SOLAR PHOTOVOLTAICS: OPTIMISING PERFORMANCE

How to get the most out of a solar PV system

Several factors influence the performance of a solar photovoltaic (PV) system. This Building Technology Resource aims to help you understand the available options, engage properly with suppliers, and make design decisions that will ultimately lead to the best possible investment.

The decision to install a solar PV system is most often an economic one, involving an up-front investment designed to defray the future expense of drawing electricity from the grid. The value of any solar PV system is therefore dictated by the price of the system and its installation, its output and the length of time the system is in operation for the investor. These factors are different for each situation, so some systems provide better financial returns than others.

FACTORS AFFECTING THE PRACTICAL OUTPUT OF SOLAR PV SYSTEMS ON BUILDINGS

Solar PV systems are built on the concept of strings: linear chains of PV modules, or solar panels, connected electrically in series. The modules convert sunlight into direct current (DC) electricity, which an inverter changes into alternating current (AC) electricity for consumption or transmission back to the grid. Several aspects of the installation, operation and maintenance of a solar PV system affect how much electrical power it generates – and thus its overall value.

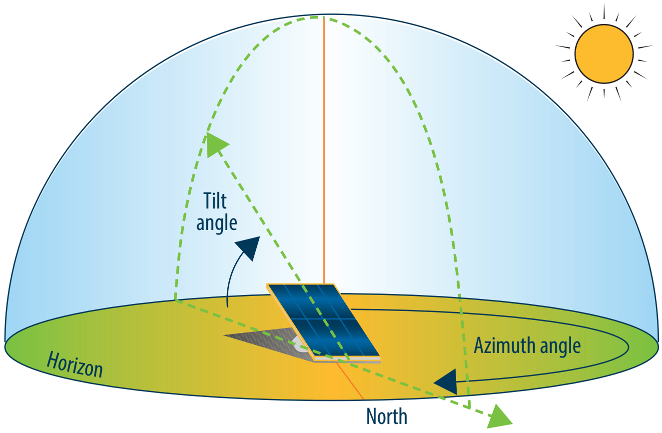

FIGURE 1 Hemisphere showing how tilt angle and azimuth angle are defined for a solar PV system.

GEOMETRY

The factor that most influences the output of a solar PV system at any point in time is the solar irradiance, or the level of sunlight, received by the system (usually measured in watts per square metre). Due to the cosine effect, the irradiance reaching the system depends on the direction that the PV modules are facing. Modules facing the sun receive the most solar irradiance, so many ground-based solar PV systems use mechanical tracking to maintain this orientation throughout the day. However, tracking is rarely practical for building-based solar PV systems, so the angular orientation of the installed system is important.

Based on solar geometry alone, the optimum alignment for a solar PV system to maximise energy generation over a year is where its azimuth angle, or compass bearing, faces the equator – i.e. true north for locations in the southern hemisphere – and its tilt angle is equal to the local latitude (Figure 1). Although a reasonable guide, this simplified optimisation ignores several factors:

- cloud effects at the site may be dominant in either winter or summer (affecting the optimum tilt angle), or in either the morning or the afternoon (affecting the optimum azimuth angle)
- shading is often more of a problem in winter, when the sun stays lower in the sky
- the operating temperature of the system is lower in winter
- self-cleaning during rain is more effective for larger tilt angles.

Furthermore, the configuration with the highest annual energy yield may not necessarily have the best economic outcome. An example is where a residential PV system is installed on a section of the roof facing north-west so that it produces the most power later in the day, to better offset consumption when the residents are home or during the peak tariff period.

In practice, most roof-mounted PV systems do not allow much flexibility in the installed geometry. Houses generally have only one or two roof sections on the equator side of the building. Space and aesthetic considerations may also constrain the installation options. It is common for an otherwise suitable roof section to have a non-ideal geometry, but this is rarely a serious hindrance. For example, data from the web-based energy yield calculator PVWatts® indicate that for solar PV systems installed in Australian capital cities, a tilt angle that differs from the optimum by ±20° reduces the annual energy yield by only ~5%; an angle that differs by ±30° reduces yield by ~12%. Likewise, the sensitivity to azimuth angle is low for directional variations up to ±45° and depends on the latitude, with the lost energy ranging from ~2% in Darwin to ~7% in Melbourne. Even for systems oriented 90° away from the ideal azimuth, the lost energy yield is only ~9% in Darwin and ~26% in Melbourne.

