1.02 Introduction to Photovoltaic Technology

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Glossary

Balance of system All components of a PV energy system except the photovoltaics (PV) modules.

Grid parity The situation when the electricity generation cost of solar PV in dollar or Euro per kilowatt-hour equals the price a consumer is charged by the utility for power from the grid. Note, grid parity for retail markets is different from wholesale electricity markets.

Inverter Electronic device that converts direct electricity to alternating current electricity.

Photovoltaic energy system A combination of a PV system to generate direct current electricity, the necessary support and cabling structure, and an inverter system to convert direct electricity to alternating current electricity.

Photovoltaic module A number of solar cells together form a solar 'module' or 'panel'.

Photovoltaic system A number of PV modules combined in a system in arrays, ranging from a few watts capacity to multimegawatts capacity.

Photovoltaic technology generations PV technologies can be classified as first-, second-, and third-generation technologies. First-generation technologies are commercially available silicon wafer-based technologies, second-generation technologies are commercially available thin-film technologies, and third-generation technologies are those based on new concepts and materials that are not (yet) commercialized.

Photovoltaics (PV) It is a method of generating electrical power by converting solar radiation into direct current electricity using predominantly semiconductors or other materials that exhibit the PV effect.

Solar cell The device in which solar irradiation is converted into direct current electricity.

1.02.1 Introduction

The discovery of the photoelectric effect by Edmund Becquerel as reported in 1839 [1] has led to a multibillion solar photovoltaics (PVs) business today. The scientific discoveries by Max Planck [2] and Albert Einstein [3] in the early 1900s led to the first silicon solar cell made by Daryl Chapin, Calvin Fuller, and Gerald Pearson in 1954 [4]. Now, nearly 60 years later, this same solar cell design, in essence, is responsible for over 40 GW of installed solar power systems worldwide.

Figure 1 shows the development of annual PV production for the past 20 years [5]. Clearly, a nearly 1000-fold increase has occurred in these two decades, while the relative annual growth has also increased steadily, averaging over 50% over the past 10 years. Popular policy measures, such as the feed-in-tariff scheme pioneered in Germany, have pushed these developments forward [6]. The growth figures have to be sustained for the coming decades to reach global installed capacity, such that PV technology will be one of the major renewable electricity suppliers in a future sustainable society [7].

PV has become better and cheaper over the past decades. Starting with an efficiency of 7% in 1954, due to considerable amounts of public and private R&D funding, crystalline silicon wafer-based solar cells now have reached an efficiency of 25%, while cells that use other materials have reached an absolute record efficiency of 43.5% (two-terminal triple-junction GaInP/GaAs/GaInNAs, at an intensity of 418 suns) [8]. The magic 50% limit now becomes within reach, as recently reviewed by Antonio Luque [9]: intermediate band cell is considered to be as one of the best candidates.

From some \$100 W_p^{-1} in the mid-1970s, present-day PV module prices have decreased to between \$1 and \$2 W_p^{-1} today. Price development seems to follow a so-called experience curve, meaning that for every doubling of the produced amount of PV modules,

