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Arvind Shah *Editor*

Solar Cells and Modules

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Solar Cells and Modules

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Preface

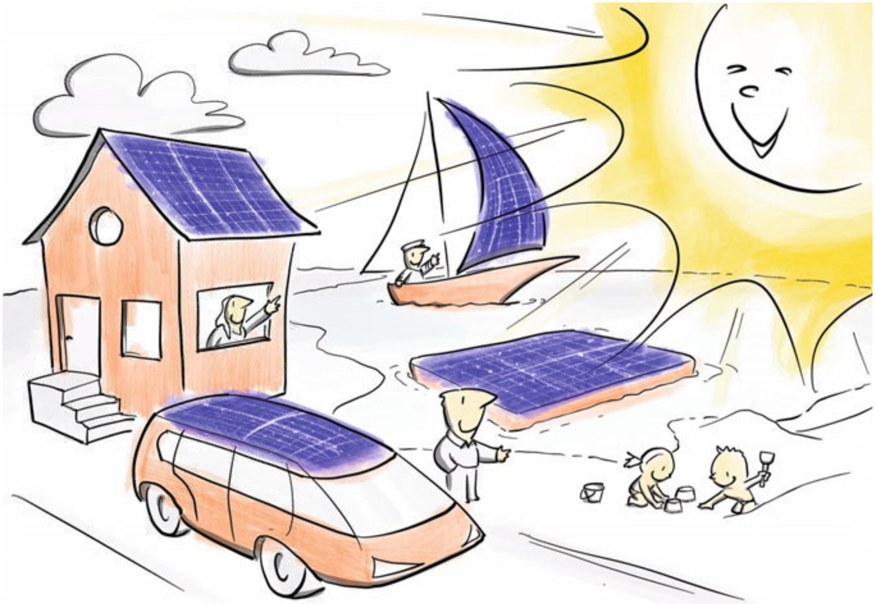
The coming years will—without any doubt—see a tremendous change in the world—climate change, globalization, political upheavals, unprecedented migration of populations and economic instability are some keywords that come to my mind in this context. Many of us are concerned about these changes and think, in particular, of climate change as a huge menace looming right in front of us.

The message of this book is, however, that there is absolutely no reason for fear; on the contrary, these changes will open up unprecedented opportunities, and new perspectives, if only we are prepared to rapidly act: collectively, collaboratively and with courage. One of the major opportunities, which is already clearly visible, lies in the field of photovoltaics (PV). This book will tell you how and why photovoltaics will constitute a decisive factor in contributing towards a very positive and favourable development of the whole world.

Let us look forward to the year 2050, just far enough that we have the time to modify by then the whole world's supply of energy; just near enough, so that fairly accurate predictions can be made. By 2050, we should be able to supply 50% of the world's total electricity with PV. Why focus on photovoltaics, rather than on other forms of renewable energy? This is because PV is truly unique. It is the only form of renewable energy that can be rapidly deployed at the necessary scale in every region of the world—on rural buildings, within cities, on mountains, in deserts and even on the surface of lakes and of the sea.

Of course, one can put PV to use in giant installations, in the same way, as one builds large gas power stations or huge hydroelectric dams. But photovoltaic systems have tremendous flexibility, in size, form and shape. Therefore, they should preferably be used in a decentralized manner—as near as possible to the current consumer, they can indeed be installed in small units, on the roof of a house, or in the midst of a pond. But will such small dispersed units really have any effect on the world's supply of electricity? Yes, they will—because there will be many millions of them.

As my mentor and guide, Shree Chamanlal Gupta of the Aurobindo Ashram in Pondicherry—the man who convinced me to start the photovoltaic laboratory in Neuchâtel—was always repeating to me:



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"Remember, Arvind, the key to solve global problems is to push ahead with local solutions".

Let us now look in more detail at the "Energy Challenge". 50% of the world's total electricity by 2050 is a tremendous amount of energy; this would be equivalent to about 12,000 TWh per year at today's (2020) levels of electricity consumption. This compares with 800 TWh per year that is generated by PV at present. So, this would be an increase by a factor of 15, within a period of just 30 years. As electricity consumption is steadily rising, mainly due to economic growth in China, India, Indonesia, Africa and South America, the actual increase we need, for PV, will probably be around a factor of 30.

Can this be done? From a purely technical point of view, the answer is certainly: «YES, WE CAN». But we have six other points to be considered: (a) raw materials and electricity needed for the production of PV modules; (b) durability and reliability of PV modules—if PV is to become a pillar of humanity's energy supply, it should be productive for 50 years or more—as all other technologies for the production of electricity do and not just for 25 to 30 years; (c) storage—solar electricity comes in, in an irregular and often unpredictable fashion, depending on climate and weather, and it has to be stored in some way before it can be used; (d) areas needed for the deployment of that huge amount of PV; (e) integration of PV into the energy system; (f) ecological production and recycling of PV modules.

