

Article 4: Solar Cell Technology

Article 4 is a survey of solar cell technologies. Eleven solar technologies are reviewed, five of them currently available and six of them still in the laboratory. A scoring system is introduced that highlights many of the issues that drive solar cell development. An underlying question is whether the current dominance of the crystalline silicon solar cell will be a permanent feature of the solar cell market for the indefinite future.

A. The Solar Cell

Light consists of discrete particles, called photons, each carrying a tiny amount of energy. A photovoltaic (PV) cell converts incident photons into electricity. If a PV cell is powered by incident sunlight, it is termed a solar cell.

At the core of most common solar cells is an interface between two semiconductors with different electronic properties. On one side of the interface is an “n-type” semiconductor with excess electrons (electrons carry *negative* charge, hence “n-type”). On the other side is a “p-type” semiconductor, which has a deficiency of electrons (equivalent to an excess of *positively* charged counterparts to the electron, called “holes”). The two materials create an internal electric field at the interface, which is called the “p-n junction.”

The device has a “band gap,” a specific amount of energy. That energy is the minimum needed to excite an electron into a state in which it can move through the device in the presence of an electric field. Upon the absorption of a photon whose energy exceeds the band gap, an electron is promoted across the band gap and makes what is normally a forbidden transition from a lower energy band (the valence band or ground state) to a higher energy band (the conduction band or excited state). At the same time, a “hole” (in effect, a missing electron) is created in the valence band. The effectiveness of a solar cell arises from the fact that the energy of the photon can be converted to electricity when the internal electric field separates the electrons and holes from one another and directs them to the two contacts of the device (through the cathode and anode, respectively).

In general, electricity is produced only when a photon with more energy than the band gap strikes a solar cell. Thus, there are materials where a blue photon is energetic enough to drive an electron across the band gap but a red photon is not. The excess energy carried by the blue photon, relative to the amount of energy that is sufficient to cross the band gap, becomes heat.

Solar Cell Efficiency

The efficiency of a solar cell is defined as the percentage of incident solar power that is converted to electric power. The efficiency is measured under laboratory conditions that mimic peak conditions, where the Sun is directly above the solar cell and high in the sky, and the day is clear. Efficiency is a solar cell’s most important attribute, because higher efficiency translates into smaller facilities on less land.

The electric power output is the product of the photocurrent and photovoltage of the solar cell. The photocurrent is directly proportional to the number of solar photons that an absorber is able to collect, while the photovoltage is determined by the semiconductor’s band gap. A material with a larger band gap provides a greater voltage but delivers less current because it absorbs less of the solar spectrum. Accordingly, there is an optimal band gap where the maximum output of solar electricity can be achieved, determined by the specific distribution of energies in the photons of sunlight. At that band gap, a solar cell with a single junction (the most common type), has the maximum possible efficiency. That efficiency is about 33 percent. In practice, the highest efficiencies achieved for single-junction cells are close to this limit: 28.8 percent for gallium arsenide and 26.6 percent for crystalline silicon.

Considerably higher efficiencies can be reached with a multijunction solar cell, where different solar cells are integrated together. A typical multijunction cell has two to five absorbers, each having a band-gap with a different amount of energy, so that complementary portions of the solar spectrum can be harvested. Multijunction solar cells are more expensive to fabricate than single-junction cells. As a result it is often worth enhancing their efficiency still further by using concentrators that intensify the strength of the sunlight that falls on these cells. The record efficiency to date is 38.8 percent for a multijunction cell without concentration, and 46 percent for a multijunction cell receiving a solar input concentrated more than 100 times.

	Efficiency	Abundance	Compatibility	Stability	Manufacturability	Versatility
Today's Technologies						
mono-Si	+2	+2	+1	+2	+2	-2
poly-Si	+1	+2	+1	+2	+2	-2
a-Si	-1	+2	+2	-1	+2	+1
CdTe	+1	-2	-2	+2	+2	+1
CIGS	+1	-1	-1	+2	-1	+1
Technologies on the Frontier						
GaAs	+2	+1	+1	+2	-2	+1
CZTS	-1	+2	-1	?	-1	+1
OPV	-1	+1	+2	?	+1	+2
DSSC	-1	+1	+1	+1	-2	+1
QD	-1	+1	-1	?	?	+1
Perovskite	+1	+1	-2	?	?	?

Table 4.1: Scores (on a four-point scale) of five current and six frontier solar technologies with respect to six attributes. The row labels are names of cells. mono-Si: monocrystalline silicon. poly-Si: polycrystalline silicon. a-Si: amorphous silicon. CdTe: cadmium telluride. CIGS: either copper indium gallium diselenide or copper indium gallium disulfide. GaAs: gallium arsenide. CZTS: either copper-zinc-tin-sulfur or copper-zinc-tin-selenium. OPV: organic photovoltaic. DSSC: dye-sensitized solar cell. QD: quantum dot. Perovskite is not abbreviated.

Will crystalline silicon ever lose its dominance?

Monocrystalline silicon and polycrystalline silicon, the two main crystalline silicon technologies, together account for about 90 percent of today's global installed solar power capacity. Will another solar cell ever beat crystalline silicon in the PV market?

Table 4.1 presents our attempt to benchmark eleven other solar technologies, five which we consider "today's technologies," and six which we place on the research frontier. We consider only single-junction cells. We compare these eleven cells across six metrics: efficiency, element abundance, compatibility with public health and the environment, stability, manufacturability, and versatility in deployment options. We use a four-point scale: +2, +1, -1, and -2 (approximating very poor, poor, fair, and good). We opt for question marks in a few instances. Below, we discuss first the six metrics and then the eleven cells.

Efficiency

The most heralded performance index of a solar cell is its efficiency. Raising the efficiency of a solar cell, other things being equal, lowers the cost of a project. Fewer structural supports, less installation labor, and less outlay in many other areas can produce the same amount of electricity when the cell efficiency increases.

Timelines of the highest efficiency achieved by each of the eleven technologies are plotted in Figure 4.1, which is a simplification of a widely cited figure prepared by the National Renewable Energy Laboratory and regularly updated on its website.¹¹ In Table 4.1, we assign the +2 score only to the gallium arsenide and the monocrystalline silicon cells. (The gallium arsenide cell, as discussed further below, is used on spacecraft but has been too costly for wide use elsewhere.) The other nine cells are scored either +1 or -1 (-2 is not used).