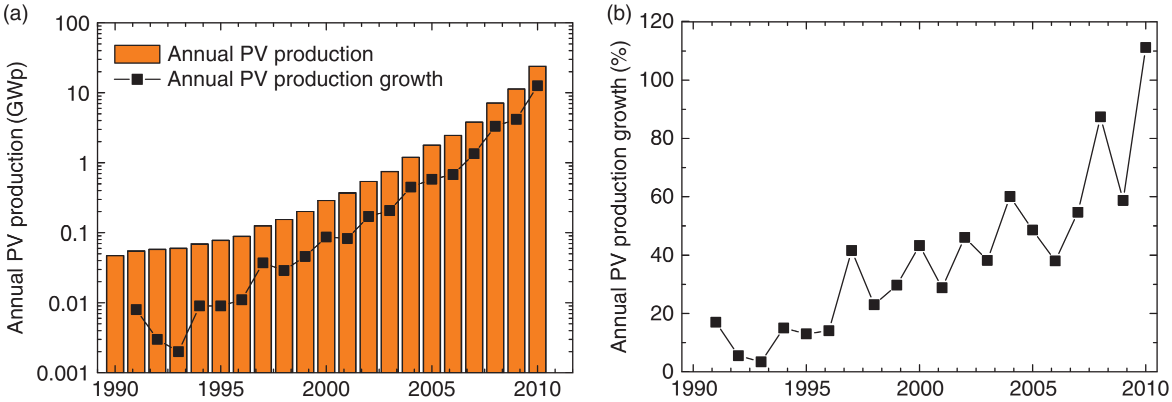

Figure 1 Twenty years of (a) annual PV production and growth and (b) annual PV production growth rate. Based on data from [5]; see also Chapter **1.03**.

the price is lowered by some 20% [10]. As modules constitute the main part of a PV system, also system prices have decreased considerably in the past decades. For example, current (2011) system prices in Europe are estimated to be in the range of €1.85–€5 W_p^{-1} [11].

In order to facilitate comparison with other electricity generation technologies, it is more useful to calculate the generation cost of PV electricity in terms of dollars or Euro per generated kilowatt-hour. The turnkey cost of a PV system is used as input to a levelized energy cost (LEC) calculation method, which requires assumptions regarding the operation and maintenance (O&M) cost, the lifetime of the system, the discount rate, and the specific energy yield (kWh W_p^{-1}). The latter mostly depends on the amount of solar irradiation (geographical location of the system, orientation), but also on specific system design (PV module technology, integration type). Typically, O&M cost are taken as 1% of the investment cost; lifetime is between 20 and 30 years, and discount rate is between 3% and 10%. The specific energy yield varies from 0.8 to 1.6 kWh W_p^{-1} over Europe [12]. With present turnkey system prices, the LEC is reported to range from €0.15 to €0.35 kWh^{-1} for Europe [11].

This LEC range brings the so-called 'grid parity' within reach for certain countries, especially those with high annual irradiation and high electricity prices. Grid parity is reached when the generation cost of solar PV in dollar or Euro per kilowatt-hour equals the price a consumer is charged by the utility for power from the grid. With LEC values between 0.15 and 0.35, PV electricity is cheaper for some retail electricity markets. With expected further reduction of turnkey system prices, in wholesale electricity markets also grid parity is forecast to be reached within 1–2 decades.

The emphasis of this volume is on PV cells and modules, which form an essential part of a complete PV system. A well-performing PV system cannot do without a well-designed direct current–alternative current (DC–AC) converter (inverter), which is to be carefully matched to the DC power output of the PV module. Their performance is important for the performance of the whole PV system. Present-day inverters show very high conversion efficiencies of 95–98% [13], thus inverter-associated power losses are small. Although inverters have seen substantial development in the past decades, they are not treated in this volume.

1.02.2 Guide to the Reader

1.02.2.1 Quick Guide

This volume is subdivided into six parts: (1) introduction; (2) economics and environment; (3) resource and potential; (4) basics of PV technology; (5) technological developments; and (6) applications. In the introduction part with three chapters, a quick overview of PV technology is presented as well as the history of PV. The second part provides seven chapters on historical and future economical developments and strategies for PV deployment such as the famous feed-in-tariff schemes in developed and developing countries. This part ends with a chapter on environmental aspects and chapters on industrial activity, a future vision for PV and storage options for PV. Part 3 contains three chapters detailing the solar irradiance resource, the application potential, and forecasting methods, which are of importance for actual PV power predictions. Part 4 then follows with two chapters, one treating the principles of PV conversion and the other on thermodynamics.

The largest part of the volume is part 5, with 16 chapters covering the so-called first-, second-, and third-generation PV technologies [14]. Commercially available solar cells based on wafer and thin-film silicon are treated as well as those based on copper indium selenide (CIS), cadmium telluride, plastic and 'dye-sensitized' solar cells, and multiple-junction III–V-based ones. New concepts, materials, and cell developments such as down- and upconversion and downshifting, intermediate band solar cells, the luminescent solar concentrator, thermophotovoltaics (TPVs), and plasmonics then are described. Nanotechnology plays a very important role in these new developments, which are summarized in Chapter 1.23. An intriguing new concept is treated in a chapter on bio-inspired solar converters.