In view of these six points, we will need the collaboration of many actors: certainly, the contribution of physicists, chemists, materials scientists and engineers. But we will also require the help of politicians, businessmen, bankers, home owners, architects, industry leaders and regional planners.

For this reason, this book is intended for a wide spectrum of readers—far wider than the narrow crowd of PV and solar energy specialists. As we are here looking into the near future—into the coming 30 years—this book is specially intended for use by the younger generation—by students and even youngsters from high school. We have therefore tried to keep this book as accessible as possible—accessible also to those who do not have a specialized scientific or technical education in photovoltaics or in any related fields. At the same time, we strived to be up-to-date and include in this book the latest developments in PV. This was a difficult task, and I do not know whether we have succeeded or not.

But as a reader of this book, do tell us whether we have really succeeded. Do tell us where we have gone wrong. Have we written a passage that you simply could not understand? Have we made a statement that you consider being wrong? Did we leave out some information that you consider important? Are there oversights or mistakes in this book?

You can very easily write to us: you have the email addresses and also the postal addresses of everyone who has contributed to this book. We promise to reply to all messages, which come to us. We are very much looking forward to hear from you.

Neuchâtel, Switzerland

Arvind Shah
Editor of the book
on behalf of all its authors

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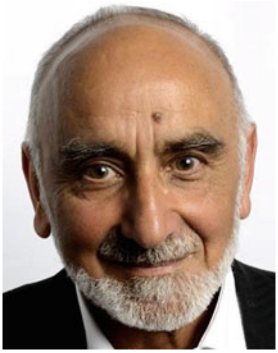
About the Editor



Arvind Shah is the founder of the Photovoltaics Research Laboratory (PV Laboratory), at the Institute of Microtechnology (IMT), in Neuchâtel, Switzerland.

PV laboratory, Neuchâtel, has, since 1985, done pioneering work in the establishment of low-cost production methods for solar cells based on silicon. In this context, PV laboratory introduced, in 1987, a novel plasma-assisted deposition method called "VHF deposition" permitting a significant increase in the deposition rate for thin-film silicon layers. In 1994, PV laboratory, Neuchâtel, introduced microcrystalline silicon, deposited by VHF plasma, and with very low oxygen content, as novel absorber layer, within thin-film solar cells. From 2003 onwards, VHF deposition has been adopted by many industries, in Europe, USA and Japan.

PV laboratory, Neuchâtel, does also significant work on the development of transparent conductive oxides, as contact layers for solar cells, with enhanced light-trapping properties.

PV laboratory, Neuchâtel, is, furthermore, active in demonstrating novel methods for the design and fabrication of lightweight, low-cost flexible solar cells.

From 1979 to 2005, Arvind was a professor at the University of Neuchâtel. From 1987 to 2005, he was additionally a part-time professor at the EPFL Lausanne.

In 1975, he founded and co-directed the Centre for Electronics Design and Technology (CEDT) at the Indian Institute of Science in Bangalore. CEDT is now one of India's leading University Centres in the field of electronics. It has a strong industrial orientation.

From 1968 to 1975, he was lecturer and R&D group leader at the Department of Industrial Research of the ETH Zürich.

Since 2006, he has been active as a scientific consultant to the PV laboratory and to various Industries, in Europe, India and the USA.

Since 2008, he has been an active member of the Green Party of Switzerland; from 2009 to 2013, he was a member of the legislative assembly of the Canton of Neuchâtel.

He received the Swiss Solar Prize, together with Johannes Meier in 2005. He received the Becquerel Award in 2007.

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Chapter 1
Introduction

Christophe Ballif

Abstract A short review on the potential of solar energy and on the dramatic improvements of photovoltaics (PV), which took place since the 50's, is given. From pioneering work on the first 6% efficient silicon solar cell in 1954 to today's mainstream modules with close to 20% efficiency, technology development and market have been intimately linked. Strong market growth has brought global PV installations to well over 600 Gigawatts (GW_p) cumulative capacity by 2020. After a short description of the various PV technologies, we show how industrialisation has driven a rapid decrease of manufacturing costs. Continuous technological improvements to processes and production equipment have led to a continuous increase in module efficiency, and to a reduction of embedded energy. The low electricity price achieved today by photovoltaic systems makes it the potential major source of electricity for decarbonising the planet—through a mix of large centralised plants and of smaller distributed systems. Integration of PV into Buildings, being particularly attractive for the future, is described in detail.

