PV EDUCATION 101:

A GUIDE FOR SOLAR INSTALLATION PROFESSIONALS

aurora

INTRODUCTION

A Booming Industry

Solar is playing an increasingly important role in the transition to a world powered by renewable energy. Over the past decade, the number of solar installations **has grown at an accelerating rate** and **with increasing affordability.** In the first quarter of 2016, over 29 GW of solar were installed in the United States.

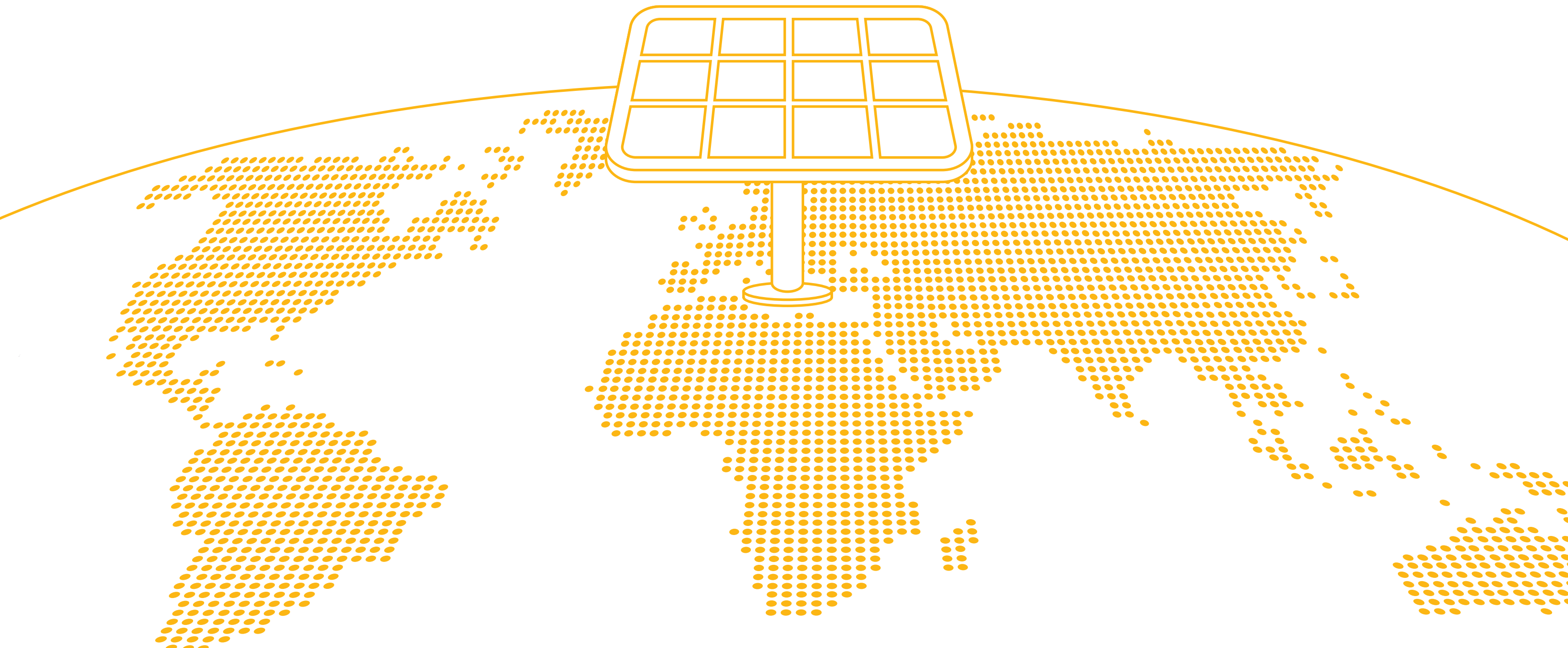
The price of a solar installation is now less than a third of what it was in 2009, while annual installations have grown more than tenfold during the same period of time.

As a **powerful engine for economic growth,** the US solar industry currently employs over 200,000 people—twice as many as in 2010—and now employs more people than the coal, or the oil and gas industries. As installed capacity continues to increase, SEIA predicts that the U.S. solar workforce will expand to 420,000 by 2020.

Welcome to the wonderful world of solar energy.

Why This Guide?

This guide is the ultimate handbook for understanding the world of solar energy. From how a photovoltaic system produces energy to mitigating shade losses, this guide contains everything you need to know to be a solar pro.



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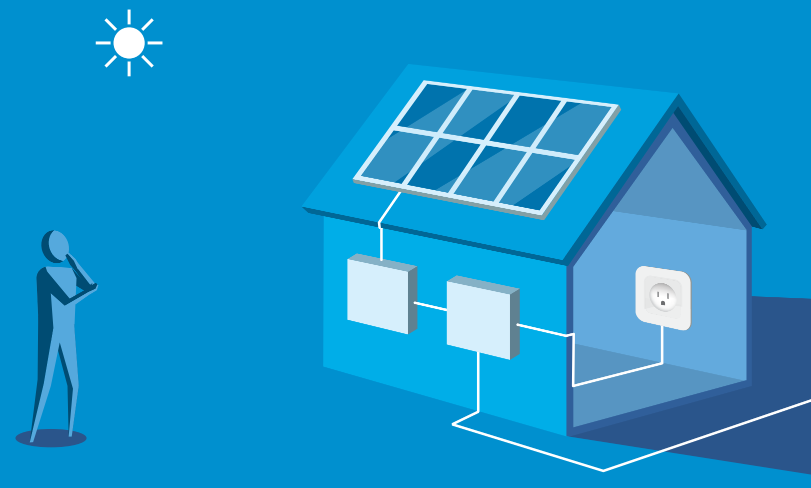
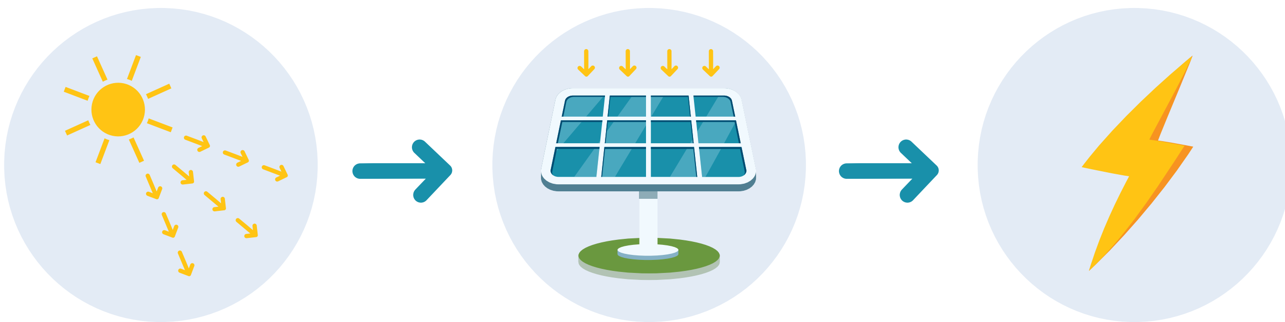
Solar Basics: Energy, Power, and Irradiance



Solar Energy, Power, and Irradiance

Solar panels convert the energy of photons, or light particles, from the sun into electricity. Photovoltaic devices, such as solar panels, permit the incoming photons to transfer their energy to electrons. These energized electrons begin to flow, creating an electric current. We use the terms irradiance or insolation to refer to the power density of sunlight on a surface.



