

Article 3. From the Sun to the Solar Project

In this article we first describe sunlight and how it falls on the earth. We then provide a high-level view (global, national, and by U.S. state) of the rate of production of solar electricity and its remarkable growth in recent years. We conclude with observations about distributed generation and other issues at the project level.

A discussion of solar projects follows, where we develop information relevant to the intriguing question of whether the mix of large and small projects characterizing current solar power will be sustained in the future. We introduce a three-part categorization of solar projects (“utility,” “mid-scale,” and “residential”). We emphasize the importance of the little-discussed mid-scale: the projects that are built on the rooftops of commercial buildings and on land owned by public and private institutions, not owned by utilities but much larger than projects on the roofs of homes. We also discuss “distributed generation” (both mid-scale and residential projects), which may conceivably become the basis of a restructuring of the current centralized utility.

We conclude Article 3 with a discussion of the “balance of system,” which is every aspect of a project other than the high-tech panel. Costs for typical projects are disaggregated to highlight the balance of system, whose cost is now at least as important as the cost of the panel. The underlying question is the extent to which “balance-of-system” costs can continue to fall in the future. The article concludes with a description of some imaginative uses of solar collectors in buildings, where the production of electricity is a side objective.

A. The Sun and the Earth

Sunlight Above the Earth

The solar energy that can be made useful to people in the form of electricity is a tiny fraction of the solar energy that the Sun produces and radiates to space. The Sun emits energy at a rate of 400 billion quadrillion (4×10^{26}) watts, uniformly and in all directions. This rate varies by about one-tenth of one percent from year to year, depending upon the number of sunspots on the Sun’s surface.

The Earth intercepts a tiny fraction of this energy: 170 quadrillion (1.7×10^{17}) watts, or about one half of one billionth of the energy emitted by the Sun. The power for space satellites exploring distant parts of our solar system is produced with solar panels that intercept sunlight which would not have hit the Earth, but with this exception only the solar energy that the Earth intercepts

is available today to power our civilization. Perhaps, someday, human beings will build structures in the solar system to harvest sunlight emitted in other directions.

It should be noted that Earth’s orbit around the Sun is not a perfect circle, so the amount of usable solar energy varies over the course of the year as the distance between the Earth and the Sun grows and shrinks. Sunlight is about 7 percent stronger when the Earth is closest to the Sun (at the beginning of January) than when it is furthest from the Sun (at the beginning of July).

Sunlight on the Earth’s Surface

The intensity of the Sun’s energy is about 30 percent greater at the top of the atmosphere, but various gases and aerosols reduce the intensity by absorbing sunlight as it travels through the atmosphere toward the Earth’s surface. Where the Earth’s surface is flat on a clear day at sea level, with the Sun directly overhead, the average intensity of direct sunlight is about 1,000 watts per square meter.

As shown in Figure 3.1, the average annual intensity of sunlight varies by location. The highest intensities are found in most of Africa, the Middle East, and Australia, as well as the southwestern U.S. and Mexico. The values mapped in Figure 3.1 include both sunlight that comes from the direction of the Sun and sunlight coming from other directions, known as diffuse sunlight. On a sunny day, levels of pollution, dust, and humidity determine the ratio of the direct to the diffuse components of incident solar radiation; averaged over a sunny day in a low-pollution environment with the Sun high in the sky, the energy arriving at a flat panel from diffuse light is about 20 percent of the total. On a fully cloudy day, a horizontal solar panel will collect two to five times less energy over a day than on a sunny day. On a partly cloudy day, the amount of sunlight incident on a solar panel can fluctuate by a factor of five or more over the course of minutes as a cloud passes between the Sun and the panel. This short-term variability is one of the key challenges to scaling up the deployment of solar power.

GLOBAL HORIZONTAL IRRADIATION

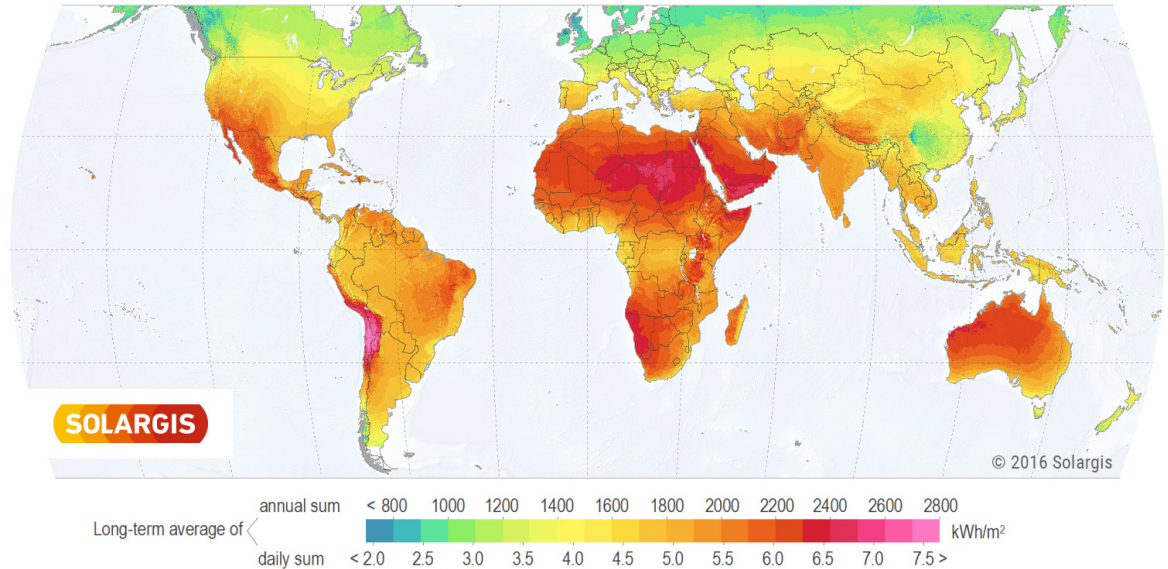


Figure 3.1: Annually averaged “irradiation” incident on a horizontal surface (the sum of direct and diffuse sunlight arriving over a period of time, presented here for an average day). The upper and lower horizontal scales are the annual and daily sums, respectively, in units of kilowatt-hours per square meter (kWh/M²) of surface area. Source: <https://www.solargis.com>