¹¹Another excellent resource for following progress in the performance of the various solar technologies is the journal, *Progress in Photovoltaics*, which periodically publishes "Solar-cell efficiency tables" for cells and modules.

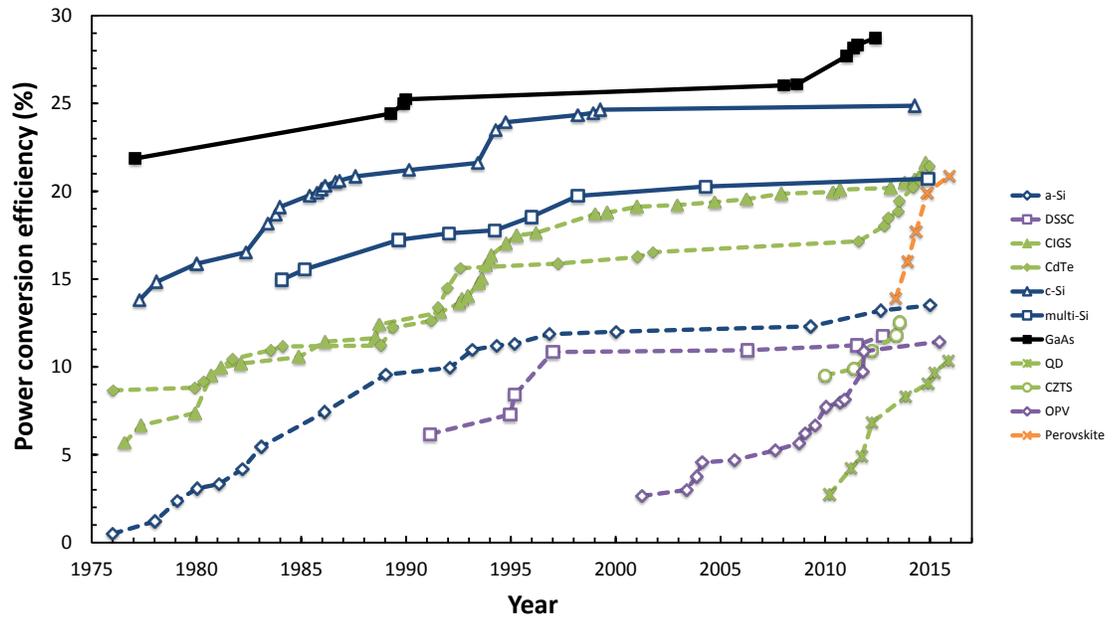


Figure 4.1: Timeline of the certified efficiency values of eleven solar-cell technologies. Source: “Best research-cell efficiencies,” a chart from the National Renewable Energy Laboratory, http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

Abundance

Solar energy systems face resource limitations, especially when they rely on relatively rare elements. A point of reference for the scoring of scarcity in Table 4.1 is the abundance of an element in the Earth’s crust. Consider the seven elements in the two thin-film non-silicon inorganic solar cells discussed under “today’s technologies” above: the CdTe cell contains cadmium and tellurium and the CIGS thin-film cell contains copper, indium, gallium, selenium, and sulfur. Add an eighth element, ruthenium, which currently is used in DSSCs. The crustal abundance of three of these eight elements is substantially greater than one part per million: the abundances are about 400, 60, and 20 parts per million for sulfur, copper, and gallium, respectively. Of the other five, tellurium and ruthenium are substantially more scarce than cadmium, indium, and selenium: the abundances of both tellurium and ruthenium are one part per billion (about the same as the abundance of platinum), while the other three, roughly equally abundant, are between 50 and 250 times more abundant than tellurium and ruthenium and about 1,000 times more scarce than sulfur, copper, and gallium.¹² The scarcity of tellurium is a substantial obstacle to the expansion of CdTe cells, even though the amount of photo-active material required for a thin film is very small. The scarcity of indium is one of the reasons why alternatives to the CIGS cell have been sought.

To be sure, crustal abundance by itself is only a weak guide to scarcity, because mineral distribution is of course not uniform over the Earth’s crust. Moreover, scarce elements are often produced not directly but as byproducts of the mining of more common elements with which they are associated (cadmium and indium are extracted primarily with zinc; selenium and tellurium with copper), resulting in much lower costs for these elements than the costs of production from dedicated mines.

Compatibility

The *compatibility* index is intended to reflect hazards both to public health and the natural environment. Our compatibility score takes note of only lead and cadmium, two heavy metals that are particularly toxic. Indeed, the replacement of nickel-cadmium batteries by other kinds of nickel batteries was in part driven by the desire to avoid cadmium’s toxicity. Similar pressure drove lead compounds out of paint and tetra-ethyl lead out of gasoline. A concern for toxicity arises throughout a material’s life-cycle, starting with the health of miners and workers in fabrication facilities; then during use when, for example, winds carrying sand can ablate and disperse the material; and, finally, during the disposal process. A prominent use of lead solder in a device affects our compatibility score slightly (it leads to a score of +1 instead of +2). Extensive use of cadmium or lead in the cell itself is given greater importance and results in a score of either -1 or -2, depending on how much metal is involved.

¹²https://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth%27s_crust.



Toxicity has not inhibited extensive use of lead, notably in the lead acid battery, which accounts for a large fraction of the lead in industrial products.¹³ The need to manage battery lead is partially responsible for the “secondary” lead acid battery industry, which rebuilds lead acid batteries in dedicated facilities that use lead exclusively taken from batteries collected from users, rather than newly mined lead. Moreover, the environmental mobility of lead in the three chemical forms found in a battery (metallic lead, lead oxide, and lead sulfate) is small. As a result, the lead battery system, in principle, can produce relatively little toxic environmental impact.¹⁴ Comparable solutions may enable the use of lead in commercial solar cells.

Stability

Stability reflects the average loss of performance over time for real-world installations. For several of the frontier technologies conclusive data are not available, and for most of the other technologies is not an issue.