Energy from the sun in the form of photons beam down to earth

Solar panels collect the photons using silicon, a semi-conductive material

Electrons begin to flow, creating a usable electric current

We typically measure energy in kilowatt-hours (kWh), and power (the rate at which energy is produced) in kilowatts (kW).

$$\text{Energy} = \text{Power} \cdot \text{Time} = 1\ \text{kW} \cdot 1\ \text{hour} = 1\text{kWh}$$

In solar, we usually define the size of a solar installation in terms of its power (in kW). Irradiance is typically reported in units of kilowatt-hours per meter squared per day (kWh/m^2-d). The amount of irradiance hitting the surface of the earth is often quoted in terms of the number of hours of “full-sun” of solar energy. A "full-sun" is defined as 1 kW/m^2.

Quantity	Units	Definition
Power	kW	Rate of energy production/output
Energy	kWh	Capacity to do work
Irradiance	kWh/m^2-d	Hours of full-sun for a square meter each day

Table 1. Important quantities used for solar energy

Solar Resource of a Rooftop

We can estimate the solar potential of a rooftop using its area and the local irradiance. NREL, the National Renewable Energy Laboratory, publishes irradiance data in its report *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.*

It is fairly straightforward to calculate rooftop solar potential of a rooftop using this data. For example, a south-facing roof plane of a home in California (Figure 2) receives an average irradiance of approximately 1,900 kWh/m^2/year. Dividing the annual irradiance value by the number of days in a year yields the average daily irradiance.

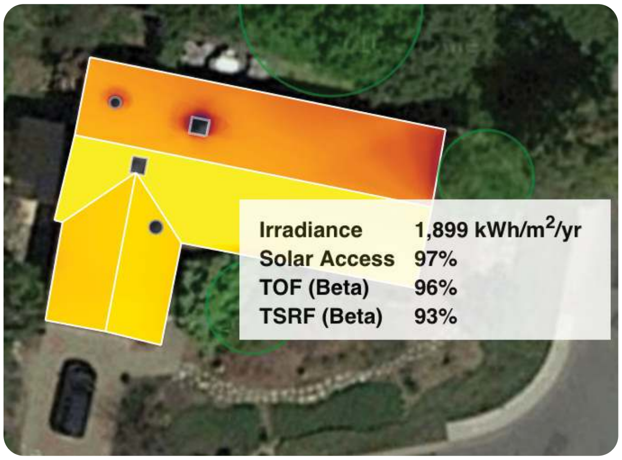


Figure 2. Annual irradiance value for a 150m^2 roof plane in California. Source: Aurora Solar

$$\text{Average Daily Irradiance} = \frac{\text{Annual Irradiance}}{\text{days/year}} = \frac{1900\text{k Wh/m}^2\text{year}}{365\text{days/year}} = 5.2\text{k Wh/m}^2\text{day}$$

To calculate the amount of solar energy available on a roof face, multiply its area by the average irradiance value.

$$\text{Rooftop Energy}\left[\frac{\text{kWh}}{\text{day}}\right] = \text{Irradiance}\left[\frac{\text{kWh}}{\text{m}^2 \cdot \text{day}}\right] \text{ x Area } [\text{m}^2]$$

If the rooftop has an area of approximately 150m^2, the solar energy available on the rooftop is as follows:

$$\text{Rooftop Energy} = 5.2\ \frac{\text{kWh}}{\text{m}^2 \cdot \text{day}} \text{ x 150m2} = 780\ \frac{\text{kWh}}{\text{day}}$$

Besides the solar irradiance, Figure 2 also displays information on three additional quantities related to the solar resource: Solar Access, TOF, and TSRF:

Solar Access:
This is the ratio of the actual solar energy available—taking into account shading cast by objects in the environment—to the solar energy that would be available in the absence of shading. You can learn more about the effects of shading on PV systems here

$$\text{Solar Access} = \frac{\text{Energy with Shade}}{\text{Energy without Shade}}$$

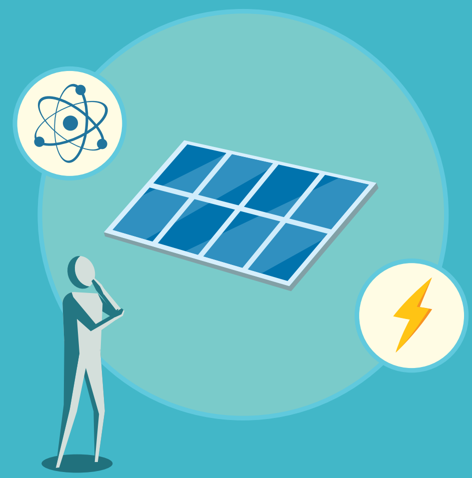
TOF (Tilt and Orientation Factor):
This is the ratio of the amount of solar energy a location receives to the amount it would receive if the orientation of the roof were optimal.

$$\text{TOF} = \frac{\text{Energy with actual tilt and orientation}}{\text{Energy with optimal tilt and orientation}}$$

TSRF (Total Solar Resource Factor):
This is the percentage of the available solar resource that a location receives as compared to what it would receive with optimal orientation and without shading. TSRF is equivalent to the Solar Access multiplied by the Tilt and Orientation Factor.

$$\text{TSRF} = \text{Solar Access x TOF}$$

How a Photovoltaic System Produces Electricity



How a Photovoltaic System Operates

As described in **Part 1**, solar panels convert the energy of photons into electricity. This process is called the photovoltaic effect.

When a photon hits a photovoltaic device, its energy is transferred from the photon to the local electrons in the material. These excited electrons begin to flow, producing an electric current.

Solar cells (within solar panels) produce **direct current (DC)** electricity, which is typically converted to **alternating current (AC)** electricity by an inverter, to deliver energy to the grid (which operates with AC electricity).

Components of a Photovoltaic System

A simple PV system contains two basic types of components:

- Solar Modules: Solar modules contain solar cells that convert sunlight into electricity.
- Inverters: A device that converts DC current to AC current.

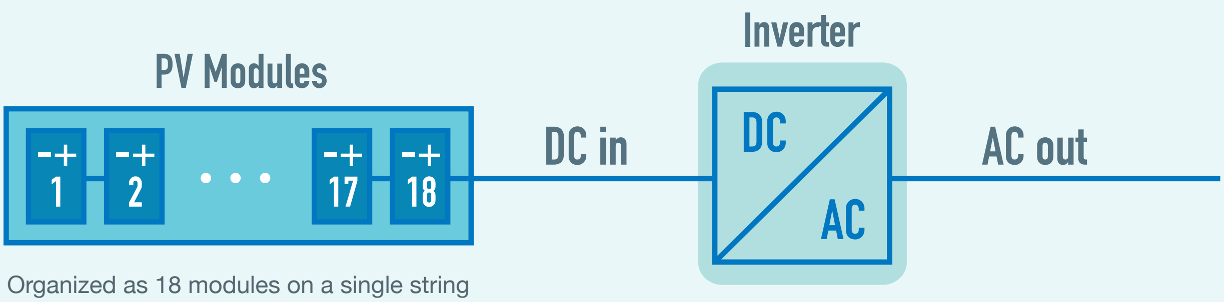


Figure 1. Diagram of a simple PV system. Source: Aurora Solar

It is common practice to refer to all components of a PV system besides the modules as **balance of system (BOS) components.** Examples of BOS components include inverters, disconnects, racking, and wiring.

Factors Affecting Solar Photovoltaic System Efficiency

It is important to note that the process of producing electricity from solar energy is not 100% efficient. Environmental factors, as well as losses in the electrical components, can affect the efficiency of a PV system. Typical loss categories include:

Temperature
The efficiency of a solar panel varies with temperature. High temperatures have a negative impact on performance.

