Chapter 2
Status of Solar Photovoltaics

Before our discussions on the technical aspects of solar photovoltaics, we will first review the status of solar photovoltaics. This chapter begins with a review on current solar cell technologies and their efficiencies. It is followed by a discussion on solar cell cost, a well-known barrier to large-scale deployment of solar photovoltaics. The third section will discuss the market for solar photovoltaics, including annual and cumulative installations, market shares by different cell technologies, and their historical trends. The chapter ends on a high note that both the potential and gap in solar energy utilization by photovoltaics are enormous.

2.1 The Efficiency

Photovoltaics stands for *light-induced voltage*. It was discovered by French physicist Becquerel in 1839 [1]. His experiment involved an electrochemical cell with a silver chloride (AgCl) electrode and a platinum (Pt) electrode in an acidic solution. When light was shed on the AgCl electrode, a voltage was observed between the two electrodes. American inventor Fritts [2] demonstrated an all solid-state photovoltaic device in 1883. He deposited an extremely thin layer of gold (Au) on semiconductor selenium (Se), so it was transparent to incident light. The energy conversion efficiency of the device was less than 1 %. Modern solar cells, in which a semiconductor p-n junction is employed, were conceived by Ohl [3] of Bell Laboratories in 1946. Chapin et al. [4] of Bell Laboratories demonstrated the first modern Si solar cell in 1954. Their cell employed a monocrystalline-Si wafer with a 2.5-μm p-type layer formed over the n-type wafer, resulting in an efficiency of about 6 %. Although modern Si solar cells have achieved 25 % efficiency [5], they all resemble the first Si cell in several key aspects, i.e. they all employ a Si wafer, either monocrystalline or multicrystalline, for sunlight absorption and a p-n junction for charge separation.

Steady progress has been made since the first wafer-Si solar cell in 1954. Figure 2.1 displays the evolution of best laboratory efficiencies for various solar cell technologies

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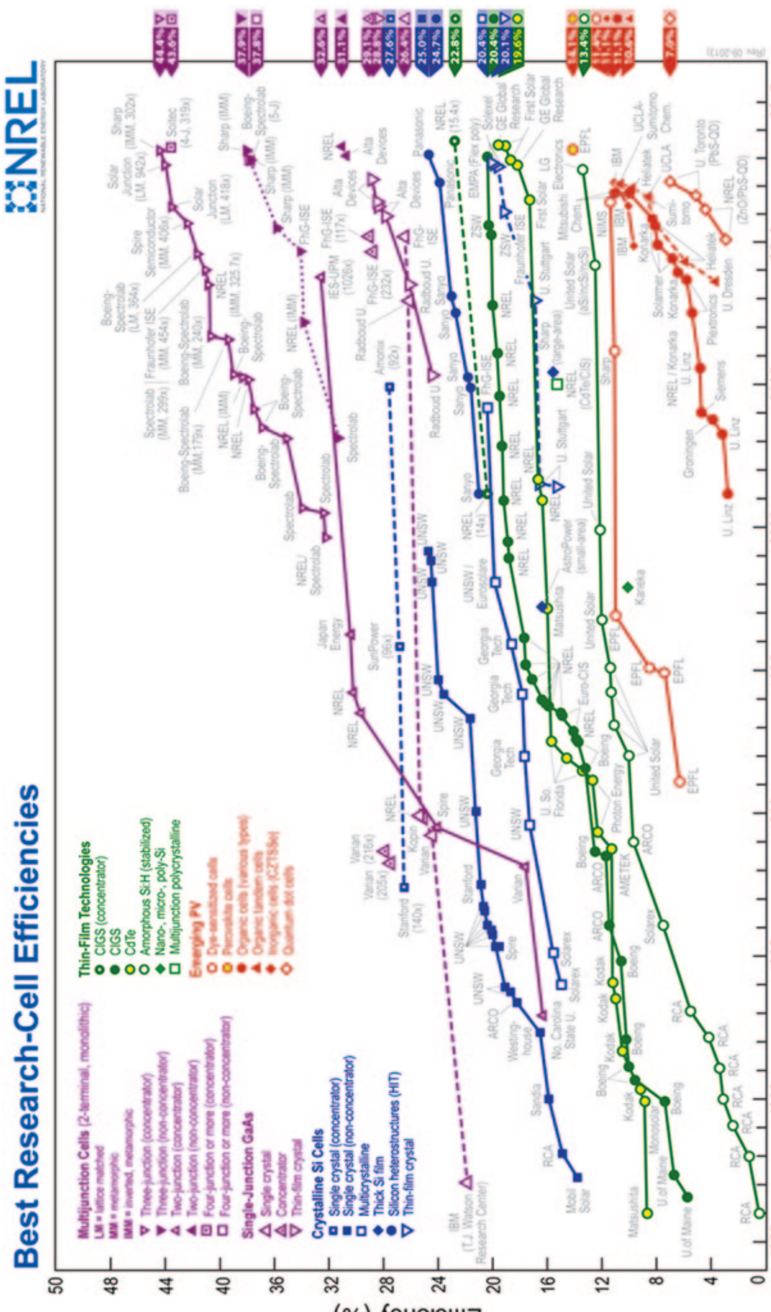

