What is the best grid-connected solar photovoltaic (PV) inverter topology and why?

STRING INVERTER VS STRING INVERTER WITH DC OPTIMISERS VS MICROINVERTERS

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Introduction

If you install solar systems or looking to purchase a solar system, you may want to know what is the best grid connected solar inverter topology and why.

Solar modules produce Direct Current (DC), which cannot be used by common household and commercial electrical appliances that use 240V Alternating Current (AC). The DC from the solar modules therefore requires conversion to AC using a device called an "inverter".

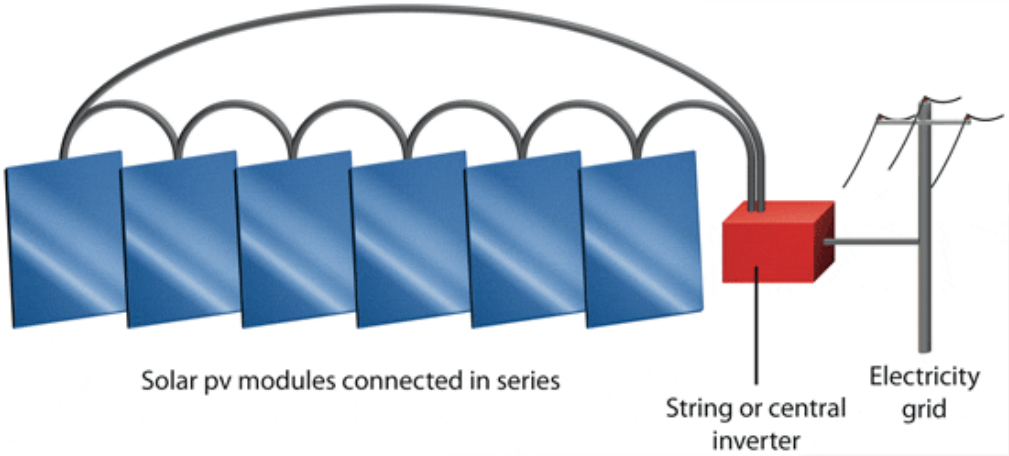
There are currently three inverter topologies available on the market.

- Central String Inverters
- Central String Inverters with DC Optimisers
- Microinverters

So which inverter topology is best and why?

CENTRAL STRING INVERTERS

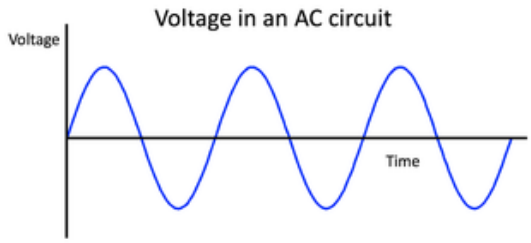
A central string inverter is a large inverter, which is used to convert the DC voltage from a string of solar panels, connected in series, into 240V AC for use by standard domestic and commercial electrical appliances.

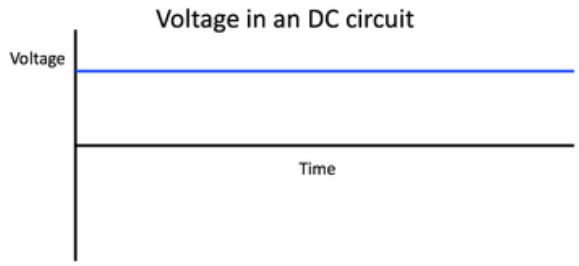


This topology was the initial approach used for the first grid connected solar systems. The name "central string inverter" was used because the device, itself, was central to the whole configuration, that is, all of the solar panels relied on the functioning of that single inverter device to perform all of the electricity conversion.

Whilst this method works, there are some key shortcomings that have been observed over the years, which is why newer topologies have been developed since.

The solar modules connected together in series results in dangerous DC voltage (200 to 1000V DC) fed from the string of solar modules on the roof down to the central string inverter, which is often mounted on an outside wall of a home or inside a garage. DC voltage is very difficult to protect against compared to AC because the voltage is constantly above zero. If a fault occurs on the DC circuit the arc is very difficult to quench because it is continuous, whereas AC voltage alternates between positive and negative (passes zero) 100 times a second (50Hz) at which point a protective device can easily isolate any arc fault which occurs. A fault on DC cabling is much more likely to arc continuously causing a fire. There is also no protection between the solar modules and the inverters so in the event of a fire or shock there is no means to isolate the supply automatically.





This is one of the key reasons AC is used to provide electricity throughout buildings in Australia. It is inherently safer than DC.