In Figure 3.1, the strength of average incident sunlight is measured in kilowatt-hours per square meter of horizontal surface per year (upper scale) and per day (lower scale). In particular, the lower scale runs from just below 2.4 kilowatt-hours per square meter to just above 7.2 kilowatt-hours per square meter. This scale is the one that the solar industry uses most frequently in quantifying the solar resource.

Dividing the numbers on the lower scale by 24 produces average power measured in kilowatt-hours per square meter per hour, which is the same as kilowatts per square meter. Thus, the average strength of sunlight ranges from just below 100 watts per square meter to just above 300 watts per square meter (square meter of *horizontal surface*). This range in the strength of incident sunlight can also be expressed as 10 to 30 percent of the peak rate, 1,000 watts per square meter, at which sunlight can be collected at the Earth’s surface (clear day at mid-day, with the collector aligned perpendicular to the Sun’s rays).

Yet another way to express the amount of sunlight that falls on a horizontal surface over a year at some location is in terms of the number of hours required to collect that much energy at that location from hypothetical panels collecting sunlight at its peak incident rate. Where the strength of incident sunlight is 20 percent of the peak rate, these panels would need to operate 20 percent of the year, and since there are 8,766 hours in an average year, they would need to operate about 1,750 hours per year. In these units, annual incident sunlight on a horizontal surface at specific locations on the globe varies from less than 1,000 hours per year to as much as 2,500 hours per year of peak sunlight.

The Solar Spectrum

Sunlight is a mixture of light of many colors; the mixture forms a spectrum. Figure 3.2 shows the spectrum of incident sunlight both at the top of the atmosphere and at the Earth’s surface. The spectrum is conventionally divided into three regions, with “visible” light in the middle (here, violet on the left and red on the right), ultraviolet (more violet than the eye can see) on one side and infrared (more red than the eye can see) on the other.

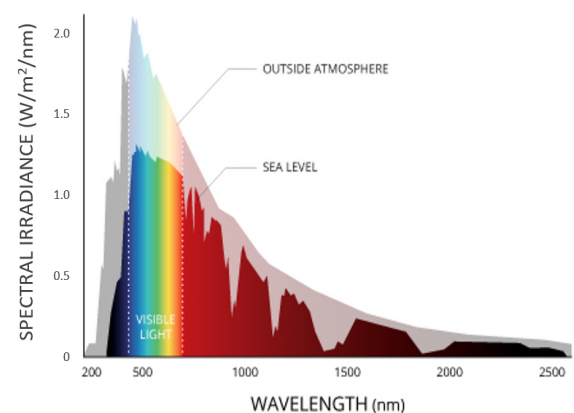


Figure 3.2: Distribution of incoming solar energy across the spectrum at the top of the atmosphere and at ground level. “nm” is nanometer, one billionth of a meter. Source: <http://www.fondriest.com/environmental-measurements/parameters/weather/photosynthetically-active-radiation/>.

The strength of incident sunlight is reduced throughout the spectrum, but unevenly. On its way through the atmosphere, much of the ultraviolet radiation is absorbed

(by ozone and oxygen). Similarly, much of the infrared radiation is absorbed (especially by water vapor), resulting in most of the notches in the curve for ground-level solar energy at the right in Figure 3.2. At the Earth's surface, about 42 percent of direct sunlight is visible light, approximately 4 percent is ultraviolet, and the remaining 54 percent is in the infrared region.

Sunlight can be thought of as a collection of individual particles (photons), each carrying a specific amount of energy. The energy of a photon depends on the color of the light. Ultraviolet light is the most energetic, then visible, then infrared; within the visible spectrum, blue is more energetic than red. In the world of solar cells, a photochemical process typically requires some minimum amount of photon energy; thus, blue light can drive some processes that red light cannot.

The Path of the Sun through the Sky over a Year

The angle between the Sun and a solar panel determines how much power the panel can generate. The angle is easiest to understand at solar noon, when, every day of the year, the Sun is either directly to the south or directly to the north. The noon positions of the Sun are shown schematically in Figure 3.3 for a summer day and a winter day at a latitude typical of China and the U.S.

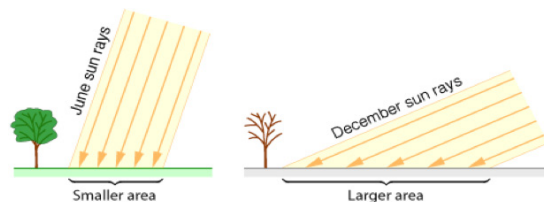


Figure 3.3: The angle of the Sun with the vertical at solar noon is displayed for a mid-latitude location in the northern hemisphere. Source: <http://physics.weber.edu/schroeder/ua/SunAndSeasons.html>

Figure 3.4 augments Figure 3.3 by showing four moments along the trajectory of the Earth around the Sun. At solar noon on March 21 and September 21, the Sun is to the south everywhere in the northern hemisphere. The angle between a line to the Sun and a vertical line is the same as the latitude at that location. For example, at the equator, where the latitude is zero, the Sun is straight overhead.