In the final and sixth part, PV applications are detailed in nine chapters; here building-integrated applications are described as well as product-integrated PV, concentrated PV, solar power satellites, and very large-scale PV plants. Also, aspects of PV performance of these applications are treated, as well as the developments in the field of standards, which is indispensable for successful deployment of massive scale PV.

1.02.2.2 Detailed Guide

1.02.2.2.1 Part 1: Introduction

Directly following the present chapter, Chapter 1.03 in this volume is contributed by Larry Kazmerski, who discusses the status and future technology, market, and industry opportunities for solar PVs. He stresses that both ‘policy’ and ‘technology’ investments are important for the future markets and competitiveness of PV. Furthermore, this chapter describes the requirement for PV to move from short-term and evolutionary developments to disruptive and revolutionary pathways in order for PV to fulfill society’s renewable needs in the coming two to three decades.

Lisa Lamont then describes in Chapter 1.04 a brief history of PV development, starting from solar use in ancient civilizations to the discovery of the photoelectric effect, which marks the start of the historic PV timeline. She further discusses the reasons behind PV development in the early years, and provides an outlook for the future. She closes with the statement that “Mankind should aim for this (PV technology) to be the primary fuel of the future and not an alternative”, which links back to Chapter 1.03.

1.02.2.2.2 Part 2: Economics and environment

In Chapter 1.05, authored by Gregory Nemet and Diana Husmann, an analysis is presented of the historical and future cost dynamics of PV. Their argue that the 700-fold reduction in PV cost, which occurred in the past 60 years, is caused by a combination of R&D, economies of scale, learning-by-doing, and knowledge spillovers from other technologies. Also, the importance of these factors varied in time. The so-called experience curves are usually employed to depict cost reductions, and benefits and limitations of this approach are discussed. For PV, both incremental and nonincremental technical improvements have led to cost reductions. Especially, nonincremental improvements are irregular and, therefore, are complicating cost projections that inform policy. A method is presented to model these incremental improvements for PV.

David Jacobs and Benjamin Sovacool describe financial support mechanisms in Chapter 1.06. They present several case studies to corroborate their findings that the level of market development is decisive in the proper selection of support mechanisms. Besides R&D funding, and tax and investment incentives, they show that the only proven support mechanisms for large-scale GW markets are feed-in-tariffs. When PV has reached grid parity, other supporting schemes should be developed that create conditions for investors that minimize their investment risks.

Magda Moner-Girona, Simon Rolland, and Sandor Szabo continue to discuss on this topic in Chapter 1.07, where they focus on off-grid PV technologies in developing countries. Renewable technologies offer the option to provide access to sustainable energy services and foster economic development, thereby contributing to the Millennium Development Goals. However, many barriers exist for their widespread diffusion, in particular of PV, of which the main barrier is a financial one. Therefore, schemes for financing off-grid PV are very important, and this chapter analyzes existing support mechanisms and incentives, particularly combining market, energy use, and socioeconomic elements. Based on lessons from the past, new solutions and adapted support mechanism are suggested for promoting sustainable energy options for remote rural areas in developing countries.

In Chapter 1.08, Vasilis Fthenakis and Hyung Chul Kim present their findings on environmental aspects of some of today’s PV technologies by using life-cycle assessment as their tool. Such an assessment describes material and energy flows as well as emissions to the environment for each stage in the life cycle. It is discussed that the lower the so-called energy payback time (EPBT), that is, the time it takes for a PV system to generate energy equal to the amount used in its production, the lower the life-cycle emissions. Comparing three commercial PV technologies, mounted on flat, fixed ground-mount systems, it is shown that the EPBT of multicrystalline Si, monocrystalline Si, and CdTe systems were estimated to be 1.7, 1.7, and 0.8 years, respectively, for average US and Southern Europe conditions. The chapter ends with a quantification of life-cycle risk indicators from which it is concluded that the PV fuel cycle is much safer than conventional sources of energy.