Fig. 2.1 Evolution of best efficiencies for laboratory solar cells between 1976 and 2013 [6]. Current commercial cell technologies include wafer Si, CdTe, thin-film Si, and $CuIn_xGa_{1-x}Se_2$. Developmental cell technologies include III–V, dye-sensitized, perovskite, organic, and $Cu_2ZnSnSe_{4-x}S_x$

over the last 37 years, which is compiled by the U.S. National Renewable Energy Laboratory in 2013 [6]. The energy conversion efficiency of a solar cell, η, is the ratio of the maximum electric power output and the incident solar power:

$$\eta(\%) = \frac{Maximum\ Electric\ Power\ Output}{Incident\ Solar\ Power}$$

The various commercial solar cell technologies in Fig. 2.1 include:

1. Wafer-Si solar cells, either monocrystalline or multicrystalline;
2. Thin-film cadmium telluride (CdTe) cells;
3. Thin-film Si cells, either amorphous or microcrystalline; and
4. Thin-film *c*opper *i*ndium *g*allium *s*elenide ($CuIn_xGa_{1-x}Se_2$ or CIGS) cells.

Current developmental solar cell technologies include:

1. III–V compound semiconductor multiple-junction tandem cells;
2. Dye-sensitized cells;
3. Perovskite cells;
4. Organic cells;
5. Thin-film *c*opper *z*inc *t*in *s*elenide *s*ulfide ($Cu_2ZnSnSe_{4-x}S_x$ or CZTSS) cells; and
6. Gallium arsenide (GaAs) single-junction cells.

The efficiency of monocrystalline-Si solar cells has reached 25.0 %, while that of multicrystalline-Si cells is 20.4 %. The record efficiency for all solar cell technologies is held at 44.4 % by a triple-junction tandem cell. This cell stacks three p-n junctions made of gallium indium arsenide ($Ga_xIn_{1-x}As$), gallium arsenide, and gallium indium phosphide ($Ga_yIn_{1-y}P$). Each junction has a different bandgap and is responsible for light absorption in a certain portion of the solar spectrum. The efficiency is measured with a concentrator under 302 suns. It is interesting that sunlight concentration adds 6–7 % in absolute efficiency for III–V tandem cells, from around 37 % to over 44 % by going from 1 sun to 300+ suns. The efficiency gain by concentration is less noticeable for wafer-Si solar cells with only 2–3 % gain in absolute efficiency, from 25 % at 1 sun to less than 28 % at about 100 suns.

Besides wafer Si, several thin-film solar cell technologies have been commercialized, including Si in either amorphous or microcrystalline form and two metal chalcogenides, CdTe and CIGS. Their record efficiencies are 20.4, 19.6, and 13.4 % for CIGS, CdTe, and thin-film Si cells, respectively. Several developmental solar cell technologies are also included in Fig. 2.1 including dye-sensitized cells, perovskite cells, organic cells, and CTZSS cells. Their efficiencies are between 7 and 11 %, with one exception. Within just a few years, perovskite cells have come out of obscurity with an efficiency of 14.1 % [7], a much faster pace than other developmental cell technologies.