Relative to its position at solar noon on March 21 and September 21, the Sun at solar noon is further north throughout the period between March 21 and September 21 and further south between September 21 and March 21. On June 21 (the summer solstice and the longest day of the year) at solar noon, it is

furthest north, 23.5 degrees further north than its location on September 21 and March 21. A person's shadow is shorter at solar noon on June 21 than at any other time of the year. On December 21 (the winter solstice and shortest day of the year) at solar noon, it is furthest south, again by the same 23.5 degrees relative to its position on September 21 and March 21. The 23.5 degrees angle is the tilt of the axis of the Earth's rotation, relative to the plane that contains the Earth's path around the Sun.

B. The Scale of Current Solar Power

The sunlight that strikes Earth in one hour carries more energy than is required to power human civilization for an entire year. This frequently encountered statement accounts for the energy consumed by power plants, vehicles, furnaces, boilers, and other facilities (in aggregate, "primary energy"), but excludes the sunlight required to grow food, to evaporate water so that we receive rain, and to enable other "ecosystem services."

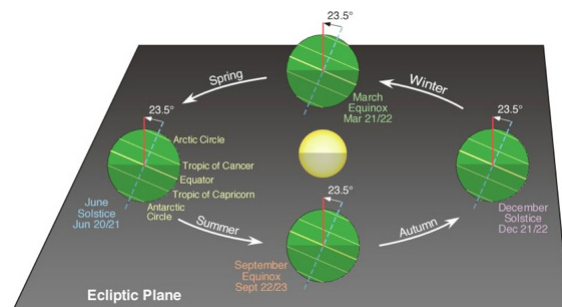


Figure 3.4: The Earth's position relative to the Sun on four key days of the year. Source: <http://www.physicalgeography.net/fundamentals/6h.html>

Electricity Production from All Sources

Of the total primary energy used by humans, about 40 percent is used to produce electricity. The rest is used directly by industry, vehicles, and buildings. Currently, the total capacity of the world's electric power plants of all kinds is approximately six billion kilowatts, and the world's annual electricity consumption is approximately 25,000 billion kilowatt-hours. Since there are 8,766 hours in an average year, the world's power plants would have produced approximately 50,000 billion kilowatt hours (6 times 8,766, rounding off) if the plants had run steadily at full capacity all year. We conclude that the world's power plants produce, on average, about half of the output that they could produce if they ran continuously at peak capacity. For any single power plant or group of plants, the "capacity factor" is the ratio of the actual production divided by the hypothetical production at peak capacity. Thus, the capacity factor of the world's power plants is currently about 50 percent (25,000 divided by 50,000).

Global Solar Electricity Production

At the end of 2016, the amount of solar photovoltaic (PV) power installed worldwide was 300 million peak kilowatts, 5 percent of the total capacity of the world's power plants of all kinds. Solar output is not as well documented as solar capacity, but if the capacity factor for global solar electricity production was 14 percent in 2016, as it was in 2014,⁶ global solar electricity consumption in 2016 would have been about 360 billion kilowatt-hours of electricity, or about 1.5 percent of that year's total electricity from all sources.

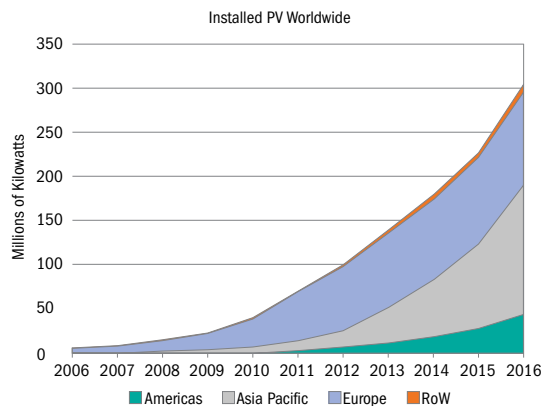


Figure 3.5: Installed generation capacity of solar photovoltaic (PV) production facilities, by world region, 2006-2016. 1 gigawatt = 1000 megawatts = 1,000,000 kilowatts. RoW is the rest of the world. Source: International Energy Agency, Photovoltaic Power Systems Program, IEA PVPS Snapshot 2017: <http://iea-pvps.org/index.php?id=trends0>.

Figure 3.5 shows the growth of global solar power plant capacity from 2006 to 2016 and its distribution over broad geographical regions. Deployment in Europe dominated global expansion initially: since 2010 the annual growth rate in the Asia-Pacific region has been larger than in Europe, and the absolute increment over the previous year has been larger in the Asia-Pacific region since 2013. In 2016 the Asia Pacific region accounted for two-thirds of the growth in global capacity. Relatively, the Americas have been small players.

Deployment by Country

Figure 3.6 shows the solar capacity in place, by country, in 2016. More than half of the capacity is located in just four countries: China, Germany, Japan, and the U.S. During the year 2016, China installed about half of the world's total added capacity, as total global capacity grew by one third. In 2016 China and the U.S. added about 80 percent and about 60 percent to their 2015 solar capacity, respectively, with the result that China ended 2016 with about twice as much installed solar capacity as the U.S., which has about the same total capacity as Germany and Japan. Germany has the most installed capacity per capita of the nations with large deployment: about 0.5 kilowatt per capita.

The U.S. was estimated to produce about 56 billion kilowatt-hours of solar electricity in 2016, out of roughly 4,000 billion kilowatt hours of electricity from all sources. For Greece, Italy, and Germany, solar electricity production accounted for about 7 percent of national electricity production from all sources.

