1

Introduction

1.1 Photovoltaics – What's It All About?

Photovoltaics is a technology involving the direct conversion of solar radiation (insolation) into electricity using solar cells. Interest in photovoltaics has grown exponentially in many countries over the past decade, with worldwide photovoltaic sector growth since 1997 ranging from 30 to 85%.

A solar cell is essentially a specialized semiconductor diode with a large barrier layer which, when exposed to light, allows for direct conversion into DC electricity of a portion of the energy in the light quanta or photons arriving at the cell (Figure 1.1).

As individual solar cells generate very low voltage, a number of such cells are connected in series and are combined into a so-called solar module. Higher output can be obtained by wiring a number of modules together to create solar generators, which can be of any size.

The first usable solar cell was developed in 1954, and solar cells were first used for technical purposes in connection with space flight. Virtually all satellites that have been put into orbit around the Earth since 1958 are powered by solar cells, which were originally called solar batteries. The high cost of these early solar cells posed no obstacle to their use, since they were extremely reliable, lightweight and efficient. Following the 1973 oil crisis, interest in renewable energy increased, particularly in terms of solar power. Interest in photovoltaics has grown even further since the Chernobyl accident in 1986, which spurred the development of simpler and cheaper solar cells for terrestrial applications. This first generation of solar cells was initially used to supply electricity to remote locations (e.g. telecommunication facilities, holiday homes, irrigation systems, villages in developing countries and so on, as for instance shown in Figures 1.2–1.9). For such applications, photovoltaics has long since been an economically viable energy resource.

The USA was in the vanguard of PV development and use in the 1980s, at which time various multi-megawatt PV power plants that had been built in desert regions were converting solar cell DC power into AC power that was being fed into the public grid. Many of these installations integrated single- or dual-axis solar trackers. The first such installation, which had 1 MW of power, was realized in 1982 in Hesperia, followed by a second, 6.5 MW, installation in Carrizo Plain. Both of these installations have since been dismantled. In the late 1980s, the Chernobyl disaster aroused interest in grid-connected systems in Europe as well. For many years Europe's largest PV installation (3.3 MWp) was the facility in Serre, Italy, which was connected to the grid in 1995. In recent years, PV power plants of 5 MWp and more have become increasingly prevalent in Germany and Spain. At the time this book went to press, the largest such plant was the 60 MWp PV power station in Olmedilla de Alarcon, Spain (around 150 km west of Valencia), which began operating in 2008. Various, even larger PV power stations are under construction or in the planning stages, including a 2000 MWp facility in China.

Photovoltaics: System Design and Practice. Heinrich Häberlin.

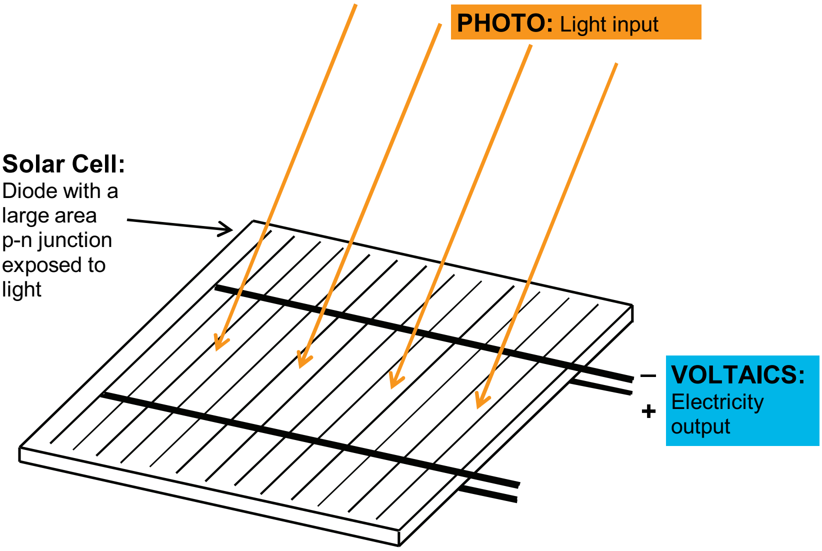

Figure 1.1 Solar cells convert light into electricity. The term photovoltaic is derived from *photo*, the Greek word for light, while 'voltaic' refers to volt, which is the unit for electric voltage

The largest PV power station in Switzerland (1342 kWp) is the BKW facility atop the new Stade de Suisse football stadium in Bern, where the first phase of the installation (855 kWp) began operating in 2005. Two years later the facility was expanded to full nominal capacity, and as at December 2009 was still the world's largest football stadium PV installation. Another large Swiss PV installation is the 555 kWp

Figure 1.2 The 400 Wp solar generators at the Monte Rosa Hostel in the late 1980s. Such hostels today commonly have PV installations with at least 3 kWp of power (Photo: Fabrimex/Willi Maag)

Figure 1.3 Solar home system in India. Even a 50–100 Wp PV installation appreciably raises the standard of living in developing countries (Courtesy of DOE/NREL)

Figure 1.4 Lighthouse PV installation (Photo: Siemens)

Figure 1.5 Solar-powered emergency phone in the California Desert (Courtesy of DOE/NREL)

Mont Soleil power station, which is located at 1270 m above sea level and was connected to the grid in 1992. Information concerning other large-scale PV installations is available at www.pvresources.com. Various grid-connected systems around the world are shown in Figures 1.10–1.16.

The PV efficiency of today's commercially available solar cells for terrestrial applications ranges up to 22.5%. Although this figure is likely to rise in the coming years, the efficiency of PV installations is limited by the laws of physics.

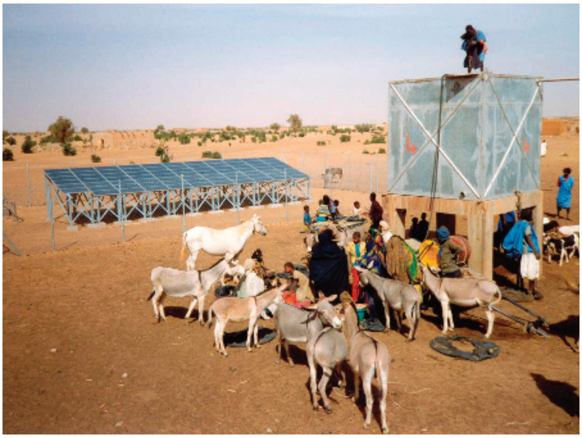

Figure 1.6 Solar-powered village well in Mondi, Senegal. As the well water is easy to store, such simple installations do not need a battery to supply power in the night; this in turn considerably reduces system costs (Photo: Siemens)

Figure 1.7 A 6 kWp stand-alone AC installation with a battery in the Chinese village of Doncun-Wushe (Photo: Shell Solar/SolarWorld)

The insolation used by solar cells constitutes an inexhaustible energy resource, unlike oil, uranium and coal, which are the most widely used energy resources today. But these resources are finite and will run out in a few decades in the case of oil and uranium, and in a few centuries in the case of coal. However, a basic problem with terrestrial photovoltaics is that many solar power applications are subject to fluctuating insolation by virtue of the sunrise and sunset cycle, cloudy and rainy weather, and seasonal changes in insolation. Hence in order for PV installations to provide an uninterrupted supply of electricity, it is necessary to use energy accumulators, which considerably drive up the cost of PV electricity. However, an existing power grid can be used as an accumulator to a certain extent, without the need for additional energy storage facility expenditures.

PV energy is extremely clean and environmentally friendly, and engenders no noise pollution, waste-gas emissions or toxic waste. Moreover, silicon, the main raw material used for solar cells, is one of the most abundant substances on Earth (in the form of sand) and can be readily disposed of when solar cells are retired. The substances used in silicon solar cells are non-toxic and environmentally friendly. Thus electricity from silicon solar cells can in a sense be thought of as 'power from sand and Sun'.