While the accumulated progress in efficiencies of these laboratory solar cells over the years is remarkable, commercial cells are typically about two thirds of these laboratory efficiencies. This is partially due to non-uniformities in materials and processing over commercial-size cells, which are usually much larger than laboratory cells. Laboratory cells are often about a few square centimeters in size. Commercial multicrystalline-Si cells are manufactured on 156 × 156 mm^2 square wafers, while commercial thin-film cells can be even bigger. Another reason is that laboratory cells can be fabricated with more sophisticated, thus more costly, processes, while commercial cells have to strike a balance between process cost and cell efficiency. For example, vacuum-based metallization such as evaporation and sputter deposition is used in the fabrication of laboratory cells but seldom in commercial cells.

There is also 1–2 % loss in absolute efficiency from cells to modules. Several factors contribute to the efficiency loss in modules. One is the optical losses such as absorption and reflection in the front glass sheet and laminating material, which is commonly ethylene vinyl acetate (EVA). Although only matched cells with similar efficiencies are used in a module, the small dispersion in efficiency leads to a mismatch loss. There are also resistive losses in module interconnects. In general, monocrystalline-Si modules can reach over 20 % efficiency, multicrystalline-Si and CIGS modules around 15 %, CdTe modules around 13 %, and thin-film Si modules around 10 %.

2.2 The Cost

Cost is the most well-known bottleneck to large-scale deployment of solar photovoltaics. The cost of solar electricity varies widely depending on many factors such as the size of the installed system, with lower costs for larger systems. Since our target for solar photovoltaics should be terawatt-scale deployment, we will focus on the cost of the largest utility-scale systems whose size is currently in the peak megawatt range (MW_p). The cost of the smallest residential rooftop systems, which are a few peak kilowatts (kW_p), can be twice as much as utility-scale systems on the basis of dollars per peak watt ($\$/W_p$). The third category in system size is commercial systems, which are nowadays in tens to hundreds of peak kilowatts. The typical sizes of today's solar photovoltaic systems are listed in Table 2.1.

There are several methods to account for the cost of solar electricity. For manufacturers of solar cells and modules, the sale price of modules in $\$/W_p$ is the most convenient method. In 2012, the prices for wafer-Si and thin-film CdTe modules were about $\$0.85/W_p$. This represents a sharp decline in price, as the prices in 2011 were about $\$1.5/W_p$. A better measure of the upfront cost of solar photovoltaics is the cost of installed systems, also in $\$/W_p$, which includes the cost of solar modules and the cost of installation. Installation costs include mounting materials (racks and wires), inverters, labor, permits and fees, financing, and installer's expenses (overhead, taxes, marketing, and profit). These costs, especially the non-hardware costs, vary widely from one region to another and are more difficult to summarize. In 2012, the installation cost for utility-scale systems was on average about $\$2.5/W_p$. For utility companies and consumers, the *l*evelized *c*ost *o*f *e*lectricity (LCOE) for solar photovoltaics is more important, which is defined as:

$$LCOE\ (¢/kWh) = \frac{Lifetime\ Cost}{Lifetime\ Electric\ Power\ Output}$$

Table 2.1 Typical sizes of today's solar photovoltaic systems and their expected future sizes

Classification	Current size	Future size
Residential system	Up to 10 kW_p	Up to 10 kW_p
Commercial system	10 kW_p–1 MW_p	10 kW_p–1 GW_p
Utility-scale system	1 MW_p and above	1 GW_p and above

Utility-scale systems have to reach peak gigawatt scales for a noticeable contribution to our future energy mix

Table 2.2 Comparison of three cost calculation methods for solar photovoltaics

Method	Unit	Pro	Con
Cost of solar module	$/$W_p$	A simple method to calculate module cost	Failure to count installation, operation and maintenance costs
Cost of installed system	$/$W_p$	A good method to calculate upfront cost	Failure to count operation and maintenance costs
Levelized cost of electricity	¢/kWh	A good method to compare with other electricity sources	Difficulty in estimating future labor and fuel costs

Each method has its pros and cons, but ultimately the levelized cost of solar electricity has to be competitive with other electricity sources

The lifetime cost includes not only the cost of installing solar systems, but also the cost for operating and maintaining solar systems. This method is useful in comparing the cost of solar electricity to electricity generated by other sources such as coal, oil, natural gas, hydropower, nuclear power, or wind. Solar photovoltaic systems have the advantage of little operation and maintenance costs, as they require no fuels and no constant labor. Occasional labor is needed for repair and cleaning, as modules accumulate dust over time which reduces the electric power output. Table 2.2 compares different cost calculation methods.