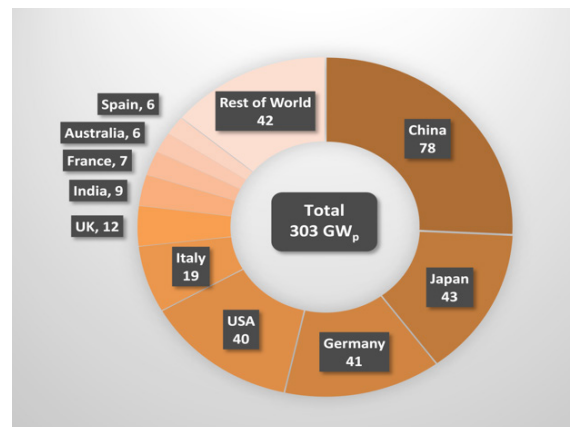


Figure 3.6: Cumulative installed solar PV capacity, in peak-gigawatts, for the ten countries having more than five peak-gigawatts (GW_p) of capacity by the end of 2016. 1 gigawatt = 1000 megawatts = 1,000,000 kilowatts. Data: International Energy Agency, Photovoltaic Power Systems Program, IEA PVPS Snapshot 2017: <http://iea-pvps.org/index.php?id=trends0>.

⁶<https://www.worldenergy.org/wp-content/uploads/2016/09/Variable-Renewable-Energy-Sources-Integration-in-Electricity-Systems-2016-How-to-get-it-right-Executive-Summary.pdf>, table on p. 2, cited also in Footnote 3.

Deployment by U.S. State

Figure 3.7 breaks down the installed solar PV capacity in the U.S. by the state in which it is installed. California is responsible for nearly half of current installed capacity. That North Carolina is in second position, New Jersey in fifth, and Massachusetts in seventh – despite being neither especially large nor especially sunny – is a reflection of consistent state-level policy support.

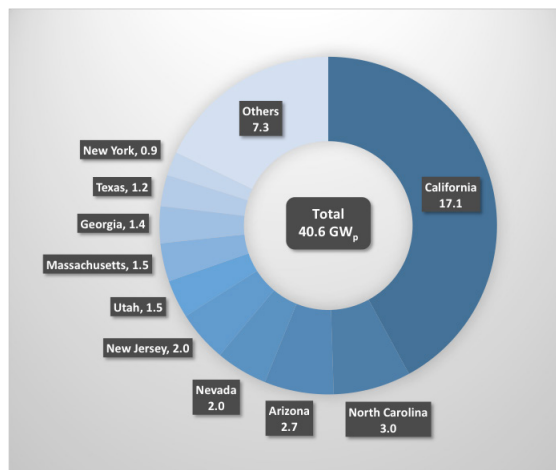


Figure 3.7: Cumulative installed solar PV capacity at the end of 2016 by U.S. state, in peak-gigawatts (GW_p). 1 gigawatt = 1,000 megawatts = 1,000,000 kilowatts. Data: Solar Energy Industry Association, <http://www.seia.org>.

Land Required to Produce Electricity from Sunlight

The route from sunlight to electricity using solar cells can be compared to another route, the “biopower” route, where sunlight enables the growth of vegetation (crops, grasses, trees), which is then harvested and converted into electricity. The land demand to convert sunlight to electricity directly with solar cells is far less than the land demand for the “biopower” route. On the other hand, competition for land is often fierce, and solar power requires dedicated land, while biopower is compatible with simultaneous use for other purposes. Dedicated land for solar power can conflict with urban green space and, on a larger scale, with demand for national parks and wilderness.

Solar power requires less land than biopower because the efficiency of conversion of sunlight to commercial energy is so much higher for solar power. A reference efficiency for solar panels today is 20 percent. A conversion efficiency of even 1 percent represents an

extremely high yield for biomass, relative to actual yields in crops and forests. The two conversion efficiencies – 20 percent for a representative solar panel and less than 1 percent for biomass – mean that biomass requires at least 20 times more land as solar panels to produce the same amount of energy. (The comparison is simplistic, to be sure, since biomass requires further processing to be useful, but on the other hand biomass not only collects solar energy but also stores it for use at a later time.) The significantly smaller land requirements for solar energy production are a fundamental reason why solar electricity has the potential to transform the global energy system.

It is instructive to calculate how much land fully devoted to PV solar power would be required to meet the entire electricity demand of a specific geographical region. For simplicity, we ignore solar collection on the roofs of residential and commercial buildings and work out the amount of land required to meet total U.S. electricity demand from horizontal stationary solar panels sited near Phoenix, Arizona. The amount of electricity consumed in the U.S. in 2015 was about 4,000 billion kilowatt-hours. Solar energy falls on Phoenix at an average rate of approximately 6.5 kilowatt-hours per square meter of land per day, or 2,400 kilowatt-hours per square meter of land per year (see Figure 3.1). Thus, 480 kilowatt-hours would be produced each year from each square meter of stationary horizontal power in Phoenix, assuming 20-percent efficiency panels. Dividing 4,000 billion kilowatt hours by 480 kilowatt-hours per square meter, 8.3 billion square meters (8,300 square kilometers, or 3,200 square miles) of panels near Phoenix could collect this much energy.

We could double this area to take into account gaps between the rows and to include supporting infrastructure beyond the site. The result, 6,400 square miles (about 1/600th of the area of the U.S.), is roughly the size of metropolitan Phoenix and is compared with



Figure 3.8: The area of land outside Phoenix, AZ, about 6,400 square miles, required to generate the entire U.S. electricity demand if fully devoted to solar power, is shown in position on a map of the U.S. and in an inset as a rectangle adjacent to the city boundaries of Phoenix. (For assumptions, see text.) The red rectangle, shown to scale in this inset, is expanded in a second inset to reveal the land required for the Topaz Solar Farm in San Luis Obispo County, California.