Manufacturability

Manufacturability refers to the current cell fabrication technology. Reasons for the scoring vary and are presented for each cell below.

Versatility

In scoring “versatility” our dominant criterion is whether the cell is crystalline or a thin film. Thin films are inherently more versatile because, relative to crystalline cells, they can be shaped and can weigh less, permitting use in a wider variety of applications. Eight of the eleven technologies in Table 4.1 are based on thin films.

B. Today’s Technologies

Five technologies in Figure 4.1 and Table 4.1 are classified as “today’s technologies.” Three of these (shown in blue in Figure 4.1) are silicon-based: monocrystalline silicon (also called single-crystalline silicon), polycrystalline silicon (also, multi-crystalline), and amorphous silicon. The other two are based on cadmium telluride and copper indium gallium diselenide cells (shown in green).

Monocrystalline and Polycrystalline Silicon Cells

In electronic devices, the silicon is extremely pure: the silicon is called “nine nines” silicon (99.9999999 percent silicon), because less than one atom in a billion in the crystal is not a silicon atom. In crystalline silicon solar cells, the silicon can be either as pure or a little less pure.

¹³<http://www.ila-lead.org/lead-facts/lead-uses-statistics>

¹⁴Lead contamination at homes near a closed secondary lead acid battery plant in California is a counterexample. <http://www.latimes.com/local/lanow/la-me-ln-exide-cleanup-expedite-20170112-story.html>.

The n-type and the p-type silicon semiconductors are formed by “doping” the silicon, that is, by introducing very small amounts of impurity atoms into silicon’s crystal lattice. Silicon is made n-type by introducing an impurity atom, such as phosphorus; the one additional valence electron of phosphorus, relative to silicon, contributes an electron to the solid, making the material rich in electrons, which are negatively charged. Silicon is made p-type by introducing boron, which has one less valence electron than silicon, creating a positive charge (a hole) in the lattice.

The result is a silicon solar cell with a band gap corresponding to the photon energy of near-infrared light (light that is slightly less energetic than red light), which enables the cell to absorb the whole spectrum of visible light as well as all light more energetic than visible light. Silicon solar cells operate close to their maximum power point (maximum product of voltage and current), which for a typical crystalline silicon solar cell is a voltage of about 0.6 volts, about half the voltage of a AA battery. To reach higher voltages for practical implementation, cells are strung in series and encapsulated into what are known as modules or panels.

The monocrystalline silicon cell is based on a single silicon crystal, whereas the polycrystalline silicon cell contains numerous crystalline grains, each a few centimeters in size. The crystalline solar cell is typically a square, 15 centimeters by 15 centimeters – about the size of a compact disk case – and the module contains dozens (typical values are 60, 72, or 96) of individual cells. These modules are then connected in series and parallel to other modules to form an array, and power conditioning elements are incorporated. The two main power conditioning elements are 1) transformers, which change the voltage, and 2) inverters, which change the direct current (DC) produced by the cell into the alternating current (AC) required by the user.

Monocrystalline silicon is more costly to produce than polycrystalline silicon, but the monocrystalline cell’s efficiency is higher, so there is a trade-off, and both are widely produced. The loss of efficiency in polycrystalline silicon results from defects that promote the recombination of electrons and holes. The efficiency of polycrystalline silicon solar cells is less than the efficiency of monocrystalline silicon solar cells by a few percentage points: roughly 20 percent for polycrystalline silicon versus 25 percent for monocrystalline silicon (Figure 4.1). Compared with other cell technologies, these efficiencies are relatively high; in fact, monocrystalline silicon is one of two technologies earning the top score (+2) for efficiency in Table 4.1 (the other is gallium arsenide).

We do not differentiate the two forms of crystalline silicon on the five attributes other than efficiency in Table 4.1. We assign +2 scores for stability and manufacturability to both cells, because the processes that produce durable cells are by now well developed. To fabricate either a monocrystalline or a polycrystalline silicon cell, a saw cuts wafers out of a large silicon crystal ingot. High temperatures are required to purify and crystallize silicon, and the energy to provide these temperatures is a major component of the total energy used to create a silicon solar panel. The polycrystalline cell can be formed into a rectangular shape in a ceramic crucible, meaning that wafers can fill the module space more efficiently than the slightly rounded monocrystalline wafers that are cut from a single cylindrical silicon ingot (Figure 4.2).

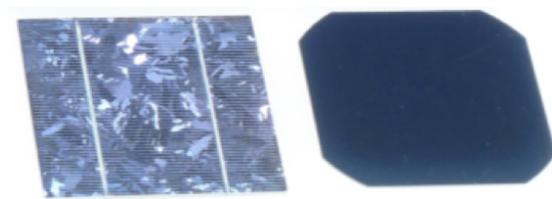


Figure 4.2: A polycrystalline silicon cell (left) and a monocrystalline silicon cell (right) Source: https://commons.wikimedia.org/wiki/File:Comparison_solar_cell_poly-Si_vs_mono-Si.png

In both cases, the wafer is typically 150-200 microns thick, thick enough to support itself when undergoing the further processing required to make it into a solar cell. (A micron is one millionth of a meter.) A thick wafer is necessary, because silicon is an indirect band gap semiconductor, meaning that photons are not absorbed very strongly, so a thick layer is needed to ensure nearly complete absorption of the incident sunlight. The need for thick layers does not pose a long-term supply issue for silicon, because silicon is the second-most-abundant element (after oxygen) in the Earth's crust.

To increase the efficiency of the silicon cell, its surface is deliberately modified. An example is shown in Figure 4.3, where a complex microstructure has been created on the surface of the silicon. The result is that when a photon is reflected off of the surface it has a higher likelihood of hitting another part of the surface and being absorbed. To the eye, it looks blacker. Another strategy to improve its efficiency is to cool the cell actively (or, alternatively, to harvest its waste heat), because the performance of a silicon solar cell is degraded when hot.

We give the two forms of crystalline silicon a -2 score for versatility because, in addition to not having the versatility of a thin film, the crystalline silicon cell must be thick as a result of its poor absorption of incident sunlight; by contrast, the one other crystalline cell on our list, gallium arsenide, can be thin because it is a strong light absorber.

