YEARS 7-10

Renewable Electricity from Solar Photovoltaic Cells

Fact sheet reference for:
Discovering Solar PV Technology

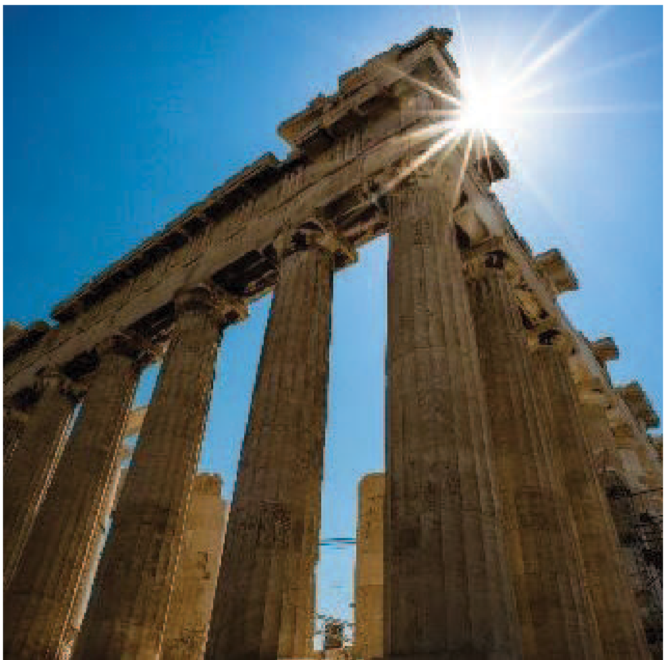
STUDENT FACTSHEET

The origin of "Photovoltaic"

When you start to investigate solar energy one of the first words you will come across is "**photovoltaic**". This word is made up of two separate mini-words: photo and voltaic. Photo comes from an Ancient Greek word, phos, which means light. This word is thousands of years old and has found its way into several modern words, such as photograph and photosynthesis.

The 'voltaic' part of photovoltaic comes from a man called Alessandro Volta, an early scientist who was born more than 270 years ago in Italy.

in 1745 and lived until 1827. Alessandro Volta is famous for inventing the first chemical battery. The Volt is the unit used to measure the amount of electrical energy carried by electrons (you can think of it as like water pressure).



Putting these two word meanings together, how do you think **photovoltaic** could be translated?

Types of Solar Panels

There are two main types of solar panel – one type is the **solar thermal panel** which heats a moving fluid, and the other type is the **photovoltaic panel** which generates electricity. They both use the same energy source: sunlight – but change this into different energy forms: **heat energy** in the case of solar thermal panels, and **electrical energy** in the case of photovoltaic panels. Photovoltaic panels have no moving parts - electricity is generated from photovoltaic cells which are a type of electronics.

What do Photovoltaics do?

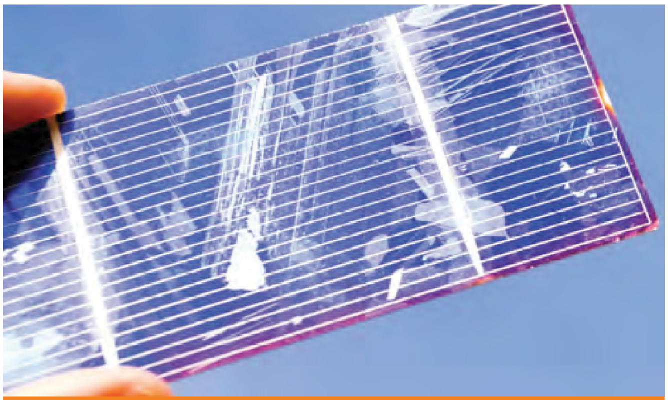
Photovoltaic cells transform (change) radiant energy from sunlight directly into direct current electricity. This electricity can be used as soon as it is generated, or it can be used to charge a battery where it can be stored (as chemical potential energy) for later use.

To generate more electricity, photovoltaic cells are connected together in series. Photovoltaic panels are built from many photovoltaic cells connected together. Until the early 2000's photovoltaic cells were mainly used for generating electricity in remote regions where it was too costly to install power lines.

