SOLAR PHOTOVOLTAICS: THE BASICS

Understanding solar photovoltaic systems for buildings

This Building Technology Resource introduces solar photovoltaic systems for rooftop electricity generation. It describes the main factors to consider when thinking about installing solar photovoltaic systems, how much electricity can be generated, and the principles of good system design.

Of all the renewable energy sources available on Earth, sunlight has by far the highest theoretical potential. The total amount of sunlight reaching the Earth's surface represents around ten thousand times the energy requirements of the human race. Although much is consumed in the atmosphere and oceans, the amount of energy reaching land near human habitation is easily enough to support our energy demands using present-day solar photovoltaic (PV) technology.

However, geometrical considerations and cloud patterns cause solar energy potential to vary – often unpredictably – across the landmass (Figure 1). When combined with the day-night cycle, this means that sunlight must be considered a variable energy resource.

THE ECONOMICS OF SOLAR PV SYSTEMS

Managing a variable energy resource is not that difficult – the world has been coping with variable electricity consumption for more than a century – but the variability complicates the economics. Whether to add a solar PV system to a building is usually an economic decision, involving an up-front investment designed to defray the future expense of drawing electricity from the grid. The investment is typically valued in terms of a payback period – that is, how long it will take before the system recoups its cost.

Payback periods vary significantly, ranging anywhere from 2 to 10 years, depending on a host of variables such as:

- the cost of the solar PV system, which depends on its size, the choice of components, installation requirements and financing options
- the amount of electricity generated by the system, which depends on its size, geometry, components and shading – and, of course, the local climate
- the cost of grid-supplied electricity, keeping in mind that pricing can vary with the time of use and, for businesses, can include special charges for periods when high power is required
- the immediate value of the electricity generated by the system.

In Australia, this last variable is perhaps the most significant. At 2018 residential prices, one kilowatt hour (kWh) of solar electricity may be worth 60 cents or more if it directly offsets grid-supplied electricity at a peak time. However, if not consumed at the time, it will be sold back to the grid for only ~6 cents. Thus, the pattern of electricity consumption is important to the economics of a solar PV system. The rapid uptake of battery storage technology may change this dynamic significantly.

Determining the precise cost–benefit proposition for a given solar PV system is complex. However, a well-designed and carefully installed system will generally perform well for at least 25 years, with a payback period that is much shorter than that. The greatest value is achieved in cases where:

- the owner retains the benefit of the solar PV system for as long as possible
- electricity consumption in the building occurs mostly when the sun is shining, and
- the performance of the system is checked periodically to avoid long periods of no output if a fault occurs.

PRINCIPLES OF GOOD SYSTEM DESIGN

Solar PV systems work by capturing sunlight via PV modules, or solar panels, which are typically installed on a building's roof (Figure 2). The modules convert the sunlight into direct current (DC) electrical power, which an inverter changes into alternating

FIGURE 1 Cloud patterns affect the potential of sunlight as an energy resource. (JARPHOTO/Shutterstock)

FIGURE 2 Solar PV system (approximately 2.8 kilowatt peak) on a residential rooftop. (chinasong/iStock)