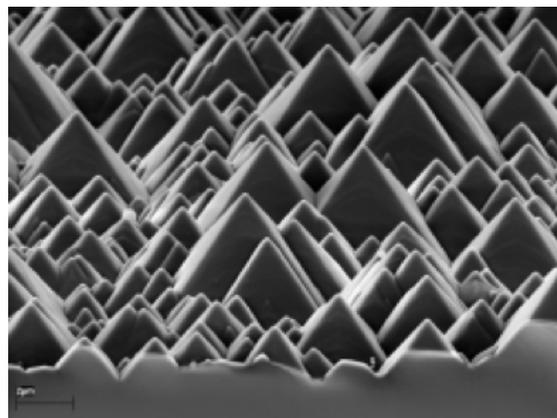


Figure 4.3: Detailed microstructure of a silicon cell whose surface has been modified to trap light and increase the probability of photon absorption. Source: <https://www.flickr.com/photos/zeissmicro/10995781963>

As for “compatibility” with public health and the environment, we stretch the definition to include not only the cell but the module in which it is contained. We score both types of crystalline silicon cells +1 rather than +2, because lead solder is used for the many metallic interconnects that join crystalline silicon cells to one another in a module.

Amorphous Silicon Cells

Amorphous silicon cells commanded more than 30 percent of the (albeit rather small) solar cell market in the late 1980s. While less expensive than the crystalline forms, amorphous silicon cells have much lower conversion efficiencies – roughly 10 percent, or around half of the efficiency of the two crystalline forms (Figure 4.1). Today, the market for amorphous silicon is largely confined to consumer products.

Amorphous silicon does not have a crystalline structure and cannot be fabricated into wafers. Rather, it is fabricated into thin films. Indeed, amorphous silicon was the first major commercial technology for thin-film solar cells. Thin-film technologies utilize films that are much thinner than wafers: they are at most a few microns thick and therefore need to be supported by a substrate – typically glass, metal, or plastic. The main benefits of thin-film technologies over those that are wafer-based are that less specialty material is used and fabrication throughput is higher – potentially lowering costs as well as the amount of energy required to manufacture the cells. These cells are also easier to integrate into building materials.

The performance of amorphous silicon solar cells is improved by adding hydrogen to the thin films. The low-temperature processing that leads to amorphous silicon results in silicon atoms with dangling chemical bonds, because the atoms are not positioned to form a crystal. (In crystalline silicon, by contrast, each silicon atom bonds to four other silicon atoms, and there are

no dangling bonds.) Hydrogen, with a single valence electron, has the capacity to terminate (passivate) the dangling bonds, improving the electronic performance of amorphous silicon.

Unless an amorphous silicon thin film is very thin, it cannot be passivated effectively. If it is made thicker, the passivation isn't stable, and the cell loses efficiency. However, a thin film can be too thin to manufacture. Therefore, to obtain sufficient thickness without sacrificing internal efficiency, several passivated amorphous silicon thin films are often placed on top of each other in a tandem architecture. To express this inherent complexity on Table 4.1, we grade amorphous silicon as +2 for manufacturability but -1 for stability. We also give amorphous silicon a +2 score for compatibility with public health and the environment, because, compared to crystalline silicon, lead solder is used in a far more limited way.

Cadmium Telluride and Copper Indium Gallium Diselenide Cells

Cadmium telluride (CdTe) solar cells are found at nearly all of the world's solar power plants that do not use crystalline silicon cells. The CdTe plants account for roughly 10 percent of global power capacity. The 550-megawatt Topaz Solar Farm shown in Figure 3.8 uses CdTe solar cells. The copper indium gallium diselenide (CIGS) solar cell accounts for about one percent of global capacity. Variants of the CIGS cell replace all or some of the selenium with sulfur. The S in CIGS, therefore, identifies both sulfur and selenium.

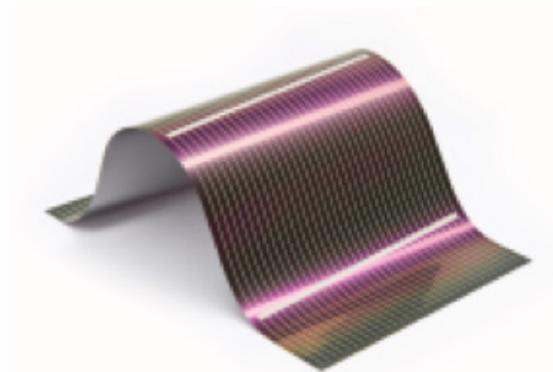


Figure 4.4: A flexible copper indium gallium diselenide (CIGS) panel. The cells form long stripes – the preferred arrangement to collect the charge built on a thin film. Source: <http://materia.nl/article/innovation-thin-film-solar-cells-at-mx2016/innovation-thin-film-solar-cells-at-mx2016-1/>

Like the amorphous silicon cell, the CdTe and the CIGS cells are thin-film cells. Panels made from thin-film solar cells can be flexed and deformed, as seen in Figure 4.4, which shows a flexible ribbon made of CIGS cells. Deformability makes thin-film panels attractive for

installations where curved surfaces are encountered (such as on vehicles) or where the objective is to integrate the cell into architectural surfaces.

Both the CdTe and the CIGS cells are named after its p-type absorber, which in both cases is a chalcogenide semiconductor – a semiconductor formed with an atom in the group of the periodic table that includes sulfur, selenium, and tellurium, known as chalcogens. Having already achieved record cell efficiencies of just below 22 percent (Figure 4.1), and still improving, chalcogenide solar cells offer a module performance that competes effectively with polycrystalline silicon.

A useful distinction among solar cells is whether the interface is a homojunction or a heterojunction. The p-type and n-type semiconductors on the two sides of the interface of a homojunction are the same, while the two materials are different for heterojunctions. The silicon cells described above have silicon on both sides of the interface (doped in different ways), so they are homojunction cells. By contrast, both the CdTe cell and the CIGS cell have heterojunctions: the n-type material is most often cadmium sulfide (CdS).

One reason why the CdTe cell has been a strong competitor is because both its p-type semiconductor and its n-type semiconductor are binary compounds (compounds with only two elements); binary compounds can be produced industrially with better reproducibility than compounds made from three or more elements.