Figure 1.8 PV telecommunication installation at a remote location in Sipirok, Indonesia (Photo: Siemens)

Figure 1.9 PV installation that supplies power to Lime Village, Alaska. This is a 4 kWp stand-alone AC installation with a battery and a backup diesel generator (Courtesy of DOE/NREL)

Figure 1.10 A 3.18 kWp grid-connected system on the roof of a home in Burgdorf, Switzerland; the installation has been in operation since 1992

Figure 1.11 A 60 kWp grid-connected system on the roof of the Electrical Engineering Department at Bern University of Applied Sciences in Burgdorf. This installation has been in operation since 1994. © Simon Oberli, www.bergfoto.ch (details from Neville Hankins) (Photo: Simon Oberli)

Figure 1.12 The grid-connected system (1152 kWp) owned by Bern University of Applied Sciences on the Jungfraujoch Mountain, which is located at 3454 m above sea level and was connected to the grid in 1993. On inception, the Jungfraujoch facility was the world's highest-altitude PV installation

Figure 1.13 The grid-connected 555 kWp system on Mont Soleil, which is located at 1270 m above sea level and was commissioned in 1992

Figure 1.14 The grid-connected system (3.3 MWp) in Serre, Italy. The installation was commissioned in 1995 (Photo: ENEL)

Figure 1.15 The 5 MWp Leipziger Land grid-connected system in Germany that was commissioned in 2004 (Photo: Geosol)

Solar cells are maintenance free and extremely reliable. If they are protected from environmental influences by a fault-free packing, monocrystalline and polycrystalline solar cells have a life expectancy of 25 to 30 years.

In contrast to solar thermal systems, which can only use direct beam radiation, PV installations can also convert into electricity the diffuse portion of insolation, which accounts for a major portion of total irradiated energy in northern climates such as Central Europe. In Switzerland's Mittelland region and large portions of Germany and Austria, diffuse radiation accounts for more than 50% of total radiation. Another important difference between solar thermal systems and PV installations is that the latter are not subject to minimum size restrictions, which means that low-energy-consumption devices such as watches, calculators and the like can be solar powered. Conversely, owing to the modularity of PV installations, they are not subject to an upper size limit either – which means that PV power plants with peak capacity in the gigawatt range can in principle be realized in desert regions [1.1].

But PV technology does have one major drawback, namely its high cost, which means that in most countries PV installations are economically viable solely for consumers who are located at a considerable distance from the nearest grid hook-up. On the other hand, exporting solar power to the public grid is not an economically viable proposition in light of the large difference between the cost of generating solar

Figure 1.16 The grid-connected system in Springerville, Arizona. Currently 4.6 MWp, the capacity of this installation is being expanded incrementally to around 8 MWp (Photo: Tucson Electric Power Company; www.greenwatts.com)

power and the price of grid electricity. However, this did not prevent numerous environmentally conscious idealists and companies from realizing grid-connected systems in the late 1980s and early 1990s, once mass-produced PV inverters in the 0.7 to 5 kW range came onto the market. Ever since the 1986 Chernobyl disaster and the subsequent freeze on building new nuclear power plants in many countries, some European power companies have expressed an interest in the possible realization of PV power plants. This interest has been largely driven not so much by a desire to produce large amounts of electricity, but rather by the wish to gain experience with this relatively new technology. However, only a limited number of individuals and power companies are willing to take on the risk and cost of building such PV installations and thus spur advances in PV technology.

In the 1990s, a handful of countries established PV subsidy programmes to promote the realization of grid-connected systems. But unfortunately the steady increase in demand for solar cells was not nearly high enough to bring about the kind of economies of scale and mass production that would have allowed for lower solar cell prices. Such economies of scale only occur in cases where sustained long-term demand for a product necessitates substantial investments in production equipment that hold out the prospect of a robust return.

By far the most efficient types of subsidies for grid-connected systems are cost-recovery feed-in tariffs, which were first introduced in 1991 by the local power company in Burgdorf, Switzerland, and which have since become known as the Burgdorf model (Figure 1.17). Under this framework, the owners of grid-connected systems that were built between 1991 and 1996 were to receive the equivalent of €0.67 per kWh for electricity fed into the grid for a period of 12 years, whereby this emolument was spread across the electricity prices paid by all customers. In conjunction with the fixed federal and cantonal subsidies amounting to a few euros per watt of peak power that were available back then, this framework constituted an emolument system that allowed for the depreciation of grid-connected systems during their lifetime. This system also resulted in the realization of a great many such systems during the ensuing years. This type of subsidy spurs not only the realization of grid-connected systems, but also the efficient operation of them; in turn, this is the most efficient way to promote advances in PV technology. A modified form of the Burgdorf model was subsequently implemented in several other cities such as Aachen in Germany, and with the passage of Germany's Renewable Energy Act (EEG) in 2000 was elevated to the status of a nationwide framework – which in turn occasioned an exponential growth in

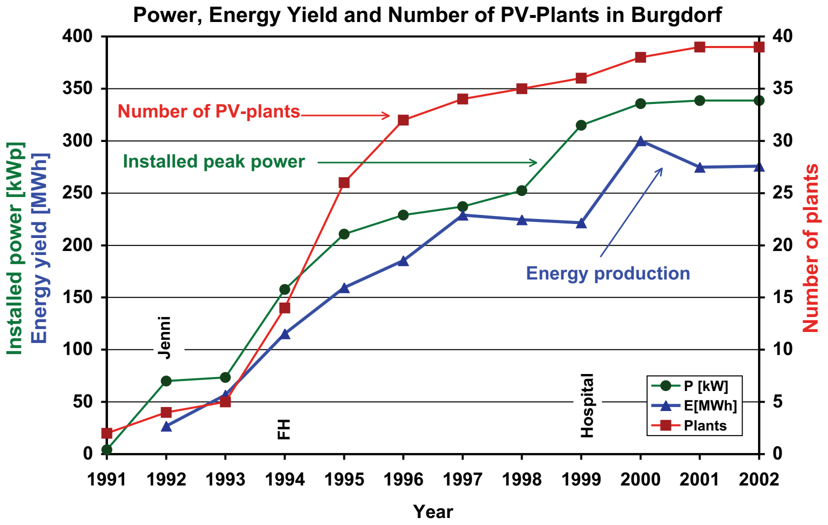

Figure 1.17 Installed peak PV capacity following the introduction of the Burgdorf model (€0.67 per kWh emolument from the local power company). The second spurt of growth in 1999 and 2000 was attributable to installation realized in connection with the 'solar electricity exchange'

Germany's PV sector and a rapid increase in installed PV capacity. A similar Swiss law (known as the KEV law), which was adopted in early 2009, has also prompted robust growth in installed PV capacity. Unlike Germany's EEG, Switzerland's KEV law calls for numerous, very low-cost coverage limits and these have inhibited growth in Switzerland's PV sector.

Since the advent of the first 3 kW inverter (the SI-3000) in 1987, the number of commercially available inverters has shot up and they are now far more reliable than they used to be. In addition, since the mid 1990s, so-called module inverters in the 100 to 400 W range have been available. Such module inverters allow for connection of anywhere from one to a handful of modules that are mounted directly on or in close proximity to the solar module. A large selection of mass-produced triphase inverters in the 20 to 500 kW range are also available.

The price of a PV installation can be reduced somewhat by integrating the system into a newly constructed building. In other words, the installation is mounted not on the outside of the building, but instead forms part of the building's shell or fulfils a key function such as shading. This kind of arrangement also lends itself to a far more aesthetically pleasing and creative realization, but can nonetheless negate the original savings by dint of architect's fees and the cost of the mass-produced modules or laminates. Such building-integrated PV installations were first realized during the 1990s. In countries such as France and Switzerland the higher emoluments that have been recently instituted for PV electricity exported to the grid from building integrated installations have spurred interest in this type of solution.

Product researchers around the world are working feverishly on the development of inexpensive and more efficient solar cells, while at the same time PV system technology is being optimized. Worldwide solar cell production has been rising at a rate of 30 to 85% annually since 1997, and increased production volumes have translated into lower prices. A combination of manufacturer learning curves and a doubling of production volumes could potentially occasion a decrease of around 20% in solar module prices. One thing is certain, however: the use of photovoltaics is set to account for a steadily increasing proportion of overall electricity production in the coming years.

1.2 Overview of this Book

The central portion of this book comprises a comprehensive introduction to PV technologies. Each term or symbol is extensively elucidated the first time it appears (see also the List of Symbols), and all acronyms and units used in this book are listed in Appendix B. The relevant calculation worksheets can be found in Appendix A. Illustrations, tables, equations and bibliographic references are sequentially numbered within each chapter. Equation numbers are in brackets (except in running text, where they are referred to, for example, as Equation 3.1), while bibliographic references are in square brackets. Apart from numerous photographs and diagrams, the text contains tables or examples that provide additional relevant information.

Each chapter ends with a bibliography on the matters discussed in the chapter, and the references are enumerated as follows: for example, [1.1] means the first listed reference in Chapter 1, [2.1] is the first listed reference in Chapter 2 and so on. In the interest of saving space, a bibliographic reference from an earlier chapter that appears in a later chapter is referenced under its original bracketed number, i.e. it is not given a new number and listed again in the later chapter. Appendix B contains a bibliography of books on photovoltaics. References from this list cited in the text begin with the first three letters of the author's (or first author's) name followed by the year of publication. Thus, for example, [Bas87] refers to a book by Uwe Bastiansen that was published in 1987.