Phoenix on a map in Figure 3.8. Additional dedicated land would be required for energy storage facilities and transmission corridors. Note that if the solar cell efficiency were 25 percent instead of the assumed 20 percent, all of these area calculations would be reduced by one-fifth. For example, our estimate of 6,400 square miles would become 5,100 square miles.

For comparison, Figure 3.8 also shows the 550-megawatt Topaz Solar Farm in San Luis Obispo County, California, one of the largest solar farms in the U.S., which went on line in 2014.

The calculated land area meets the *current* demand for electricity, but not the additional demand that would be required if the U.S. economy were completely electrified – where cars run on batteries, houses are electrically heated, and all industrial processes are powered by electricity. Currently, about 40 percent of U.S. primary energy is used for electricity; thus, as a very rough estimate, the required land area to power a totally electrified U.S. economy might be 2.5 times the area calculated in Figure 3.8. This figure would be approximately 16,000 square miles, which is roughly the size of Maryland.

C. Solar Energy Projects

Utility, Mid-scale, and Residential Projects

Commercial solar power is arriving at all sizes at once. The usual distinction for solar projects is between 1) *utility* projects that deliver power directly to a utility (sometimes called projects “in front of the meter”), and 2) *distributed generation* projects (“behind the meter”), where a portion of the produced electricity is consumed on site.

We have found it useful to divide distributed generation group into residential projects (a billing category widely used by the industry) and *mid-scale* projects, which are all distributed-generation projects that are not residential projects. Mid-scale projects are almost always larger than residential installations but smaller than utility arrays. *Commercial* projects (another billing category) are included in the mid-scale category: these are the projects on rooftops of warehouses and on other private property. Also in the mid-scale category are the many installations on public land, including those on or around schools, hospitals, parks, municipal centers, and parking structures.

Residential and utility projects have recognizable archetypes, seen in Figure 3.9: a residential installation

of rooftop panels (left) and a project comprising fields of panels delivering power directly to utilities (right). Mid-scale projects, like Princeton University’s project (bottom), by contrast, are rarely included in the visual imagery of solar power.



Photo by Tom Grimes.

Figure 3.9: A representative residential PV installation (upper left, 10 kilowatts, estimated), Solarpark Meuro, the largest installation in Germany (upper right), more than 150,000 kilowatts, not all shown), and the Princeton University mid-scale project (bottom, 5,400 kilowatts). Source: <https://www.habdank-pv.com/en/portfolio-item/soft-soil>.

Solar PV Projects in New Jersey

Mid-scale projects dominate the deployment of solar energy in New Jersey. They account for 58 percent of New Jersey’s solar capacity, even though they account for only about one tenth of all projects. Utility projects account for 23 percent of capacity, and residential projects account for the remaining 19 percent (even though residential projects constitute almost nine tenths of all projects). These findings come from a database of nearly all of New Jersey’s solar PV projects, maintained by the New Jersey Board of Public Utilities.⁷ The data are displayed in Figure 3.10 and further reported in Table 3.1. Projects smaller than 10 kilowatts contribute roughly one-fifth of the total capacity, those between 10 kilowatts and 1,000 kilowatts add another two-fifths, and those larger than 1,000 kilowatts contribute the remaining two-fifths. Half of New Jersey’s solar PV projects have a capacity below 8 kilowatts.

Even New Jersey’s largest projects are far smaller than the largest utility solar projects found in the southwestern U.S. The largest single project in the New Jersey database is a 19.9-megawatt utility project, whereas in 2016 there were six solar projects in the U.S. whose capacity exceeded 300 megawatts – three in California, two in Nevada, and one in Arizona.⁸

⁷The Board of Public Utilities database catalogs all projects eligible to receive New Jersey’s solar renewable energy credits (SRECs). As of February 29, 2016, the database included more than 40,000 projects totaling more than 1,600 megawatts of generating capacity.

⁸Globally, there are 14 projects whose capacity exceeded 300 megawatts. Two of the world’s three largest solar projects are in India and the third is in China. See https://en.wikipedia.org/wiki/List_of_photovoltaic_power_stations.

	Residential	Mid-Scale	Utility	Total
Number of Projects	38,859	4,827	136	43,822
Percent of all Projects	88.7	11.0	0.3	100
Capacity (Megawatts)	314	952	377	1,643
Percent of All Projects	19	58	23	100
Median (Kilowatts)	7	50	1,246	8
Mean (Kilowatts)	8	197	2,772	37

Table 3.1: Summary statistics for all solar projects in New Jersey. “Residential” and “Utility” are categories used in the database; utility projects provide power directly to a utility. “Mid-scale” groups together all other categories. Source: New Jersey Board of Public Utilities, <http://www.njcleanenergy.com/renewable-energy/project-activity-reports/project-activity-reports>.