1.1 Photovoltaics: Potential and Orders of Magnitude

Photovoltaics (PV) is now seen as the major source of electricity for the second half of the century. It will become the strongest contributor to the decarbonisation of the world's energy system for the following reasons:

- Sunlight is abundant and available to everybody.
- PV is already now, in many regions of the World, the source of electricity with the absolutely lowest cost; and it is rapidly becoming even cheaper.
- PV is a "clean" technology with low CO_2 emissions. Electricity from PV can in future conveniently power electric vehicles and be used for heating/cooling needs. It can already do so, in many cases, more economically than fossil fuels.

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- PV electricity is manageable: it can be dispatched and used on demand, thanks to the possibility of storage, e.g. in batteries or via pumped hydroelectric systems.
- With further decreasing costs, it will become convenient and cost-effective to transform solar electricity into chemical fuels (power-to-gas), enabling versatile long-term storage.

Hence, photovoltaics not only has the potential to become, in the foreseeable future, the World's major source of electricity—it could also become, by the second half of the century, the major source of energy, in general, via the transformation and storage of electricity.

This book is primarily concerned with the core component of a photovoltaic (PV) system—with solar cells and modules; it will describe the different types of solar cells and their assembly into entire modules, as well as various aspects of their application.

1.1.1 Is There Enough Energy from the Sun?

When the sun shines, it typically brings a power of 1000 W per m^2 on the ground. Thus, an area covered by a PV module with an efficiency of 20% (a typical value for a high-quality module today) will provide a peak power of approximately 200 W (referred to as Watt Peak or W_p). Depending on the location, every year the sun brings on each square metre of the ground 800–2700 kWh, as illustrated in Fig. 1.1. A well-oriented module at 40° latitude (Rome, New York, Beijing) receives around 1500–1600 kWh/m^2 every year, i.e. the energy equivalent of one barrel of oil (159 litres).

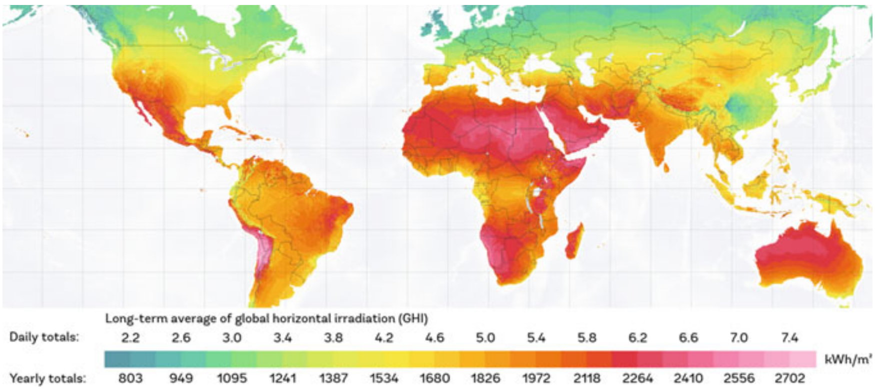

Fig. 1.1 Daily and yearly total global horizontal irradiation (GHI) values—given per m^2 and representing the energy received by a flat, horizontal surface. (Map obtained from the "Global Solar Atlas 2.0, a free, web-based application developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). *For additional information:* https://globalsolaratlas.info)

This is a high amount of energy! Equipping a roof with 1 m^2 of 20% efficient panels allows you to drive a car, with an electric engine, 1800 km annually, as far as 159 litres of petrol does for a typical combustion-engine car.

Indeed, a simple back-of-the-envelope calculation shows that for most industrialized countries in the world, the available roof surfaces could already provide for a significant fraction, in the range of 30–100%, of the electricity needs, if covered with PV[1].

As a case study, we can consider the small (40,000 km^2) and densely populated country of Switzerland (8.5 million people). A recent study [1] shows that the current energy system, which is based on 75% of energy from fossil fuels, could be almost entirely decarbonised by installing 50 GW_p of PV panels. This is less than the potential surfaces available on roofs and façades (see an example of a façade in Fig. 1.2b)—they have an estimated potential of ~70 GW_p. This massive penetration of PV should be accompanied by curtailment of PV production at certain times in the year; it would take place simultaneously with the following steps: (a) a shift to electro-mobility; (b) an improved thermal isolation of all buildings: (c) a widespread employment of heat pumps for the heating of most buildings. Thereby, a large part of the fossil energy presently used could be totally suppressed. Hydroelectric power and electric cars could, in such a scenario, provide most of the required system flexibility.