The following is an overview of the subject matter of each of the 11 chapters that go to make up this book.

The present chapter contains a general introduction to photovoltaics, definitions of key PV terms and an overview of recommended figures for estimating: (a) PV guide values; and (b) the amount of space required for such installations.

Chapter 2 discusses solar insolation on horizontal and tilted surfaces. Two insolation calculation methods are presented, one very basic and easy to use, the other more robust but also more labour intensive to allow basic shading scenarios to be taken into account. Detailed charts for locations between 60°N and

40°S and that apply to both methods are provided in Appendix A. PV installation energy yield can be determined far more precisely if solar generator surface irradiation arising from local solar insolation is known.

Chapter 3 is concerned with the following: the structure and functional principle of solar cells; the impact of various solar cell materials and technologies on solar cell efficiency; solar cell designs; the solar cell manufacturing process; and possible solar cell development in the future.

Chapter 4 centres around solar modules, laminates and solar generators, and discusses in detail solar cell and solar module wiring options, particularly in scenarios involving partially shaded solar generators or module data scatter. This chapter also discusses solar generator configuration and how solar generators can be integrated into buildings or infrastructure installations.

Chapter 5 contains detailed information on the layout and configuration of PV installations. The chapter contains two main sections, the first discussing stand-alone systems and the second grid-connected systems, and also provides information on the key components of PV systems, particularly batteries and inverters. This chapter also discusses the electromagnetic compatibility of PV installations and the problems that can arise when such installations are connected to the public grid.

Chapter 6 begins with a brief introduction to lightning protection and then goes on to discuss in detail lightning current and surge protection measures for PV installations.

Chapter 7 is concerned with normalized presentation methods for PV installation energy yield and power output, which are extremely useful when it comes to determining whether PV installations are functioning properly. Such presentation methods also simplify and systematize the energy yield calculations discussed in the subsequent chapter.

Chapter 8 discusses PV installation sizing and energy yield calculations, based on the insolation calculations and normalized energy yield presentation methods described in Chapters 2 and 7 respectively. Detailed tables for use with these methods can be found in Appendix A.

Chapter 9 takes up the subject of the economic viability of PV installations from both financial and energy standpoints.

Chapter 10 describes selected grid-connected systems (both building-integrated and ground-based PV installations) that are currently in operation in Germany, Switzerland, Spain, Italy, Australia and the USA. The energy yields of these installations and the consequent learning curves are also discussed.

Chapter 11 briefly reviews the topics discussed in the book as a whole and offers a number of cautious predictions on the future of photovoltaics.

Appendix A begins with detailed weather data charts, as well as insolation calculation tables for tilted surfaces worldwide between 60°N and 40°S. Also included are: (a) insolation maps for the entire world; (b) figures that enable estimated horizon-induced shading to be folded into the sizing calculations for sites in the northern hemisphere; (c) PV installation energy yield calculation charts; and (d) numerous maps showing insolation around the world.

Appendix B contains a list of key web sites, a bibliography of books on photovoltaics, a list of the acronyms used in this book, a list of useful conversion factors, and a number of key physical constants. The List of Symbols and Acknowledgements appear separately.

1.3 A Brief Glossary of Key PV Terms

This section provides a brief glossary of key PV terms [SNV88], all of which are discussed in detail later in this book and illustrated with diagrams and photos.

1.3.1 Relevant Terminology Relating to Meteorology, Astronomy and Geometry

Solar radiation: Radiation originating from the Sun, in the 0.3 to 3 μm wavelength spectrum.
Solar spectrum: Distribution of solar radiation intensity as a function of wavelength or frequency.
Direct solar radiation: Solar radiation arriving at a plane directly from the solar disc.
Diffuse solar radiation: Solar radiation arriving at a plane after scattering by atmospheric particles (e.g. water droplets, clouds) or ambient reflection.

Global radiation: The sum of direct and diffuse solar radiation (i.e. aggregate radiation originating from the Sun) arriving at a level surface.

Global irradiance *G*:

Power density (power/area) of the global radiation arriving at a plane. Unit: W/m^2.

Irradiation *H* (radiation energy):

Energy density (energy/area) of the global radiation arriving at a plane within a certain time interval, calculated by integration of irradiance *G* over this time interval. Common time intervals are one year (a), one month (mt), one day (d) or one hour (h). Units: kWh/m^2 and MJ/m^2 (kWh/m^2 is more expedient for PV applications). Conversion: 1 kWh = 3.6 MJ and 1 MJ = 0.278 kWh.

Pyranometer: Instrument for measuring global radiation (global irradiance *G*) on a level surface over the whole wavelength range between approx. 0.3 and 3 µm. Based on the thermoelectric principle, pyranometers are highly accurate but expensive instruments that are mainly used by weather services.

Reference cell: A calibrated solar cell for measuring global radiation *G* on a level surface. Reference cells are much cheaper than pyranometers. Like an actual solar cell, a reference cell only utilizes a portion of total incident insolation and is calibrated such that under standard conditions (standard spectrum AM1.5, where $G = 1$ kW/m^2) it exhibits the same insolation as a pyranometer. In practice there are discrepancies ranging up to several per cent between the values indicated by pyranometers and reference cells, depending on the weather conditions.

Solar altitude h_S: Angle between the direction of the Sun (centre of the solar disc) and the horizontal plane.

Solar azimuth γ_S: For $\varphi > \delta$, the angle between south and the projection of the direction of the Sun on a horizontal plane. For $\varphi < \delta$, the angle between north and the projection of the direction of the Sun on a horizontal plane. In both cases, $\gamma_S < 0$ for deviations to the east, $\gamma_S > 0$ for deviations to the west (φ = latitude, δ = solar declination; for details see Section 2.1.2).

Solar generator tilt angle β: Angle between the solar cell plane and horizontal.

Solar generator orientation (solar generator azimuth) γ: In the northern hemisphere, the angle (clockwise) between south and the normal projection (vertical) of the solar cell and horizontal. In the southern hemisphere, the angle (anticlockwise) between north and the normal projection of the solar cell and horizontal. In both cases, $\gamma < 0$ for deviations to the east, $\gamma < 0$ to the west.

Relative air mass number (AM): Ratio of (a) the actual atmospheric mass (optical thickness) through which solar radiation travels to (b) the minimum possible atmospheric mass at sea level (applicable when the Sun is at its zenith). The following applies in this regard:

$$\text{Air mass AM} = \frac{1}{\sin(h_S)} \cdot \frac{p}{p_o} \tag{1.1}$$

where p = local air pressure and p_o = air pressure at sea level.

Examples (for locations at sea level):

AM1: $h_S = 90°$
AM1.1: $h_S = 65.4°$
AM1.2: $h_S = 56.4°$
AM1.5: $h_S = 41.8°$ (convenient mean value for Europe)
AM2: $h_S = 30°$
AM3: $h_S = 19.5°$
AM4: $h_S = 14.5°$

According to Equation 1.1, AM values of less than 1 can occur in mountainous regions (e.g. in the Alps during summer).