The second method in Table 2.2, the cost of installed systems, can be used to compare the upfront costs of various electricity generation technologies. For utility-scale solar systems, it is about $3.3/$W_p$ in 2012. Solar systems produce no power at nights and little in early mornings and late afternoons. The time-averaged output of a solar system is somewhere between 10–20 % of its peak output, depending on several factors such as local solar intensity, weather, air quality, and landscape. For comparison purposes, the cost of installed solar systems needs to be converted from dollars per peak watt to dollars per watt. A $3/$W_p$ solar system with 10–20 % time-averaged output is equivalent to $15–30/W, several times higher than the upfront costs of nuclear or coal-fired power plants.

Figure 2.2 illustrates the average annual factory-gate price for solar modules between 2005 and 2012 [8]. Figure 2.3 shows the cost of installed residential (less than 10 kW_p) and commercial (larger than 100 kW_p) solar systems in the U.S. between 1998 and 2012 [9]. The module price has dropped by a factor of 4 from $3.8/$W_p$ in 2005 to $0.85/$W_p$ in 2012. Meanwhile the cost of installed residential systems has come down by a factor of about 1.7 from $8.8/$W_p$ in 2005 to $5.3/$W_p$

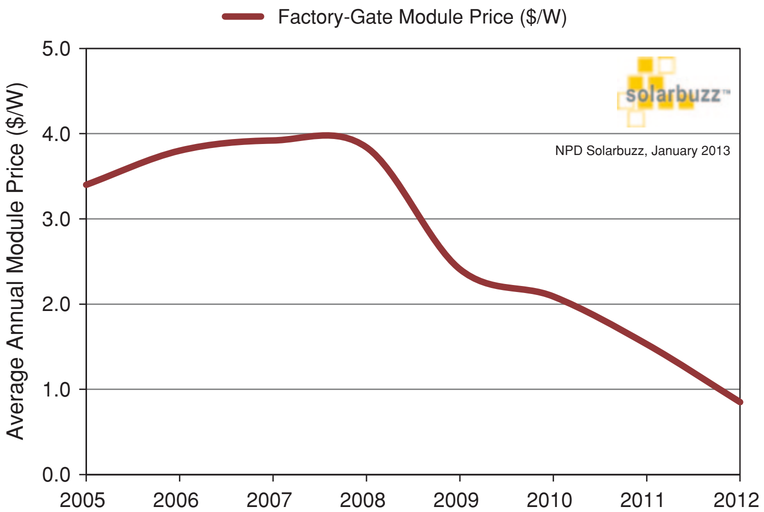

Fig. 2.2 Average annual factory-gate price for solar modules between 2005 and 2012 [8]. Reprinted with permission of NPD Solarbuzz. The module price has dropped by a factor of 4 between 2005 and 2012. The bounce-back between 2005 and 2008 was due to high demands and limited production capacities

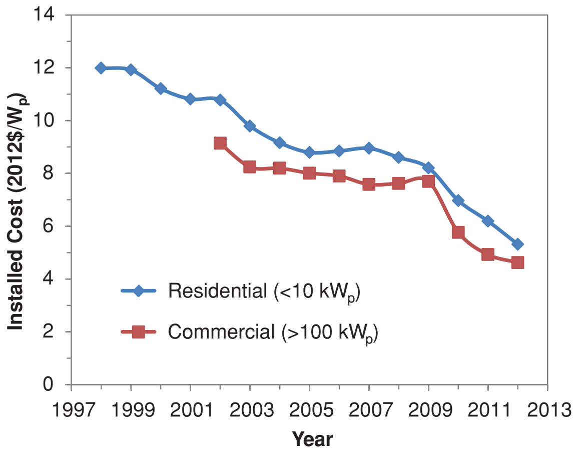

Fig. 2.3 Cost of installed solar systems in the U.S. between 1998 and 2012 for residential (less than 10 kW$_p$) and commercial (larger than 100 kW$_p$) systems [9]. The cost of residential systems has dropped from \$8.8/W$_p$ in 2005 to \$5.3/W$_p$ in 2012

