites, and is standardized by the so-called *AM0* spectrum, which is shown as the ASTM E-490 spectrum in Figure 1.1.3. *AM* stands for Air Mass. The indicator (0 in *AM0*) is the air mass coefficient, which is the ratio of the direct optical path length of solar irradiance through the Earth's atmosphere, L_θ, relative to the path length with the zenith as an origin, called the zenith path length, L. The air mass coefficient at average sea level can easily be calculated using Equation (1.1.3):

$$AM = \frac{L}{L_\theta} \sim \frac{1}{cos\,\theta} \qquad\qquad (1.1.3)$$
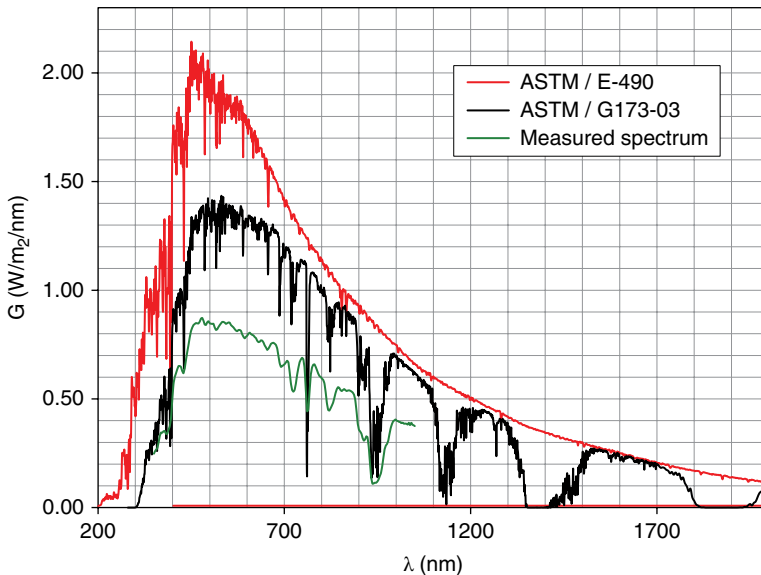
Figure 1.1.3   Solar spectra: ASTM E-490 representing AM0 (black line), ASTM G173-03 representing AM1.5 (red line), and a measured spectrum (green line) showing the differences that can occur in reality. Data from ASTM and University of Twente, The Netherlands. Courtesy of A. Reinders, University of Twente. (*See insert for color representation of the figure*)

where θ is the zenith angle of incidence of irradiance. Equation (1.1.3) provides a good approximation for the air mass coefficient for θ up to around 75°, that is, for air mass up to around 4.

In 2000, the American Society for Testing and Materials (ASTM) developed an *AM0* reference spectrum (ASTM E-490, 2000) for use by the aerospace community, see Figure 1.1.3. The ASTM E-490 solar spectral irradiance is based on data from satellites, space shuttle missions, high-altitude aircraft, rocket soundings, ground-based solar telescopes, and modeled spectral irradiance (NREL, 2015) with an integrated spectral irradiance of 1366.1 W/m² representing the value of the solar constant as accepted by the space community.

The photovoltaic industry developed another spectrum for terrestrial applications, which is represented by the standard ASTM G-173-03 containing specific *AM1.5* spectra, and it is referred to as "Standard Tables for Reference Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37 Degree Tilted Surface" (ASTM, 2012), see Figure 1.1.3. This is a revised version of the earlier single standard, which was available from 1999. The ASTM G-173 spectra represent terrestrial solar spectral irradiance on a surface of specified orientation under one and only one set of specified atmospheric conditions with an air mass of 1.5 (solar zenith angle 48.19°). The receiving surface is defined in the standards as an inclined plane at 37° tilt toward the equator, facing the sun, that is, tilted South on the Northern hemisphere, and tilted North on the Southern hemisphere. The specified atmospheric conditions are defined by a specific temperature, pressure, aerosol density, air density and molecular species density specified in 33 layers (Gueymard, 2004).

Apart from the standardized extraterrestrial and terrestrial solar irradiance spectra a measured solar irradiance spectrum is presented in Figure 1.1.3, to show the difference between reality and the standards. Given the discourse about the effect of the optical path length of solar irradiance through the atmosphere on the solar irradiance spectra received on an earthly surface, it is logical that solar irradiance strongly depends on the moment of the day and the day of the year and hence the related sun positions. Moreover, the irradiance depends on the composition of the atmosphere and, as such, weather, including the cloud formation and the precipitation, the particles and water vapor in the atmosphere, and the gasses that are contained by the atmosphere. These factors all contribute to the absorption and reflectance of irradiance at various wavelengths. For more details about the properties and behavior of solar irradiance in the earthly atmosphere and on terrestrial receiving surfaces, we refer to Sengupta *et al.* (2015).

1.1.2.3   Refraction, Reflection and Transmission

As already mentioned in Section 1.2.1, the wave theory of light (Maxwell, 1865) works very well for the representation of purely optical phenomena. This is a good basis for non-quantum phenomena in photovoltaics, in particular, since the propagation of light waves in matter is an important topic in the field of photovoltaic solar energy. Therefore, in this section, we will provide information about the most important laws and equations regarding the propagation of light in matter.

The speed of light in a vacuum, c, is a physical constant which is exactly 299.792.458 m/s. However if light propagates through a medium, which could be, for instance, air, glass or silicon, its speed is reduced to v, the phase velocity of light in media, where v is lower than c. The refractive index of a material, n, is an indicator of the speed of light in media, since it is

equal to the ratio of the speed of light in vacuum, c, and the phase velocity in the medium, v. Logically, in media n is always larger than 1.