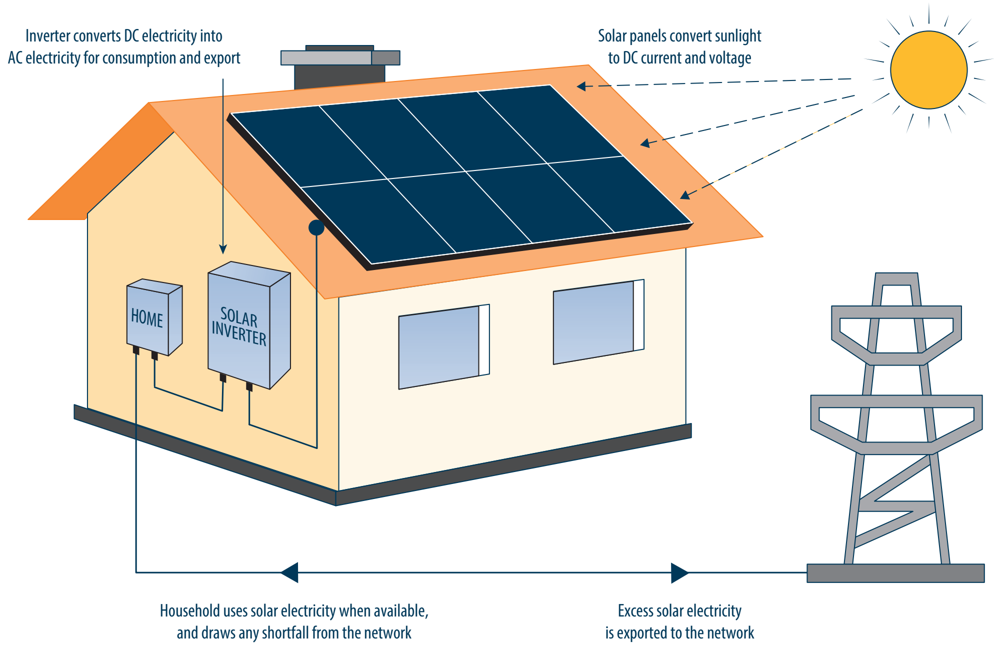

FIGURE 3 How a household solar PV system works.

current (AC) power for consumption or transmission back to the grid (Figure 3).

> **HOW IS A PV MODULE RATED?**
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> Because solar PV modules experience a wide variety of solar conditions in their lifetime, the best way to compare their performance is to measure the power output under an agreed set of reference conditions, usually in a laboratory. The International Electrotechnical Commission defines the Standard Test Conditions for PV as: a module temperature of 25°C, an irradiance (light level) of 1000 watts per metre squared (W/m^2), and a reference light spectrum (colour distribution) based on a computer simulation of sunlight with some agreed input parameters.
>
> The power extracted from a solar PV module or system depends on the electrical load it is connected to. For a perfectly optimised load, a 'p' (short for 'peak') is added to the nameplate rating: Wp or kWp. Modern power inverters are designed to present the solar PV system with an optimised load at all times, even if the solar conditions change. This means that solar PV systems can and do exceed their nameplate output rating, for example, when the solar irradiance exceeds 1000 W/m^2.

One of the strengths of solar PV technology is that the fundamental building block, the PV module, remains the same whether the system is a tiny 1 kilowatt peak (kWp) residential system with 3–4 modules or a huge 500 megawatt peak (MWp) solar farm with 1–2 million modules. The kWp or MWp value, which represents the capacity, or size, of the system, is based on the number of modules in the system and the power rating of those modules (see 'How is a PV module rated?').

Regardless of their size, all solar PV systems are built on the concept of strings: linear chains of modules connected electrically in series. Typically each string is connected to an inverter. Connecting the modules in series means the electrical current in the string remains the same as for a single module (approximately 10 amps for conventional crystalline silicon modules in maximum sunlight). However, the string voltage, and hence the electrical output power, become the sum of the individual module voltages (powers).

The number of modules in each string is designed to match the voltage input requirements of the inverter. If the string has too many or two few modules, the inverter will cease working at high or low sunlight levels, respectively. Larger systems must therefore be split into more strings and hence use either more inverters or larger inverters with inputs for multiple strings. Solar PV systems for use on a house frequently have only one string and a single inverter.

A well-designed solar PV system:

- fits aesthetically and robustly onto a building. In Australia, this usually means the roof; in countries further from the equator, vertical surfaces can also be used.
- is positioned to avoid shading at any time other than the very beginning or end of the day.
- is installed facing the direction of the equator as closely as possible.
- has an appropriate power rating, such that the system can produce a reasonable portion of the occupant's electricity needs under the local solar conditions, without being so large as to export most of its output to the electricity grid.
- has the ideal number of modules per string. This number is a function of the PV modules being used and the local weather conditions, so will depend on each installation.
- has all modules in a string facing precisely the same direction and tilt. If a building-mounted system is to be split across more than one section of roof, either the sections must have identical geometry or each section must have a separate string, requiring either a new inverter or an inverter with multiple inputs.
- has a reliable inverter with an appropriate power rating. A higher-power inverter allows for the addition of more PV modules in the future, whereas a lower-power inverter may be more cost-effective. It is reasonable to use an inverter with a lower capacity than the nameplate rating of the installed modules. While 'undersizing' the inverter leads to some discarded output when the solar irradiance is very high, this is usually compensated by more efficient operation under modest solar conditions, which occur much more frequently.
- is attached to the building in such a way as to allow good ventilation for natural cooling.
- is located so as to permit safe access for maintenance, inspection and cleaning if necessary.
- is installed in a manner fully compliant with Australian Standard AS/NZS 5033.