An overview of the PV industry is given by Arnulf Jäger-Waldau in Chapter 1.09, who provides a regional breakdown of production growth over the past decade. Both China and Taiwan show the largest annual production growth in the past 5 years, and together account for more than 50% of the worldwide production. The present market is dominated by wafer-based silicon (80%), but thin-film technology is gaining market share. The top 20 solar cell producers are listed and described as well as the top 10 polysilicon manufacturers. Finally, a brief outlook is given in which several growth scenarios are compared.

The subsequent Chapter 1.10 by Eleni Despotou, Alexandre Roesch, Gaetan Masson, Giorgia Concas, Marie Latour, and Pieterjan Vanbuggenhout presents the industry vision for the future development of the PV market. The impressive market growth and the decrease of price bring PV toward full competitiveness on the electricity markets. PV will enter new markets and provide electricity to a growing number of consumers. The shift from households consuming electricity to households producing electricity will revolutionize the way power grids will operate and how market will deal with electricity. Electricity markets with double-digit PV market penetration are envisaged, for which the grid should be restructured to include an increased level of intelligence: smart grids.

As essential part of such a grid system with intermittent energy sources such as PV (and wind), electricity storage may play an important role. This is described in Chapter 1.11 authored by Vasilis Fthenakis and Thomas Nikolakakis. Storage technologies can smoothen the variability of PV. A number of technologies are discerned, based on their power quality, bridging power, and energy management. The main difference between them is the timescales over which they operate, and the extent to which power and energy are needed.

1.02.2.2.3 Part 3: Resource and potential

In Chapter 1.12, Daryl Myers addresses measurements, modeling, and databases of solar energy potential. These are essential for identifying, locating, and prospecting for the appropriate quantity and quality of solar resources for PV systems, and are critical to system designers, investors, financial backers, utilities, governments, and owner/operators in assessing the performance, return-on-investments, and investment risks of planned or existing PV projects. This chapter addresses the fundamentals and state of the art for measuring, modeling, and applying solar radiation resource data to meet decision-making needs.

In Chapter 1.13, the operation of installed PV systems, in particular their expected performance, is treated by Elke Lorenz and Detlev Heinemann. Depending on meteorological conditions, the generated power is variable; therefore reliable forecast information for management and operation strategies is required. This chapter provides an overview on different applications and state-of-the art models for solar irradiance and PV power prediction, including time series models based on on-site measured data, models based on the detection of cloud motion in satellite images, and numerical weather prediction-based models. The chapter further shows evaluation results for selected irradiance and power prediction schemes.

1.02.2.2.4 Part 4: Basics of PV

The conversion of sunlight into electricity is governed by the photoelectric effect, but it will only occur in a device that exhibits charge generation by photon absorption and charge separation. In Chapter 1.14, Louise Hirst describes the principles of the PV action in a semiconductor single *p-n* junction in detail. The maximum efficiency of such a device under 1 sun irradiation is 31%, which is denoted as the Shockley–Queisser limit, named after William Shockley and Hans Queisser, who were the first to derive this detailed balance limit [15]. It is possible to exceed this limit by addressing the various loss factors; several examples are described in various chapters in Part 5 on specific third-generation-type solar cells.

Subsequently, Viorel Badescu discusses various thermodynamic aspects of photovoltaics in Chapter 1.15. In this chapter, first elementary concepts about thermodynamics of undiluted and diluted thermal radiation are presented. Then, the mathematical description of reversible solar radiation concentration is developed by using a simple formalism based on the Lagrange invariant, the étendue. The basic thermodynamics necessary to describe the operation of PV devices is presented, followed by the principle of building the detailed balance equation models. Examples are given for single-gap solar cells and for omnicolor PV converters.

1.02.2.2.5 Part 5: Technology

This part starts off with a chapter on the workhorse of the PV industry: wafer-based crystalline silicon solar cells. To extend its success story, it is important to further bring down the costs of these cells. The cost distribution of a crystalline silicon PV module is clearly dominated by material costs, especially by the costs of the silicon wafer. Stefan Glunz, Ralf Preu, and Daniel Biro argue in Chapter 1.16 that besides improved production technology, the efficiency of the cells and modules is the main leverage to bring down the costs even more. They describe the state-of-the-art process for silicon solar cells and give insight into new advanced processes and cell designs.