The World's global electricity consumption was, in 2018, totally ~22,000 TWh (1 TWh = 1 Terawatt hour = 1000 GWh). The current total world energy demand of ~160,000 TWh, largely based on fossil energy, could be reduced, thanks to the gain in efficiency if one switches to energy systems based on electricity. Hence, going to a zero-carbon society could be technically done by installing 50–60 TW_p of PV, assuming a gain by a factor 3 in energy efficiency—by switching e.g., from fossil fuel cars to electric cars, from direct fossil fuel heating to heat pumps. If photovoltaics is to cover around 2/3 of the renewable energy required by 2050 with around 34 TW_p, over 1000 GW_p (or 1 TW_p) of new PV panels should be installed in average every year until 2050 [2]. This means increasing—by at least a factor 10—the current

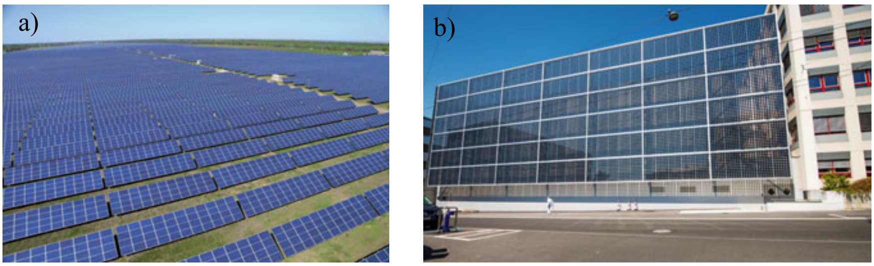

Fig. 1.2 **a** Large 43 MW_p solar farm at Starokazache (Ukrainia); **b** Solar screen with bifacial silicon heterojunction solar cells on the façade of CSEM (Switzerland)

[1] Another alternative to harness the sun's abundant energy is biomass, but the area required to grow these crops is much larger than for PV, because it is a factor 20–100 times less efficient in terms of final energy and would require surfaces which are simply not available.

production. The required area, with 20% efficient modules covering half the surface of the solar power plants (Fig. 1.2a), would be in the range of 340,000 km^2. This corresponds to a modest 3% of the area of the Sahara desert, or, alternatively, to 3.4% of the territory of the USA or China.

1.2 Photovoltaics: A Choice of Technology

There are many possible semiconductors with which to make solar cells, and there are different ways to process these materials into solar cells. However, the three main commercialized categories can be summarised as follows:

- Crystalline silicon solar cells (c-Si): these are based on silicon wafers cut from ingots, which are either mono- or multicrystalline. The wafers, which are typically 120–180 micrometres (μm) thick, are processed into solar cells; the latter are then interconnected by soldering before they are packaged in a module. c-Si constitutes at present for more than 90% of all solar cells.
- Thin-film solar cells: thin layers of semiconductors (typically 0.1–5 μm thick), which are deposited directly onto glass substrates, or on foils. Examples of materials used are CdTe, Cu(In,Ga)Se_2 (CIGS), amorphous silicon (a-Si) and perovskites. Between the processing steps, the solar cells are usually patterned and interconnected by a conductive layer, in a so-called monolithic integration.
- III-V multi-junction solar cells: originally developed for space applications, these solar cells are grown epitaxially on crystalline wafers and can reach efficiencies over 35%. They are too costly to be directly used for power generation on earth—But light can be focused on them, with a concentration factor from 200 to 1000, leading to concentrated photovoltaics (CPV). Despite high cell efficiencies, the delicate system aspects (need for light focussing and for highly accurate sun tracking), have not allowed CPV to gain sizeable market shares.

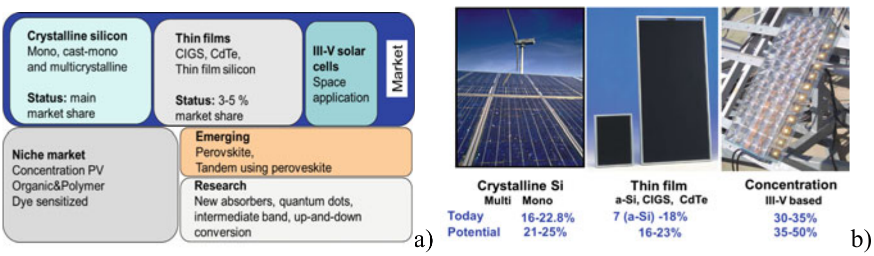

Fig. 1.3 **a** Classification of various PV technologies; **b** three major commercial photovoltaic technologies, with today's best module commercial efficiency and their estimated practical long-term potential

Figure 1.3 gives a brief overview of the various solar cell technologies, including those in a pre-commercial phase. It also indicates the typical efficiency of commercially available PV modules, and their long-term efficiency potential. It should be noted that individual record solar cell efficiencies are typically 15–30% higher than the efficiencies of commercial modules[2].

The focus of this book will be on those solar technologies, which are most widely applied, in particular on crystalline silicon (c-Si), because of its high share (95%) of the PV market: This branch of PV technology will be discussed in **Chaps**. 5 **and** 7. **Chapter** 8 will treat existing thin-film technologies, which make up most of the remaining 5% of the PV module market.