1.3.2 PV Terminology

Crystalline silicon (c-Si): Silicon that has solidified into atoms arranged in a crystal lattice, i.e. crystals.
Monocrystalline silicon (sc-Si, mono-c-Si): Silicon that has solidified into a single large crystal. Production of this substance is very energy intensive and pulling of the single crystal is time consuming.
Polycrystalline or multicrystalline silicon (mc-Si): Silicon that has solidified into many small crystals (crystallites) in any orientation. Energy consumption for production is significantly lower than for monocrystalline silicon. Polycrystalline and multicrystalline are often used as synonyms, although in some cases a distinction is made between the raw material (polycrystalline silicon) and the material used for producing solar cells after the silicon is cast into ingots and sliced into wafers (multicrystalline silicon, or mc-Si; see Section 3.5.1).
Amorphous silicon (a-Si): Silicon whose atoms are not arranged in a crystal lattice.
Solar cell: Semiconductor diode with a large barrier layer exposed to light, which generates electrical energy directly when sunlight strikes it.
Solar module: A number of galvanically connected solar cells (usually connected in series) arranged in a casing to protect against environmental influences.
Solar panel: A unit consisting of several mechanically joined solar modules (often pre-wired) that are delivered pre-assembled and are used for configuring larger solar generators. In technical jargon, solar panel is often incorrectly used as a synonym for solar module.
Solar generator (array): A series of solar panels or solar modules that are arranged on a mounting rack and wired to each other (including the mounting rack).
Solar generator field (array field): An arrangement of several interconnected solar generators, which together feed a PV system.
Photovoltaic system (PV system, PV installation): Aggregate components used for direct conversion of the energy contained in solar radiation into electrical energy.
Grid-independent PV system (autonomous system, stand-alone system): A PV electricity generation system that is not connected to the public grid. Such systems usually require batteries to store energy in the night and to balance load peaks. This storage system increases electricity costs.
Grid-coupled PV system (grid-connected system): A PV system that is connected to the public grid, which is used as a storage medium, i.e. any excess energy is fed into the grid while energy is obtained from the grid at times of insufficient local production.
Current/voltage characteristic ($I = f(V)$): Graphic display of current as a function of the voltage of a solar cell or a solar module (at a specific irradiance G and cell temperature).
Open-circuit voltageV_{OC}: Output voltage of a solar cell or solar module in open-circuit condition (no current), at a specific irradiance G and cell temperature.
Short-circuit current I_{SC}: Current in a short-circuited solar cell or solar module, i.e. with output voltage 0 V, at a specific irradiance G and cell temperature.
Standard test conditions (STC): Usual test conditions, as follows, for the purpose of specifying solar cell and solar module guide values: irradiance $G_o = G_{STC} = 1000\ \mathrm{W/m^2}$, AM1.5 spectrum, cell temperature 25 °C.
Peak power $P_{\max}$: Maximum output power (product of voltage × current) of a solar cell or solar module at a specific insolation and solar cell temperature (usually under STC) at the maximum power point (MPP).

Metric: 1 watt = 1 W and 1 Wp (watt peak).

Peak power is often expressed in Wp rather than W to indicate that it is a peak power value under laboratory conditions, which is rarely reached under real operating conditions.
Fill factor FF (of a solar cell or a solar module): Ratio of peak power to the product of multiplying open-circuit voltage by short-circuit current at a specific insolation and solar cell temperature. In practice FF is always less than 1. The following equation applies to the fill factor FF:

$$\mathrm{FF} = \frac{P_{\max}}{V_{OC} \cdot I_{SC}} \tag{1.2}$$

Packing factor PF of a solar module:
Ratio of total solar cell area to total module area (including the frame). PF is always less than 1.
Photovoltaic efficiency or solar cell efficiency η_{PV}:
Ratio of peak power $P_{\max}$ of a solar cell to the radiation power arriving at the solar cell. Solar cell efficiency decreases somewhat at lower insolation and higher temperatures.

The following equation applies to solar cell efficiency (where A_Z = solar cell area):

$$\eta_{PV} = \frac{P_{\max}}{G \cdot A_Z} \tag{1.3}$$

Solar module efficiency η_M:
Ratio of peak power of a solar module to the radiation power arriving across the whole module area (including the frame). In practice η_M is always less than η_{PV}.

The following therefore applies to module efficiency:

$$\eta_M = \eta_{PV} \cdot \mathrm{PF} \tag{1.4}$$

Energy efficiency (utilization ratio, system efficiency) η_E:
Ratio of the usable electrical energy produced by a PV system to the solar energy incident on the whole solar generator area over a certain period (e.g. a day, month or year).

The following applies: $\eta_E < \eta_M$.

1.4 Recommended Guide Values for Estimating PV System Potential

The figures indicated in this section will enable the reader to estimate guide values for PV installations. More precise calculation methods are described in later chapters.

1.4.1 Solar Cell Efficiency η_{PV}

Solar cell efficiency, which is mainly of interest to solar cell researchers and manufacturers, is nowadays (2009) as follows for commercially available solar cells under STC ($G = G_o = 1$ kW/m^2, AM1.5 spectrum, cell temperature 25 °C):

For monocrystalline Si solar cells (sc-Si):	$\eta_{PV} = 13$–22.5%
For polycrystalline (multicrystalline) Si solar cells (mc-Si):	$\eta_{PV} = 12$–18%
For amorphous Si solar cells (a-Si): (the higher figures apply to a-Si triple cells only)	$\eta_{PV} = 3.5$–8.5%
For CdTe solar cells:	$\eta_{PV} = 7.5$–12%
For CuInSe$_2$ (CIS) solar cells:	$\eta_{PV} = 8$–12.5%

The efficiency of the counterpart lab cells is several percentage points higher.

Solar cell efficiency is inherently limited, however, by: (a) the fact that sunlight is composed of various colours comprising varying and sometimes not fully usable light quantum energy; and (b) the principles of semiconductor physics (see Chapter 3).

1.4.2 Solar Module Efficiency η_M

Solar module efficiency is mainly of interest to PV installation designers and installers. Its calculation should always be based on total module surface area and not just on solar cell surface area. The efficiency of currently available (2009) solar modules under the test conditions referred to in Section 1.4.1 is as follows:

For monocrystalline Si solar modules (sc-Si):	$\eta_M = 11\text{–}19.5\%$
For polycrystalline (multicrystalline) Si solar modules (mc-Si):	$\eta_M = 10\text{–}16\%$
For amorphous Si solar modules (a-Si): (the higher figures apply to a-Si triple cells only)	$\eta_M = 3\text{–}7.5\%$
For CdTe solar modules:	$\eta_M = 7\text{–}11\%$
For $CuInSe_2$ (CIS) solar modules:	$\eta_M = 7.5\text{–}11.5\%$

1.4.3 Energy Efficiency (Utilization Ratio, System Efficiency) η_E

PV installation energy efficiency is always considerably lower than the module efficiency of the installation's solar modules, on account of the additional power losses that occur in the installation's wiring and diodes on the DC side and on account of the following: module data scatter; module soiling and shading; elevated solar cell temperatures; elevated reflection resulting from non-perpendicular incident light; non-usable energy under very low-insolation conditions; DC to AC conversion loss in the inverter (for grid-connected systems) and battery storage loss (stand-alone installations).

The energy efficiency η_E of Central European grid-connected systems with monocrystalline solar cells ranges from around 8 to 14.5% over the course of any given year.

Low though the energy efficiency attainable using today's commercial components may seem now, as in the past, the efficiency of commercially available solar cells will increase steadily, albeit not as quickly as the efficiency of laboratory solar cells; in turn this means that PV installation efficiency as a whole will improve considerably in the long run.

1.4.4 Annual Energy Yield per Installed Kilowatt of Peak Installed Solar Generator Capacity

Thanks to the modularity of PV installations, they can be realized in greatly varying sizes. In view of this fact, when comparing annual energy yields, the specific annual energy yield kWh/kWp/a derived from peak installed solar generator power P_{Go} should be indicated either as: (a) the annual value Y_{Fa} for the so-called final yield Y_F in kWh/kWp/a; or (b) after truncating via kW, the number of full load hours t_{Vo} (in hours/year) for peak installation capacity P_{Go} (at STC):

$$\boxed{\text{Specific annual energy yield } Y_{Fa} = t_{Vo} = \frac{E_a}{P_{Go}} \qquad (1.5)}$$

where E_a = annual energy yield (E_{AC} for grid-connected systems) and P_{Go} = peak solar generator capacity.

By rearranging Equation 1.5 and inserting the Y_{Fa} value (if known; see the recommended values in Table 1.1), the potential annual energy yield for a PV installation of a specific size can be readily estimated.

Apart from the fact that Alpine installations exhibit higher annual energy yield, their winter energy production is far greater than for installations in low-lying areas. For example, a façade-mounted installation in the high Alps can attain winter energy output relative to total annual yield ranging from around 45 to 55%, as opposed to 25 to 30% for typical installations in Central European lowland areas.

The energy yield of selected Swiss grid-connected systems has been monitored since 1992 via a joint BFE–VSE project, whose data mainly stem from annual reports filed by installation owners based on monthly meter readings. These data reveal that from 1995 to 2008 the mean energy yield of the monitored

Table 1.1 Recommended values for determining energy yield for fixed solar panel installations

Installation site	Y_{Fa} (kWh/kWp/a) and t_{Vo} (h/a)
Façade-mounted installation in a low-lying area in Central Europe	450–700
Suboptimal or foggy sites in low-lying regions in Central Europe	600–800
Well-situated or optimally situated site in a low-lying area in Central Europe	800–1000
Sites in inner Alpine valleys, in the Alpine foothills, or just south of the Alps	900–1200
Southern Europe; Alpine regions	1000–1500
Desert regions	1300–2000
Recommended approximate value for flashover calculations	1000

installations was 833 kWh/kWp/a, a figure that should be interpreted in light of the following: (a) most of these installations are located in lowland areas; (b) many of these installations integrate components that are a number of years old (owing to the fact that few new installations have been realized in recent years); and (c) some of the installations are suboptimally oriented or are subject to shading.