These data suggest that for houses with low-pitched roofs, even a roof section facing away from the equator can be a good candidate for a solar PV system. Special tilt racking is sometimes used to achieve the optimal geometry, but the small gain in output may not compensate for the aesthetic and economic costs of the racking. Building owners should be aware of these considerations, so that such decisions are not left entirely to the installer.

SHADING

Although a solar PV system can continue to produce some power when the sun is shaded by clouds, partial shading of the system must be avoided where possible (Figure 2). Because the

FIGURE 2 Partial shading of a solar PV system can significantly reduce its power output. (zstock/shutterstock)

PV modules and the cells within them are connected in series, compromising the output of one module or even one cell can affect the performance of the entire string. Furthermore, the inverter continues to optimise the string as a whole, so the compromised modules can become sinks for the power from the unshaded modules. This can result in overheating and damage to the shaded module. Fortunately, modern PV modules contain bypass diodes that limit the risk of overheating, but shading can still severely limit output.

The likelihood of shading by trees, neighbouring buildings or other structures on the roof is not always easy to determine for all times of the day and year. A competent installer should be able to describe the shading vulnerability of a proposed solar PV system in detail. In complex shading environments, this information is often generated using specialised equipment that combines wide-angle sky images taken from the rooftop with calculations of the sun's path throughout the year.

REPLACING A DAMAGED MODULE

In principle, a single PV module can be replaced if damaged. In practice, this situation poses several challenges:

- identification of the damaged module often requires specialised infrared imaging techniques
- changes to the design of modules over time often mean that the manufacturer no longer makes a module similar enough to be used with your system
- shipping of a single module is relatively expensive.

OPERATING TEMPERATURE

In all solar PV systems, the power output decreases slightly as the module temperature increases. This effect is much smaller than the effect of fluctuating irradiance, but it is not insignificant. Despite absorbing sunlight very well, PV modules typically convert only 15–20% of that energy into electricity. The remaining absorbed energy heats the module to an operating temperature that depends on the irradiance, ambient temperature, wind speed and installation configuration. In strong sunlight (~1000–1100 W/m^2) and low wind conditions, operating temperatures are typically 25–30°C above the ambient temperature for modules in an open rack installation, and even higher for modules mounted close to a surface, such as a rooftop, where air movement is restricted.

The impact of elevated temperature on the output of a solar PV system is described by a parameter known as the temperature coefficient. The strongest effect occurs in modules made from crystalline silicon, which typically have a temperature coefficient around -0.4%/°C, meaning that the power output drops by 0.4% for every 1°C increase in temperature. The difference in module temperature between a well-ventilated and a poorly ventilated system may easily be 10°C at peak irradiance and 5°C at average irradiance, meaning a difference in the energy yield over time of around 2%.

Thin-film PV modules typically have lower temperature coefficients than crystalline silicon modules. Under Australian conditions, a thin-film PV system will usually have a 1–6% higher annual energy yield than a crystalline silicon system of the same power rating, depending on the particular technology used and the location of the system.

Even if there is limited scope to influence the way in which a solar PV system is installed, it is useful to understand the potential impact of ventilation. At the very least, this is another reason to inspect the system regularly. Birds sometimes nest in the space between the modules and the roof, leading to reduced airflow and significantly higher operating temperatures.

SOILING

The build-up of foreign matter on the surface of PV modules can reduce the system's output by cutting the amount of light reaching the solar cells. Extreme examples include snow, salt (for installations very close to a breaking ocean) and dust (for installations in desert environments). In high-soiling environments, it is important to be aware of the impact of soiling and inspect and clean the system at appropriate intervals. Snow is particularly effective at scattering light, and even a relatively thin layer can significantly reduce a system's power output.