Chapters 2, 3 and 4, next up, will discuss basic concepts used for all PV Technologies:

- **Chapter** 2 will describe the solar spectrum under various atmospheric conditions
- **Chapter** 3 deals with the Basic Theory of Solar Cells
- **Chapter** 4 describes losses within solar cells—optical losses and electrical (recombination) losses.

Chapter 6 will discuss amorphous silicon layers and solar cells; the latter are today mostly used for indoor applications or for the internet of things (IOT). The full fabrication of modules will be treated in **Chap**. 9, whereas the system aspects of PV will be presented in **Chaps**. 10–12. Finally, **Chap**. 13 will focus on the role of PV in the global energy system.

Considering the continuous PV market growth, and a future annual volume production in the range of TW_p, research is still ongoing, both for improving existing commercialized technologies, and for figuring out processes allowing for higher efficiency. In parallel, one is preparing for future technologies, in particular those which will be able to surpass the efficiency of crystalline silicon, as will be discussed later.

1.3 Photovoltaics: Technology Evolution

By switching from selenium-based solar cells, which had an efficiency of 0.5% in 1952, to silicon, Chapin et al. were able to demonstrate 6% efficient solar cells in 1954 [3]. These results triggered research and commercialisation, initially mostly for space applications. For several decades, the terrestrial PV market was limited to off-grid applications. The low manufacturing volumes translated into high prices per Watt-peak ($7–8 per W_p in 1990), for both c-Si and thin film (a-Si): this prevented massive deployment of PV for power generation.

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[2]They are several reasons for the efficiency difference between record solar cells and commercial modules; those include: the space between the solar cells, the non-active area close to the module edges, the electrical losses in interconnection ribbons, the simplified processes used in mass production, the reduced homogeneity for large devices, etc.

From the 1980's to the early 1990's, the most important technological bricks for the realisation of high performance industrial solar cells were developed. Those were inspired by microelectronics research in the case of silicon, and related to pure PV research for amorphous silicon, CIGS, and CdTe. The challenge, was to find a way to reduce manufacturing costs down by a factor 20–30 to make PV a more competitive source of electricity.

In the years 2000–2010, a stronger market development was triggered by incentives in several countries. This created a high demand for PV modules, with healthy margins for module makers. This is illustrated in Fig. 1.4a by the high average module price between 2005 and 2010, which was then well above the production costs. However, the strong market growth (+30% per year from 2000 to 2010), mostly based on c-Si, led to a lack of refined polysilicon from 2007 to 2010, with solar grade Si material reaching up to \$400/kg (compared to \$30–50/kg earlier). The silicon shortage had two major effects. First, it led to large investment into polysilicon production plants. Second, it also led to increased investments in thin-film technologies, such as CIGS, CdTe, and thin-film silicon, which typically utilize 100–1000 times less semiconductor material than c-Si solar cells. After several decades of research, thin-film companies started mass production in the early years of the twenty-first Century, with some companies reaching multi-gigawatt production capacity.

With a market still growing in size, a large part of the new production capacity for solar cells and solar modules took place in Asian countries, and in particular in China. The bottleneck in silicon feedstock, which was quickly overcome, because it was not inherent to the technology, eventually led to plummeting silicon feed-stock prices. With many companies looking just at the long-term high-volume potential, there was, however, a massive over-investment in the production capacity for solar modules. This led to PV module oversupply from 2012 to 2015. The resulting decrease in selling prices, in particular for silicon-based modules, often to levels below production

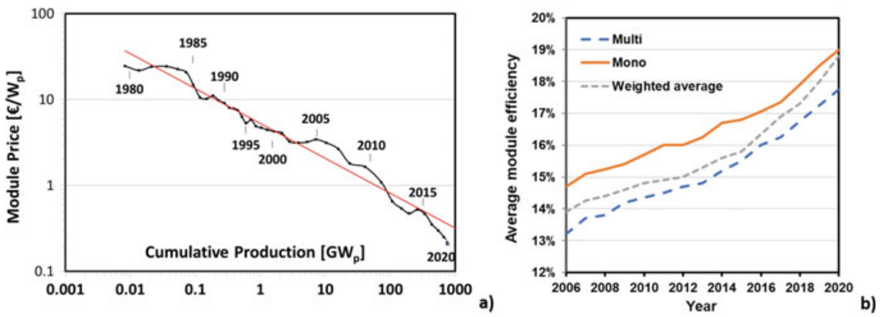

Fig. 1.4 **a** The learning curve for PV module price. The red lines shows the historical trend of 20–24% reduction in module manufacturing cost with each doubling of cumulative production. This rate of reduction might even have accelerated in the last 5 years; **b** Average efficiencies for mono- and multicrystalline PV modules over time. The weighted average considers the market share of mono and multicrystalline silicon. *Source* Fraunhofer ISE: Photovoltaics Report, updated: March 2019, and in-house estimation for 2019 and 2020

costs, forced many companies to stop activities, in particular companies with low production volumes.