A fault on these DC circuits can produce a continuous arc, which can cause fire – the arc can melt steel, glass and cause most building materials to ignite. DC voltage is used for arc welders because a continue arc is what is required to melt steel.

There have been numerous house and building fires as a result of faults on the DC wiring on solar systems. The faults have been occurring at the DC isolators located on the roof or elsewhere, DC connections at the array, at the inverter, any connections or anywhere along the DC cables from the roof to the inverter.

A fault can occur from the following:

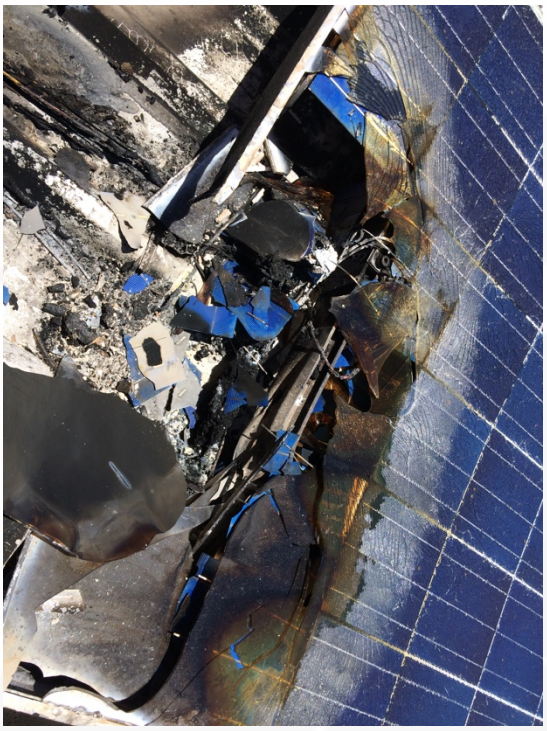
Poor installation of DC cabling - loose terminals, DC plugs not plugged together correctly, mismatched DC plugs, damaged insulation, incorrect cable sizing, use of non DC components, inadequate UV protection or water ingress

Poor quality DC components - poor quality DC isolators, poor quality DC connectors, water ingress, or poor quality DC cables used.

Damage to the DC cabling - Damage caused by rodents, possums, birds, insects etc or future building works (for example a tradesman or home owner drilling through the DC cables damaging insulation)

Aged DC wiring - A fault can occur simply due to ageing of the DC cabling, isolators and connectors age. As DC connections age they corrode and the impedance increases to a point where an arc fault can occur. The DC cabling insulation degrades with time resulting in an arc fault or waterproof seals deteriorate and allows water ingress.

Examples of failed DC Isolators



Solar fire caused by dangerous DC voltage arc. The arc started on the DC cabling inside the building and continued up to the array igniting the building along the way.

Fire brigade extinguished the fire.

The likelihood of faults on dangerous DC voltage increases as the solar system ages.

As an attempt to address this problem Australian Standards have introduced new design requirements to help reduce the risks however unfortunately these are engineering controls that only help to reduce 'some' of the risks.

Australian Standards require that the DC cabling from the array to the string inverter be installed in heavy-duty conduit to help prevent damage to the insulation of the cables (eg vermin, renovations etc). Installation of heavy-duty conduit from the roof to the inverter can often be onerous and increase the cost of the installation. Whilst installing heavy-duty conduit does reduce the risk of future damage to conductor insulation, the risks of poor connections, conductor insulation degradation over time and damage to insulation during installation, water ingress, corrosion all still remain. Also, should an arc fault occur within or below the heavy-duty conduit (eg DC isolator near the inverter) the conduit ensures the DC conductors are in close proximity allowing the arc to propagate up through the building.

The pictures above are a recent installation with heavy-duty conduit installed to Australian Standards where this has occurred.

There is also a requirement to install a DC isolator on the array so that in the event of a fire emergency services can isolate the array to reduce fire or shock.

In Australia, there have been hundreds of roof fires caused by DC solar systems and DC isolators and there have been a wide variety of DC isolators recalled.

In the example above the fire brigade extinguished the fire and as there was no protection between the solar modules and the inverter, and the DC isolator could not be operated, the fire reignited as they were preparing to leave. The sun was shining on the solar modules hence they were still producing electricity. Fortunately, the fire fighters heard the arcing and disabled the solar system completely.