in 2012, indicating a much slower pace in reducing installation costs for solar systems. There was a short-lived price bounce-back between 2005 and 2008. At the time the oil price was flying high, resulting in high demands for solar modules. The solar cell industry could not expand fast enough to keep up with the demands, leading to a price hike for solar modules.

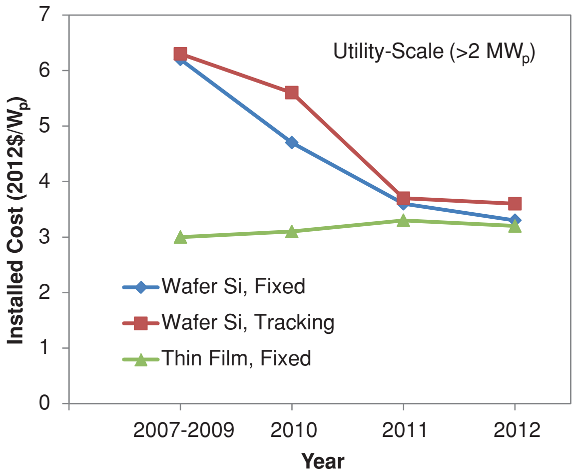

Fig. 2.4 Capacity-weighted average cost of installed utility-scale solar systems in the U.S. between 2007 and 2012 [9]. With the small number of utility-scale systems, the cost is calculated for the systems installed between 2007 and 2009. The average cost for installed utility-scale systems in 2012 is about \$3.3/W_p

The capacity-weighted average cost for utility-scale systems installed in the U.S. between 2007 and 2012 is presented in Fig. 2.4 [9]. The number of installed utility-scale systems is small at 11 systems between 2007 and 2009. Therefore, the capacity-weighted cost is calculated for the 11 systems between 2007 and 2009. There are 18 installed systems in the figure for 2010, 53 installed systems for 2011, and 106 systems for 2012. The cost of installed utility-scale wafer-Si solar systems, which have about 90 % of the market, has decreased from \$6.25/W_p for 2007–2009 to \$3.4/W_p in 2012. It is clear by comparing Figs. 2.3 and 2.4 that the economy of scale works for solar systems, with residential systems, which are typically less than 10 kW_p each, at \$5.3/W_p versus utility-scale systems, which are above 1 MW_p each, at \$3.3/W_p in 2012.

The cost breakdown of installed solar systems is worth some discussion, as shown in Fig. 2.5 [10]. Si wafers are the biggest contributor to the overall module cost at about 40 % as of 2012. Cell fabrication accounts for about 25 % of the module cost and module fabrication adds another 35 %. When the price of polycrystalline-Si feedstock was flying high in 2008 due to shortage, Si wafers were an even bigger factor accounting for 50–60 % of the module cost. In 2012, the price of solar modules was about \$0.85/W_p and the cost of installed utility-scale solar systems was about \$3.3/W_p. The cost breakdown for installed solar systems is thus modules 26 % and installation 74 %.