Miro Zeman and Ruud Schropp treat thin-film silicon solar cell technology in Chapter 1.17. It is one of the promising PV technologies for delivering low-cost solar electricity. Single-junction amorphous and microcrystalline silicon cells are responsible for most thin-film silicon modules presently on the market; tandem amorphous/microcrystalline silicon modules will take over in near future. Both cell designs are presented. In order to increase the absorption in thin absorber layers, novel approaches for tandem solar cells and for photon management are developed. Finally, also module production and application areas are briefly described.

In Chapter 1.18, chalcopyrite-type thin-film materials and solar cell devices are reviewed by Thomas Unold and Christian Kaufmann. These types of polycrystalline materials are versatile and multinary with excellent optical and electronic properties and a high degree of chemical flexibility, and thus are naturally suited for high-efficiency thin-film solar cells. A thorough understanding of the material physics and device properties of the heterojunction solar cells is required to reach high efficiencies. A wide variety of deposition techniques are used, each having its own advantages and disadvantages regarding cost, scalability, and throughput. Recently, commercialization of chalcopyrite thin film has been scaled up to the gigawatt range, proving the competitiveness of this technology with regard to crystalline silicon solar technology.

Chapter 1.19 by Tim Gessert reviews the history, development, and present processes used to fabricate thin-film CdTe-based solar cells. It shows why certain processes may have commercial production advantages, and how the various process steps can interact with each other to affect device performance and reliability. The chapter concludes with a discussion of considerations of large-area CdTe PV deployment including issues related to material availability and EPBT.

In Chapter 1.20, plastic or organic solar cells are described by Lothar Sims, Hans Egelhaaf, Jens Hauch, René Kogler, and Roland Steim. Organic solar cells are also considered a great promise to reduce costs as well as energy consumption during production compared with wafer-based silicon PV technologies. Properties such as transparency, flexibility, and various colors also make them attractive from an aesthetic point of view. This chapter describes the working principles of these cells, important materials, such as

P3HT:PCBM (poly(3-hexylthiophene):phenyl-C_{61}-butyric-acid-methyl ester), ways for improving the efficiency and stability, production methods, and ends with a short outlook on the future development of organic solar cells.

Anders Hagfeldt, Ute Cappel, Gerrit Boschloo, Licheng Sun, Lars Kloo, Henrik Pettersson, and Elizabeth Gibson discuss the developments in mesoporous dye-sensitized solar cells (DSCs, also called Grätzel cells) in Chapter 1.21. In these cells, a dye is distributed over a porous material with a large surface area, and electrons which are excited upon absorption of photons are transferred from the dye to the porous substrate and collected via external contacts. It is shown in this chapter that the chemical complexity of DSCs has become clear, and the main challenge for future research is to understand and master this complexity, in particular at the oxide–dye–electrolyte interface. A challenging but realistic goal for the present DSC technology is to achieve efficiencies above 15% that are also stable. As DSCs perform relatively better compared with other solar cell technologies under diffuse light conditions, an overall goal for future research will be to collect data and develop models to make fair judgments of the DSC technology with regard to energy costs. Possible introduction of niche applications such as consumer electronics and successful development of manufacturing processes are expected.

Multiple-junction solar cells based on III–V materials are described in Chapter 1.22 by Masafumi Yamaguchi. These types of solar cells are capable of reaching efficiencies of up to 50% and are used for space and terrestrial applications, in particular in concentrator solar cell modules, as the cell cost is high. This chapter presents principles and key issues for realizing high-efficiency multiple-junction solar cells, as well as issues related to development and manufacturing, and applications for space and terrestrial uses.

New concepts, materials, and cells are developed, denoted as third-generation PVs. The application of micro- and nanotechnologies are becoming more and more important to solar PVs, as Loucas Tsakaloukos shows in Chapter 1.23. In conventional thin-film solar cells, the use of nanoparticle inks are evidenced, as well as improving performance by using novel optical films. There are also efforts to develop novel micro/nanoarchitectures such as nanowire or nanocomposite-based devices. Finally, various quantum-based concepts are considered and progress toward demonstration of devices is discussed. The chapter ends with a perspective on the future of micro/nanosolar technologies in PVs and the potential manufacturing issues that are anticipated as these new technologies develop.