This did not prevent mass industrialisation to continue with a further volume growth of around 25% per year in the decade starting in 2010. Indeed, the low price of modules led to lower and lower electricity prices, triggering further market development. The mark of 100 GW_p annual PV module production was reached in 2018, with the strongest market share (95%) for crystalline silicon, and the remaining 5% for thin-films led by CdTe, followed by CIGS and thin-film silicon.

The most striking feature of PV market development is the evolution of the PV module prices, illustrated in Fig. 1.4a. The price per Watt-peak has gone down a factor of 35 since the 1990's, reaching today prices the range of 20–30 Eurocents per W_p for standard PV modules. From the 1980's to now, the average reduction rate is between 20 and 24%. This means 20–24% reduction in module price for each doubling of cumulative production. The price decrease, dictated by offer and demand, reflects directly the manufacturing costs: standard PV modules have now become commodities with a low profit margin and a strongly competitive environment. Hence, there is an excellent correlation between selling price and manufacturing costs.

The low modules prices, a similar reduction in the costs of inverters, and partially on the engineering and mounting costs, have brought PV electricity to an amazingly low price. With total investments in the range of 50–70 €cts/W_p, large, ground-mounted, solar parks can now produce electricity at 3.6–4.5 €cts/kWh in Central Europe and as low as 1.8–2.7 €cts/kWh in sunnier regions.

1.4 Photovoltaics: Manufacturing Chain and Efficiency Increases

In addition to sheer volume effects, each solar technology benefits from continuous improvements linked to R&D, and can gain from developments made for other sectors. For instance, silicon technologies benefited originally from the immense amount of work done in microelectronics. One reason for the success of c-Si technologies can be found in the ease with which the manufacturing chain for c-Si from sand to module, can be split into individual production facilities, as illustrated in Fig. 1.5. Each step can indeed be optimised independently, with improvements almost on a daily basis, at the levels of polysilicon purification, ingot manufacturing, wafer casting or pulling, wafer sawing, solar cell processing, and module lamination.

Another key feature of the c-Si industry is the continuous increase in module efficiency. Over the last decade, an absolute efficiency improvement of 0.3–0.4% per year has taken place both for mono- and multicrystalline Si, as illustrated in Fig. 1.4b. This progress was first obtained using the so-called Aluminium Al-Back surface field (Al-BSF) process illustrated in Fig. 1.5, and continued by a shift to the PERC (passivated emitter and rear contact) technology. In 2020, the following typical average efficiencies were obtained for commercial PERC mono-crystalline products:

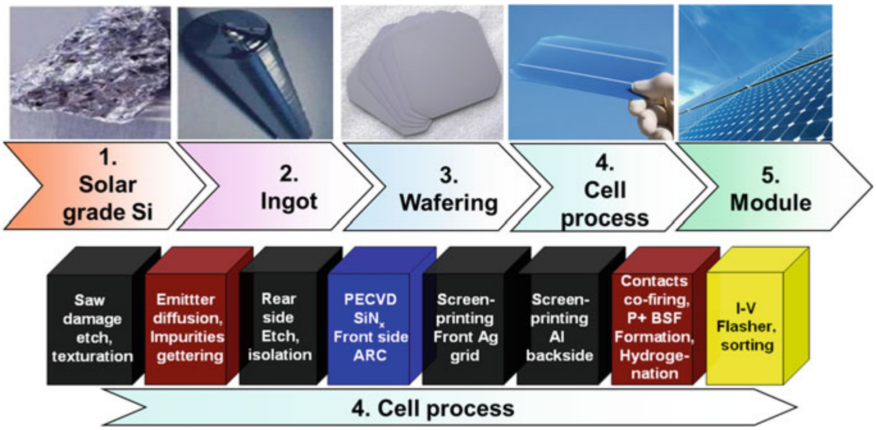

Fig. 1.5 Top: The main manufacturing steps of c-Si modules; Bottom: The six process steps, followed by power measurement on an I-V flasher, of the classical Al-BSF silicon solar cell

Cells 21.5–22.5%, modules 19–20%. In the coming decade, the cell efficiency will further increase and the difference in efficiency between solar cells and modules efficiencies will be further reduced, e.g. by using half-cells, or by shingling narrower solar cells on top of each other to avoid the presence of busbars at the front of the solar cells. From Fig. 1.3b, one can extrapolate an average efficiency for modules based on monocrystalline Si of 22–23% before 2030. Standard modules by then will hence reach today's best commercial module efficiency, up to 22.8% [4]. The latter modules are based on a more complex manufacturing process and sell at a higher price. Concurrently, PV module manufacturing costs will continue to decrease [5, 6]. Assuming a market growth of 16% annually until 2030, a learning rate of 20–24%, could lead to module manufacturing costs down to 10–12.6 €cts/W_p, for low and high efficiency "standard" c-Si modules, respectively, i.e. 21–31 €/m^2.