The German solar advocacy organization Solarförderverein maintains a Web-based information service (www.pv-ertraege.de) that gathers information in the manner described above. However, the data available on this web site are more up to date as they are entered monthly. Noteworthy in this regard is that, owing to the realization of numerous new PV installations in recent years, Germany's mean energy yield for 1995 to 2008 is 869 kWh/kWp/a, which is higher than the figure for Switzerland despite that country's higher insolation (Figure 1.18).

From the low number of new PV installations realized in Switzerland, up until 2006, the technical improvement entailed by the new installations was for the most part cancelled out by the age of older installations. In contrast, because of the passage, in 2000, of Germany's EEG, it predominantly has new installations which, from their optimized components, use the available insolation more efficiently. The rate of new PV installation realization did not begin to pick up in Switzerland until 2007 (see Sections 1.4.7 and 1.4.9).

A similar monitoring programme realized in Austria in the mid 1990s revealed an annual energy yield amounting to 803 kWh/kWp/a, which means that the situation was apparently much the same as in Switzerland [1.6].

The use of dual-axis solar trackers in lieu of stationary mounting structures allows for more efficient use of direct beam energy and increases PV installation energy yield by 25 to 40%, albeit at the cost of higher

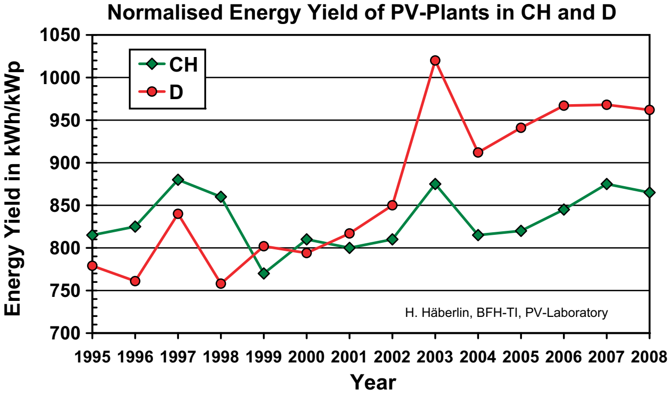

Figure 1.18 Mean specific energy yield for grid-connected systems from 1995 to 2008 in Germany and Switzerland. Early in this period, Switzerland's energy yield outpaced that of Germany because of Switzerland's higher insolation. But as from 2000, when Germany's Renewable Energy Act (EEG) was enacted, the proportion of new and technically superior installations in Germany increased substantially. *Source*: [1.4], www.pv-ertraege.de

capital expenditures for mechanical and control components. These expenditures mainly pay off with large PV power plants in desert regions.

1.4.5 PV Installation Space Requirements

The following equation applies to the nominal peak power P_{Go} of a solar generator field with n_M solar modules, peak capacity P_{Mo} and module surface area A_M ($G_o = 1\,\mathrm{kW/m^2}$):

$$P_{Go} = n_M \cdot P_{Mo} = n_M \cdot A_M \cdot G_o \cdot \eta_M = A_G \cdot G_o \cdot \eta_M \tag{1.6}$$

Thus the total area needed A_G for the solar generator field is determined as follows:

$$A_G = n_M \cdot A_M = \frac{P_{Go}}{P_{Mo}} A_M = \frac{P_{Go}}{G_o \cdot \eta_M} \tag{1.7}$$

The ground or roof area needed to mount a solar generator is

$$A_L = \mathrm{LF} \cdot A_G. \tag{1.8}$$

where:

n_M = number of solar generator solar modules

P_{Go} = nominal peak solar generator power (at STC)

P_{Mo} = peak solar module power at G_o

G_o = global irradiance for which P_{Mo} is defined ($G_o = G_{STC} = 1\,\mathrm{kW/m^2}$)

A_G = total solar generator field area

A_M = surface area of a solar module

η_M = solar module efficiency

A_L = space required for a ground-based or rooftop solar generator field

LF = Land Factor (between around 2 and 6 in Central Europe) for the avoidance of reciprocal shading in cases where a series of solar generators are arranged behind each other in a large installation.

1.4.6 Cost per Installed Kilowatt of Peak Power

Relative to the figures indicated in [Häb07], current prices for large numbers of solar modules have decreased and as of December 2009 were as follows, per watt of peak power:

For crystalline silicon solar modules:	€1.6–3.2
For thin-film CdTe solar cells:	€1.5–3
For thin-film amorphous Si solar cells:	€1.5–3

The manufacturing costs for certain components have also gone down considerably, e.g. for CdTe, around US$0.9 per Wp (€0.65 per Wp), which is extremely good for manufacturers' bottom lines. The tremendous production capacity increase on the part of many manufacturers in recent years is likely to result in further price reductions. Solar cell costs have also dropped considerably, and for crystalline Si cells now range from about €1 to €1.9 per Wp.

Laminates are nearly as expensive as framed modules, with some manufacturers selling them at a price that is a few percentages points lower than for framed modules of the same type.

Table 1.2 German feed-in tariffs, in eurocents per kWh, for PV installations that went into operation in 2010 or later, pursuant to the 2008 version of the EEG. These tariffs (those indicated here were valid as at December 2009) will be paid at a constant level for 20 years and will be subject to a further reduction as from 2011 (for further information visit www.erneuerbare-energien.de)

Installed capacity	Ground-based PV installations (cents per kWh)	Installations mounted on buildings or noise barriers (cents per kWh)
Up to 30 kW	28.43	39.14
30–100 kW	28.43	37.23
100–1000 kW	28.43	35.23
More than 1000 kW	28.43	29.37

New types of thin-film solar cell modules (e.g. CdTe) exhibit high efficiency, sell for far less than crystalline modules Si modules, and since 2006 have come into increasing use in Germany for large-scale ground-based PV installations as the statutory feed-in tariffs are lowest for them, according to Germany's EEG (see Table 1.2). Triple-cell amorphous Si modules are often mounted on roofs as well. But if these modules are unduly inefficient, this considerably ramps up the costs of wires and other system components, as well as the amount of space needed for the installation.

In keeping with the Staebler–Wronski effect, amorphous silicon solar cells are prone to light-induced degradation early on, resulting in an efficiency drop of 10 to 30% during the first few months of operation. Hence the life span of these cells may be shorter than that of monocrystalline and polycrystalline solar cells. Moreover, as amorphous Si cells (particularly the single-film variety) are less efficient, they require a larger installation space. For these reasons, amorphous Si cells are mainly used in small devices such as calculators, watches, radios and the like, and are rarely integrated into large PV installations for energy production purposes.

As at December 2009, the cost of a complete grid-connected system ranged from €2.7 to €7 per Wp. The lower price applies to large-scale ground-based PV installations with thin-film solar cells in Germany, while the higher price applies to small building-integrated monocrystalline cell installations.

1.4.7 Feed-in Tariffs; Subsidies

In the early 1990s, various Swiss power companies had begun subsidizing PV electricity by paying relatively high feed-in tariffs for PV installation electricity exported to the grid. The first power company to opt for this extremely effective subsidy instrument (now referred to as the Burgdorf model) for the technological advancement of photovoltaics was Industriellen Betriebe Burgdorf (IBB; now known as Localnet), which paid the equivalent of €0.77 per kWh for a 12-year period for all PV installations that went into operation before 1997. This exemplary European model was then implemented by certain municipalities in a modified form, and was later instituted in Germany, where it is referred to as the Aachen model.

However, a major breakthrough in the development of PV technology was the nationwide implementation in 2000 of cost-recovery feed-in tariffs in Germany under the EEG, which prompted a rapid rise in installed PV capacity. The tariff limitations called for by the original law were abolished in the amended version of the EEG that was adopted in 2004. The Act was amended again in 2008.

In 2003, Austria imposed a nationwide performance-related limit of 15 MWp on total installed PV capacity and subsequently amended its EEG to include the payment of cost-recovery feed-in tariffs for 13 years at a rate of 60 cents per kWh [1.7]. However, the capacity limit was soon reached and installed PV capacity in Austria rose only slightly (see Figure 1.21).

