Article 2: Key Concepts and Vocabulary

In this article we introduce key concepts and specialized vocabulary for solar energy. We explain some quantitative characteristics of the individual solar panel, including electricity produced, cost, and carbon dioxide saved. We work out deliberately oversimplified numerical examples. Our objective is to demystify.

Watts and Watt-Hours

The Watt

Some electrical devices produce electricity and others consume it. The rate at which electricity is produced or consumed is measured in watts, and the amount is measured in watt-hours. Producing or consuming electricity at the rate of 1 watt for an hour results in the production or consumption of 1 watt-hour.

A 60-watt light bulb consumes electricity at the rate of 60 watts when turned on, a toaster making toast consumes power at a rate of about 1,000 watts, or 1 kilowatt, and the largest jet engines can produce power at a rate of about 100 million watts, or 100 megawatts.

Notably for this Distillate, the intensity of sunlight on a surface perpendicular to the Sun's rays when the Sun is high in the sky on a clear day (peak conditions) is approximately 1,000 watts for each square meter of surface. A typical solar panel has an area of 1.5 square meters. It therefore can receive sunlight at a rate of 1,500 watts under peak conditions.

The Watt-Hour

The dash (hyphen) in watt-hour means that a multiplication is involved. A 60-watt bulb will consume 60 watt-hours when it is turned on for one hour and 120 watt-hours when it is on for two hours.

The kilowatt-hour is the unit most commonly used to track electricity consumption and production, and it is the unit that appears on home electricity bills. Electricity is also often measured using the megawatt-hour, which is equivalent to 1,000 kilowatt-hours. In energy markets where solar energy certificates are bought and sold, one certificate represents 1 megawatt-hour of solar electricity production.

Watts and watt-hours are frequently confused, in part because the watt is one of the few rates with a name of its own.[2] Dividing watt-hours (a unit of energy) by hours (a unit of time) yields watt-hours per hour, or watts. If a home consumes 360 kilowatt-hours of electricity in a 30-day month, it consumes at an average rate of half a kilowatt (500 watts), since a 30-day month has 720 hours.

Conversion Efficiency

The most cited attribute of a solar cell and solar panel is its efficiency, which is electricity output divided by solar energy input. A "rated efficiency" is determined in the laboratory in a simulation of direct sunlight.

The panel efficiency is approaching 20 percent in projects being built today. Cells with efficiencies of 10 percent or less have special applications, and a conversion efficiency above 30 percent can be achieved today with some expensive composite ("multijunction") solar cells.

We return to our 1.5 square-meter panel that receives 1,500 watts of solar energy under peak conditions. If it has a conversion efficiency of 20 percent, it can produce electricity at a peak rate of 300 watts. It is called a "300-watt panel," and 300 watts is its rated output.

Capacity Factor

The "capacity factor" is a widely used index of performance, applicable to any power plant. It is the *actual* production of electricity produced at a power plant, divided by the maximum amount of electricity the plant could have produced if it had run at full rated capacity (over some common period such as a year). It is not unusual for a modern nuclear power plant to achieve a capacity factor of 90 percent, given that nuclear plants run at nearly their maximum capacity almost every

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[2] Others units that describe rates include the ampere (a rate of flow of electric current) and the knot (a measure of nautical speed).

day of the year. Some power plants follow and respond quickly to the ups and downs of electricity demand in a region and have capacity factors near 50 percent. Still others are "peaking plants," designed to run only during the few times of the year when demand is particularly high (for example, on an extraordinarily hot summer afternoon); these have capacity factors in the single digits.

The capacity factor for a solar power plant is the electricity produced by the plant over some time interval, divided by the electricity the plant would have produced if all of its panels had produced electric power at their rated output throughout the same time interval. The capacity factor is affected by the sunniness of the location, how steeply the panels are tilted relative to a horizontal surface and their compass orientation, and whether the panels are stationary or track the sun. The capacity factor is reduced to the extent that the plant's panels at certain times are covered with snow or debris, or they are in the shadow of trees, nearby buildings, or other panels. The capacity factor is also reduced when a plant is shut down for maintenance, or if a plant is producing electricity but a manager of an electric grid forbids an operating plant from sending its electricity onto the grid because of some grid-management issue.

The capacity factor for the world's solar power (an average over all the solar power plants) in 2014 can be estimated from estimates that global installed capacity was 181 million kilowatts and global solar production was 211 billion kilowatt-hours.[3] Global production, therefore, was equivalent to production at full capacity for 1,160 hours and no electricity production during the rest of the year. Rounding up to 1,200 hours and dividing by the 8,766 hours in an average year gives a capacity factor of 14 percent.

Combining the Capacity Factor and the Conversion Efficiency

The capacity factor and the conversion efficiency are entirely different concepts, but they combine multiplicatively to determine the output of a solar power plant. The capacity factor measures how much sunlight falls on the panels. The conversion efficiency measures how much electricity is produced by that sunlight.

Quantitatively, the capacity factor and the conversion efficiency are of comparable importance. A representative value for both is 20 percent: a power plant located in a favorable location has a capacity factor of 20 percent or more, and the conversion efficiency of most commercial solar panels is close to 20 percent.[4] Moreover, in both cases most values for real projects fall between 10 to 30 percent.[5]

To be sure, for a specific solar facility, the actual scores within these two ranges are critically important determinants of its attractiveness as an investment. A facility with two scores of 30 percent produces roughly nine times as much power as an identical facility where both scores are 10 percent.