1.5 Photovoltaics: Impact of Technology on Energy Pay-Back Time

While PV systems generate electricity from a renewable source, their production has an environmental impact. Thin-film technologies have low energy payback times because of the small amount of semiconductor used in their fabrication. Crystalline silicon technology had, initially, a more critical starting position, because of the large quantity of silicon required, but some major technical modifications have made c-Si technology "greener"[3]. These are:

[3]"greener" meaning "more ecologically compatible".

- *Reduced energy in the preparation of pure polysilicon*: the most energy-intensive step is crystallization of polysilicon from a purified gas containing silicon. This is done in what is known as a "Siemens reactor". Today's reactors use multiple filaments or tubular filaments, to speed up polysilicon deposition, and highly-reflective coated jars to keep the wall colder. They can produce up to 10 tons of polysilicon per run, ensuring energy usage in the range of 40–50 kWh per kg of silicon [7], against 130–250 kWh per kg a decade ago.
- *Reduction in the amount of silicon per wafer thanks to advanced multi-wire sawing*: Between 2016 and 2019, the entire industry switched from SiC-slurry based multi-wire sawing to diamond wire sawing. In the latter process, steel wires incorporating small diamonds are used to cut the ingot into wafers. The typical kerf loss (material losses) between two wafers of 150–200 microns has been quickly reduced down to 60 microns, allowing an increase of 30–40% in the number of wafers sawn from the same ingot. This is accompanied by a regular decrease in wafer thickness (Fig. 1.6).
- *Reduction of the amount of silicon for a given module power, through efficiency increase*: the 3–4% gain in efficiency during the last decade allows a direct reduction per W_p of all material volumes (silicon, encapsulation polymers, metallization materials, glass).

Rough calculations show that silicon usage has been reduced from 10 g/W_p down to 3–4 g/W_p over the last decade, as illustrated in Fig. 1.6. With state-of-the-art processes, the typical energy consumption is estimated in the range of 0.8–1 kWh/W_p to produce a module (from sand to the finished product), meaning that the module energy payback time is in the range of six months up to one year depending on the location of the Solar system. The CO_2 equivalent emission depends on the source of energy used to make electricity. For instance, values of 300 g of CO_2 equivalent per

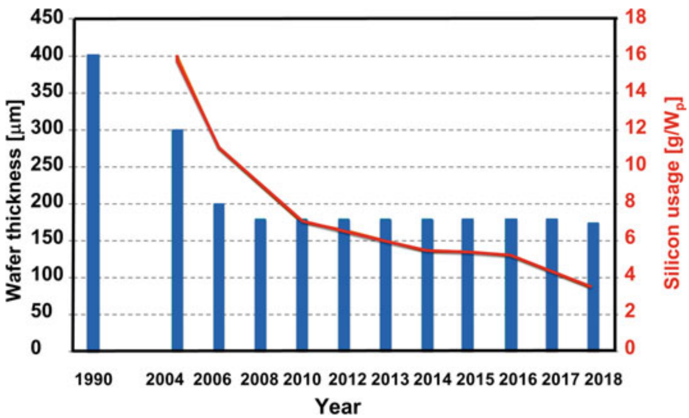

Fig. 1.6 Silicon wafer thickness [µm] and silicon usage [g/W_p] as a function of the years. *Data source* Fraunhofer ISE: Photovoltaics Report, updated: March 2019

W_p at the module level are now reported for mono-crystalline Si modules[4]. Assuming a module lifetime of 25 years, the corresponding module emissions depends on the location, but would be in the typical range of 10–13 g of CO_2 per kWh, to be compared to 400 g for a gas power plant and 900 g for a modern coal power plant. Efficiency improvements, which lead to a direct reduction per Watt-peak of all other material contributions, such as glass and encapsulates, and the ongoing reduction in wafer thickness (Fig. 1.6), will continue to improve the ecological impact of photovoltaics, even more if the sources of electricity used for the production of PV modules are also decarbonized. Finally, thin-film modules can have even less embodied energy thanks to the reduced usage of semiconductors.

1.6 Beyond Silicon Single-Junction Solar Cells

Current record efficiencies for solar cells of size larger than 1 cm^2: 22% for CdTe, 23.3% for CIGS, 26.7% for c-Si [8]. What could come next, in terms of efficiency? A possibility is given by single-junction GaAs solar cells, where record cells reach up to 29.1% [8]. The 2.4% difference between the record values for GaAs and c-Si can be attributed in a large part to intrinsic limitation of silicon, namely its indirect bandgap and Auger recombination. These material properties limit the efficiency of Silicon solar cells to 29.4–29.6% [9, 10].