Switzerland finally instituted a modicum of nationwide PV subsidies via passage in 2008 of the KEV law governing cost-recovery feed-in tariffs (see Table 1.3), which are financed by a surcharge equivalent to 0.4 eurocents per kWh on electricity rates. Hence total Swiss subsidies for all renewable energy technologies are currently limited to the equivalent of around €220 million a year. Moreover, owing to the

Table 1.3 Swiss feed-in tariffs in eurocents per kWh (1 SFr. equivalent to 0.67€) as at February 2010 for PV installations commissioned in 2010 or later. These tariffs, which vary according to installation mounting modality and size, will be paid at a constant level for 25 years as from commissioning and will be reduced by 8% annually for each year of operation thereafter. For further information and actual valid values visit www.swissgrid.ch

Installed capacity	Ground-based PV installations (eurocents per kWh)	Surface mounted (eurocents per kWh)	Integrated (eurocents per kWh)
Up to 10 kW	36	41	49
10–30 kW	30	36	41
30–100 kW	28	34	37
More than 100 kW	27	33	34

very low spending limit imposed for photovoltaics (around 5% of the total amount at present), these subsidies involve an extremely bureaucratic application procedure and the available funds were exhausted two days after they became available. This ceiling will be raised to 10%, then 20% and then 30% when PV costs are equivalently less than €0.33, €0.27 and €0.20 higher than grid electricity, respectively.

Some Swiss power companies sell solar power at cost-recovery tariff prices (e.g. with a surcharge equivalent to €0.54 on the standard rate). This power is derived partly from the power companies' own PV installations and partly from so-called solar power exchanges operated by electricity contractors, which provide electricity at cost-recovery tariff prices that are guaranteed for an extended period. In view of the enormous profits that this higher priced electricity entails for the power companies, there is of course little demand for it; this programme is only a drop in the ocean in terms of bringing about a monumental increase in installed PV capacity and instituting substantial subsidies for PV technology development.

Although Switzerland had far and away the highest per capita installed PV capacity in Europe in the early 1990s (see Figure 1.22), it is now ranked somewhere in the middle and is unfortunately one of the European laggards when it comes to growth in installed PV capacity. The institution of PV electricity feed-in tariffs in 2007 has spurred this growth to some extent (see Table 1.4 and Figure 1.21), although the low multi-level limits on PV subsidies will retard PV sector growth for the foreseeable future. Swiss PV

Table 1.4 Peak installed PV capacity (in MWp) in selected countries, according to IEA data [1.16]

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Australia	18.7	22.5	25.3	29.2	33.6	39.1	45.6	52.3	60.6	70.3	82.5	104.5
Austria	2.2	2.9	3.7	4.9	6.1	10.3	16.8	21.1	24	25.6	27.7	32.4
Canada	3.4	4.5	5.8	7.2	8.8	10	11.8	13.9	16.7	20.5	25.8	32.7
Denmark	0.4	0.5	1.1	1.5	1.5	1.6	1.9	2.3	2.7	2.9	3.1	3.3
England	0.6	0.7	1.1	1.9	2.7	4.1	5.9	8.2	10.9	14.3	18.1	22.5
France	6.1	7.6	9.1	11.3	13.9	17.2	21.1	26	33	43.9	75.2	179.7
Germany	41.8	53.8	69.4	114	195	278	431	1034	1897	2727	3862	5340
Israel	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.9	1	1.3	1.8	3.03
Italy	16.7	17.7	18.5	19	20	22	26	30.7	37.5	50	120	458.3
Japan	91.3	133	209	330	453	637	860	1132	1422	1709	1919	2144
Korea (S)	2.5	3	3.5	4	4.8	5.4	6	8.5	13.5	34.7	77.6	357.5
Mexico	11	12	12.9	13.9	15	16.2	17.1	18.2	18.7	19.7	20.8	21.75
Netherlands	4	6.5	9.2	12.8	20.5	26.3	45.9	49.5	51.2	52.7	53.3	57.2
Norway	5.2	5.4	5.7	6	6.2	6.4	6.6	6.9	7.3	7.7	8	8.34
Portugal	0.5	0.6	0.9	1.1	1.3	1.7	2.1	2.7	3	3.4	17.9	67.95
Sweden	2.1	2.4	2.6	2.8	3	3.3	3.6	3.9	4.2	4.8	6.2	7.91
Switzerland	9.7	11.5	13.4	15.3	17.6	19.5	21	23.1	27.1	29.7	36.2	47.9
Spain				1	3	7	11	22	45	143	655	3354
USA	88.2	100	117	139	168	212	275	376	479	624	831	1169
TOTAL	305	385	509	715	974	1318	1809	2832	4154	5584	7841	13412

subsidies fall far short of those in many other countries. Some Swiss legislators are currently making efforts to raise or abolish these statutory limits.

Spain, France, Italy and a number of other European countries have in recent years instituted feed-in tariffs that have spurred marked growth in installed PV capacity. An example of how extremely successful such subsidies can be is provided by Spain, whose feed-in tariffs: (a) are not subject to a national installed-capacity limit for PV installations commissioned up to September 2008; (b) are far more economically beneficial than in Germany by virtue of Spain's far higher insolation relative to Germany; and (c) in 2008 resulted in a jump in installed PV capacity to more than 3 GWp. However, a national capacity limit has since been imposed in order to keep the costs of this programme within reasonable bounds.

As the tariffs and regulations in this domain change all the time, a discussion of the applicable laws has been forgone here. Such information is better obtained from professional journals, which are more up to date and for some larger countries are available in a nationwide edition [1.9]. Switzerland's originally planned feed-in tariffs for 2010 were reduced owing to the major price reductions that occurred in 2009 (see Table 1.3). German feed-in tariffs (see Table 1.2) are slated for further reduction as at 1 July 2010, amounting to 11%, 15% and 16% depending on the type of installation. For further information in this regard, see the web sites indicated at Tables 1.2, 1.3 and in Appendix A.

1.4.8 Worldwide Solar Cell Production

Figure 1.19 displays worldwide production of solar cells from 1995 to 2008 according to [1.8] (1995–2000) and [1.9] (2001–2008). These data were published each year during the spring.

It is noteworthy here that since 1997 worldwide solar cell production has been largely unaffected by the overall economic situation in that this sector has exhibited steady annual growth ranging from 30 to 85% – a trend that has prompted a number of solar cell manufacturers to expand their production capacity. Most solar cells are still made of silicon (Si). The proportion of thin-film solar cells made of cadmium telluride (CdTe), which is currently the most inexpensive technology, has increased substantially. Other materials such as copper indium diselenide ($CuInSe_2$, CIS) or copper indium gallium diselenide (Cu(In, Ga)Se, CIGS) are used for only a fraction of the thin-film solar cells made worldwide.

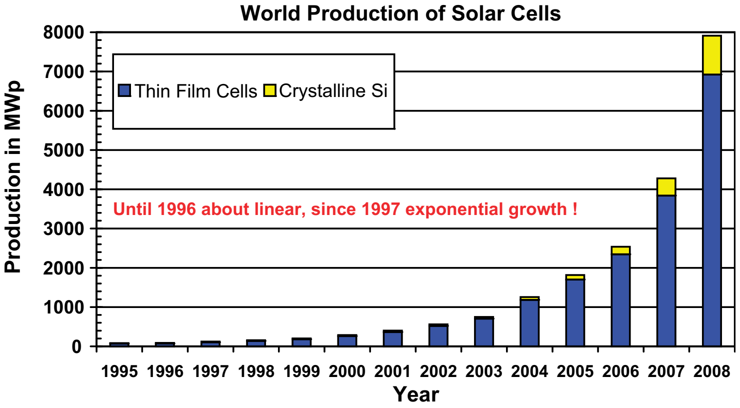

Figure 1.19 Worldwide solar cell production (*Sources*: [1.8] and [1.9]). Of the thin-film solar cells manufactured in 2008, around 51% were made of CdTe, around 41% were made of amorphous or micromorphous silicon and around 8% were made of CIS and CIGS [1.9]

1.4.9 Installed Peak Capacity

It is difficult to estimate the total installed worldwide capacity of all PV installations used for energy production (as opposed to calculators and the like), because reporting such data is not required by law.

It would seem that, as at the end of 2008, some 14.8 GWp of PV capacity was installed worldwide, around 9.6 GWp of it in Europe [1.17]. This figure: (a) was obtained by using the 1987 figure indicated in [1.10], which was then updated using the worldwide 1988 to 2008 production figures in [1.8] and [1.9]; and (b) is predicated on the assumption that 96% of all crystalline solar cells are used to generate electricity. Inasmuch as thin-film solar cells were initially used for the most part in consumer products, it was assumed that 30, 40, 50, 60 and 70% of these cells were used in PV installations as from (respectively) 1991, 2000, 2005, 2007 and 2008. Figure 1.20 displays the peak worldwide PV power thus calculated for 1995 to 2008.