As a large proportion of building-mounted solar PV systems in Australia are located away from sources of dust and in areas with at least semi-regular rainfall, soiling is a relatively minor concern – except perhaps in times of drought. Rain is reasonably effective at removing soiling for modules at tilt angles greater than ~5°, particularly where the rain either persists for several hours or is moderately intense for shorter periods. The effectiveness of cleaning by rainfall generally improves as the tilt angle increases, up to the point at which a high angle limits the amount of rain hitting the module. In the case of dust, although rain often doesn't remove all of the coating, the residual layer usually has negligible impact on the system output.

Rain is less effective at removing bird and bat droppings. Small droppings have little effect, but large droppings can in principle reduce the life of a solar PV system by partially shading cells and leading to overheating (Figure 3). It is thus usually worthwhile to inspect the system at appropriate intervals and to remove any persistent localised soiling as soon as is practical. Locating the solar PV system on an easily accessible part of the roof is often a wise decision in this respect – no soiling problem is worth the risk of a fall from a ladder or rooftop.

FIGURE 3 Large bird or bat droppings can in principle reduce the lifespan of a solar PV system. (CSIRO)

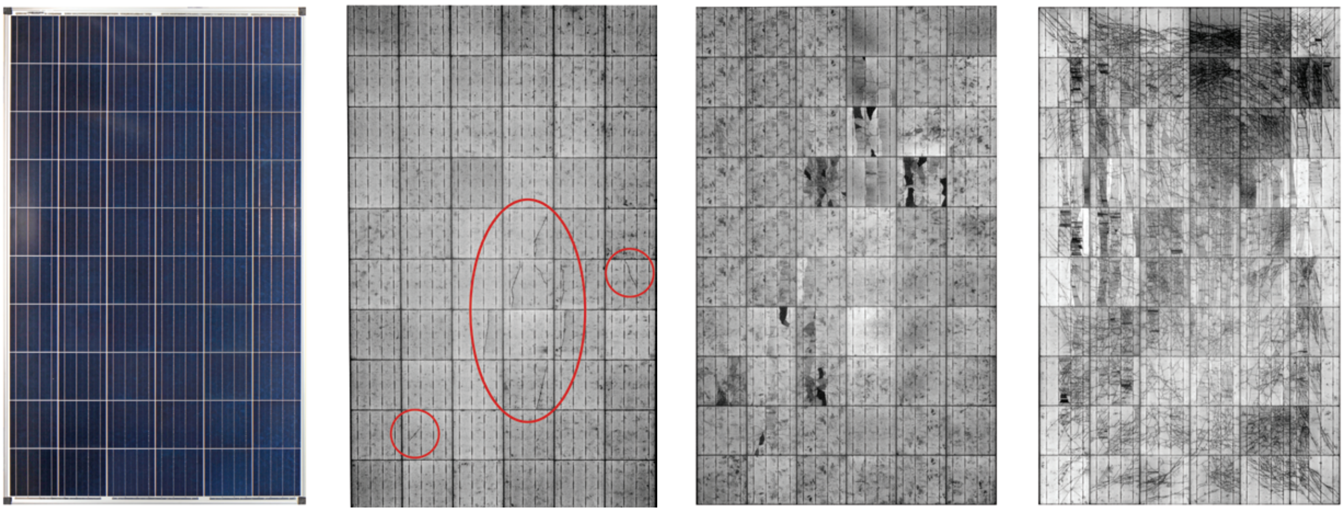

FIGURE 4 Electroluminescence imaging of a multicrystalline silicon PV module (pictured at far left) reveals (from left to right) minor hairline cracking (highlighted in red), unacceptable cracking with cell damage, and extensive cracking. (Chris Fell)

DAMAGE

The silicon cells in most PV modules are fragile and extremely thin. Although they are adhesively bonded to the underside of a relatively hard glass cover – which is usually designed to withstand the impact of a 25 mm hailstone travelling at 120 km/h – any bending of the module readily causes cracks. Cracks often originate near busbars or solder joints, where residual stress exists as a result of localised heating during manufacture.