Both the CdTe cell and the CIGS cell are very stable. However, the extreme scarcity of tellurium and the relative scarcity of indium lead to the -2 and -1 abundance scores for the CdTe and CIGS cells, respectively. Also, the toxicity of cadmium in combination with its relative prevalence in the cell leads to compatibility scores of -2 for CdTe and -1 for CIGS. CdTe cells (made from two elements) are easier to manufacture than CIGS cells (made from four or even five elements). Both cells can be made to be rigid or flexible, enhancing their versatility.

The Learning Curve

Historically, many industries realize lower costs and therefore lower prices over time. The solar industry is no exception, as shown in Figure 4.5, which shows the “learning curve” for the crystalline-silicon solar panel (module). The average module price is plotted as a function of cumulative module shipments, and data are shown for the 40 years from 1976 to December 2016. Among the contributing factors to “learning” are steady improvements in efficient production processes and throughout the supply chain, as well as benefits from research and development and from the spillover of positive results achieved by other industries.

The fit to the data seen in Figure 4.5 (which has a logarithmic scale on both axes) corresponds to a 22.5 percent reduction in module price for each doubling in cumulative production. Between the first and last data point, cumulative production increased by a factor of about one million, from 0.3 megawatts to 300,000 megawatts: a million is approximately 20 doublings. With 0.225 as the learning curve parameter, the price should have fallen by a factor of 0.775 (1.0 minus the learning curve parameter) for each doubling, or by a factor of approximately 160 for 20 doublings. Actually, the 2016 data point lies considerably below the learning-curve line, meaning that the price fall has been even faster.

Figure 4.5 also shows a vertical line that represents the solar capacity that would be required to meet *all* of the 2016 global electricity use, which was approximately 24,000 billion kilowatt-hours. We again assume that, on average, one kilowatt of installed solar capacity will produce 1,200 kilowatt-hours of electricity each year. Then, the required solar capacity would be 20 million megawatts, which is about 70 times more than current capacity (about six more doublings would be required). This estimate implicitly assumes the existence of abundant electricity storage, so that sufficient solar electricity can be delivered to the user at all times. It also assumes that the losses of electricity associated

with storage (charging and discharging a battery, for example) are negligible.

There is a price bubble in Figure 4.5 corresponding to the years 2001-2010, when the average sales price was above the long-term learning curve. The high module price was due to a sharply rising price for pure silicon, the raw-material precursor to the silicon wafers that are used by both the solar cell and microelectronics industries. Silicon's price rise was the result of a surging solar market (a growth that began in the early to mid-1990s) that caused demand to increase well beyond supply. The price of pure-silicon feedstock increased from less than \$30 per kilogram in the early 2000's to more than \$400 per kilogram in 2008. This price increase created incentives for new suppliers to enter the market and for current providers to increase capacity, which led to an oversupply. By 2010, when much of the added silicon production capacity had come online, the price of silicon feedstock had dropped to about \$50 per kilogram, and today it is relatively stable at about \$20 per kilogram.

During the decade-long price bubble, non-silicon competitors, most prominently cadmium telluride, had a chance to prosper. In the absence of another price bubble, it is not clear how a new technology would be able to enter the market.

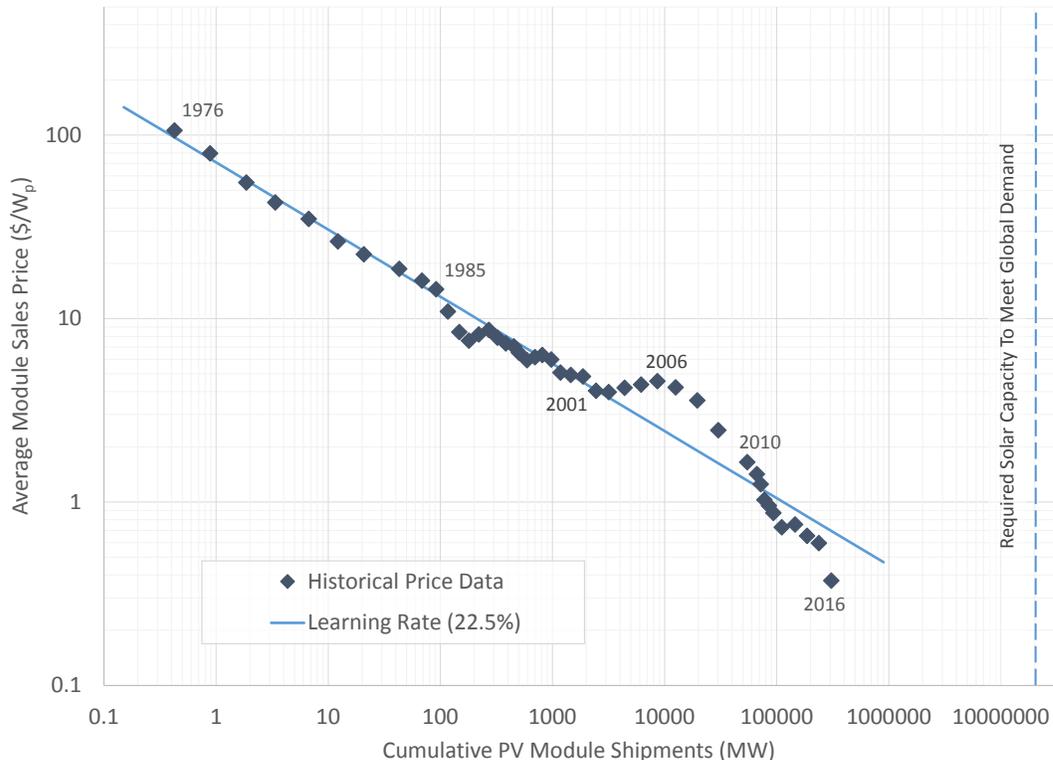


Figure 4.5: Learning-curve analysis of the solar panel with crystalline silicon cells. The average panel price (in units of 2016 U.S. dollars per peak-watt, \$/Wp) is plotted against the global cumulative capacity of panel shipments (in units of thousands of kilowatts, or megawatts, MW), 1976-2016. The straight line represents a learning rate (LR in the figure) where the price falls by 22.5 percent for each doubling of cumulative production. The data extend across 20 doublings of cumulative production. The vertical line identifies the required global solar capacity (approximately 20 million megawatts) to satisfy the entire global demand for electricity, assuming perfect storage. Source: International Technology Roadmap for Photovoltaic, Eighth Edition, March 2017, Figure 3: <http://www.itrpv.net/Reports/Downloads/>.