CAN A SOLAR PV SYSTEM MEET MY NEEDS?

When planning a rooftop solar PV system, the most basic consideration is whether the system will be able to supply a reasonable portion of the building's electricity requirement. Ideal rooftops have at least one large, contiguous, sloped area facing somewhere near the direction of the equator and away from trees,

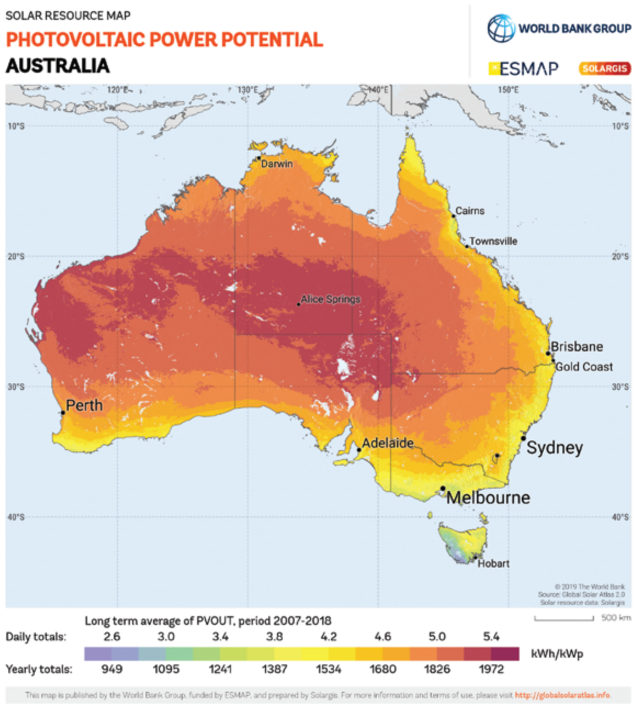

FIGURE 4 Energy yield potential for ideally oriented solar PV systems in Australia. (© 2019 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.)

structures and other buildings that may create shadows on the system.

PV modules for buildings are around 1.6–1.8 m^2 in area with power ratings presently in the range of 300–400 Wp. This means that a solar PV system would typically require around 5 m^2 of roof area per rated kWp. In practice, 20–50% more roof area is required for access between rows of modules. If tilt racks are used, even more space is necessary to avoid shading between rows.

A consequence of the way PV modules are rated is that a 1 kWp system does not produce 1 kW of electrical power at all times: the actual output depends on the amount of sunlight received, which rises and falls smoothly between sunrise and sunset, even on sunny days. In Australia, the average PV power output over daylight hours for optimised systems is typically 20–30% of the system's power rating, leading to annually averaged daily energy yields of ~4 kWh per kWp of system nameplate rating. Determining this value for specific sites requires a complex calculation, but has become simpler for consumers through the development of solar mapping tools. An example is the Australian PV Institute's SunSPoT tool for high-resolution maps of selected local government areas within Australia. For a global perspective, world maps and Google Earth overlays are available online from data provider Solargis.

Based on solar energy potential data provided by Solargis, solar PV systems with an ideal design in Australian capital cities should expect to produce average daily energy yields (in kWh per kWp) of 3.8 in Sydney; 3.6 in Melbourne; 4.0 in Brisbane; 4.2 in Canberra; 4.0 in Adelaide; 4.4 in Perth; 4.2 in Darwin; and 3.6 in Hobart (based on data shown in Figure 4). In practice, factors such as sub-optimal installation geometry, shading and soiling often lead to a slightly lower energy yield.

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.

Australian PV Institute (2021) APVI Solar Potential Tool (SunSPoT). <http://pv-map.apvi.org.au/sunspot>

Australian Standard AS/NZS 5033 Installation and safety requirements for photovoltaic (PV) arrays

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>

Solargis (2019) Solar resource maps and GIS data for 200+ countries. <https://solargis.com/maps-and-gis-data/>

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