Since the mid-2000s there has been an exponentially increasing amount of activity installing photovoltaic panels where there is also a connection to the electricity network of power lines. The electricity network is widely known as "the grid":

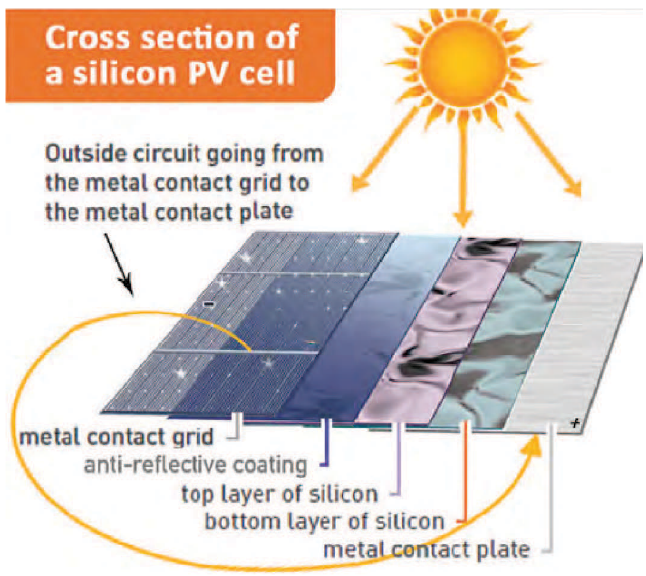
What are they made from?

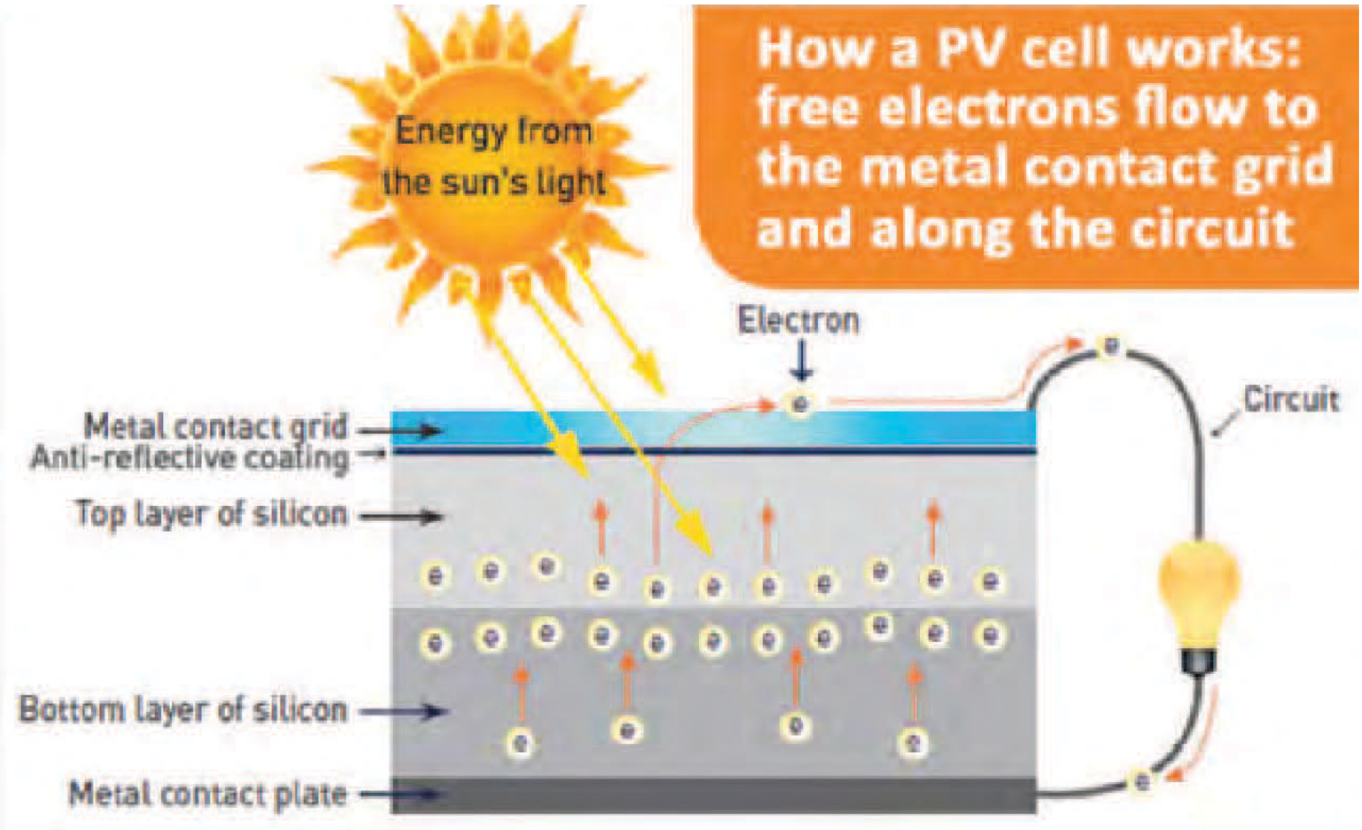
Photovoltaic cells, the building blocks of photovoltaic panels, are usually made of two layers of silicon.



A single photovoltaic cell showing licon crystals glinting in the sunlight. Also note the thin metal lines. A typical photovoltaic cell is 15 cm on each side and only about 0.2 mm thick. Silicon is very brittle by itself.