Today, monocrystalline and polycrystalline silicon modules are being sold at shrinking profit margins, and some high-cost producers and small-volume producers are unable to operate profitably. The result is a widespread consolidation in the PV industry. It is expected that in the next decade only a limited number of major suppliers will remain – a consolidation that is not without precedent, as recent history shows similar consolidation phases for both the microelectronics and electronic display industries.

C. The Photovoltaic Frontier

Recognizing that technologies based upon crystalline silicon will continue to rule the PV marketplace for years to come, research is proceeding in two directions. In one direction, research focuses on further improving today's commercial technologies. For example, in 2014, the 25 percent efficiency record for crystalline silicon that had stood for 15 years was broken with improvements to an architecture based on a heterojunction between the crystalline silicon absorber and an amorphous silicon charge-collection layer.

In the other direction, the goal is to find new technologies and materials that can achieve some combination of dramatically higher performance and dramatically lower costs. Because the cost of crystalline silicon devices is only a small fraction of total system costs, a new kind of solar cell might become competitive, for example, if it lowered balance-of-system costs or served significant niche markets. A successful entrant into the PV cell market need not outcompete silicon, at least initially, as long as it can offer features not possible with silicon. For example, if it can be lower in weight, a system built around a thin-film cell rather than a crystalline silicon cell might be able to be integrated in roof shingles or building façades, and it might have mobile applications.

Here, we take note of six emerging options: gallium arsenide cells, copper-zinc-tin-selenium (or sulfur) cells, organic photovoltaic cells, dye-sensitized solar cells, quantum-dot cells, and perovskite cells. Their efficiency trajectories are plotted in Figure 4.1 (quite a few pages back), alongside today's cells.

Gallium Arsenide Cells

The gallium arsenide (GaAs) solar cell has a specialized use today: powering space satellites. It is the solar cell of choice for this application because of its high efficiency and ability to withstand the radiation in space with limited damage. It possesses a nearly optimal direct band gap, and in fact the record for the efficiency of a single junction cell (28.8 percent) was achieved with this material (see Figure 4.1, shown in black).

The GaAs cell has limited uses on Earth, because high-throughput, low-cost production has not been achieved. Accordingly, we place this cell on the technological frontier, and we assign this cell (and only one other) a score of -2 for manufacturability. The high-efficiency GaAs cell produced today requires a monocrystalline wafer 100 to 200 microns thick, which must be fabricated by slow deposition to realize the proper p-n junction formation. However, given its direct band gap, the cell could be as thin as a few microns. Efforts are therefore underway to develop fabrication processes in which the costly substrate on which the cell is grown is used multiple times. For each use, the top layer containing this solar cell can be peeled off, and the substrate is cleaned and reused. If successful, this approach could propel GaAs technology forward.

Some of the potential of the GaAs cell comes from the abundance of the elements of which it is composed, the low toxicity of the material (arsenic is toxic, but in the cell it is tightly bound to gallium and not easily mobilized), and its stability. The GaAs cell is also versatile: thin versions of the cell are lightweight and efficient, and the cell's performance degrades relatively little over time when subjected to the radiation beyond the atmosphere, which adds to its attractiveness for space applications.

Copper-zinc-tin-sulfur and Copper-zinc-tin-selenium Cells

To overcome the scarcity of tellurium and indium, a chalcogenide cell that might replace the CdTe cell or the CIGS cell is being investigated which uses copper, zinc, and tin instead. This cell is the CZTS cell (C for copper, Z for zinc, T for tin, and S – as with the CIGS cell above – for either selenium or sulfur or both). As with the CdTe and CIGS cells, cadmium sulfide (CdS) is the n-type semiconductor in the highest efficiency version of CZTS cell. The efficiency of the CZTS cell has reached 12.6 percent (see Figure 4.1, where, like the other chalcogenide semiconductors, the CZTS cell is shown in green). The cell can be processed with high throughput via solution-based coating techniques, but precise manufacturing is difficult. The major challenges for further efficiency gains lie in better controlling the ratios of the constituent elements while the polycrystalline material grows and in constructing a heterojunction that increases the photovoltage. The similarity of cadmium use in CIGS and CZTS cells leads us to assign the CZTS cell the same -1 score for compatibility. The stability of the CZTS cell is a current concern and may ultimately remove this cell from contention as a commercial product. Even if this happens, the CZTS cell's role in solar cell research will have been important, because it is inspiring extensive efforts to explore chemical element substitution, with the objective of replacing specific scarce or toxic elements with more abundant or less hazardous ones.

Organic Photovoltaic Cells and Dye-sensitized Solar Cells

Scientists are also exploring solar cells based on thin-film organic (carbon-containing) molecular absorbers. Particularly effective at absorbing solar photons are “conjugated” organic molecules (molecules that contain alternating carbon-carbon single and double bonds). Two promising versions of this technology are organic photovoltaic cells (OPV cells) and dye-sensitized solar cells (DSSCs), both of which have achieved efficiencies of approximately 12 percent (see Figure 4.1, data points in purple). In both cases, the conversion of sunlight to electricity is a two-step process. When light falls on a molecular absorber, electrons and holes are not produced directly; rather, the molecular absorber’s internal energy is increased (the absorber is in an “excited” state). Much of the absorbed energy can then be transferred to a second, adjacent electronic material in which electrons and holes are produced. In combination, the two materials make the solar cell.