DC voltage in this range can also damage cells and solar modules in the array. This occurs when voltage potential and leakage current drive ions from the semiconductor material to other elements such as the module frame and glass resulting in yield losses, increased O&M, hotspots, electrochemical corrosion, increase in series impedance and decrease of shunt impedance.

When using solar modules connected in series to a central string inverter, the entire solar system's performance is only as good as its weakest solar module. If shading, soiling, or even a potential defect reduces the power output of one solar module, then all of the solar modules in that string are affected proportionally since they are all connected together in series.

Solar modules typically have a 'positive tolerance' of 5%, which means that a box of 250-Watt solar modules will have modules that range from 250-Watts to 262.5-Watts, so in a central string inverter topology, the weakest module will limit the higher power-producing modules.

Temperature also affects the performance of solar modules (each make and model has a specific temperature coefficient). The higher the temperature the solar module is operating at the lower the power it produces. Solar modules at the edge of an array tend to perform better than solar modules located within the array because the modules at the edge are exposed to cooling breezes. This variation can be significant with commercial arrays.

Solar module performance degrades over time and some degrade faster than others so as time goes on solar systems with string inverters reduce in performance at the rate of the weakest solar module.

Mismatch in solar modules makes it difficult for string inverters to utilise the full potential of the solar arrays actual capacity.

Another limitation with string inverters is that all of the solar modules have to be installed at the same orientation and tilt angle otherwise the arrays performance is affected by the panels with the access to the least amount of solar resource at any given time. This can make it difficult to design the solar system to match the load profile.

If you wish to add more solar modules you will need to increase the capacity of the inverter and also add an entire new string of solar modules. You will need to find the same make and model of solar modules for the upgrade so that DC voltages are the same. Sourcing solar module models that are a few years old are almost impossible so upgrading a string inverter system is often difficult and costly.

Some solar installers supply large inverters to allow for future upgrades. However, inverters are most efficient when operating at full rated power. The efficiency drops off if there is significantly less solar capacity. So while you are waiting to upgrade you will have a poorly performing system and, when you do get around to upgrading the inverter it may be close to the end of its design life.

Central string inverters need to convert a large amount of energy at higher voltage and require large electrolytic capacitors to do this. Large electrolytic capacitors are often the weakest component in the circuitry and are not long-lasting — as often, the dielectric paste becomes brittle and cracks or simply leaks out of the casing - hence the reason why central string inverters typically last for only around 5 years resulting in multiple string inverters required over the life of a given solar system.

String inverters need to be sized for each solar system size, so manufacturers have to produce a large number of models sharing their engineering design resources across the range, which is why there are often reliability problems with various models of string inverters. Installers need to carry a variety of makes and models so that you ideally match the inverter to the solar system size. For large commercial systems string inverters can often be bespoke (custom made for the project) increasing the likelihood of reliability issues.

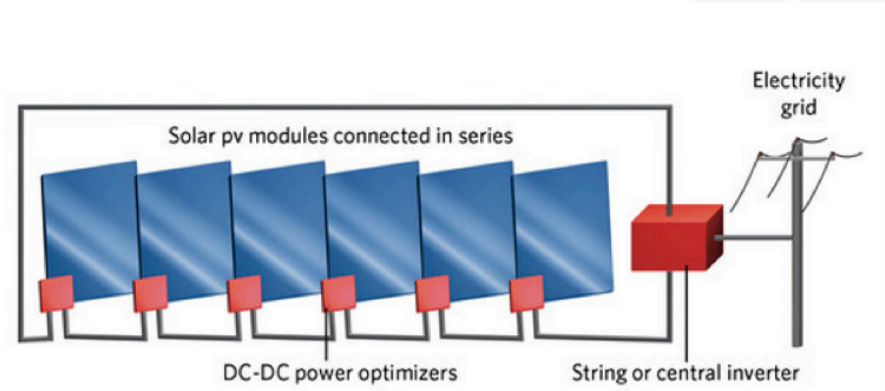
A string inverter failure results in the solar system not producing power until a suitable replacement inverter is sourced and installed. Often a failure is not noticed until an unfavourable electricity bill is received and then replacement is required immediately. For large commercial systems replacement can take months once identified.

CENTRAL STRING INVERTERS WITH DC OPTIMISERS

To address some of the limitations with central string inverters, DC optimisers were developed. DC optimisers are designed to reduce the effect of uneven shading of the array.

This was achieved by individually tuning the performance of the solar panel through maximum power point tracking, and optimally tuning the output to match the performance of the string inverter.

Power optimisers are useful when the performance of the power generating components in a distributed system vary widely, differences in equipment, shading of light, being installed facing different directions or widely separated locations.