Silicon is the 14th element on the Periodic Table. The silicon generally has a crystalline structure. Photovoltaic cells use a slightly modified type of silicon for each layer- the top layer has another element such as **phosphorus** added in small quantities to the silicon, and the bottom layer has another element such as **aluminium** added also in very small amounts.





The top layer of silicon has a metal contact grid overlaid on top of it- a bit like a wire netting. The metal contact grid is generally made of the element silver due to its property of being very electrically conductive. This metal contact grid links up with an outside circuit that eventually returns the electric current to a metal sheet sitting below the bottom layer of silicon.

The addition of small quantities of other elements, modifies the electrical properties of silicon and is called doping - this is the basis of electronics. To find out more about how PV cells work see the School-gen poster: **The Science of Solar Energy**.

Because silicon has the physical property of being shiny, it would normally reflect a lot of the sun's light. Reflected light cannot be used since it goes elsewhere. To solve this problem, the photovoltaic cells are covered with a very thin layer or coating of anti-reflective material that allows the sunlight to travel into the silicon where it can be absorbed. The anti-reflective coating gives the silicon surface a dark blue or black appearance because it is absorbing most of the light that falls on it – this is the opposite of reflection. The energised, free electrons cross onto the metallic contact grid where they flow as a 'stream' or current on to the metal wires, through the circuit where they give away their energy, and then back to the metal sheet at the bottom of the photovoltaic cell.

When the electrons, depleted of energy, arrive back at the bottom layer of silicon, they join back up with the atoms ready to repeat the journey if they meet another bit of sunlight.

What happens when sun shines on silicon?

When a bit of sunlight (called a **photon**) hits a silicon atom, the energy from the sunlight can cause some of the silicon's outer orbiting electrons to be knocked away- this allows it to break free from its parent atom. The **free electron** carries some of the energy that it gained from the light.

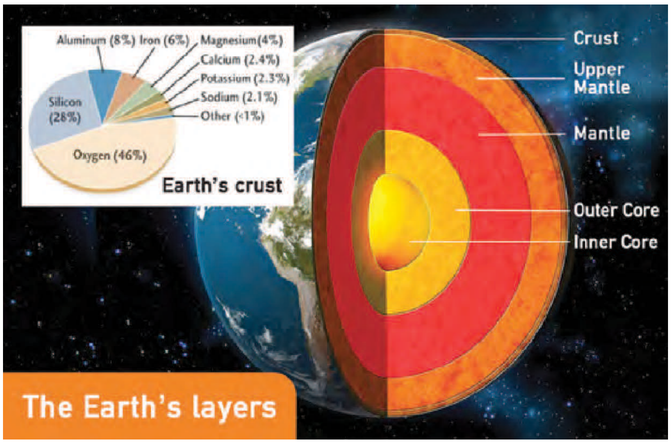
The free electrons rise from the bottom layer of silicon to the top layer (because of the effects of the two contrasting silicon layers). This flow of trillions of electrons is really a flow of energy that can be used to power lights, motors, computers and any other electrical device or technology.

Is all of the sun's energy used?

Some of the sunlight's energy just passes through the silicon without knocking electrons free, so it can't be used to generate electricity. The maximum amount of solar energy that a silicon photovoltaic cell can transform into electrical energy is about 25% (but usually only about 15%). The solar energy which can't be used gets transformed into heat energy. This is because not all of the sunlight has the right amount of energy to free the outer electrons in the silicon.

To find out more about how PV cells interact with light see the School-gen poster: **The Science of Solar Energy**.

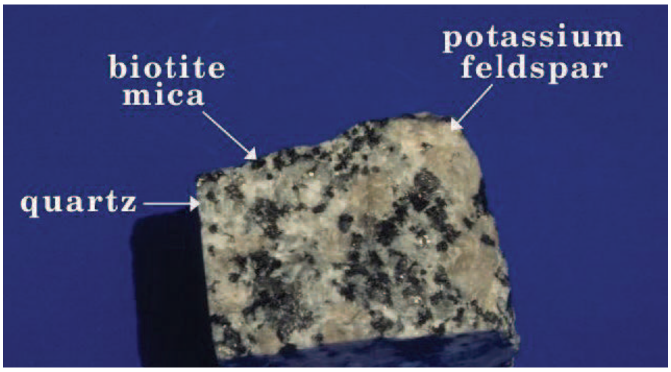
The different colours in the solar spectrum have different amounts of energy (which is why they look different to our eye!) Some of the colours in the invisible infrared part of the spectrum for example do not possess enough energy to knock electrons free. Some of the colours have more than enough energy, and any excess energy gets transformed into heat. Some energy is lost because the light hits the shiny metal contact grid and gets reflected away.



Where could I find some silicon?

Silicon is the second most common type of atom in the Earth's crust but silicon does not naturally exist by itself in a pure state – you can't go out to a rock outcrop and find a lump of silicon! Silicon atoms as they occur in the Earth are always bonded (joined) with other atoms such as oxygen, aluminium and iron.