Chapter 1.24 deals with upconversion. Upconversion is defined as the conversion of a low-energy photon, which cannot be absorbed in a solar cell, into a higher-energy photon, which can be absorbed. In this chapter, Timothy Schmidt and Murad Tayebjee present the theory of upconversion as applied to PV devices using an equivalent circuit formalism. They analyze three circuits, corresponding to symmetric intermediate band and upconverting solar cells. The leading approaches to upconversion, rare earths and organic molecules, are described. Upconversion efficiencies are defined, and achieved efficiencies of both rare earth and photochemical upconversion are compared. The future prospects of photochemical upconversion are discussed in the light of a kinetic model, which reveals the parameters which currently limit the efficiency.

In Chapter 1.25, downconversion is described by Gavin Conibeer, Murad Tayebjee, and Timothy Schmidt. Downconversion is defined as the conversion of a high-energy photon into a lower-energy photon. The theory of downconversion as applied to PV devices is revised from a thermodynamical standpoint, and downconverting as well as carrier-multiplication scenarios are analyzed. State-of-the-art technology is described comprising of downconversion using rare-earth ions and so-called singlet fission in organic molecules and semiconductor nanostructures.

Yoann Jestin describes in Chapter 1.26 the use of downshifting to enhancing the performance of solar cells. In this chapter, after a brief description of the downshifting process, a review of the most common downshifting elements and their use in solar cells will be presented. To conclude, an overview of patent filing and commercial applications will be given.

The luminescent solar concentrator is described in Chapter 1.27 by Jan Christoph Goldschmidt. These concentrators have the ability to concentrate direct and diffuse radiation, which is directly related to the Stokes shift that occurs between absorption of incoming light and subsequent emission. To achieve efficiency potential in the range of 10%, further progress in the development of luminescent materials that cover the visible and the near-infrared range of the solar spectrum, showing high luminescent quantum efficiencies and low reabsorption, is necessary. Furthermore, current progress in the research on photonic structures needs to be exploited for its application in luminescent concentrator systems.

Chapter 1.28 by Johan van der Heide gives an overview of TPV energy conversion, including a historical introduction. After a description of all elements present in a typical TPV system, a detailed overview of the different TPV cell concepts is given. Subsequently, some examples are given of TPV systems built in the world followed by an estimation of the TPV market potential.

The intermediate band gap solar cell is described by Elisa Antolin, Antonio Marti, and Antonio Luque in Chapter 1.29. This cell was proposed to increase the current, while at the same time preserving the output voltage of solar cells, leading ideally to efficiencies above the Shockley–Queisser limit. In this chapter the concept is described, as well as the use of quantum dots. Present efficiencies are still low, and possible ways to overcome the issues involved are discussed. It is foreseen that these types of solar cells will be able to operate in tandem in concentrators with very high efficiencies or as thin cells at low cost with efficiencies above the present ones.

In Chapter 1.30, the use of plasmonics for PVs is treated by Supriya Pillai and Martin Green. This light-trapping approach based on scattering by metal nanoparticles allows amplifying the interaction between light and matter. The rapid advancement in fabrication and characterization techniques for nanoscale particles and the increased understanding of mechanisms behind the enhancement process is leading the way to the realization of a mature technology. The ability of light to interact with particles that are much smaller than the wavelength of light opens ways to modify and manipulate local light fields to suit various applications. This is particularly interesting as the trend is toward high-performance miniature devices.

The final chapter in this part is on a very challenging concept: the artificial leaf. Anjali Pandit and Raoul Frese describe in Chapter 1.31 how bio-inspired solar energy converters could be designed. The term 'artificial leaves' is used to describe artificial photosynthetic devices assembled from interacting bio-based or bio-inspired components. After a brief description of natural photosynthesis and how its design principles have inspired artificial photosynthesis, the integration of biological components in artificial devices is discussed as well as recent developments in the design of biomimetic light-harvesting and charge-separation systems. The chapter ends with an outlook for the design of a fuel-producing solar cell.