Soiling
Material that accumulates on the surface of PV panels can block light from reaching the solar cells, thereby reducing the generated power. The power loss due to soiling is highly variable, depending on the type of soiling (such as dust or snow), and how frequently the panel is cleaned.

Figure 2. Soiling, such as dust, on PV modules reduces power output.
Source: Ferretti and Berghold, PV Tech Power

Shading
Shading is the obstruction of irradiance due to trees, buildings, terrain, and other objects in the environment. The effect of shading on the power output of a solar installation is highly variable. To understand the causes and consequences of shading, as well as strategies to reduce shading losses, please visit this article.

Wiring and connections
Resistance in the electrical connections of a solar installation typically results in energy losses of a few percent.

Mismatch
Due to manufacturing variations, modules of the same type can have slightly different electrical characteristics. This mismatch between modules can lead to a performance loss.

Inverter Efficiency
Converting DC into AC current via an inverter is typically around 96-97% efficient. Inverters typically have higher efficiency when the DC input power is high. The conversion efficiency takes a big hit when the input power is much less than the inverter's rated power.

Age
Solar panels produce less energy the older they get. Typically the decrease in performance is assumed to be around 0.5% per year.

Term	Typical Value
Temperature	-0.5%/°C above 25°C
Inverter Efficiency	96.5%
Mismatch	98%
Wiring/Connections	98%
Soiling	95% (highly variable)
Age	-0.5%/year
Shading	Highly environment dependent

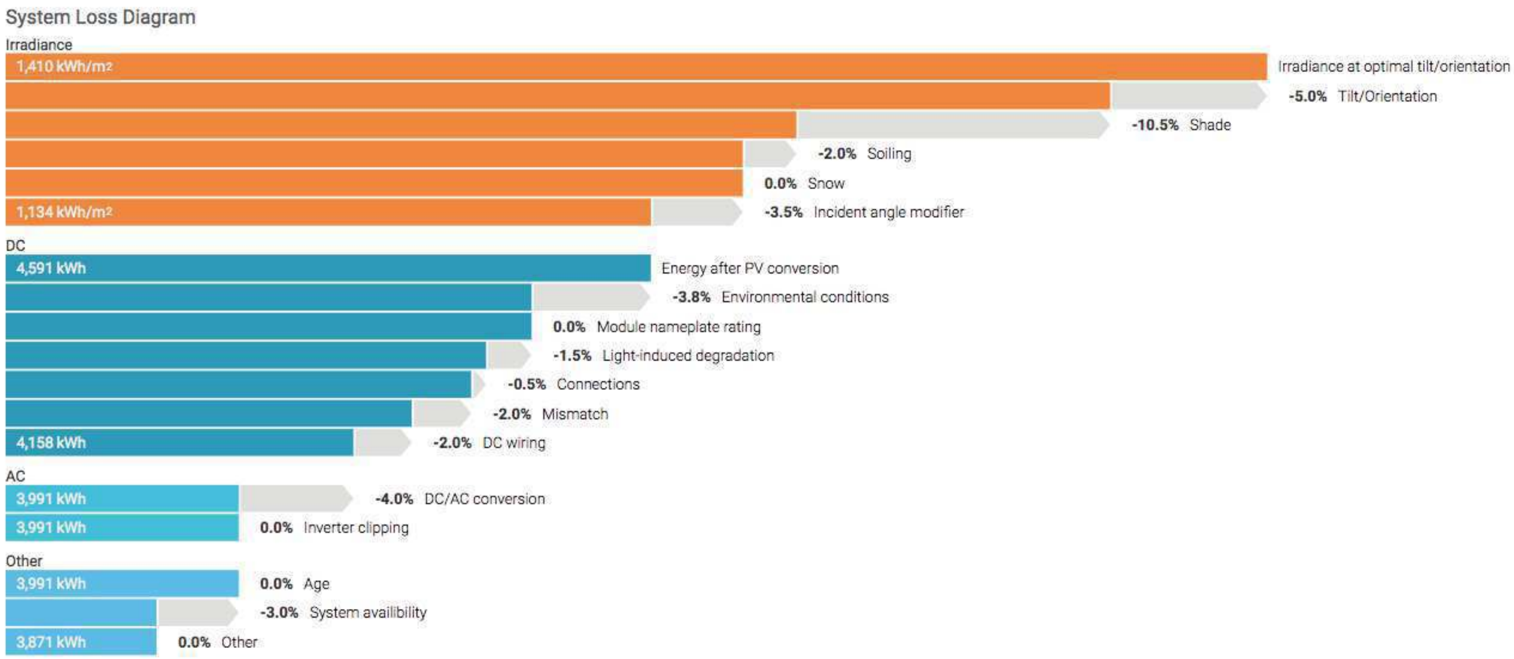
Table 1. Typical efficiency values.

The above factors are combined in a coefficient called the **system derate factor** to represent the overall losses of a solar installation. For instance, PVWatts, an NREL supported PV system energy production calculator, uses a default system derate factor of 86%. However, depending on the system design or environmental conditions, this value can be higher or lower.

Module efficiency denotes what portion of irradiance a module converts into electricity under standard test conditions (STC; irradiance of 1000W/m2, ambient temperature of 25°C). As a general rule of thumb, you can estimate a PV system's efficiency in converting irradiance into electricity (under STC) using the following formula:

Overall System Efficiency = Module Efficiency × Derate Factor

It is important to note that these are merely back-of-the-envelope calculations. To get an energy production analysis, you need a software application, such as Aurora, that incorporates all of a PV system's environmental, mechanical, and electrical characteristics.



Aurora automatically generates a system loss diagram for any design, which can be manually adjusted if needed.

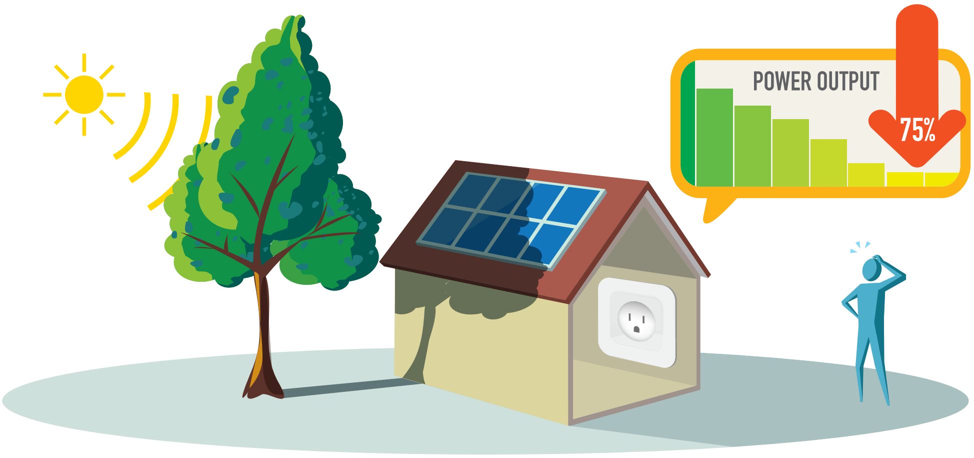
Solar's Dark Side: Mitigating Shade

Effects of Shade on PV Output

Since PV systems generate electricity based on the amount of sunlight they receive, it makes sense that when a shadow is cast on a panel, for example by a nearby tree, its power output decreases. However, the decrease in power could be a lot worse than it initially seems.