DC optimisers are added to each solar module and communicate with a central string inverter. So a central string inverter compatible with the DC optimisers must be used.

While DC optimisers improve the performance and safety of traditional string system design they do not address the all of issues associated with DC cabling. DC cables need to be installed in heavy-duty conduit from the roof to the string inverter, which increases installation costs. The solar system requires a DC isolator, which has been a source of failure with string systems.

Adding DC optimisers increases the possible points of failure with additional components and additional points of connection. If the string inverter fails the whole solar system will stop working until an inverter, which is compatible with the model of DC optimisers that are on site, can be sourced.

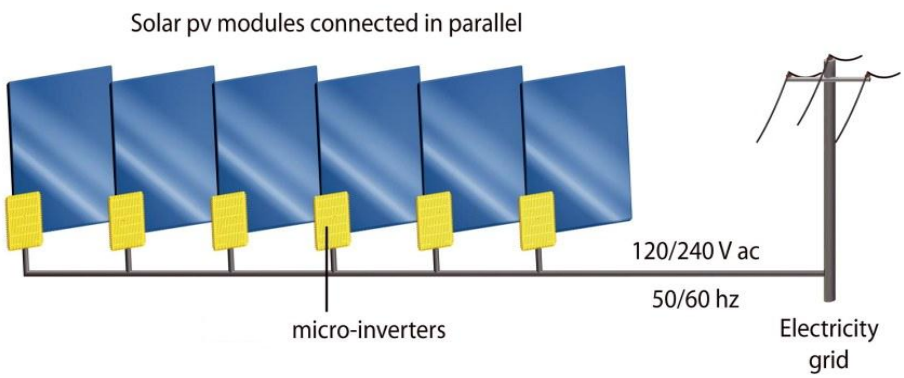
Being essentially a central string inverter system, if you wish to add more solar modules you will need to increase the capacity of the inverter and also add an entire new string on solar modules. You will need to find the same make and model of solar modules and DC optimisers for the upgrade so that DC voltages are the same. Sourcing solar module models and DC Optimisers that are a few years old can be challenging so upgrading a central string inverter system in future is often difficult and costly.

Central string inverters with DC optimisers need to be sized for each solar system. So you will need to carry a variety of makes and models to ideally match the inverter to the solar system size.

MICROINVERTERS

Microinverters were developed to eliminate dangerous DC voltages in solar systems, improve the performance of the solar array by providing maximum power point tracking (MPPT) for each solar module, improve reliability and provide ease of upgrade. Solar modules can be easily added to the array.

Microinverters convert a small amount of power at low DC voltage hence the stress on electronic components is reduced. The inverter is very small so the components can be encapsulated in a compound for protection and improved thermal efficiency.



A key benefit of microinverters over string inverters is that only one inverter is designed and manufactured for all solar system sizes. Whether it is a single solar module array or 1MW of solar modules, one inverter is required. This provides manufacturers with an opportunity to optimise design by focussing all engineering resources on just one model and manufacture using mass production techniques improving reliability and reducing costs.

The use of microinverters ensures there are no dangerous DC voltages in the system, therefore eliminating risk of fire completely.

Elimination of a hazard is the optimum solution in risk management compared to engineering controls so you do not need to rely on arc protection devices operating as designed, which does not always occur in fault conditions.

Hierarchy of hazard control commonly used for electrical equipment

Solar modules can be installed in any orientation and a variety of tilt angles. The solar modules with low access to solar resource will not limit function of others in the array as each solar module acts independently. Mismatch of solar modules does not affect the solar system. Each module operates to its peak. So the overall array performance is increased.

Also unlike central string inverters and DC Optimisers, microinverter systems start producing power as soon as there is sunlight on one solar module and will keep producing power until sunlight leaves the last solar module. Central string systems and DC Optimisers do not start to produce power until sunlight is on a number of solar modules in the array.

If an inverter fails only one solar module is affected. The remainder of the solar array continues to supply power while a replacement is being sourced. It does not result in an emergency call out.

Additional solar modules can be added at any time. There is no need to source the same solar modules as installed because they are all connected in AC. The latest model solar modules can be added even if they are larger and have different DC voltages.

For example 310w solar modules can be added to an array of 250w solar modules and each solar module will perform at its peak.

You do not have to overinvest in a large solar system now to meet future increased energy usage. You can start out small and add solar modules as you can afford them while using the latest model solar modules at the time.