1.02.2.2.6 Part 6: Applications

Chapter 1.32 by Wilfried van Sark provides an overview of PV system design aspects, such as the various components used and their interplay in the system. Basics of PV cell and module performance are described, briefly touching upon the loss factors in PV systems. Two case studies are shown exemplifying PV system design issues.

In Chapter 1.33, Tjerk Reijenga and Henk Kaan focus on building integration photovoltaics (BIPVs) in architecture and urban planning. They argue that to increase market acceptance for PV, it is important to show architecturally elegant, well-integrated systems. The main factors for successful integration are suitable buildings, and a reason for building integration. For newly constructed sustainable buildings, BIPV will be part of the energy strategy. For existing buildings there must be a valid reason for integrating PV systems. Building renovation, including the roof and façade, often provides an opportune time for selecting BIPV. In this chapter, criteria have been formulated for judging building integration of PV. These criteria are useful for manufacturers and technicians who are involved with building integration from the engineering and technical aspects of the building process. However, it is the task and responsibility of the individual architect to adapt the criteria to his or her own aesthetic standards.

In Chapter 1.34, Angèle Reinders and Wilfried van Sark present experiences with product-integrated photovoltaics (PIPVs) for various product categories: consumer products, lighting products, business-to-business products, recreational products, vehicles, and transportation and arts. The term PIPV indicates that PV technology is integrated in a product by positioning of PV cells on the surfaces of a product. An overview is given of existing solar-powered products and the design of PIPV will be presented from the context of design processes. This chapter demonstrates that many relevant issues regarding PIPV have not been explored thoroughly so far, in particular energy-efficient management of PIPV-battery systems, environmental aspects of PV technology in products, manufacturing of integrated PV in products, and user experiences with PIPV in different product categories. As PIPV can offer energy to products with a wide range of power demand, it is expected in future to become common, for instance, in public lighting products, sensors, boats, cars, and in urban furniture.

Very large-scale photovoltaic (VLS-PV) applications are addressed in Chapter 1.35 by Tomoki Ehara, Keiichi Komoto, and Peter van der Vleuten. VLS-PV was presented over a decade ago by the International Energy Agency-Photovoltaic Power Systems Programme (IEA-PVPS) Task 8 group [16]. This concept is to generate electricity in a desert region where solar irradiation is abundant. It also aims to achieve socioeconomic development in the region. A wide range of feasibility studies of the VLS-PV concept performed in the past 12 years is presented; these include not only technical perspectives, but also economic and environmental point of views. Further, current trends and actual projects are described.

Concentration photovoltaics (CPV) is one of the PV applications with highest efficiency in the field. Chapter 1.36 by Maria Martinez, Oscar de la Rubia, Francisco Rubio, and Pedro Banda state that since 2005, CPV systems are becoming commercially available and are experiencing a technological and industrial development momentum, complementing the growth of the global renewable energy market. Standardization and evaluation of demonstration systems are helping to establish reliability and quality standards for the CPV industry. CPV is sensitive only to direct radiation, which is collected by optical components and concentrated onto very high-efficiency solar cells. Systems are mounted on high-accuracy dual-axis trackers for their operation in the high solar resource areas of the world. Finally, this chapter presents operational results, showing that CPV technology is capable of performing optimally in regions with very high radiation and temperatures, but it also performs reasonably well in medium radiation regions like Spain.

Chapter 1.37 by Geoffrey Landis presents an old idea that is recently revitalized: solar power satellites. These collect solar irradiation and transfer the electrical energy using microwaves to large earth-based antennae. It is shown that the fundamental physics are feasible, but economical feasibility is as yet an open question. Although a space location for the solar panels gets more sun than a ground location, the bottom line numbers show that it is not that much more solar energy than the best ground locations. The added power mostly comes from 24 h sunlight, but much of the power may thus be produced when the need is low.

In Chapter 1.38, Nicola Pearsall and Ralph Gottschalg address performance monitoring of PV systems. Monitoring allows the determination of its energy output and any operational issues over its lifetime. As PV systems have moved from demonstration of the technology to commercial energy generation, the main purpose of the monitoring has also changed. This has resulted in new approaches and services meeting the requirements of the system owners. This chapter describes the principles of PV system monitoring and how it is now achieved in practice.