The solar cell industry is extremely cost conscious. This is in sharp contrast to the semiconductor industry, where performance plays a critical role in driving the industry, although the same semiconductor, Si, is used in both industries. This can

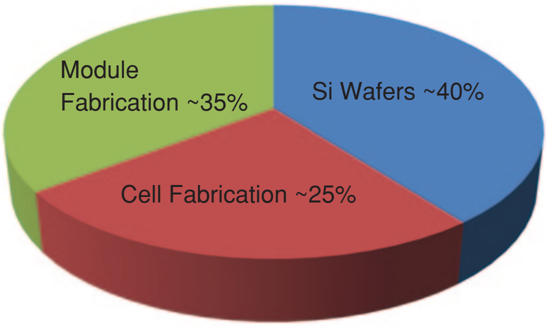

Fig. 2.5 Cost breakdown of solar modules as of 2012 [10]. Si wafers contribute to about 40 % of the module cost, cell fabrication accounts for 25 %, and module fabrication 35 %. In 2012 the module price is $\$0.85/W_p$ and the utility-scale system cost $\$3.3/W_p$, so the cost breakdown of installed solar systems is modules 26 % and installation 74 %

be illustrated by solar-specific materials, processes, and equipment developed solely for the solar cell industry. One example is the directional solidification process for growth of multicrystalline-Si ingots to replace the Czochralski process for monocrystalline-Si ingots. Directional solidification requires roughly 15 kWh/kg of electricity (meaning 15 kWh of electricity to produce 1 kg of Si), versus about 100 kWh/kg for the Czochralski process, i.e. an 85 % reduction in electricity cost. The efficiency of multicrystalline-Si solar cells is lower than that of monocrystalline-Si cells, but the industry is willing to trade a little efficiency for a large return in cost. Another example is screen printing for metallization, which prints silver (Ag) and aluminum (Al) pastes onto Si cells as the front and back electrodes. In comparison, metallization in most record-efficiency Si cells is performed by vacuum-based deposition, e.g. evaporation or sputter deposition, and photolithographic patterning. Again, the industry trades efficiency for cost.

Innovative approaches to efficiency improvement in solar cells are being pursued worldwide. It is important to remember that efficiency improvement is often accompanied with additional cost, so it has to be done in a cost-effective manner. As an example, let us assume that a new technology promises an increase in cell efficiency from 15 to 18 %, i.e. a relative 20 % increase in efficiency. At the current module price, $\$1/W_p$, the additional cost for the new technology cannot exceed 20 % of $\$1/W_p$, i.e. 20¢/$W_p$, in order to keep the cost constant on a dollars per peak watt basis. In other words, a 100 W_p module now outputs 120 W_p with the new technology, and can be sold for up to \$120 at the current module price of $\$1/W_p$:

$$\frac{\$120}{120\,\mathrm{W_p}} = \$1/\mathrm{W_p}$$

In fact, the additional cost often has to be lower than 20¢/W_p, to provide incentives to cell and module manufacturers for their adoption of the technology.

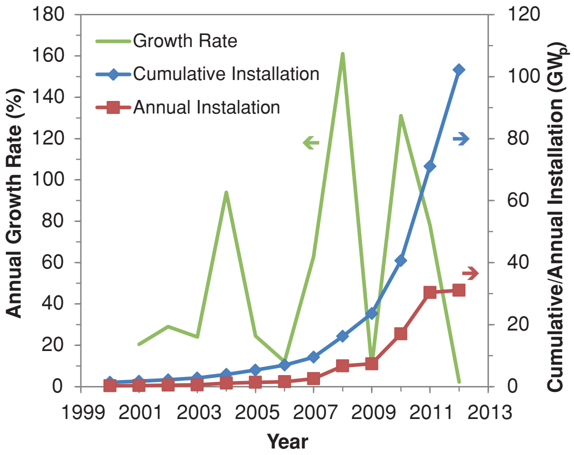

Fig. 2.6 Global cumulative and annual installations of solar photovoltaics between 2000 and 2012 [11]. The annual installation is just over 30 GW_p and the cumulative installation just over 100 GW_p in 2012. The year-to-year growth rate is calculated from the annual installation data

2.3 The Market

The solar cell industry has been experiencing phenomenal growth, about 50 % annually on average, since 2005 when the latest round of oil price hikes started. The crude oil price was about $30/barrel in 2004 and shot up to over $140/barrel in 2008. The higher oil prices played an important role in bringing public attention to the grand energy challenge we are facing, and prompted the rapid growth of the solar cell industry. Nevertheless, the solar cell industry is starting from scratch and the current fossil-fuel based energy industry is enormous in size. Today solar electricity makes a negligible contribution to our energy mix, providing roughly 0.3 % of the global electricity capacity. It will take the industry decades of phenomenal growth to make solar electricity a noticeable source of energy in our life.