Until the mid 1990s, the lion's share of worldwide installed PV capacity was concentrated in stand-alone installations. Thus, for example, in 1994 grid-connected systems accounted for only around 20% of world output, whereas the figure for stand-alone installation systems was 61% and for consumer products 19% [1.12]. However, since then there has been a steady increase in the proportion of worldwide PV production accounted for by grid-connected systems in industrialized countries such as Germany, Japan and Spain that offer relatively high feed-in tariffs. By the end of 2008, a minimum of 86% of worldwide installed PV capacity was apparently concentrated in grid-connected systems; in IEA states (Table 1) the figure was around 94% (13.4 GWp of installed capacity) [1.16].

Installed capacity as at the end of 2008 was around 47.9 MWp in Switzerland [1.16], where PV installations were at first mainly realized in the form of numerous, small stand-alone installations for remote sites such as holiday homes, telecommunication installations and so on. However, Switzerland has seen the advent of numerous 1–1000 kWp grid-connected systems realized by private citizens, power companies and municipalities. These installations accounted for around 44.1 MWp of Switzerland's total installed PV capacity as at the end of 2008 [1.16].

German peak installed PV capacity as at the end of 2008 amounted to 5340 MWp, 5300 MWp of which was grid connected [1.16].

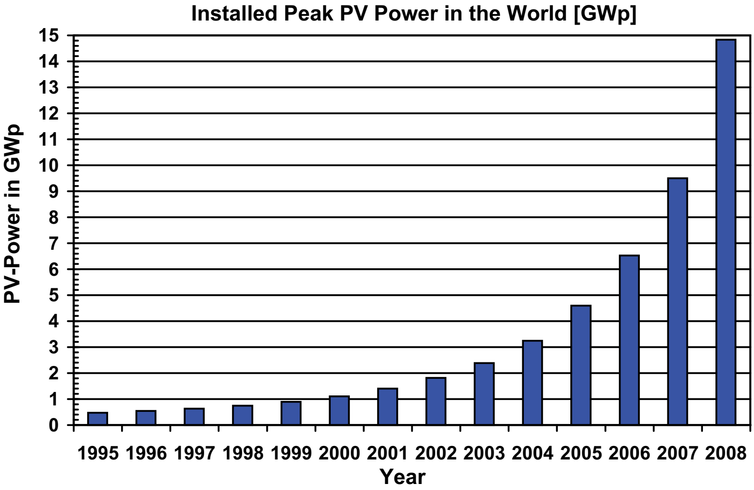

Figure 1.20 Worldwide installed solar generator capacity as at the end of the year, from 1995 to 2008. The new cells made in any given year are factored in only partly, as they must first be integrated into modules and then into PV installations. The 2004 figure is consistent with that indicated in [1.11]

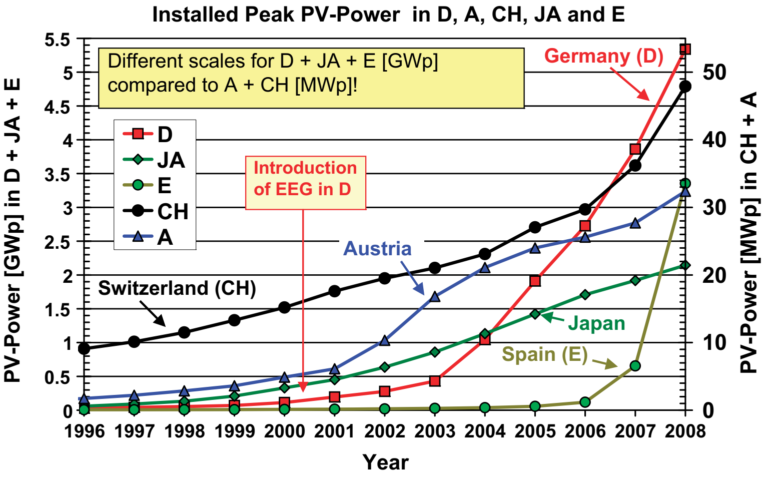

Figure 1.21 Total installed peak PV capacity in selected countries from 1996 to 2008 (*data source*: [1.16]). The 2008 figures are consistent with the estimates in [1.9], [1.16], [1.17], [1.18] and elsewhere

Austrian peak installed PV capacity as at the end of 2008 amounted to 32.4 MWp, 29 MWp of which was grid connected [1.16].

Owing to an extensive subsidy programme introduced in the late 1990s, Japan's total installed PV capacity as at the end of 2008 amounted to 2144 MWp, around 2053 MWp of which was grid connected [1.16].

In Spain, which only recently began subsidizing solar power in earnest (for installations commissioned prior to 1 October 2008), peak installed PV capacity as at the end of 2008 amounted to 3354 MWp, of which around 3323 MWp was grid connected [1.16].

Figure 1.21 displays peak installed PV capacity for 1996 to 2008 in these countries [1.16].

Switzerland long exhibited the highest per capita installed PV capacity owing to the early implementation of extremely extensive subsidies. Figure 1.22 displays per capita installed PV capacity in selected countries for 1996 to 2008. Switzerland's performance in this regard was outstripped by Japan in 2000 owing to that country's extensive PV subsidies, in 2002 by Germany owing to passage of the EEG, and in 2007 by Spain owing to the rapid increase in installed capacity there. In 2008, Spain had the highest per capita installed PV capacity owing to the monumental increase in capacity during that year, but was overtaken by Germany in 2009.

1.4.10 The Outlook for Solar Cell Production

Despite occasional recessionary trends in the world economy, from 1997 to 2008 world solar cell production grew annually by around 30 to 85%. If these growth rates are extrapolated by 30, 40 or 50%, the trend displayed in Figure 1.23 is obtained for solar cell production going forward.

Up until around 2007, solar cells were manufactured using silicon waste from semiconductors made for other applications. But the amount of such waste that is currently available is insufficient to cover the rapid growth in solar cell production. This has prompted the development in recent years of alternative silicon production modalities to meet the demand entailed by the growth shown in Figure 1.23. Solar cells not subject to particularly high efficiency requirements can be made using a

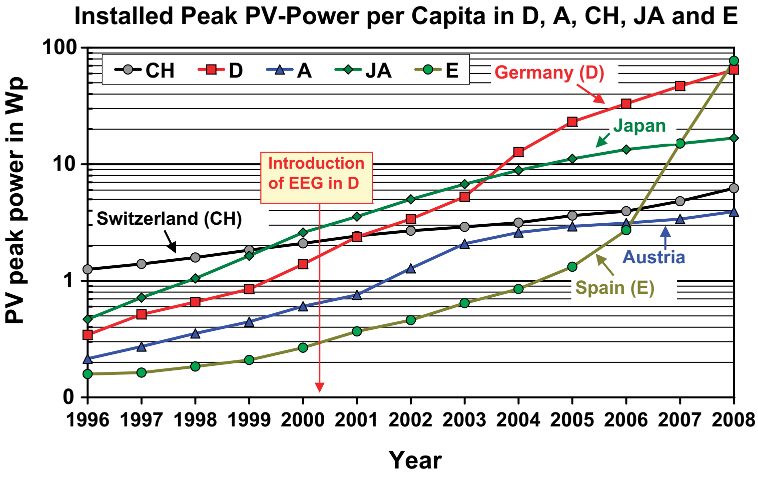

Figure 1.22 Per capita installed peak PV capacity in selected countries from 1996 to 2008, based on the figures in Figure 1.21

somewhat impure material known as solar grade silicon, which is more inexpensive to manufacture. A shortage of silicon in the face of rising demand for this material has spurred efforts on the part of various manufacturers to find innovative methods that will reduce the amount of silicon per Wp needed to make solar cells – for example, by using thinner silicon wafers (see Chapter 3).