The last chapter in the volume deals with standards of PV technology: Chapter 1.39 by Heinz Ossenbrink, Harald Müllejans, Robert Kenny, Nigel Taylor, and Ewan Dunlop. The international standards relevant for PV devices and their measurement are developed within technical committee 82 (TC82) of the International Electrotechnical Committee (IEC). The way to new standards is normally paved by scientific research, first by single institutions and then applied by others of the international community. This might lead to some national standards. Eventually, however, once agreement in the international scientific community has been reached, an IEC standard is prepared. This chapter describes the international standards relevant for the determination of the electrical performance of PV devices.

1.02.3 Conclusion

It has been a long road to reach the present competitiveness for PV in predominantly retail electricity, and clearly still further developments are needed to ensure further deployment and increased competitiveness of PV in wholesale electricity in the coming decades. This volume on PV technology, as part of the *Comprehensive Renewable Energy* volume-set, presents a 39-chapter overview of the status in PV technology and its applications, its economic and technological development over the past decades, and future directions in PV technology R&D and applications. It is intended to provide a wealth of information for the fast growing and diverse group of professionals globally active in R&D and deployment, as all are needed together to join forces in reaching the ambitious targets set to help mitigate climate change by the middle of this century.

References

[1] Becquerel E (1839) Mémoire sur les effets électriques produits sous l'influence des rayons solaires. *Comptes Rendus de L´Academie des Sciences* 9: 561–567.
[2] Planck M (1901) Ueber die elementarquanta der materie und der elektricität. *Annalen der Physik* 309(3): 564–566.
[3] Einstein A (1905) Über einen die erzeugung und verwandlung des lichtes betreffenden heuristischen gesichtspunkt. *Annalen der Physik* 322(6): 132–148.
[4] Chapin DM, Fuller CS, and Pearson GL (1954) A new silicon p-n junction photocell for converting solar radiation into electrical power. *Journal of Applied Physics* 25: 676.
[5] Data from various issues of *Photon International* (February, 2009, 2010, and 2011), and PV News (June, 2011) see also Chapter 2.
[6] Lipp J (2007) Lessons for effective renewable electricity policy from Denmark, Germany and the United Kingdom. *Energy Policy* 5: 5481–5495.
[7] European Climate Foundation, Roadmap 2050: A practical guide to a prosperous, low-carbon Europe, 2010. http://www.roadmap2050.eu/(accessed 21 February 2012).
[8] Green MA, Emery K, Hishikawa Y, *et al*. (2011) Solar cell efficiency tables (version 38). *Progress in Photovoltaics: Research and Applications* 19: 565–572.
[9] Luque A (2011) Will we exceed 50% efficiency in photovoltaics? *Journal of Applied Physics* 110: 031301.
[10] van Sark WGJHM, Alsema EA, Junginger HM, *et al*. (2008) Accuracy of progress ratios determined from experience curves: The case of photovoltaic technology development. *Progress in Photovoltaics: Research and Applications* 16: 441–453.
[11] European Photovoltaic Industry Association (EPIA) (2011) Solar photovoltaics competing in the energy sector – On the road to competitiveness. Brussels: EPIA.
[12] Sinke WC (2009) Grid parity: Holy Grail or hype? – Photovoltaic solar electricity on its way to competitiveness. *Sustainable Energy Review* 3(1): 34–37.
[13] Reich NH, Mueller B, Armbruster A, *et al*. (2012) Performance ratio revisited: Are PR >90% realistic? *Progress in Photovoltaics* 20 (in press).
[14] Green MA (2003) *Third Generation Photovoltaic: Advanced Solar Energy Conversion*. Springer Series in Photonics, Vol. 12. New York: Springer.
[15] Shockley W and Queisser HJ (1961) Detailed balance limit of efficiency of p-n junction solar cells. *Journal of Applied Physics* 32(3): 510–519.
[16] International Energy Agency-Photovoltaic Power Systems Programme (IEA-PVPS), Task 8. http://www.iea-pvps.org/index.php?id=35 (accessed 27 October 2011).