The different propagation of light in two different isotropic media results in refraction at the interface of these media, according to Snell's law:

$$\frac{\sin \theta_i}{\sin \theta_t} = \frac{n_2}{n_1} \tag{1.1.4}$$

where θ_i is the angle of incidence (towards the normal of a surface), θ_t is the angle of refraction of the outgoing beam, n_1 is the refractive index of the medium through which the incident beam of light passes and n_2 is the refraction index of the medium through which the refracted beam goes, see Figure 1.1.4. From Snell's law it can be derived that when light propagates from a medium with a higher refraction index to a medium with a lower refractive index (hence, $n_1 > n_2$), total internal reflection occurs for incidence angles greater than the critical angle, θ_{crit}, leading to refraction into the medium with the higher refraction index

$$\theta_{crit} = arsin \frac{n_2}{n_1}$$

The law of refraction states that if light hits an interface between two media with a different refractive index, the angle of reflection. θ_r, is equal to the angle of incidence, θ_i.

Snell's law does not explain what share of the energy contained by the incident irradiance, I_i, is subject to transmission or reflection. However, the law of conservation of energy states that the sum of the transmission coefficient, T, and the reflection coefficient, R, should be 1: $T + R = 1$ where $T = I_t / I_i$ and $R = I_r / I_i$ for non-magnetic materials.

The values of T and R depend on the polarization of irradiance. If the vector of the electric field happens to be perpendicularly oriented towards the plane that contains both the incident, refracted and reflected irradiance (this is called s-polarization), then the reflection coefficient is indicated by R_s. If it happens to be in line with the plane of incidence, the so-called p-polarization,
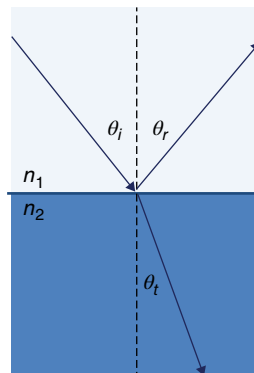
Figure 1.1.4 Scheme representing incident, refracted and reflected irradiance at the interface of two media

we can talk about R_p. The respective transmission coefficients are given by the law of conservation of energy, namely, $T_s + R_s = 1$ and $T_p + R_p = 1$.

R_s and R_p are given by the Fresnel equations for non-magnetic materials:

$$R_s = \left[\frac{\sin\left(\theta_t - \theta_i\right)}{\sin\left(\theta_t + \theta_i\right)} \right]^2 = \left[\frac{n_1 \cos\left(\theta_i\right) - n_2 \cos\left(\theta_t\right)}{n_1 \cos\left(\theta_i\right) + n_2 \cos\left(\theta_t\right)} \right]^2 = \left[\frac{n_1 \cos\left(\theta_i\right) - n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}{n_1 \cos\left(\theta_i\right) + n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2}} \right]^2$$

(1.1.5)

$$R_p = \left[\frac{\tan\left(\theta_t - \theta_i\right)}{\tan\left(\theta_t + \theta_i\right)} \right]^2 = \left[\frac{n_1 \cos\left(\theta_t\right) - n_2 \cos\left(\theta_i\right)}{n_1 \cos\left(\theta_t\right) + n_2 \cos\left(\theta_i\right)} \right]^2 = \left[\frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2} - n_2 \cos\left(\theta_i\right)}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2}\sin\theta_i\right)^2} + n_2 \cos\left(\theta_i\right)} \right]^2$$

(1.1.6)

Equations (1.1.5) and (1.1.6) are frequently used to calculate the reflectance and transmittance at the interface between two materials of different refractive indexes at various angles of incidence.

1.1.3 Structure of the Book

After this short introduction to basic physics related to irradiance, Part 2 presents the basic functional principles of photovoltaics, including an introduction to semiconductor materials and several topics related to solar cell device physics in general. Next, in Part 3, design aspects and the actual functioning of crystalline silicon solar cells, the most dominant solar technology in the current PV market, are presented. Subsequent parts will introduce the reader to other material systems for photovoltaic devices, that is, chalcogenide thin film solar cells in Part 4, thin film silicon-based PV technologies in Part 5, organic photovoltaic cells in Part 6 and III-V solar cells, including their concentrator applications, in Part 8. Since photovoltaic research is based on appropriate diagnostics, one Part (Part 7) will be fully devoted to characterization and measurement methods for materials contained by PV cells and PV modules. The second half of the book will focus more on applications of photovoltaic technologies. To start with, Part 9 will explore PV technologies that are applied in space. Next, Part 10 will present PV modules and their manufacturing processes. In Part 11, PV technologies applied in systems, buildings, and various products are placed in the spotlight. The use and issues of PV power production in interaction with conventional electricity grids are discussed in Part 12. Finally, Part 13 will complete this book, covering financial aspects, user aspects, and standards for the PV sector.

List of Symbols

Symbol	Unit	Meaning
E	eV	Energy of a photon
I	W/m^2	Energy contained by irradiance
L	m	Zenith path length of solar irradiance
L_θ	m	Optical path length of solar irradiance
λ	m	Wavelength
n	dimensionless	Refractive index
ν	Hz	Frequency
v	m/s	Phase velocity of light in media
R	dimensionless	Reflection coefficient
θ	º	Angle
T	dimensionless	Transmission coefficient

Constants

Symbol	Value	Name
c	$2.998 \cdot 10^8$ m/s	Speed of light in a vacuum
h	$6.626 \cdot 10^{-34}$ J$\cdot$s	Planck's constant
q	$1.602 \cdot 10^{-19}$ C	Elementary charge

List of Acronyms

Acronym	Meaning
AM	Air Mass
ASTM	American Society for Testing and Materials
CO_2	Carbon dioxide
O&M	Operation and Maintenance
PV	Photovoltaic
SI	Système International d'unités
STC	Standard test conditions

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