In OPV cells, both the organic absorber and the adjacent electronic material are organic, whereas in DSSCs the adjacent material is a metal oxide, often titanium dioxide, usually chemically bonded with the organic absorber. In OPV cells, the molecular absorbers are either polymers (containing many repeated chemical units, called monomers) or specific small organic molecules. In DSSCs, the molecular absorbers are more complicated organic molecules, incorporating a metal atom. The “abundance” score for OPV cells in Table 4.1 is +1 rather than +2, because the OPV cell uses a small amount of indium in one of its electrodes. As for the +1 score for the DSSC, it reflects the fact that currently the best DSSCs have the very rare element, ruthenium, at their core, but only a small amount of ruthenium is present (there is only one ruthenium atom per molecule). Moreover, it is likely that similar DSSCs without ruthenium will be developed, either fully organic dyes or ones that use fewer rare metal atoms.

In both OPV cells and DSSCs the band gap can be sensitively tuned by small changes in the chemical structure of the absorber, enabling devices built from these cells to absorb and emit only a small fraction of the incoming solar spectrum, thereby producing a specific color; the nearly infinite range of colors of flowers is evidence of the variety of selective organic molecular absorbers found in nature. A combination of such devices has created the colorful curtain wall at the SwissTech Convention Center (Figure 3.15). Other cells absorb incoming solar radiation only at ultraviolet wavelengths, or only at infrared wavelengths, or at both ultraviolet and infrared wavelengths but still not where light is visible to the eye. Such absorbers open up the possibility of use in window coatings that at the same time are totally transparent and a source of electrical energy; the harvested electricity could be used, for example, to change some property of the window glass, like its ability to transmit heat in summer vs. winter.

OPV cells can be made lightweight and flexible relatively easily. The combination of flexibility and color variability lead us to assign the highest score (+2) for versatility uniquely to the OPV cell in Table 4.1. DSSCs score only +1 on versatility, because the most efficient thin films of DSSCs must be kept rigid in order to encapsulate its liquid electrolyte. As for manufacturability, DSSCs get the lowest score, -2, for two reasons related to the requirement of rigidity. First, the preparation of the titanium dioxide layer requires a high-temperature process, which makes the DSSC incompatible with any lightweight and flexible substrate. Second, the encapsulation of the liquid electrolyte requires a pair of glass substrates.

Key issues that remain for both the OPV cell and the DSSC are long-term stability and fabrication at low cost with high throughput. For improved stability, the cells must be sealed to prevent air from contacting the organic absorbers, which are sensitive to photo-oxidation. Low-cost encapsulation will be critical for commercialization.

Quantum-dot Cells and Perovskite Cells

Two technologies are new entrants to frontier research on solar cells: quantum dot (QD) and perovskite cells. Both involve new materials, and as seen in Figure 4.1, neither has a data point before 2010. Quantum dots are nanometer-scale inorganic crystals, fabricated by deposition of inks, often using lead sulfide. QD cells have efficiencies of just over 10 percent (see Figure 4.1, where its data points are in green because a sulfide is a chalcogenide, and the other three solar cells shown in green also involve chalcogenides). We assign a score of -1 to the QD cell for public health compatibility because of lead’s toxicity; current research seeks a substitute for lead that does not compromise performance. The QD cell’s versatility results from the ability of the band gap to be tuned by varying the physical dimensions of the dot. We assign a score of +1 rather than +2 for abundance to both the QD and perovskite cells, because, like the OPV cell, indium is used in one electrode.

Perovskites are crystal structures, the most studied of which is methylammonium lead iodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$), which contains both an organic molecule and an inorganic metal halide and which can be processed at low temperatures from solutions to form highly crystalline layers. This perovskite has a direct band gap near the theoretical optimum for single-junction cells and can be produced with relatively few defects, even though deposition is at a relatively low temperature. Benefiting from the knowledge of thin-film solar cells gained over the last decades, the efficiency of perovskite solar cells has had a meteoric rise, from 3 percent in 2013 to 22 percent in 2016 (see Figure 4.1, where the perovskite data points are the only ones in orange, reflecting the distinctiveness of these materials).

The properties of perovskites addressed in Table 4.1 are still emerging, leading us to assign question marks to perovskites under “stability,” “manufacturability,” and “versatility.” We assign a -2 score for “compatibility,” because of the lead in current perovskites. Lead accounts for a large fraction of the perovskite’s weight, and the most efficient perovskites today, unlike the quantum dots, are soluble in water. Thus, the leaching of lead from the cell into the local environment is a real possibility, raising public health concerns and complicating the management of the cell over its lifecycle, from manufacture through disposal. Research is under way to render perovskites insoluble in water and to find alternative perovskites that do not use lead.

Multijunction cells

The eleven solar cells we have discussed here should not be thought of as alternatives because they can be used in combinations, creating multijunction cells. Indeed, the cells we have grouped as belonging to the “photovoltaic frontier” may turn out to be particularly useful when layered with “today’s technologies” cells. For example, much work is underway to create a “tandem” solar cell (a multijunction cell with just two components) that adds a thin-film perovskite cell to a crystalline solar cell. The result is a multijunction cell whose efficiency exceeds the efficiency of a crystalline silicon solar cell on its own: the perovskite layer and the crystalline silicon layer have different band gaps and thus function in combination to absorb more of the solar spectrum. The result is less wasted photon energy and less generation of heat. If such an enhanced crystalline silicon cell becomes commercially competitive, a future for solar electricity based on solar cells made without crystalline silicon would become even less likely.

Earlier, we reported that multijunction cells have been developed principally to enhance the efficiency of high-cost cells for applications where extra efficiency is worth a high premium. New kinds of tandem solar cells will alter this perspective, if it turns out that the performance (efficiency and durability) of the low-cost cells required for commercial electric power can be enhanced with tandem cells produced from inexpensive materials with inexpensive manufacturing.

D. Energy and Greenhouse Gas Performance Indices, End of Useful Life

In this section we consider three indices that are used to evaluate solar panels: 1) the energy to make a panel versus the energy it produces, 2) the analogous question for greenhouse gases instead of energy, and 3) the cost

of avoided greenhouse gas emissions. We conclude with a brief discussion of alternative strategies for managing solar power systems when they are no longer useful.