The only proven concept to increase efficiency significantly is the combination of solar cells in a *multi-junction configuration*, i.e. where solar cells are stacked on top of each other. This allows for a better utilization of the light spectrum, thanks to the fact that each partial cell within a multi-junction configuration can be optimized for a part of the solar spectrum. The top cell absorbs the short-wavelength light (blue, green) and delivers a high voltage. The bottom cell absorbs the long-wavelength light (red, infrared) and delivers a lower voltage. Figure 1.7a illustrates the two classical configurations of 4 and 2 terminal devices. In the 4-terminal configuration the two partial solar cells are made separately and work independently, and each partial cell needs to be contacted separately. In the monolithic 2-terminal configuration, the top solar cell is directly grown on the bottom solar cell. It is easier to manufacture, but requires a similar current generation in the top and bottom cells, as the two cells are connected in series.

The highest stable efficiencies were usually reached by multi-junction devices made from materials within the GaAs system (alloys of Ga, Al, In etc.,), in combination with a Ge bottom cell. Recently solar cells having efficiencies up to 38.8% with 5 junctions using deposition on GaAs and InP wafers were reported [12]. As costly substrates are used and as the deposition process is expensive, such cells are,

[4]These carbon footprint values are certified and required for PV tenders in France. See for instance https://www.pv-magazine.com/press-releases/q-cells-modules-earn-further-low-carbon-certification-for-french-tenders/.

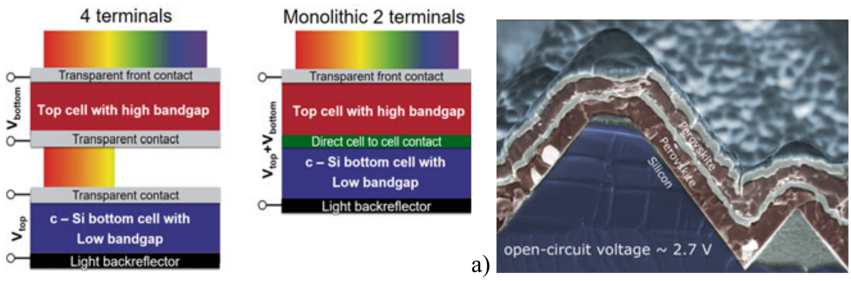

Fig. 1.7 **a** Example of two basic configurations for multi-junction solar cells. Left: 4-terminal solar cell, right: monolithic 2-terminal solar cell. More junctions can be added; **b** Scanning electron microscopy cross-section image of the first proof of concept of a triple junction 2 terminal monolithic tandem perovskite/perovskite/silicon reaching an open 2.7 V open circuit voltage, with a potential to reach over 35% efficiency (from [11])

however, about 200–1000 times costlier than c-Si cells per W_p, and they are therefore only used for niche applications, such as PV in space. A potential application domain for these cells is in the field of concentrated photovoltaics (CPV), where the area of solar cells is reduced by a factor of 200–1000 by focusing the light. This allows for system efficiencies over 30%. CPV requires a complex system to track the sun accurately and a high cleanliness to focus the light efficiently. It will be briefly mentioned in **Chap.** 10.

Let us therefore consider here only flat plate-modules without concentration. Using c-Si as "low cost" bottom cells, record efficiencies could be obtained combining GaAs on silicon and GaAs/InP on silicon at 32.8% and 35.9% respectively, in 4-terminal configuration [13]. Even though the cost problem linked to GaAs or GaInP persists, these results shows that silicon can form an ideal bottom cell for multi-junction cells.

In this context, tandem cells with potentially low manufacturing costs could be based on the combination of a Perovskite (PK) top cell with a silicon bottom cell. In 2018, the first tandem devices in 2-terminal configuration with efficiencies over 25% were reported [14], with a record now at 29.1% [8]. The efficiency potential for such devices is over 30%—and even higher if triple-junction PK/PK/Si configurations are considered (see an example in Fig. 1.7b). The major challenge here is the demonstration of reliable products, as PK devices are more sensitive to extrinsic and intrinsic degradation phenomena. As such tandems are not yet commercially available[5] they will not be treated in this Book.

Considering the growing importance of photovoltaics, pushing efficiencies to their limit in the laboratory and in mass production, investigating new material systems to break efficiency barriers will continue for the decade to come to be a topic of high interest, both for academia and industry.

[5]The stability of Perovskite cells has increased dramatically over the last years, but a full control the reliability of such tandems will still require a large research effort.