The Earth's crust is the thinnest outer layer of the solid Earth. The crust is thinner under the oceans and thicker on the continents. Silicon is the second most common element by mass in the Earths' Crust. Other common elements found in rocks are also shown.



What's in a grain of sand?

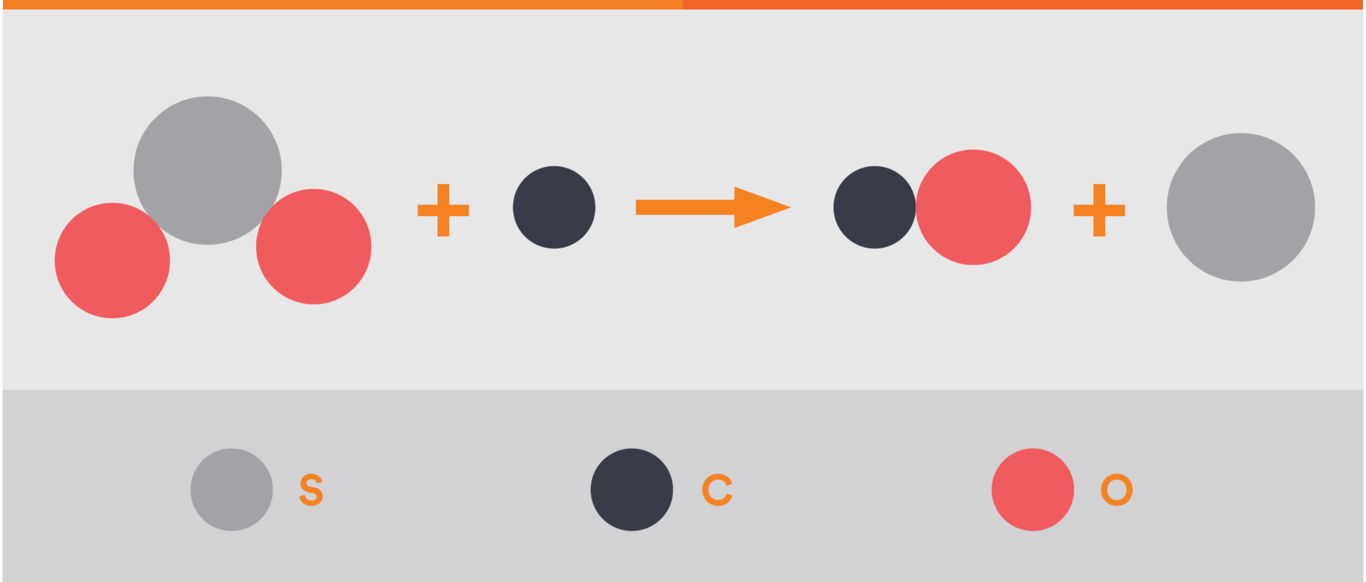
Before you can make a photovoltaic cell, or a computer chip, the silicon must first be extracted from minerals containing a lot of silicon like quartz sand. Quartz is a very common naturally-occurring compound of silicon and oxygen atoms bonded together. Silicon can be extracted by chemical processes from compounds with a lot of silicon in them.

The mineral quartz, well known to occur as beautiful large crystals, usually occurs in less spectacular forms such as quartz sand. Quartz and other common minerals, such as feldspar, weathers out of quartzrich rocks such as granite during the rock cycle. Because quartz is very hard and resistant compared to many other minerals found in rocks, it lasts longer and is often concentrated in large quantities in certain areas such as beaches and dunes. The quartz sand is a common raw material used to make silicon.

Quartz is also used to make glass, which is a compound not an element.

Mining pure quartz sand for processing into silicon.

Specimen of granite, a common rock in the Earth's Crust containing quartz and other silicon bearing minerals.