Figure 2.6 illustrates the global annual and cumulative installations of solar photovoltaics between 2000 and 2012 [11]. In 2012, the annual installation of solar modules was just over 30 GW_p, while the cumulative installation reached 100 GW_p. About 70 % of the cumulative installation and about 55 % of the annual installation in 2012 were in Europe. It is revealing to compare the capacity of solar photovoltaics to the global electricity capacity, which is just over 5 TW in 2010 according to the U.S. Energy Information Administration [12]. 100 GW_p of solar photovoltaics provides 10–20 GW of time-averaged output, roughly 0.3 % of the global electricity capacity. Solar electricity will remain an insignificant source of energy for many years to come.

Figure 2.6 also calculates the year-to-year growth rate of the solar cell industry from the annual installation data. As an industry in its infancy, its growth has witnessed huge ups and downs. The year-to-year growth rate has been as high as 160 % and as low as 2 %, and on average about 50 % between 2000 and 2012. With an average annual growth rate of 40 %, the capacity of solar photovoltaics could reach 10 TW_p in 15 years, providing about 30 % of the current electricity capacity, if there were no fundamental roadblocks to its future growth. However, as discussed later

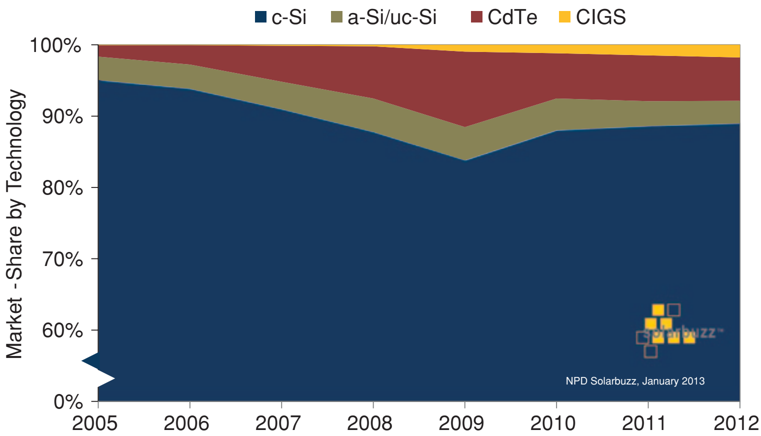

Fig. 2.7 Historical market shares by different solar cell technologies between 2005 and 2012 [8]. Reprinted with permission of NPD Solarbuzz. Wafer-Si solar cells dominate the solar cell industry with about 89 % of the market in 2012. CdTe is the second with roughly 6 % of the market. Thin-film Si has close to 4 % of the market, and CIGS slightly over 1 %

in this book, the future growth of the solar cell industry will likely be constrained by multiple roadblocks and bottlenecks such as large-scale storage of solar electricity, recycling of large-quantity solar modules, and availability of natural resources including raw materials and electricity. In this book, electricity is considered as a natural resource since it is largely generated using natural resources of limited supply: coal, oil, natural gas, nuclear fission, hydropower, or wind. On the other hand, as the base of the solar cell industry expands, its growth will naturally slow down even without these roadblocks and bottlenecks.

Out of all the solar cell technologies in Fig. 2.1, wafer-Si solar cells, either multicrystalline or monocrystalline, dominate the solar cell industry with about 89 % of the market in 2012 (Fig. 2.7). CdTe is the second market leader with roughly 6 % of the market. Thin-film Si solar cells, either amorphous or microcrystalline, have close to 4 % of the market, and CIGS slightly over 1 %. It is interesting that III–V triple-junction tandem cells have practically no market share, although they are commercially ready and they hold the efficiency record at 44.4 %. This further illustrates the cost-driven nature of the solar cell industry, as triple-junction tandem cells are prohibitively expensive. They are primarily employed in space and military applications, where performance is the determining factor.