Energy and Greenhouse Gas Performance Indices

Energy Payback Period and Energy Return on Energy Invested

Consider the energy required to make a renewable energy system. Two common metrics are frequently used: *the energy payback period* and *the energy return on energy invested*. The energy payback period is the amount of time needed for the system to generate the amount of energy expended to make it. The energy return on energy invested, a closely related concept, incorporates an estimate of the expected operating life of the system; specifically, it is the energy produced throughout the life of the facility divided by the energy invested to make it. For example, if it takes 1,000 energy units to produce a solar-panel system, and the system produces 200 energy units each year for 20 years, *the payback period is five years and the energy return on energy invested is four*. Here, the energy to make something includes the energy to mine the elements and to transport components at various stages of production from place to place; in all, this is called the “embodied energy” of the device.

A recent meta-analysis of research published on the energy payback and energy returns for solar panels showed that the energy payback period for monocrystalline and polycrystalline panels is about four years.¹⁵ With the further assumption of a panel lifetime of 20 years, *the energy return on energy invested would be about five*. The energy-intensive step of creating crystalline silicon wafers from pure silicon feedstock dominates the front-end energy investment. By contrast, some new thin-film cells require far less energy to build and have *payback periods as short as one year*.¹⁶

If the energy return on energy invested is less than one (equivalently, if the energy payback period is longer than the lifetime of the system), the system never breaks even. Although panels are designed to last 20-30 years and to lose less than one percent of their conversion efficiency each year over that time period, the performance of a solar panel may fall short. For example, solar panels located in deserts can be degraded by windstorms carrying sand. Panel surfaces can also be fouled by dust and bird droppings. To limit the resulting damage, panels are routinely wired together in ways that assure the shading or fouling of one cell will not degrade the performance of the entire panel.

¹⁵New estimates suggest even shorter payback periods are now being achieved. <http://www.sciencedirect.com/science/article/pii/S1364032116306906>.

¹⁶<http://www.sciencedirect.com/science/article/pii/S136403211500146X>.

Greenhouse-gas Payback Period

Similar calculations can be done for the *greenhouse-gas payback period*. The greenhouse gas emissions required to make and install a solar collector system can be compared to the reductions in greenhouse gas emissions each year achieved by making electricity from the solar collector system instead of some other electricity source. These calculations are highly site-specific for two reasons. (For simplicity, we consider only carbon dioxide – the most important greenhouse gas, but not the only one.) First, the calculation depends on the greenhouse gas emissions associated with the energy expended to produce the device: the electrical heating of the silicon ingot (prior to the cutting of the wafers) may have used coal-based electricity or windpower, for example. Second, there can be big differences in the amount of greenhouse gas not produced because the solar energy source produced that energy instead: the solar source could have resulted in a reduction of electricity production from hydropower (with almost no greenhouse gas emissions) or from natural gas (with considerable greenhouse gas emissions).

Thus, greenhouse gas emissions appear in two ways in a calculation of the greenhouse gas payback period: emissions associated with 1) the energy required to produce the device, and 2) the energy displaced from the grid each year when the device is producing electricity. If the two emissions are equal (for the same amount of energy produced), the energy payback period and the greenhouse-gas payback period are identical; for our example, *the greenhouse-gas payback period would be four years*. But if a device is produced in China, where the grid is dominated by coal, and then used in California where the grid is much less carbon-intensive, the greenhouse payback period might be twice as long as the energy payback period.¹⁷

A full estimate of greenhouse-gas intensity must include not only emissions related to energy flows but also emissions relative to chemical treatment. For example, nitrogen trifluoride (NF₃), a particularly potent greenhouse gas, is used currently to etch openings into the coatings of the silicon wafer to enable electrical contact.

Cost of Avoided Emissions of Greenhouse Gasses

A related index, for solar power and other technologies that reduce greenhouse gas emissions, is the cost of avoided emissions per ton of reduced greenhouse gasses. To illustrate this calculation, consider a large utility facility whose construction cost is \$1 per peak

watt. Also assume that the capacity factor is 20 percent (about 1,750 hours per year), so that 1.75 kilowatt-hours of electricity are produced each year for each dollar spent. One must also decide how many years the facility will operate; If it operates for 20 years (clearly, a critical assumption), it will produce 35 kilowatt-hours of electricity. The carbon intensity of the power that it displaces must be specified: assume 500 grams of carbon dioxide emissions for each kilowatt-hour produced (an average value, and about twice as much where electricity is produced from coal), so 17.5 kilograms of carbon dioxide emissions will be avoided. In the usual units for this topic, the cost of emissions reduction is then *about \$60 per ton of carbon dioxide*. (Among the issues ignored here are costs associated with operation and maintenance during the life of the plant, as well as emissions associated with construction, as discussed above.) These costs are somewhat higher than the “social cost of carbon” introduced by the Obama Administration and currently being set aside by the Trump Administration.

End of Useful Life

The infrastructure for the management of solar cells at the end of their useful life scarcely exists, but it will become important. Reduce-reuse-recycle is a well-known hierarchy. Reducing the amount of material requiring handling comes along with improvements in a solar cell’s conversion efficiency, since much of the bulk of a solar device is in its balance of system, and less balance of system is required for the same power output when the system is more efficient.

Reusing the balance of system after treatment is easy to imagine, but even the cell may be designed for reuse.

As for recycling, whether the valuable materials in a solar cell will be recycled is not clear. They often represent only a small fraction of the total weight of the device. Yet platinum is so valuable that it is often retrieved from the catalytic converters of junked cars. The recycling of cadmium and tellurium retrieved from CdTe cells, which would be analogous, got off to a halting start when the largest manufacturer of CdTe panels first announced that it was embedding the cost of recycling in the panel cost, but then decided to defer the recycling cost.

Finally, disposal. The two principal managed destinations today are the landfill and the incinerator, each of which can be state-of-the-art, with hazardous materials well contained.

¹⁷A careful definition of the greenhouse gas emissions associated with electricity produced in some particular political region requires taking into account not only production within the region, but also imports of electricity into the region and exports from it. Strictly speaking, for an intermittent resource like solar power, one should also identify the hours of the year when the system displaces other power sources and consider greenhouse gas emissions only for those hours. Moreover, one should identify the marginal, rather than the average, power source that will be added to the grid in order to manufacture the panels and the specific source that will be taken off the grid when the panels produce power.