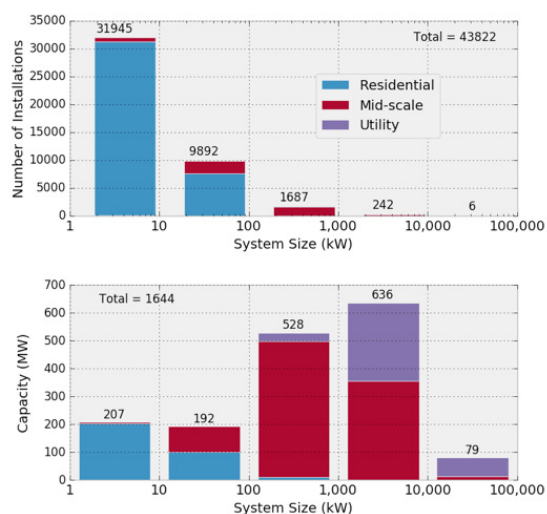


Figure 3.10. Contributions to the total solar generating capacity of New Jersey, as of February 29, 2016, binned by size (capacity). The more than 40,000 installations (top panel) overwhelmingly have a capacity less than 10 kilowatts, but the roughly 1.6 million kilowatts of total capacity (bottom panel) is dominated by large facilities. Numbers above each bar are totals for that bar; totals are in thousands of kilowatts (megawatts) in the bottom panel. Bars and segments of bars are colored to sort projects into our three categories. Source: New Jersey Board of Public Utilities, <http://www.njcleanenergy.com/renewable-energy/project-activity-reports/project-activity-reports>. Data as of February 29, 2016.

D. Distributed Generation

Large solar plants, like those in the deserts of the southwestern U.S., fit nicely with century-long trends: the size of the individual power plant of all kinds has increased steadily, as has the distance between the site of power production and the site of electricity use. By contrast, residential and mid-scale solar power production reverses historical patterns. A household can meet its annual power requirements from a collector on the roof and trade power with its utility, buying or selling depending on whether household demand exceeds or is less than the collector’s supply. Several households can link themselves together and locate their collector in a nearby field, creating a solar power system with its own microgrid. Private companies and public institutions of all kinds can do the same. In each case, a specialized business can own the collectors and rent them to the households and companies, achieving economies of scale. And in each case, the project can be augmented by electricity storage: add enough batteries and any of these entities can disconnect from the grid entirely. This is the new world of “distributed generation” of solar power.

“Distributed generation” is a general concept. It describes not only dispersed solar production facilities but also dispersed electricity production from other energy sources, notably dispersed production of electricity from natural-gas. In principle, distributed generation can take over the entire electricity system, displacing central station power entirely. More credible is a future grid that combines large amounts of both distributed power and centralized power. Such a grid can be more resilient and flexible than a grid consisting only of large power plants, especially if the sites for

distributed components are chosen so as to reduce congestion and relieve bottlenecks in transmission of bulk power. Distributed generation also provides back-up power when natural disasters or hacking produce widespread outages at centralized facilities.

A major constraint on the expansion of such a mixed system becomes the grid itself, which must be developed in new ways. The grid must continue to provide reliable electricity service; electric utilities often affirm that reliability is their most important objective. The entire infrastructure needs to remain reliable, including the distribution system of power lines running down every street, even as new sources of electricity are introduced at the outermost branches of the distribution system, leading to two-way flows of electric current on lines that were designed for one-way flow. When a decentralized generator fails, the grid must provide an alternative.

Distributed electricity storage is key to the future of distributed energy. The first solar power projects in homes and on farms came with banks of batteries, enabling a user to become completely independent of any grid, but these early systems were largely supplanted when grid connection was offered on favorable terms. Now, once again, distributed solar electricity storage is being offered in combination with distributed power generation, and the two are being tied to each other and to the grid by “smart” information sharing. Down this road, decentralized solar power becomes dispatchable, back-up by the grid becomes less demanding, and back-up of the grid becomes more credible.

Community Solar Power

Constituting a new class of mid-scale projects are “community solar” projects (also called “shared solar,” “solar gardens,” and “community distributed generation”). The objective of a community solar project is to expand solar energy access to renters, homeowners with unsuitable roofs, low-income and moderate-income consumers, and others who cannot otherwise “go solar.” A community solar project could be organized by a solar company, a local organization, or some other entity; its participants are “subscribers” who purchase fractions of the project’s installed capacity or fractions of its electricity production. The project’s solar power need not be produced on the premises of any of the subscribers, and it need not be delivered to the subscribers.

States with community solar programs require utilities to credit all participants for the solar power their portion of the project produces, lowering their monthly utility bills. Unused credits typically roll over to the following month, but in some states credits expire at the end of the calendar year. Colorado, Massachusetts, Minnesota, and New York have been pioneers in the development of community solar projects. They and eleven other states, as well as Washington, D.C., have enacted policies authorizing community solar programs.⁹

E. Balance of System

A PV system is much more than just solar panels. We use the term “balance of system” to refer to everything related to a solar project *other* than the panels – both non-panel hardware and so-called “soft costs.”¹⁰ Non-panel hardware includes panel mounts, transformers, wiring, enclosures, and the inverters which convert electricity from direct current (DC) to alternating current (AC). Soft costs include the costs associated with land, customer acquisition, financing, permitting, property taxes, installation labor, and installer profit. Balance of system costs do not include costs for integrating a project into an electricity grid, such as associated electricity storage or back-up power; grid-integration costs are treated extensively in Article 5.

Both the PV panel and the balance of systems have become steadily less expensive, as seen in Figure 3.11, which shows representative costs for 2009 through 2016 for residential, commercial, and utility installations, for projects modeled by the National Renewable Energy Laboratory. (The “commercial” category is roughly equivalent to our Distillate’s “mid-scale” category.) Panel costs, which are presumed to be the same for the three kinds of projects, are about three times more expensive at the beginning of the period than at the end. Balance-of-system costs also fall, although not as dramatically.