Intuition suggests that power output of the panel will be reduced proportionally to the area that is shaded. However, this is not the case. In his book *Renewable Energy and Efficient Electric Power Systems,* Stanford University's Gil Masters demonstrates how shading just one out of 36 cells in a small solar module can reduce power output by over 75%.

Figure 1. Solar panels in partial shade.
Source: lowcarbonlivingblog.wordpress.com



Waterflow Analogy

To conceptualize why shading results in such severe losses, it is helpful to use the analogy of water flowing in pipes. The flow rate of water through the pipe is constant, much like the current through a cell string is constant for a given irradiance level.

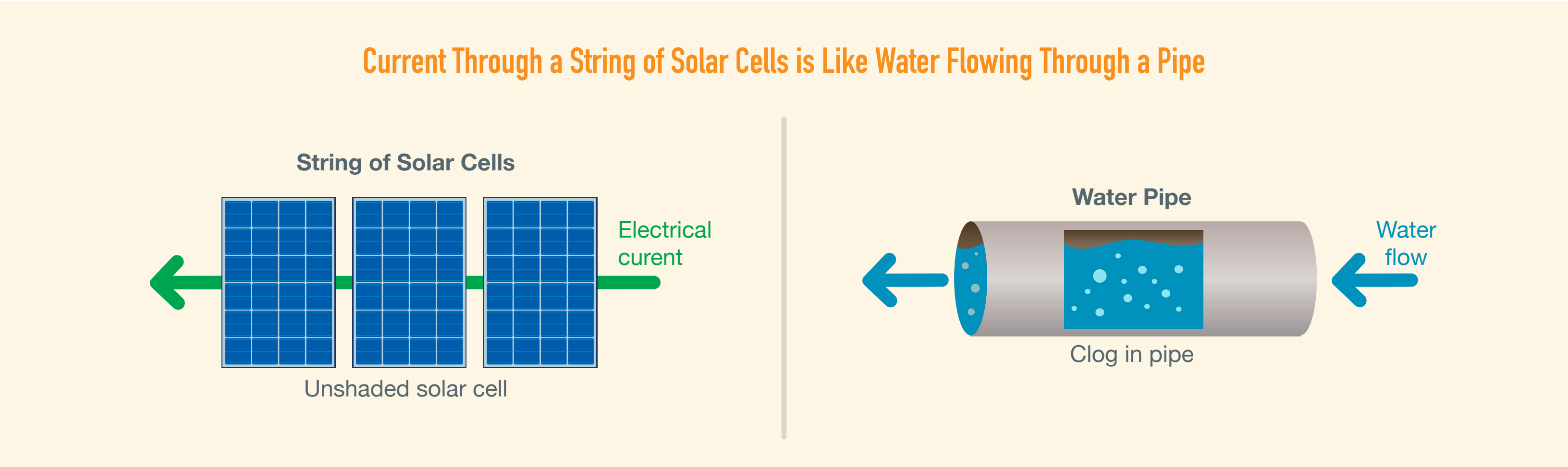


Figure 2. Analogy of a water pipe to a string of solar cells.

Shading a solar cell is similar to introducing a clog in a pipe of water. The clog in the pipe restricts the flow of water through the entire pipe. Similarly, when a solar cell is shaded, the current through the entire string is reduced.

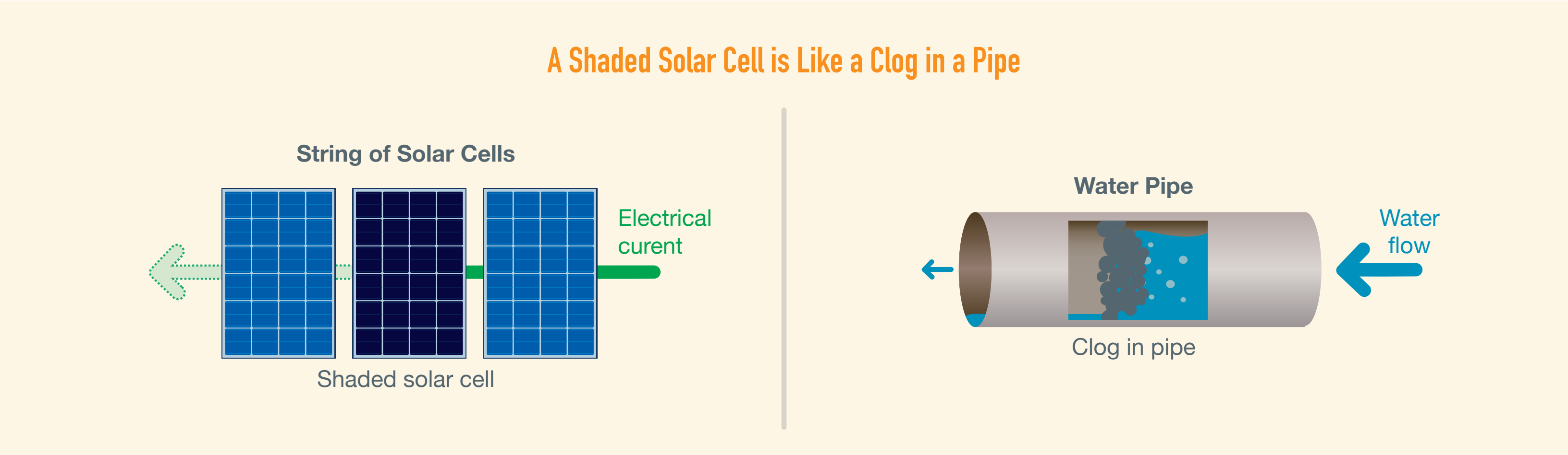


Figure 3. A shaded solar cell is similar to a clog in a water pipe.

This is significant because every cell in the cell string has to operate at the current set by the shaded cell. This prevents the unshaded cells from operating at maximum power. Therefore, only a small amount of shading can have a dramatic effect on the power output of a solar panel.

Similar principles apply to PV modules connected together. The current flowing through an entire string of modules can be heavily reduced if even just a single module is shaded, leading to potentially significant loss of power output.

Approaches to Reduce Shading Losses

Fortunately, there are a number of different approaches that can be applied in PV system design to reduce shading losses. These include the use of different stringing arrangements, bypass diodes, and module level power electronics (MLPEs).

Stringing Arrangements

Modules connected in series form strings, and strings can be connected in parallel to an inverter. The current through all the modules of a string has to be the same, and the voltage of parallel strings has to be the same. As we saw in the last section, a shaded module in a string can bring down the power output of the string significantly. However, a shaded module in one string does not reduce the power output of a parallel string. Therefore, by grouping shaded modules into separate strings, the overall power output of the array can be maximized.

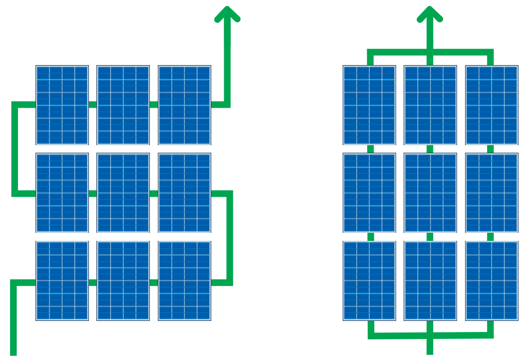


Figure 4. PV arrays with modules connected in series (left) and in parallel (right).

For example, in a commercial system with parapet walls, it can be beneficial to group modules that receive shade from the parapets into strings, and keep modules that do not receive shade from the parapets in separate, parallel strings. This way the unshaded strings can maintain a higher current and power output.