We return again to our 1.5 square-meter, 20-percent-efficienty panel with a rated capacity of 300 watts. If its capacity factor is also 20 percent, it will produce electricity at an average rate of 60 watts. Over a year, it will produce (rounding off) about 500 kilowatt-hours of electricity (60 watts, multiplied by 8766 hours, equals 526 kilowatt-hours).

Panel Economics: Balance of System and Payback Period

The "payback period" is the amount of time required for an investment to break even. To find the payback period for a residential solar project, we require the cost of residential electricity and the cost of the residential project.

Representative costs for electricity in the U.S. are 5 cents per kilowatt-hour for wholesale electricity (the cost to the utility of producing the power) and 15 cents per kilowatt-hour for retail electricity (the cost of electricity provided to a household by the utility). The difference is attributable to the capital and operating costs of the transmission and distribution system and overhead (maintenance, billing, profit, etc.).

The average cost of a panel in the U.S. has recently dropped below $1 per peak-watt and is still falling. Non-panel costs, referred to as "balance of system" costs, make up the majority of project costs today, and their costs are falling too. Representative (conservative) total project costs are $2 per peak-watt for a utility-scale system and $4 per peak-watt for a residential rooftop system. With these cost assumptions, a single 300-watt panel installed at a utility-scale project will cost its owner $600, and the same panel installed on a residential roof will cost $1,200.

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[3] 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.

[4] In several examples in this Distillate, we use 20 percent for both.

[5] A 30-percent capacity factor can even be exceeded if a panel is located in a desert and is mounted on a motor-driven support that tracks the sun.

You can walk past a house with a solar panel array and estimate its cost by counting the number of panels. The average capacity of the solar collection system in a U.S. home is approximately 5,000 peak-watts, which corresponds to a home with about 16 panels and a cost, at today's prices, of about $20,000. A large solar power plant in the desert in the southwestern U.S. rated at 300 million peak-watts has about one million panels; if built today, at $2 per peak-watt, it would cost $600 million.

We can work out the payback period for this 300 peak-watt, $1,200 residential panel, knowing that it produces 500 kilowatt-hours of electricity annually. Valuing the 500 kilowatt-hours at the retail rate above, the panel saves the residential customer $75 of purchased electricity each year. If a homeowner spends $1,200 to save $75 per year, her payback period (the time to break even) is 16 years.

Here, we have not included any state or federal incentives. In Article 5 this calculation is redone with specific New Jersey and federal incentives included, and the payback period is found to be three times shorter, or about five years.

Value of Improved Efficiency

Improvements in solar cell efficiency translate into reduced costs for the balance of the system, per unit of electricity produced, because more electricity is produced for the same balance of system cost. We work out an example, starting from the 300 peak-watt, $1,200 rooftop panel, above, where the panel costs $300 and the balance of system costs $900. We assume that a homeowner decides to install six of these panels to meet her budget and provide the solar electricity that she wants. She spends a total of $7,200: $1,800 for the six panels and $5,400 for the balance of system. We further assume that the available panel is 20 percent efficient in converting sunlight to electricity.

Now, a new panel becomes available which costs exactly the same but is one-fifth more efficient (24 percent efficient), so she can buy five panels instead of six panels and get the same amount of solar electricity. We make the rough approximation that that the cost of the balance of system depends only on the number of panels, and is now five-sixths as much, or $4,500, because there are now five panels instead of six. (We neglect costs, like permitting, which might not come down when there are fewer panels.) The more efficient panel has reduced the balance of system cost by $900. The homeowner should be willing to pay up to $900 more for the five panels, or $180 more per panel, and still come out ahead. Since the original panel costs $300, the homeowner should be willing to pay as much as $480 per panel for the more efficient panel, 60 percent more. This example thus illustrates the trade-off, where paying more for increased efficiency results in paying less for the balance of system.

Levelized Cost of Electricity

The levelized cost of electricity is the cost of building, operating, and maintaining a facility over its lifetime, divided by the amount of electricity it produces in its lifetime. If we make the assumption that the residential panel above, which produces 500 kilowatt-hours of electricity each year, will have a lifetime of 20 years, then it will produce 10,000 kilowatt-hours over its lifetime. If we further make the simplifying assumption that the only significant cost for the panel is the $1,200 installation cost at the beginning (for example, we neglect maintenance costs), then the levelized cost of electricity is 12 cents per kilowatt-hour. This is higher than the levelized cost of new natural gas power today, but lower than the levelized cost of new nuclear power. The levelized cost would be much lower for a panel used at a large utility project. The levelized cost is a problematic concept for solar power because complications due to its intermittency are ignored.

Cost of Avoided Emissions of Carbon Dioxide

How cost-effectively does the residential panel, above, reduce carbon dioxide emissions to the atmosphere? Our panel produces 10,000 kilowatt-hours of electricity over its 20-year lifetime, and so, presumably, some mix of other power plants that serve the same region produce 10,000 kilowatt-hours less. Thus, the answer depends on the carbon dioxide emissions of the other power plants: the displaced electricity could be assignable to either coal plants or nuclear plants, for example. Let's assume that what is displaced is an average U.S. power plant, which emits a ton of carbon dioxide for each 2,000 kilowatt-hours of power produced. In that case, about five tons of carbon dioxide is not emitted into the atmosphere thanks to our residential panel. Since the cost of the panel is $1,200 (ignoring all costs after the panel is installed), it costs $240 to prevent one ton of carbon dioxide from entering the atmosphere. The corresponding estimate could be several times less for a panel at a large utility installation in a favorable location, and after costs have fallen further. This calculation neglects the carbon dioxide emissions associated with manufacturing the panel in the first place; including manufacturing emissions will decrease the net emissions reduction achieved by the panel and increase the cost of avoided emissions.