Mild damage has a relatively small impact on power output in the short term, but cracks can lead to localised overheating and subsequently reduce the lifespan of the module. It only takes one underperforming module to decrease the output of the entire string.

Most crack damage to PV modules occurs during transport and/or installation, from impacts due to vehicle vibrations, falls or bumps, and even people stepping on the module. Because cracks cannot be seen with the naked eye, damage to PV modules can be observed only by using a technique called electroluminescence imaging (Figure 4), which is performed at specialised test laboratories.

The best way for a building owner to ensure that a solar PV system installer follows good transport and handling practices is to choose a well-established business that can provide evidence of a long history of complaint-free installations.

MODULE SELECTION

When shopping for a solar PV system, the customer will usually be given a choice between two or more models of crystalline silicon PV module. (Thin-film modules are rarely available in Australia today, due to their lower efficiency and hence higher cost after installation is taken into account.) Products may differ in their underlying technology, efficiency, energy yield (kWh/kWp) and lifetime. Often a supplier will offer one budget model and one premium model to choose between.

Making an informed decision between models on the basis of the manufacturers' performance and durability claims can be difficult, because the claims are usually qualitative rather than quantitative and are often backed with little or no supporting information. Features like lower temperature coefficients or better low-light performance can improve energy yield, but usually by no more than a few percent. There is no significant difference between the performance of polycrystalline (multicrystalline) and monocrystalline PV modules, although the latter are usually slightly more efficient (see 'What is the efficiency of a solar panel and is it important?').

Ultimately, the best choice is likely to be the module that will last the longest. The more established manufacturers are generally better in this respect. The more modules a particular brand has in the field (and the longer the brand has existed), the more likely the manufacturer is to design durable modules and handle them appropriately – and to have replacement modules available in future.

WHAT IS THE EFFICIENCY OF A SOLAR PANEL AND IS IT IMPORTANT?

The efficiency of a PV device is the ratio of the electrical power output to the solar power input when the device is connected to an optimised load. Practical considerations in manufacturing mean that commercially available solar PV modules currently have efficiencies of 15–20%. Although most modules are priced primarily on a dollars-per-watt basis, higher-efficiency modules attract a price premium because they allow a larger system to fit on a given roof area. However, the higher price is partially offset in the final price of the installed system, as less time and fewer mounting components are required for installation.

SYSTEM FAULTS

Solar PV systems are generally very reliable, which is important because their financial payback accumulates over time. Modern PV modules, particularly those from larger manufacturers, are rarely the cause of system faults (unless they have been mishandled or damaged).

Unlike PV modules, inverters are complex electrical devices with hundreds of components. They perform several critical functions to enable the modules to gather usable energy. The failure of any of these functions generally brings down the entire system, so inverter failures are responsible for nearly half of all system failures. For this reason, the choice of inverter is important (Figure 5). Customers will usually be offered a choice between budget, mid-priced and premium inverters, at prices ranging from 10% to 25% of the total system cost. When calculating the cost–benefit proposition for their system, customers should consider the inverter's lifespan and warranty.

Other potential causes of system faults include water ingress into connectors and conduits, and DC arcs. The best way to mitigate faults is first to choose a well-established installer with a long history of satisfied customers, and then to monitor the system output so that any failure is detected as soon as possible. After-market monitoring systems are popular, but many owners simply check their system output using the information screen on their inverter. Inverters report the instantaneous electrical power output in kW and the accumulated daily energy generated in kWh. Developing a feel for what these numbers should be for your system under various conditions is a cheap and effective way to see if a fault has developed.

FIGURE 5 A good quality inverter is important for avoiding common causes of system failure. (zstock/shutterstock)

MORE INFORMATION

Additional information can be found in the following resources. Please check your local authorities for specific legislation, codes and guidelines, as they can vary between states and territories.

Clean Energy Council <www.cleanenergycouncil.org.au>

Clean Energy Council (2021) Buying solar: Advice for purchasing a new solar system. Melbourne: Clean Energy Council. <https://assets.cleanenergycouncil.org.au/documents/consumers/solar-guide-for-consumers-october-2020.pdf>

PVWatts® Calculator <https://pvwatts.nrel.gov/>