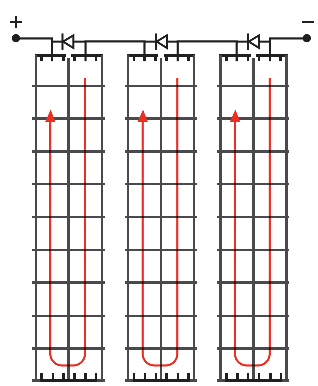


Figure 5. PV module containing three cell strings in series, each with a parallel bypass diode.

Bypass Diodes

Bypass diodes are devices within a module that allow the current to “skip over” shaded regions of the module. By utilizing bypass diodes, the higher current of the unshaded cell strings can flow around the shaded cell string. However, this comes at the expense of losing the output of the cells that are skipped over.

Although it would be theoretically ideal to have a bypass diode for each solar cell, for cost reasons a typical solar module will have three bypass diodes, effectively grouping the cells into three series cell strings (Figure 5). For instance, a 60-cell module will typically have one bypass diode for every 20 cells.

Module Level Power Electronics (MLPEs)

MLPEs are devices that are attached to individual modules in order to increase performance under shaded conditions (though there are other benefits, such as mismatch mitigation and module-level monitoring). This is done by performing maximum power point tracking (MPPT) at the module level. MLPEs include DC optimizers and microinverters.

- **DC Optimizers**

  A DC optimizer adjusts its output voltage and current to maintain maximum power without compromising the performance of other modules.

  For instance, when a shaded module produces electricity with a lower current, the DC optimizer will boost the current at its output to match the current flowing through the unshaded modules; to compensate, the optimizer reduces its output voltage by the same amount it boosts the current. This allows the shaded module to produce the same amount of electrical power without impeding the output of other modules. A system utilizing DC optimizers still needs an inverter to convert electricity from DC to AC.

- **Microinverters**

  As opposed to having a single inverter servicing all of the panels, each panel can have a small inverter attached to it to convert its output from direct current (DC) to alternating current (AC). Since each microinverter has an MPPT, and their outputs are connected in parallel, each panel will operate at its maximum power point, without impacting other panels.

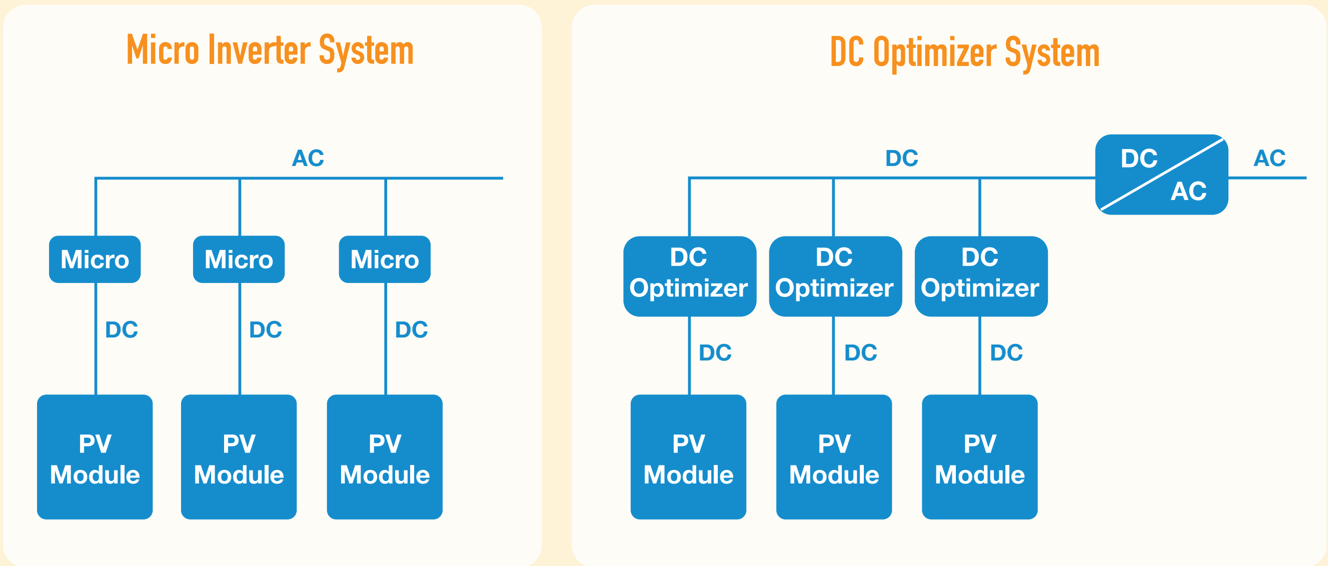


Figure 6. Simplified schematic of a PV system utilizing microinverters (left) and a PV system utilizing DC optimizers (right).

Effects of MLPEs on PV System Performance

Using Aurora's simulation engine, we compared the performance of three different PV systems subject to significant shading.

As shown in Figure 7, we placed a 3.12 kW system near the edge of a roof, which has tall trees next to it. Note that while this design effectively showcases the performance difference of these system topologies in shaded conditions, it is not an optimal—or even a practical—design. Our findings are summarized in Table 1.

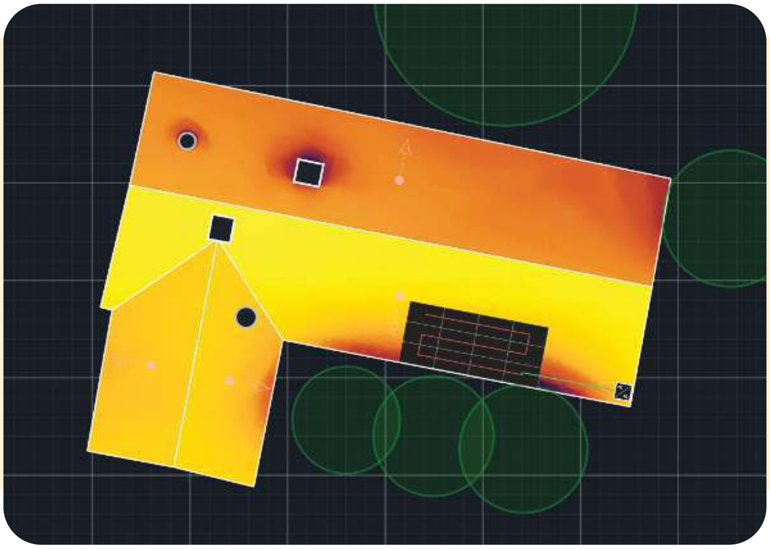


Figure 7. The system analyzed for this case study featured a 3.12 kW system that is partially shaded by trees.

System Topology	Annual Yield	Improvement with MLPEs
String Inverter	2,585 kWh/year	N/A
Microinverters	3,033 kWh/year	+17.3%
DC Optimizers	3,035 kWh/year	+17.3%

Table 1. Results from performance simulations of PV system on a California home utilizing different MLPE components. The difference between the two MLPE outputs is attributed to the differences in their inverters' efficiencies.

Source: Aurora Solar.

Our results show that using MLPEs under these conditions increases system output by 17.3% annually, showing the benefit of using these components for shade mitigation. Additionally, the effective yield of a system using a microinverter or a DC optimizer is approximately the same, although there could be small differences (on the order of 1%) in some cases due to differences in efficiency curves.

For the same reason that they can mitigate shade losses by decoupling module output, MLPEs can eliminate module-to-module mismatch losses. These losses are typically caused by manufacturing variations that lead to slight differences in the electrical characteristics of two modules of the same type. Since MLPEs allow the modules to operate independently from one another, these variations will not impact the system's overall performance.