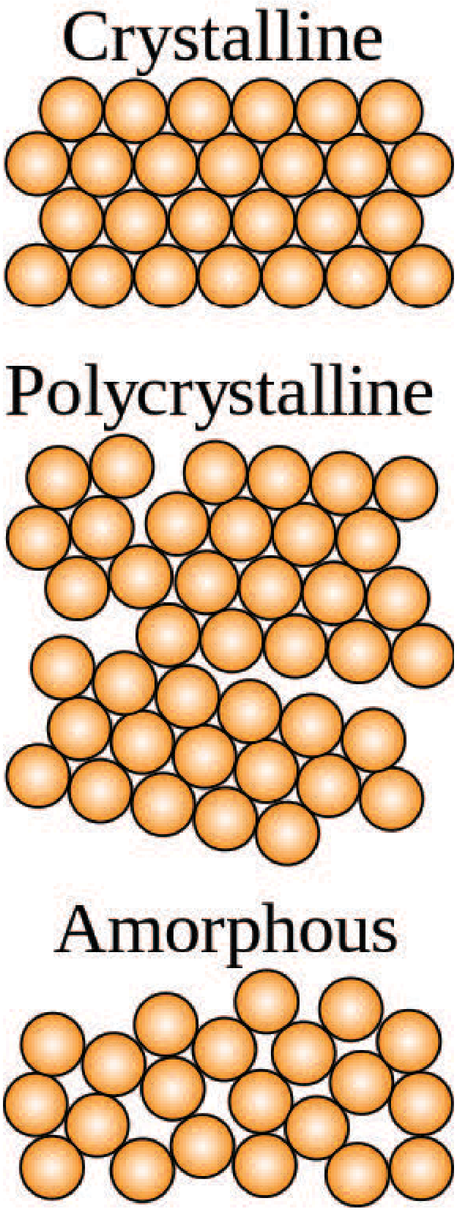


How to extract silicon from sand

Quartz is made of silicon and oxygen atoms. The chemical name for quartz is silicon dioxide (SiO2). The oxygen needs to be removed by a chemical reaction called reduction (this is the opposite of oxidation). The simplified chemical reaction is: Silicon dioxide + Carbon → carbon monoxide + Silicon. The only time this reaction can happen is with very high temperatures. This is carried out industrially in an electric-arc furnace with temperatures above 1450°C. The raw silicon is then processed to make it extremely pure and then grown into crystals where it can then be cut into silicon wafers to be made into photovoltaic cells or computer chips.

Different Types of Silicon

The three most studied materials in history are concrete, steel and silicon. This is because of their massive importance to technology and to human civilisations. Silicon atoms can arrange themselves in three main ways; crystalline, polycrystalline and noncrystalline (or amorphous). Crystals have extremely well-ordered arrangements of atoms. Non-crystalline substances have more random arrangements of atoms.



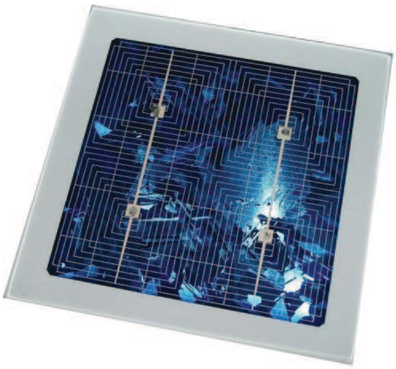
Crystalline Silicon

Most photovoltaic cells are made from thin slices that are sawed from a large chunk of purified silicon. The silicon chunk can be a single giant crystal (called a boule), or a block of multiple crystals all inter-grown together (called an ingot). Slices of silicon made from the giant crystal are called mono-crystalline silicon, and those that are sliced from the block are called polycrystalline silicon. Photovoltaic cells are made from either mono-crystalline or polycrystalline silicon. Mono-crystalline silicon is slightly more efficient but there is not a lot of difference in practice.

Amorphous or Non-Crystalline Silicon

Another kind of photovoltaic cell is also made from that common element silicon but in this case it is not given the chance to slowly grow into a crystal structure. Materials without a crystalline structure are called amorphous- glass is a good example of an amorphous material. Amorphous silicon has the advantage of being easily made into extremely thin layers or films, much thinner than crystalline silicon can be cut. By using less silicon (and also energy) they are cheaper to make. They can also be made flexible, unlike brittle crystalline silicon, by depositing the silicon on flexible metal foil or even plastic. The disadvantage of thin-film silicon is that you need a lot more area of thin-film silicon to generate the same amount of electrical power as with crystalline silicon.

Polycrystalline silicon ingot



Photovoltaic cell cut from mono-crystalline silicon

Photovoltaic cell cut from the polycrystalline silicon - notice the intertwined crystals

Boule of monocrystalline silicon grown from a silicon seed crystal

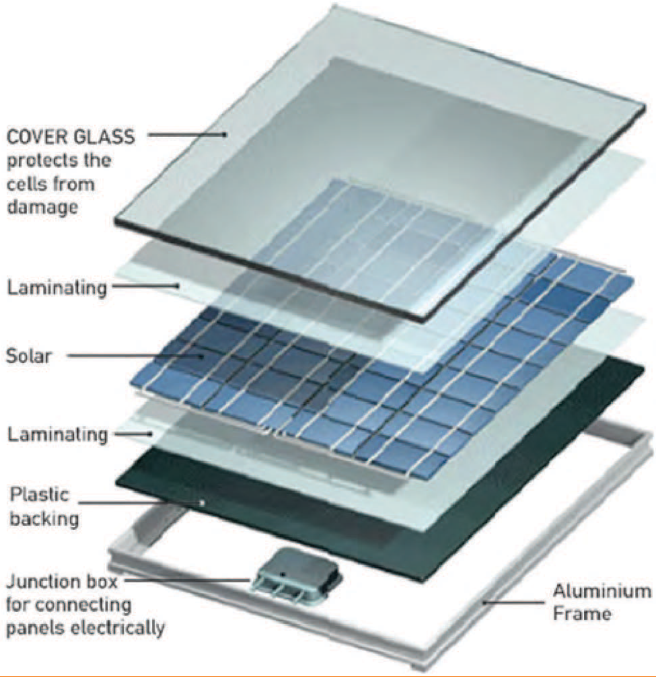
Thin-film silicon on glass used with the Lake Tekapo Schoolgen installation. Note the larger area of the panels to generate the same amount of electricity.