BATTERY COMPATIBILITY

The most widely used rechargeable battery technology in use is the Lithium-ion battery. Sony first developed the lithium ion technology in Japan in 1991.

They are commonly used in various mobile devices, computers, mobile phones, power tools, toys, electric vehicles and now storage for solar systems.

Lithium ion technology is very sensitive to charging. If the charge voltage is too high, the battery can be susceptible to thermal runaway and cell rupture. In extreme cases this can lead to combustion.

Incorrect charge voltages can lead to permanent damage to the battery and hence reduce life and performance of the battery.

Lithium ion is perfectly safe if the charger is perfectly matched to the battery. It is also important that the charging system has fail-safe circuitry that disconnects the battery when its voltage is outside the safe range.

Basically there are two types of batteries available on the market for use of storing solar energy

- **DC Battery**; and
- **AC Battery.**

DC batteries require an external battery charger and inverter to convert the DC to 240V AC for use in the home or business. The inverter/chargers and the DC batteries are often designed and produced by separate manufacturers. The choice of which inverter/charger to use is ultimately made by the solar installer which poses the risk of not matching the battery correctly and hence resulting in poor performance and voiding warranty of both components.

DC batteries have dangerous DC voltage cabling between the battery and the inverter/charger which can cause arcing; they also require the use of a DC solar system, which has the associated issues with performance, reliability, safety and flexibility to upgrade as discussed earlier.

AC batteries have an interactive inverter/charger incorporated into the battery. The inverter/charger is perfectly matched to the battery and covered by one manufacturer so there is no charge voltage risk. AC

batteries are wired to the switchboard using a single AC cable as per Australian Standards AS3000. There are no dangerous DC voltages:

The leading AC battery technology on the market is the Enphase AC battery.

ENPHASE AC BATTERY

The Enphase AC Battery is a new approach to energy storage. This is a modular style AC battery which has an interactive inverter/charger incorporated into the battery enclosure. The inverter/charger is designed specifically for the battery eliminating the risk of inverter/charger mismatch and installer design/selection liability. The Enphase AC Battery uses Lithium Iron Phosphate (LFP) which is the most robust battery chemistry in the Lithium-ion range today.

If there is a problem with combined performance of the battery, inverter or charger it is addressed by one manufacturer.

The batteries are modular in design so that the size of the battery system can be determined based on the storage requirements. To increase the battery capacity AC batteries can be easily added, even if the new battery is a different model with completely different battery chemistry. They are connected in AC.

The Enphase AC battery is controlled by the 'Envoy-S Metered', which measures the home's energy usage and solar generation and directs excess solar energy into the battery for use at night. It has CT's (Current Transformers) for the solar supply and CT's for the mains supply. Two CT's for single phase and six CT's for three phase.

This system is designed to calculate and display the balance between solar generation and energy consumption in an installation (the amount of solar energy being exported) – so the energy storage components can be confidently and ideally sized to suit the home's specific needs. The modular approach of the Enphase AC Battery enables the optimum amount of storage to be installed. Ongoing monitoring enables the continuing optimisation of the system should energy consumption or generation patterns change over time.

For example, if a 5kW solar system is installed on a home where much of the energy generated during the day is used there may only be a small amount of excess solar energy available to charge the battery for use at night. In this situation one or two Enphase AC Batteries may be all that is required to optimise the system. It would not be sensible or cost effective to install a large expensive battery in this situation. If daytime energy usage reduced for some reason in the future, one or more AC Batteries can be easily added to ensure energy is not wasted and exported to the grid for little return.

The Envoy-S Metered can be installed and the energy usage of the home or business can be monitored so the ideal battery size can be determined.

The Enphase AC Battery is small, wall mounted and very quick and easy to install. It is wired directly into the existing switchboard using standard AC cabling. There is no external DC wiring or control wiring and hence no dangerous DC voltages which can be the cause of fire or shock – so it is a much safer system than DC energy storage options.

The Enphase AC battery is part of a fully integrated energy management system, meaning that there is no need to match a hybrid inverter with it from another manufacturer as is required in many DC battery storage systems. If any warranty issues arise these can be addressed with a single supplier as opposed to having to potentially deal with multiple equipment manufacturers. This is particularly important when dealing with battery warranty claims because battery manufacturers often point the finger of blame at the

device controlling the charging and discharging of the battery. There is also no design liability risk to the installer matching the battery with the inverter/charger.

The Enphase AC battery can also be fitted to existing AC or DC solar systems. It has CT's (Current Transformers) for the solar supply and CT's for the mains supply. The solar CT's can be installed on the output of the string inverter. This avoids the need to upgrade an existing solar system with a new inverter capable of charging batteries in order to implement energy storage.