Sizing a PV System

Sizing a PV System from an Electricity Bill

An electricity bill typically reveals information about a residential or commercial customer's total monthly energy consumption. From this value alone, it is possible to approximate the required size of a PV system that offsets monthly energy usage.

Take a hypothetical monthly energy consumption of 500 kilowatt-hours, which is on the lower end for a household in California. Assuming there are 30 days in a month, an average daily energy use value can be reached by dividing the monthly use by 30.

$$\text{Daily Energy Use} = \frac{\text{Monthly Energy Use}}{\text{Days in Month}} = \frac{500\text{kWh/mo}}{30\text{days/mo}} = 16.7\text{kWh/day}$$

Next, insolation values are needed. As mentioned in Chapter 1, insolation values are reported in kWh/m-day. Since a "full-sun's" worth of incoming solar energy is approximated as 1 kW/m, insolation values reported in kWh/m-day approximate the hours of full-sun equivalent that a location receives over the course of a day.

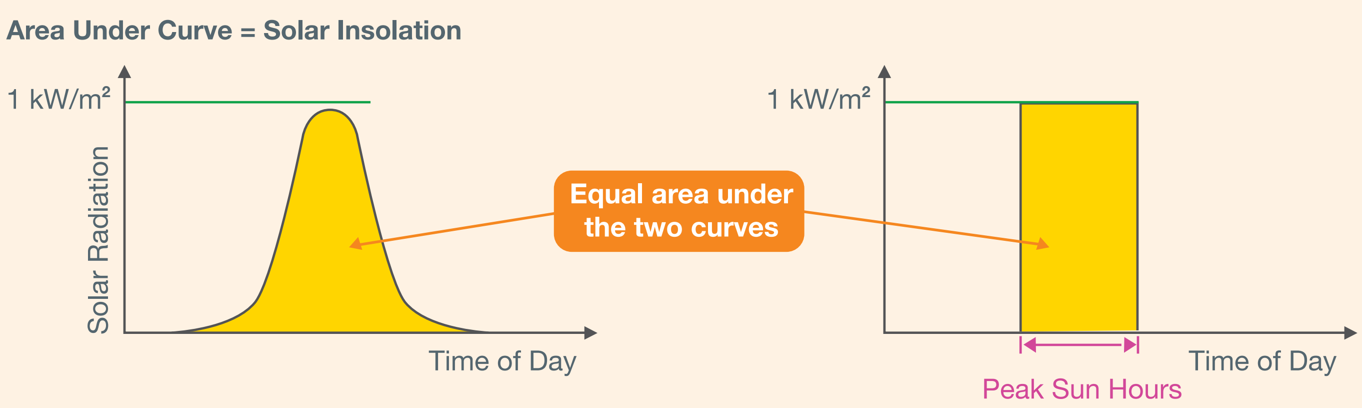


Figure1. Visualization of how total solar insolation received over the course of a day (left) can be represented by number of full-sun hours (right). Source: pveducation.org

For a Californian home, the average daily irradiance value is 5.2 kWh/m-day. By dividing the daily energy usage by hours a day of full sun, the power output required by the PV system is calculated.

$$\text{Power Output} = \frac{\text{Daily Energy Use}}{\text{Days hours of full sun}} = \frac{16.7\text{kWh/day}}{5.2\text{hours/day}} = 3.21\text{kW}$$

This would be the size of the PV system required, if our system was 100% efficient. However, that is not the case because all PV systems have a corresponding derating factor that takes into account the inefficiencies of the overall system, such as soiling of the panels and imperfect electrical connections.

According to the National Renewable Energy Laboratory's PVWatts calculator, a typical derate factor is 0.84. For the sake of this calculation, we assume the derate factor be 80%, or 0.8. In order to determine the size of the PV system, divide the required power output by the derate factor.

$$\text{PV System Size} = \frac{\text{Power Output}}{\text{Derate Factor}} = \frac{3.2\text{kWh}}{0.8} = 4.01\text{kW}$$

From this analysis, the approximate size of a PV system required to completely offset the average monthly energy usage of a 500 kWh/month home in California would be about 4 kW.

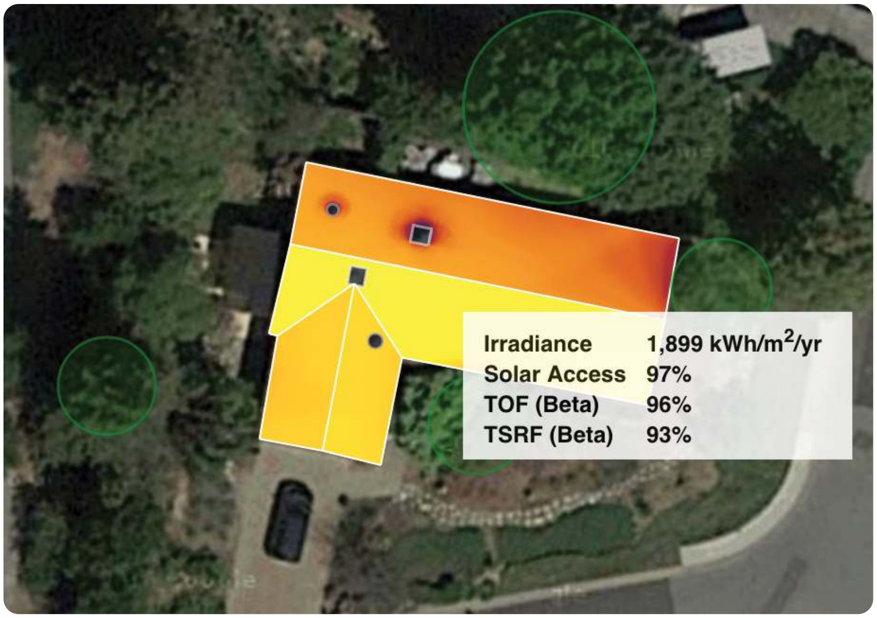


Figure 2. The California home used for this PV system sizing exercise. Source: Aurora Solar

Green Talk:
PV System Costs

Costs Associated with a PV System

In order to determine financial returns, it is important to have a solid understanding of the basic economics that dictate PV system costs. There are two general categories of PV systems costs: capital costs and operation and management (O&M) costs.

Capital Costs

Capital costs refer to the fixed, one-time costs of designing and installing the system. Capital costs are categorized into hard costs and soft costs.

Hard costs are the costs of the equipment, including modules, inverters, and BOS components, as well as installation-related labor. Soft costs include intangible costs such as permitting, taxes, customer acquisition costs, etc.