The market share by CdTe is particularly worth noting. It was about 1.5 % in 2005, and within 4 years it expanded to over 10 % in 2009. This becomes more impressive when we consider the rapid growth of the solar cell industry as a whole during the same period, from 5.36 GW_p annual installation in 2005 to 23.6 GW_p in 2009 (Fig. 2.6). The solar cell industry as a whole grew more than 4 times in 4 years between 2005 and 2009, while the production of CdTe modules grew over 25 times in the same period. Since 2009 CdTe has been losing its market share, and this trend is expected

Table 2.3 Required installations of solar photovoltaics for different contributions to our future energy mix

Contribution (%)	2050 (30 TW) (TW_p)	2100 (46 TW) (TW_p)
10	15–30	23–46
20	30–60	46–92
30	45–90	69–138
40	60–120	92–184
50	75–150	115–230

Tens to hundreds of peak terawatts of solar photovoltaics are required to make it an important source of energy in the future

to continue as long as the solar cell industry continues its rapid growth. This book will explain the reasons behind the shrinking market share by the CdTe technology.

Let us now examine future market opportunities for solar photovoltaics. The global energy demand is projected to reach 30 TW by 2050 and 46 TW by 2100 [13]. These future energy demands will have to be met largely by carbon-free sources. The required amounts of carbon-free energy depend on our target for atmospheric CO_2 concentration. If the target is 750 ppm, Fig. 1.1 suggests about 11 TW carbon-free energy by 2050 and about 30 TW by 2100, or roughly 37 % of the total energy demand in 2050 and 65 % in 2100. Solar photovoltaics is one of the few carbon-free energy sources which are ready for large-scale commercial deployment. If solar photovoltaics is to help stabilize the atmospheric CO_2 concentration, it will have to provide a significant percentage, at least 10 %, of our future energy demands. Table 2.3 lists several scenarios for different contributions from solar photovoltaics to our future energy mix. The required installation of solar photovoltaics for 30 % contribution in 2050 is somewhere between 45 and 90 TW_p depending on the time-averaged output of the modules. In 2100 the required installation for 30 % contribution is 69–138 TW_p. Comparing these numbers with the current cumulative installations, about 100 GW_p in 2012, the capacity of solar photovoltaics will have to expand at least 500 times by 2050 and about 1,000 times by 2100 from its current level. Both the potential and gap for solar photovoltaics are enormous!

In order to install, say, 60 TW_p of solar modules by 2050, the size of the solar systems has to increase dramatically. The current size of the largest utility-scale systems is a few peak megawatts (Table 2.1). At 1 MW_p each, we would have to install 60,000,000 solar systems to reach 60 TW_p, i.e. about 4,500 1 MW_p solar systems each day between now and 2050. Table 2.1 suggests that the future size of utility-scale systems has to be at minimum 1 GW_p each. 60 TW_p of solar photovoltaics by 2050 requires 3–4 solar systems of 1 GW_p capacity every day between now and 2050, with the balance provided by smaller-scale residential and commercial systems.

Let us now estimate the required annual production rate of solar photovoltaics. Assume that our goal is to maintain 60 TW_p steady-state installation. At an average lifetime of 25 years, 2.4 TW_p of solar modules would go through their life cycles each year and need to be replaced, i.e. the required annual production for 60 TW_p steady-state installation would be about 2.4 TW_p/year. This is roughly 80 times the 2012 annual production at about 30 GW_p/year.

Although the potential for solar photovoltaics is enormous, the actual role of solar photovoltaics in our future energy mix depends on our success in removing roadblocks and bottlenecks to terawatt-scale deployment of solar photovoltaics. Besides cost and efficiency, the roadblocks to terawatt solar photovoltaics include terawatt-scale storage of solar electricity, recycling of terawatt-quantity solar modules, and availability of natural resources such as raw materials and electricity. If we fail to remove these roadblocks, solar photovoltaics may always be small demonstration projects and other solar technologies, such as solar fuels or concentrated solar power systems, could dominate our future energy mix. This book will provide an analysis on some of the roadblocks and bottlenecks to terawatt solar photovoltaics, with a focus natural resource limitations. It also attempts to identify sound technological approaches to overcoming these roadblocks and bottlenecks.

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