Also seen in the most recent bars in Figure 3.11, balance-of-system costs now dominate total costs for residential and commercial projects and account for about half of total costs for utility projects. And within balance-of-system costs, soft costs have become the major component of balance-of-system costs, especially for smaller projects. Figure 3.12 elaborates this argument with an independent estimate of balance-of-system costs, where 36 percent are hardware costs and 64 percent are soft costs, and the soft costs are distributed into nine categories, none of them

⁹<http://www.communitysolaraccess.org/wp-content/uploads/2016/03/CCSA-Policy-Decision-Matrix-Final-11-15-2016.pdf>.

¹⁰An alternative use of the phrase, “balance of system,” restricts its meaning to non-panel hardware.

dominant. One of the reasons that the hardware component of the balance-of-system cost has fallen, when measured in dollars per peak-watt of capacity (the unit used in Figure 3.11), is that solar cells have become more efficient. Less balance-of-system hardware is required for the same amount of electricity produced, even when the exactly the same hardware is used to mount and connect the panel.

Soft costs are being steadily reduced. Strategies internal to the solar industry to reduce these costs include standardization of hardware, workforce training, and financial risk management. Local governments are also contributing, to the extent that they modify local land use and zoning policies to encourage (or at least not inhibit) solar projects and simplify the acquisition of construction permits.

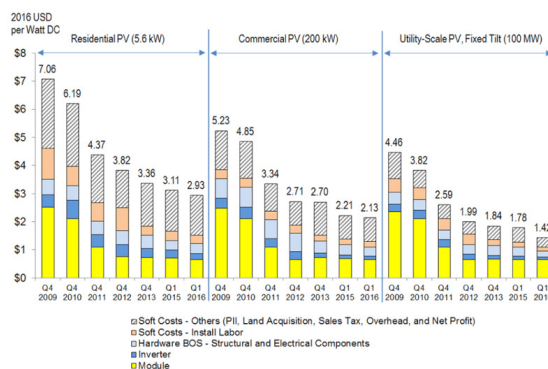


Figure 3.11: Costs for representative residential, commercial, and utility solar projects modeled by the National Renewable Energy Lab (NREL). Q1 and Q4 are a year's first and fourth quarters, respectively. PII is "Permitting, Inspection, and Interconnection." BOS is "Balance of System." Source: NREL, "NREL report shows U.S. solar photovoltaic costs continuing to fall in 2016." <http://www.nrel.gov/news/press/2016/37745>.

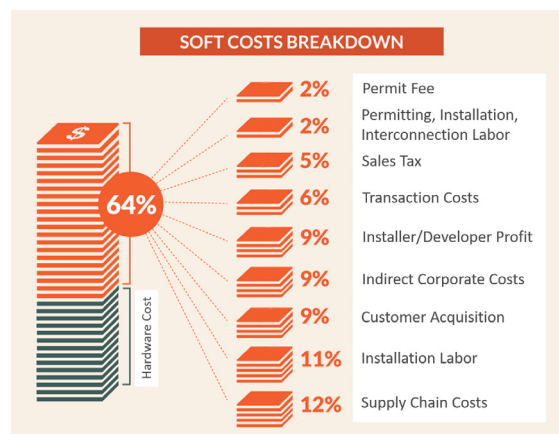


Figure 3.12: A representative distribution of the "soft-cost" component of balance-of-system costs. Source: U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy: <http://energy.gov/eere/sunshot/soft-costs>

Fixed Panels versus Tracking Panels

There are two strategies for collecting sunlight on a flat panel. The panel can be placed on a rigid mount, or it can be placed on a movable tilted frame. Many fixed panels lie flat on the roofs of buildings, their orientation and tilt dictated by the roof's orientation. Other fixed panels are mounted on the ground, in which case the orientation and tilt can usually be freely chosen. In the northern hemisphere a typical ground-mounted fixed panel will be tilted so that its north edge is higher than its south edge and will be oriented due south, thereby benefiting more from the path of the Sun through the sky than if the panel were lying flat.

The strategy of moving a panel during the day is called "tracking," because the panel tracks the Sun's path through the sky. Tracking adds initial costs and maintenance costs, but tracking results in greater amounts of solar energy striking the panel. The most expensive tracking, "double-axis tracking," maximizes solar collection by keeping panels perpendicular to the Sun throughout the day, every day of the year. This strategy requires the mount to be able to rotate around two axes, so as to change both its east-west orientation and its tilt relative to the horizon.

More common is "single-axis tracking," where the panel rotates around a fixed axis that has a single orientation throughout the year. The axis of rotation for single-axis tracking is usually horizontal, resulting in a panel that moves like a seesaw and is horizontal at noon. The axis can also be vertical, resulting in a panel that is vertical and (in the northern hemisphere) faces due south at noon. Still a third option is for the axis to be oriented at an angle between horizontal and vertical.

Moving clockwise from the top-left, the three photos in Figure 3.13 show panels mounted with a fixed tilt, two-axis tracking, and one-axis tracking. The orientation of the axis of the single-axis tracking system is north-south at a small angle relative to horizontal, resulting in panels that at noon face south at that same angle.

The cost of land can be a determining factor in choosing between fixed panels and tracking panels. In general, tracking panels require extra land (for the same amount of solar power capacity) relative to fixed-axis panels, because tracking panels cast larger shadows. Expensive land can drive the choice toward fixed panels over tracking panels or toward tracking panels placed closer together (accepting more shadowing).