Protecting the Photovoltaic Cells

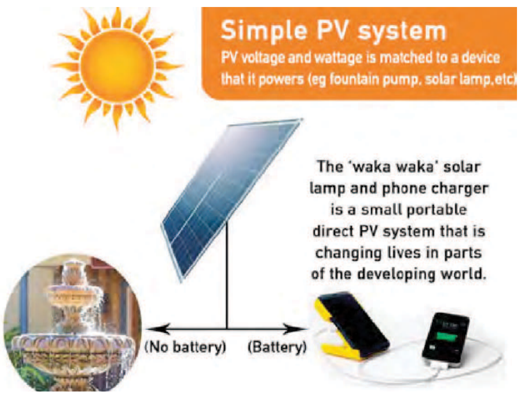
In a solar PV panel, usually consisting of 60 or 72 photovoltaic cells, a strong protective glass cover sits on top of the photovoltaic cells to shield them from impacts, dirt and the weather. The glass used is very tough to resist impacts such as from large hailstones. It is also much clearer than ordinary glass and lets through more light, including invisible forms of light such as infrared and ultraviolet. The whole panel is further strengthened with an aluminium frame. This process of protecting the photovoltaic cells in a panel is called encapsulation. See the diagram of the exploded panel below.

Types of Photovoltaic Systems

A photovoltaic system can be as simple as a panel connected directly to an appliance such as a pump, fan, or light. The electric current produced from a photovoltaic cell is Direct Current (DC), the same as that produced by a battery. Direct current can be used to power specially designed DC appliances, including lights, televisions and refrigerators. However, most appliances we use require Alternating Current (AC) to operate.

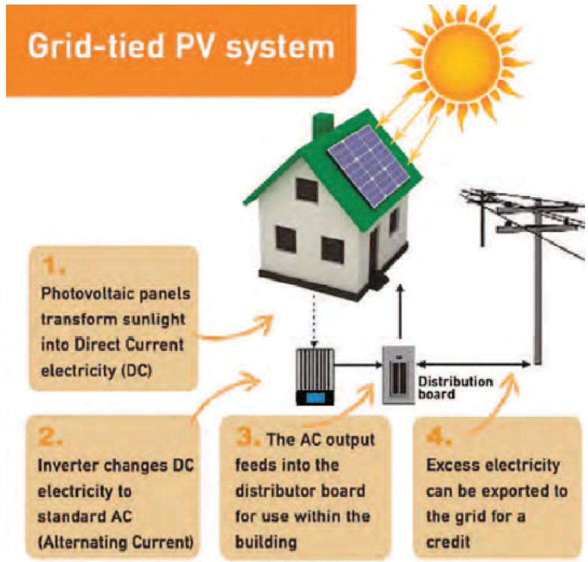


Exploded view of a photovoltaic panel showing how the PV cells are protected to withstand any weather conditions and to allow them to last at least 25 years.



On-Grid ("Grid-tied") PV Systems

Most appliances we use require AC electricity because most buildings are connected to "the grid" (outside power line network). The grid transports electric energy generated in power stations which is always AC. In New Zealand, power stations produce AC power



Inverter for typical grid-tied system used in some Schoolgen Schools

that alternates (moves back and forth) fifty times a second (50 Hertz). An important piece of equipment in many photovoltaic systems is the inverter. An inverter changes DC from the solar panels into AC so that it can be used by everyday appliances. The inverter could be described as a "DC-AC converter". All photovoltaic systems that are connected to "the grid" (outside power line network) will need an inverter. An inverter can also export any extra power you have generated with your solar panels back into the grid where it can be used by other consumers (eg your neighbour.)