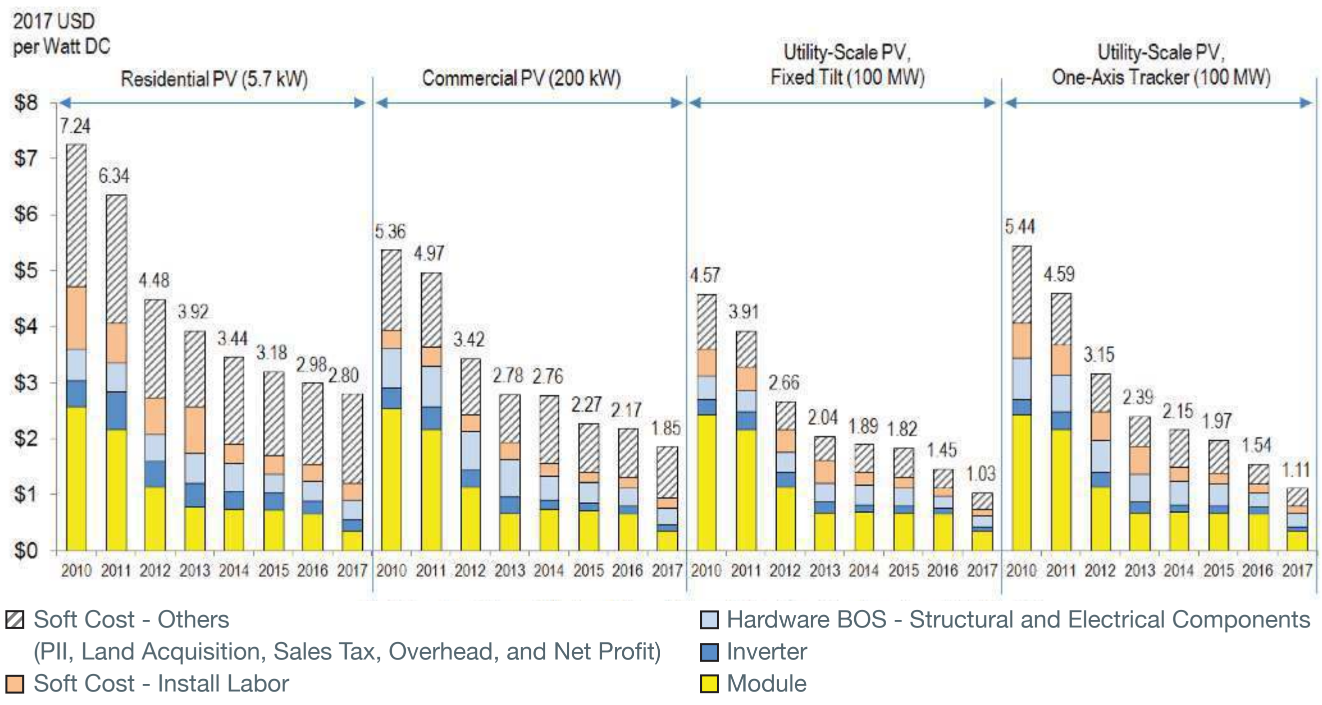


Figure 1. NREL PV system cost benchmark summary (inflation adjusted), 2010–2017

Figure 1 illustrates the relationship between soft and hard costs, and breaks down hard costs into its components. According to SEIA, while hard costs have come down dramatically over the last decade, soft costs have remained largely constant.

Operation and Management Costs

O&M costs refer to costs that are associated with running and maintaining the system. These can include fuel, repairs, and operation personnel. PV systems generally have low O&M costs.

Incentives and Policies that Benefit Solar Energy

The high capital costs are one of the biggest factors that discourage people from going solar. To combat this, there are a number of incentives and policies in place to make PV systems financially competitive.

Cost-Based Incentives

Cost based incentives, such as the Solar Investment Tax Credit (ITC), allow those who invest in a solar system to apply a tax credit towards their income tax. The incentive is determined by the cost of the system, and is independent of its performance.

Performance-Based Incentives

Performance based incentives (PBIs) encourage PV system owners to install and maintain efficient systems through payments that are based on the monthly energy production of the system.

Net Energy Metering

In addition to incentives, many states, such as California, implement a net energy metering (NEM) policy that allows consumers who generate excess electricity to be reimbursed at the then-prevailing rate of electricity.

For instance, if a residential PV system produces an excess of 100 kWh over the course of the month, the owner will be reimbursed for 100 kWh at the market rate of electricity for that time period. The owner is then free to use that reimbursement credit towards electricity they consume from the grid when solar is not meeting their current energy load. Therefore, households with solar PV and NEM are able to significantly reduce their electricity bill.

An average NSW household in Winter

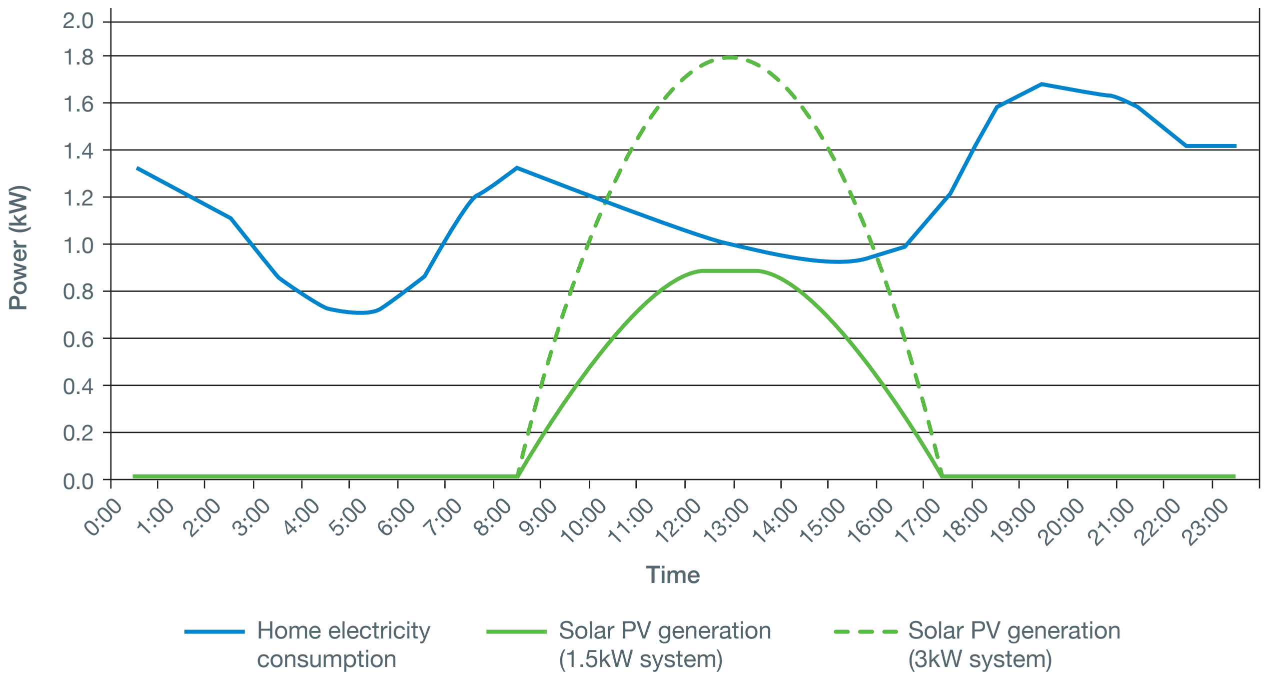


Figure 2. Visualized relationship between PV energy production and household electricity use for an average home in New South Wales, Australia. Source: solarchoice.net.au

Figure 2 shows the relationship between PV electricity production and electricity consumption during the day. Note that while the PV system can generate more than enough electricity during the daytime, it can fail to deliver electricity during peak consumption hours.

Basic Financial Calculation for a Residential PV System

In return for a large upfront investment in a solar installation, homeowners that go solar benefit from a reduced monthly electricity bill. Thus, for NEM regimes the benefit of solar comes in the form of avoided costs.

For instance, assume that upon installing a rooftop PV system, a home electricity bill is reduced by $1,500 per year and the cost of the hypothetical PV system is $10,000 after incentives. In order to calculate the simple payback period, which is the approximate time for a PV system to pay for itself, we divide the cost of the PV system by the savings.

$$\text{Simple Payback Period} = \frac{\text{System Cost}}{\text{Annual Savings}} = \frac{\$10{,}000}{\$1{,}500/\text{year}} = 6.7\text{years}$$

Thus, the payback period for a system that costs $10,000 and reduces the electricity bill by $1,500 per year is 6.7 years.