Costs Related to Voltage and Current

Even when residential, mid-scale, and utility installations utilize the same PV panels, the optimal designs for the management of the electricity output can be very different. Panels on the roof of a residence are easily



Figure 3.13 Panels in a fixed array at Eastern Mennonite University, Harrisonburg, Virginia (top left); with double-axis tracking in Toledo, Spain (top right); and with single-axis tracking in Xitieshan, China (bottom). Sources: Top left: https://upload.wikimedia.org/wikipedia/commons/c/c5/Eastern_Mennonite_University_Solar_Array.jpg Top right: <https://upload.wikimedia.org/wikipedia/commons/8/8f/Seguidor2ejes.jpg> Bottom: By Vinaykumar8687 - Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=35401850>.

linked together at low voltage to feed power either to the building, or, when the panels produce excess power, back through the residential meter to the utility's low-voltage distribution system. By contrast, utility-scale solar arrays are stepped up to high grid voltages in order to use the utility's mid-voltage and high-voltage transmission lines.

As for mid-scale projects, grid connection presents more individualized challenges. One general observation is that any project exceeding 100 kilowatts of capacity requires a significant investment in inverters to convert the DC power produced by the modules to the AC power required by the grid. The cost of these inverters has not fallen as quickly as the cost of modules.

F. Building-integrated Photovoltaics

Balance-of-system costs can become opportunities for systems design. In the building sector, roof and façade not only can support attached solar panels, but can actually be *constructed* of solar panels—an approach known as “building-integrated PV.” While a number of companies have integrated solar modules into roof shingles, Tesla’s “solar roof” recently popularized the technology (see Figure 3.14, where two other examples of structural PV are also shown).

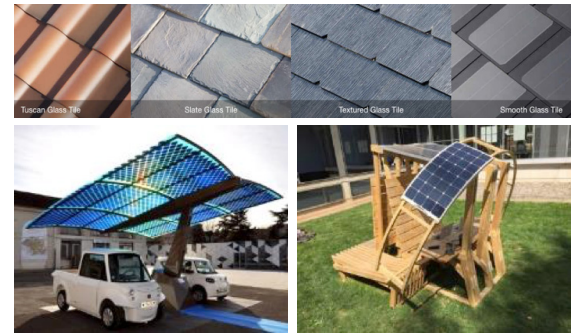


Figure 3.14: Examples of building-integrated solar PV. Top: Tesla’s “solar roof” offerings. Lower left: A car shade made of PV collectors. Lower right: A solar umbrella that tracks the Sun so that the table’s surface is always shaded. Sources: www.tesla.com/solar (top); https://en.wikipedia.org/wiki/Photovoltaic_system#/media/File:Ombri%C3%A8re_SUDI_-_Sustainable_Urban_Design_%26_Innovation.jpg (lower left); Meggers CHAOS lab (lower right).

Another class of novel specialty applications of PV cells features lightweight, colorful, and semi-transparent photoactive materials and devices to enhance aesthetic value while also generating electricity. An example is shown in Figure 3.15: the installation of dye-sensitized transparent solar cells in the façade of the SwissTech Convention Center in Lausanne, Switzerland. These cells have a conversion efficiency of only a few percent, but



Figure 3.15: SwissTech Convention Center installation of dye-sensitized solar cells in a large glazed wall. The cells help prevent overheating in the afternoon while simultaneously generating electricity. Source: © FG+SG fotografie de architectura, <http://www.archdaily.com/519434/epfl-quartier-nord-swisstech-convention-center-retail-and-student-housing-richter-dahl-rocha-and-associates/53a84e94c07a80c112000101-epfl-quartier-nord-swisstech-convention-center-retail-and-student-housing-richter-dahl-rocha-and-associates-photo>.

they serve additional functions as shades and filters. In addition, the cells maintain a relatively high efficiency in diffuse light, making them well suited for vertical surfaces.

Similarly, at Princeton University, the panels containing monocrystalline silicon solar cells on top of the Frick Chemistry Laboratory (Figure 3.16) provide both shade and energy. In designing the building, architects and engineers recognized that shading surfaces function best when aligned perpendicular to the Sun's rays, as is also true of solar panels. Hence, glass-mounted solar panels were used to shade the building's central atrium, intercepting the majority of glare-inducing intense sunlight while effectively letting light through between the cells. The principal justification for the panels is aesthetic interest, not the electricity they generate, which is only about one percent of the building's electricity, less than the panels save by reducing the need for cooling. But the incremental cost may also have been minimal, perhaps not exceeding what would have been spent for an internally integrated shading system.

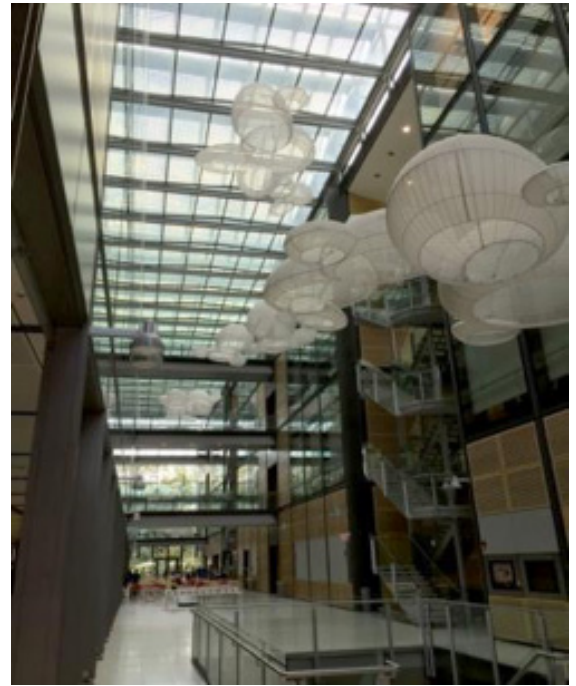


Figure 3.16: Frick Chemistry Laboratory at Princeton University, where solar panels above the atrium are used both for shading and for electricity generation. Source: Forrest Meggers.