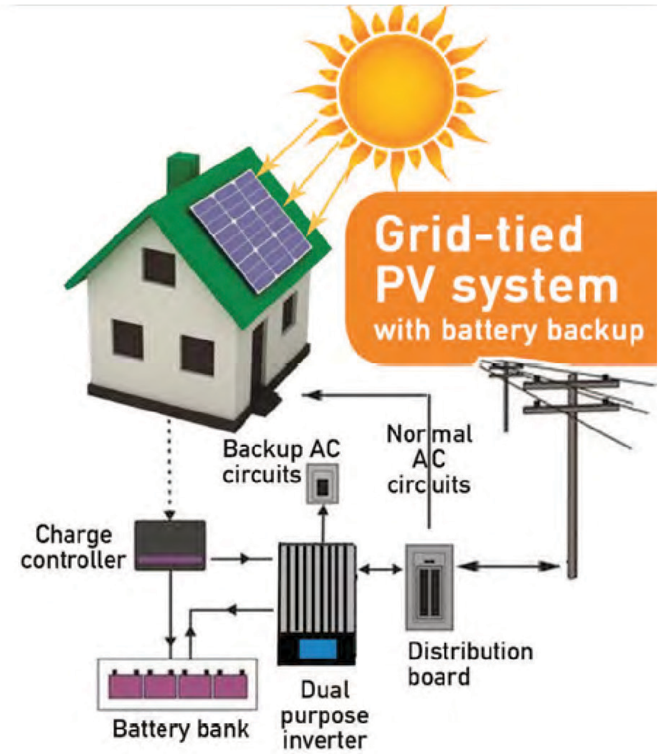
Off-Grid PV Systems

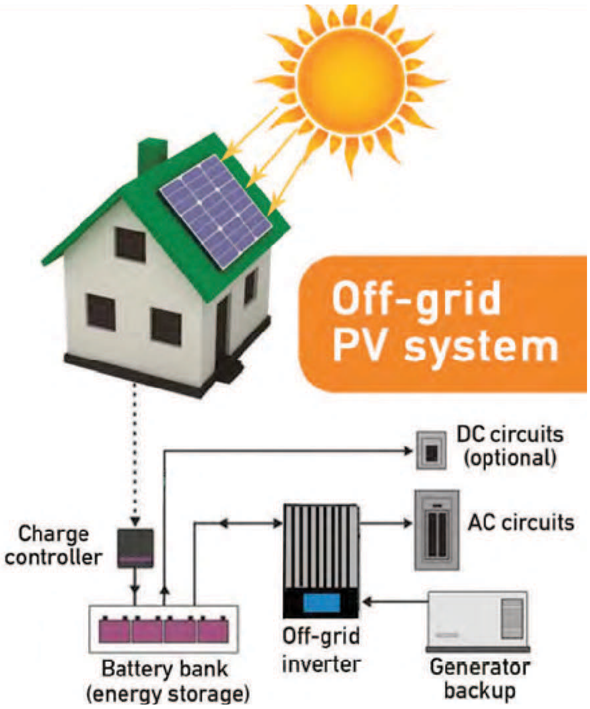
Off-Grid Systems, sometimes called stand-alone systems, may be necessary in remote areas where it is too expensive to build power lines to connect to the grid. Systems not connected to the grid will not be able to import (get from the grid) any extra electricity required, such as at night or during very cloudy weather. Off-grid solar systems always need a backup form of generation such as diesel, biomass, hydro or wind. Usually an off-grid system will have a way to store any excess electricity generated from solar during the day. Storage of energy is usually done with a battery or battery bank.

Other promising ways of storing energy such as ultra-capacitors and hydrogen are being developed. Energy storage is a rapidly moving field so it is recommended that you research what the latest development are.

Grid-tied with energy storage

These systems are a hybrid between and on-grid and off-grid system. In the event of a power-cut, normal grid-tied photovoltaic systems automatically shut down for the safety of electricians who might be called in to work on the lines nearby. However essential appliances and equipment can still be run from energy stored in the batteries, while the solar panels can also continue to charge the batteries.





Another advantage of battery backed systems is that if the photovoltaic panels cannot supply enough electrical energy to the appliances (eg if a cloud passes over), then the energy is just topped up from the battery. The disadvantage is that it is a lot more expensive to install and the batteries need more frequent maintenance and replacement. Lake Tekapo School, one of the Schoolgen Schools, was set up with a battery system to allow the school to operate as an emergency community centre for the town in the case of a power outage with enough energy for up to 5 days.

How to get the most out of Solar PV

There are several factors that can affect the amount of electricity produced by a solar photovoltaic system. The amount of sunlight and the orientation of the panels (direction and tilt angle) are two of these factors. You can't do much about the amount of sunlight as this is determined by geography, time of day, season and weather. For fixed panels there is an optimum direction and tilt for the panels which will maximise the output in certain conditions, so if building a new house or selecting a building, this is an important consideration.

Orient panels correctly

Orientation is the direction that the panels are facing when viewed from above, and also the tilt angle of the panels. A true north facing roof is optimal for New Zealand and other places in the Southern Hemisphere.

This is because when the sun is highest in the sky, at solar noon, the sun is shining from true north (not to be confused with compass north). The panel tilt is usually the same as the roof but panels can also be installed on tilt-frames to have a different tilt than the roof – see Whakatane Intermediate School's solar panels. Photovoltaic panels at Whakatane Intermediate School with north facing orientation on a tilted frame. Note the south sloping roof angle.