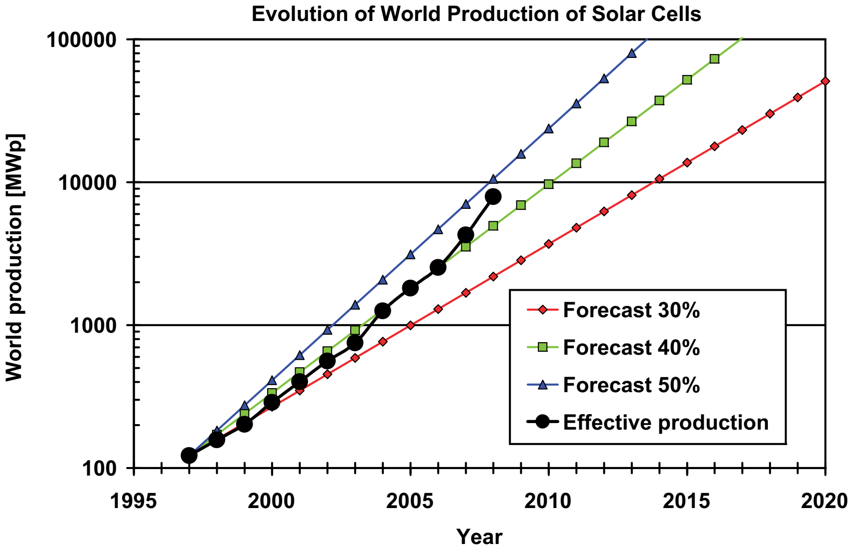

Figure 1.23 Projected worldwide solar cell production rate. These figures were obtained by extrapolating the growth figures for 1997 to 2008, during which period the growth rates were roughly as follows: 30% from 1997 to 1999; 35% from 2000 to 2003; 40% from 2004 to 2006; 70% from 2006 to 2007; and 85% from 2007 to 2008

1.5 Examples

Problem 1 (polycrystalline module)

At 1 kW/m^2 and a cell temperature of 25 °C, a Kyocera KC120 polycrystalline module exhibits the following characteristics: peak power 120 Wp; open-circuit voltage 21.5 V; short-circuit current 7.45 A. The module is composed of 36 15 cm $\cdot$ 15 cm solar cells and its outer dimensions are 96.7 cm $\cdot$ 96.2 cm.

Determine the following:

(a) Solar cell efficiency η_{PV}.
(b) Packing factor PF.
(c) Solar module efficiency η_M.
(d) Fill factor FF.

Solution:

(a) For a solar cell: $P_{\max} = P_{Zo} = P_{Mo}/36 = 3.333\,\text{W} \Rightarrow \eta_{PV} = P_{\max}/(G_o \cdot A_Z) = 14.8\%$.
(b) Packing factor $\text{PF} = 36 \cdot A_Z/A_M = 0.81\,\text{m}^2/0.9303\,\text{m}^2 = 0.8707$.
(c) Module efficiency $\eta_M = \eta_{PV} \cdot \text{PF} = 12.9\%$.
(d) Fill factor $\text{FF} = P_{Mo}/(V_{OC} \cdot I_{SC}) = 0.749$.

Problem 2 (20 kWp PV installation)

A PV installation should exhibit peak solar generator power amounting to $P_{Go} = 20.4$ kWp at 1 kW/m^2 and a cell temperature of 25 °C. BP 585 solar modules with a peak output of 85 Wp and module efficiency of $\eta_M = 13.5\%$ are to be used for the solar generator.

Determine the following:

(a) The requisite number of modules n_M.
(b) The requisite solar generator area A_G.
(c) The annual energy yield E_a if the installation's annual full load hours t_{Vo} for peak solar generator power P_{Go} at the installation site typically amounts to 950 h/a.
(d) The annual electricity cost savings realized if the installation owner uses the installation's electricity (for an installation not covered by the KEV law on cost-recovery feed-in tariffs) and if the maximum feed-in tariff is SFr 0.24 per kWh, which is equivalent to the current rate in the Bern canton.
(e) Net earnings from the sale of electricity to the local power company based on Germany's EEG with a feed-in tariff of 57.4 cents per kWh and based on the assumption that the installation was realized in 2004.

Solution:

(a) Module count $n_M = P_{Go}/P_{Mo} = 240$.
(b) $A_G = n_M \cdot A_M = P_{Go}/(\eta_M \cdot G_o) = 151.1\,\text{m}^2$. ($A_M = P_{Mo}/(\eta_M \cdot G_o) = 0.6296\,\text{m}^2$).
(c) $E_a = P_{Go} \cdot t_{Vo} = P_{Go} \cdot Y_{Fa} = 19\,380$ kWh/a.
(d) $S_{Electricity} = E_a \cdot$ SFr 0.24 per kWh = SFr 4651.20 per year.
(e) $S_{Electricity} = E_a \cdot$ €0.574 per kWh = €11 124 per year.

Problem 3 (replacing energy produced by a nuclear power plant with PV electricity)

A nuclear power plant with 950 MW of installed capacity is operated for 7700 hours per year. This amount of energy is to be provided by PV power plants at three different sites, with fixed solar module mounting structures and 14% module efficiency.

Determine the following:

For all three sites specified below under (a), (b) and (c):

The peak power P_{Go} of the solar generator at STC, the total solar generator area A_G and the amount of land or roof area A_L for

(a) Switzerland's lowland region (Mittelland): annual full load hours $t_{Vo} = 900$ h/a, land factor LF = 3.
(b) Alps: annual full load hours $t_{Vo} = 1400$ h/a, land factor LF = 2.
(c) Sahara Desert: annual full load hours $t_{Vo} = 1900$ h/a, land factor LF = 1.6.

Solution:

$E_a = 950\,\text{MW} \cdot 7700\,\text{h/a} = 7.315\,\text{TWh/a}$.

(a) $P_{Go} = E_a/t_{Vo} = 8.128\,\text{GWp}$, $A_G = P_{Go}/(\eta_M \cdot G_o) = 58.06\,\text{km}^2$, $A_L = \text{LF} \cdot A_G = 174.2\,\text{km}^2$.
(b) $P_{Go} = E_a/t_{Vo} = 5.225\,\text{GWp}$, $A_G = P_{Go}/(\eta_M \cdot G_o) = 37.32\,\text{km}^2$, $A_L = \text{LF} \cdot A_G = 74.64\,\text{km}^2$.
(c) $P_{Go} = E_a/t_{Vo} = 3.850\,\text{GWp}$, $A_G = P_{Go}/(\eta_M \cdot G_o) = 27.50\,\text{km}^2$, $A_L = \text{LF} \cdot A_G = 44.00\,\text{km}^2$.

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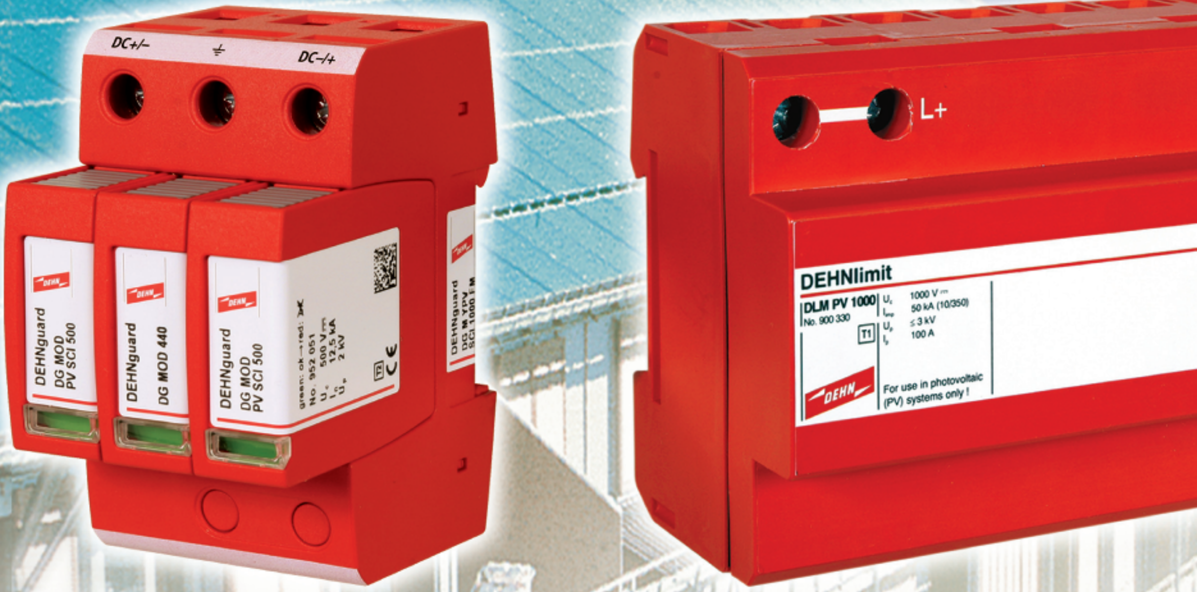
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