However, a PV system can last much longer than the duration of its payback period. A typical roof-top PV system has a lifetime of about 25 years. This means that for the last 18 years of its life, after it has paid itself off, the hypothetical PV system described above will generate revenue in the form of additional savings. To calculate this revenue, we multiply the annual savings by the remaining lifetime of the system, after it has paid itself off.

Net Revenue = Annual Savings x Years left in lifetime after system is paid of

Net Revenue = $1,500/year x 18.3year = $27,450

Based on this simple analysis, the system will generate approximately $27,450 in savings over its lifetime. It is important to note that this is an approximation, and does not take into account factors such as maintenance costs, changes in electricity price and usage, as well as system degradation over time.

The figure below shows another financial analysis for a hypothetical residential PV system. In both graphs, the y-axis is the dollar amount and the x-axis is the year.

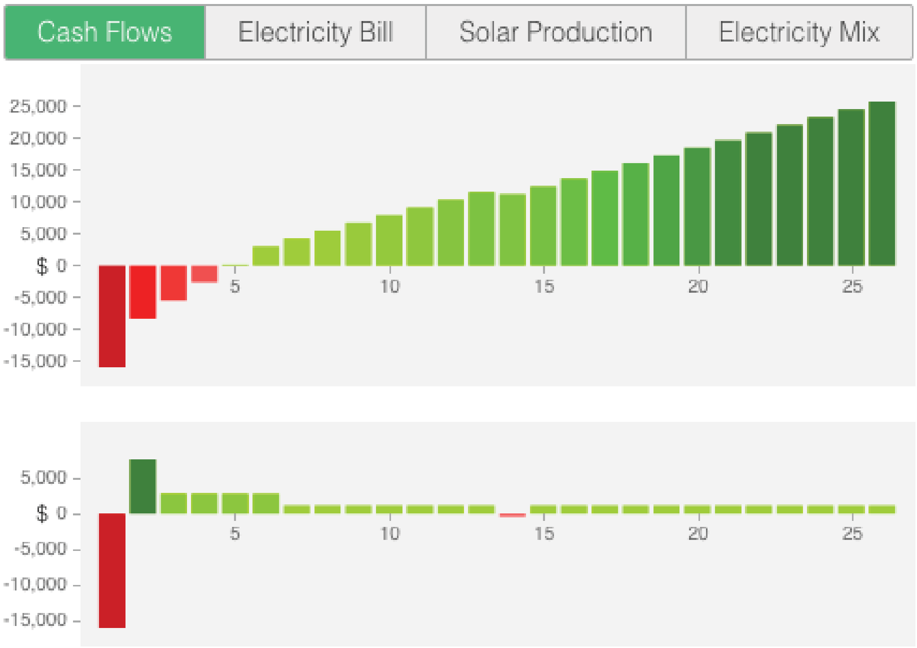


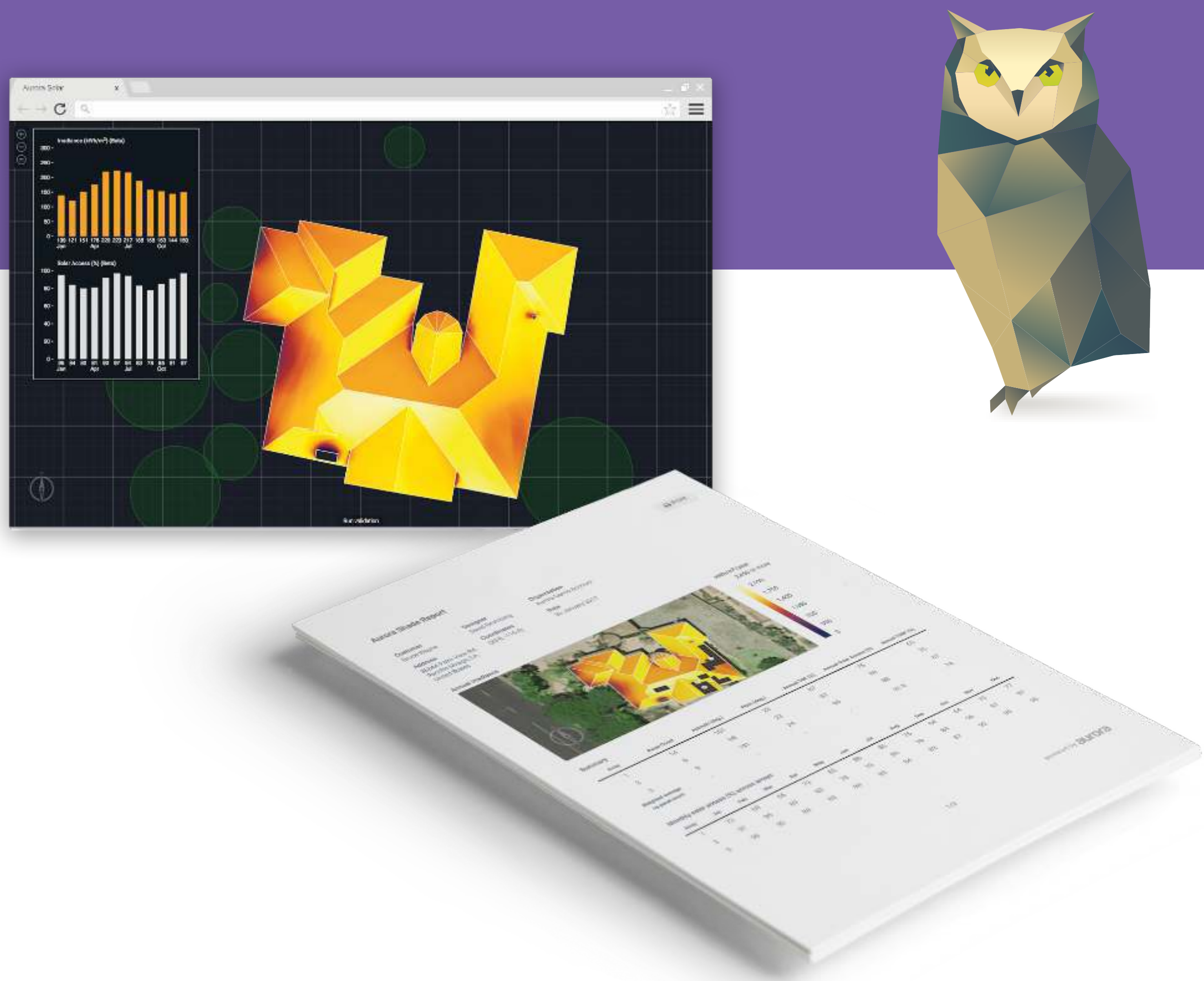
Figure 3. The cumulative (top) and annual (bottom) cash flows of a hypothetical PV system. Source: Aurora Solar

The top graph, which shows the cumulative cash flow of the project over time, and indicates that the project has a payback period of approximately four years. Additionally, the dollar amount in the 25th year, which is about $25,000, is the cumulative net revenue that the system generated. The bottom graph is the annual cash flow of the project. The first year is characterized by a large negative cash flow, due to the large upfront cost required to install the system, but after that there is positive annual cash flow with the exception to this is in the 14th year, which is when the inverters are being replaced.

Congratulations on finishing your introductory primer on the fundamentals of solar PV!

Aurora's solar sales and design software automatically takes into account everything you've just learned to help you present clear financial information to customers about their solar purchase.

See how to design and sell better solar with Aurora



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