Photovoltaic panels at Whakatane Intermediate School wirh north facing orientation on a tilted frame. Note the south sloping roof angle

For grid-tied systems it is often recommend Wed to tilt the panels at an angle equal to the latitude minus ten degrees. This will maximise the overall output for the year. However, if you want to improve the performance in winter, when the sun is lower in the sky, it is necessary to have a steeper tilt on the panels.

Two schools with quite steep panel tilts are Whakatane Intermediate School in the Bay of Plenty (about latitude, 38 degrees), and Taupo College in the Central North Island (about 45 degrees). You can compare these schools winter/summer performance on the Schoolgen website.

Avoid shading

Shadows lower the performance of solar panels so avoid any trees or buildings that will cast shadows across the panels. If some of the cells on a panel are shaded this will restrict the current through the whole panel, limiting its power output.

This is because the photovoltaic cells in a panel are all linked in series – the electric current travels through each photovoltaic cell in a line – so the weakest link in the chain limits the amount of electrical current produced by the whole panel. Even if only one tenth of a photovoltaic panel is in shadow, the electrical current produced can be reduced by as much as one half.

Keep panels clean

For a similar reason to shading, any buildup of dirt, pollen, lichen or bird droppings on the panels will result in a loss of power output. In New Zealand where there is quite high rainfall the panels are to some extent self-cleaning, but they still benefit from occasional cleaning.

Allow heat to ventilate

As photovoltaic panels heat up in the sun, the power output decreases slightly for each degree of temperature increase. Ventilation at the back of the panels ensures that heat can escape easily and not cause the panels to become excessively hot. Since most panels are mounted on roof racks there is a gap between the roof and the panel which allows air to flow and regulate temperature.

High winds

It is very rare for solar panels to be blown off a roof, but it is important to ensure that support structures for the panels are strong enough to withstand high winds. To keep a panel very secure, its position on a roof is also important: if the panels are installed near the edges rather than in the centre of the roof, the force of the wind can increase by a factor of three.

Ensure good quality equipment and installation

There are hundreds of brands of photovoltaic panels and inverters. Quality varies however, so it is best to choose a reputable and reliable brand of panel and inverter. It is also important to have a reliable company to install the panels. An organisation with a proven track record will be able to advise the most suitable system configuration and arrange the necessary consents and paperwork. The electrician who installs the system needs to meet all of the required standards. Finally, an electrical inspector from the lines company will need to "sign off" the system to prove that it meets all the necessary safety standards.

Planning to install a Photovoltaic System

There are a number of factors that will influence the decision to install photovoltaic panels on either a new building or an existing one. Some people will install solar panels mainly because of environmental concerns and to increase their sustainability and decrease their carbon footprint. In the early days of photovoltaic technology when it was very expensive and uneconomic for most situations, "early-adopters" drove the expansion of this green energy technology. Photovoltaic technology is now mainstream in most parts of the world such as Europe, Australia and the USA.

Economic factors

Now that the cost of panels has dropped dramatically, and looks set to continue falling, it is close to reaching the point where it is economic for building owners in New Zealand to install them - and to expect a positive payback from doing so.

The economic factors are:

- The cost of buying and installing the PV system.
- The amount of electricity in kilowatt hours it will generate over its life.
- The current price of buying electricity (cents per kilowatt hour).
- The possible future price of buying electricity.
- The price paid to you for exporting extra solar electricity to the grid.

Time of Use: When do you use electricity?

If you are a school or business you probably use more energy during the day. If you are not at home during the day you probably use more electricity at night. What changes could you make to shift electricity use to the daytime?

Advantages and disadvantages of installing a home PV system

Advantages	Disadvantages
Generate your own sustainable electricity	Depends on the amount of sunlight
Electricity used straight away is most cost effective	Need to shift energy use to during the day
Low maintenance	If off-grid will need batteries which are expensive.
System will slowly pay itself off over time	Substantial upfront costs to install. Exported electricity pays less money
Long life (25 year panel guarantee)	Panel output decreases about 0.8 % per year
No greenhouse gas emissions	Fighting global warming will take more than just solar panels

How much electricity do you need to generate from solar?

If you are connected to the grid the best option is a grid-tied system. This way you don't need batteries to store energy for use at night or on very cloudy days, and you don't have to put in a huge photovoltaic system to supply all your energy needs in winter. You can also install as small or large a system as you want. For some houses a 1 kW system will supply a decent proportion of their electricity needs, whereas a larger house with more occupants might install a 5kW system.

A 1 kW system would typically generate between 1100 - 1400 kWh of electrical energy per year depending on your location and the factors above. The average NZ home uses about 8000 kWh of electricity per year but much of this will be used at night or when the sun is not shining much so this electricity is simply drawn from the grid.

Sometimes you would generate more than your daytime use- typically in summer, and in winter you would probably generate less than you used. By having a grid-connection you can import the shortfall and export the excess.