Compared to other forms of battery technology the performance of the Enphase AC battery is very impressive. The AC battery is designed to discharge to 95% depth of discharge (DOD), which is a huge leap forward from lead acid and other battery technologies whose life would be drastically shortened if used to this depth of discharge. The high allowable depth of discharge is one of the key reasons why the Enphase AC Battery is so compact in size compared to other technologies.

The Enphase AC Battery has a warranty of 10 years and 7,300 cycles. That's 2 cycles every day for 10 years. By comparison the typical warranty on a high quality car battery is just 2 years.

Often battery prices are compared on the basis of dollars per unit of capacity (kWh). This is a valid method of comparison only if apples are being compared with apples. A DC battery price usually only includes the cost of the battery, and sometimes the battery management system (BMS). The Enphase AC Battery includes the BMS as well as an interactive inverter and the interface with the integrated energy management system. Once these additional costs, the ease of installation, performance and safety considerations are taken into consideration, the price for the Enphase AC Battery represents excellent value for money.

DC BATTERY

There has been a lot of money spent on the marketing of DC batteries. However the architecture of the design is old and based on central string inverter systems. Fundamentally, DC batteries require an inverter charger from another manufacturer that exposes risks to incorrect charging voltages and design/component selection liability.

There is often dangerous DC voltage cabling required to connect the battery and the solar systems would need to be a DC solar system which has the various design shortcomings as listed above.

The DC cabling will vary from site-to-site and will be determined by the solar installer, which exposes the risk of incorrect voltage drop and hence charge voltage variation.

Customers will need to purchase a large system at high capital cost even if their storage requirements are a lot less than the capacity of the battery. Whereas a lower capital cost AC battery solution would achieve the same result with improved safety and flexibility.

Often people believe that it is more efficient to use the DC directly from the solar modules to charge the batteries. However, often DC batteries are made up of a large number of small DC batteries which all have varying charge and discharge characteristics. The charging and discharging performance (efficiency) of a large DC battery is often influenced by the weakest battery within the DC battery.

AC Batteries are small and modular and hence control a smaller number of batteries within the battery compared to large DC batteries, so the efficiency of each AC battery exceeds the efficiency of a large DC battery because they perform independently. So while there are some losses by converting DC to AC of less than 3% (inverter losses) this is often eclipsed by the battery round trip efficiency (RTE) variation.

THE BEST INVERTER TOPOLOGY

We believe the optimum inverter topology is microinverters due to the improved safety, performance, reliability and flexibility of design and upgrade, and battery ready capability.

They incorporate well with AC battery technologies and provide the user with a well-developed integrated energy solution.

For installers, microinverters in conjunction with an AC battery provides the flexibility to meet every customers specific energy needs.

All of the major high quality inverter manufacturers produce microinverters.

Below is a summary of the key differences between the various inverter topologies:

Key Criteria	String Inverters	String Inverters with DC Optimisers	Microinverters
Safety	Dangerous DC Voltage • Risk of fire or shock • Heavy duty conduit required from roof to switchboard as per AS5033 • DC isolators required which are a major point of failure	Dangerous DC Voltage • Heavy duty conduit required from roof to switchboard as per AS5033 • DC isolators required which are a major point of failure • Some DC Optimiser systems have arc detection protection.	NO dangerous DC voltage
Performance	String Inverter systems are negatively affected by: • Shading (clouds, trees, aerials etc) • Uneven solar module degradation • Uneven soiling (bird droppings, leaves, dust etc) • Maximum Power Point Tracking of strings • Does not start to produce power until sunlight is on all of the solar modules	DC Optimisers improve the performance of String Inverter systems System does not produce power until a number of solar modules are exposed to sunlight	Provides an improved performance over DC optimisers by up to 3.1%. Starts to produce power when the first solar module is exposed to sunlight and keeps producing power until the last solar module is exposed to sunlight. Maximum Power Point Tracking of each solar module
Reliability	Inverter is exposed to higher voltage and converts large amounts of power increasing stress.	Inverter is exposed to higher voltage and converts large amounts of power increasing stress.	Inverter is exposed to low voltage and converts a small amount of power reducing stress

	If the inverter fails the solar system stops generating electricity until a replacement is sourced and installed. A replacement inverter needs to be selected to suit the DC string voltage and array capacity which may limit the range of inverters available The inverter needs to be installed by an accredited installer with experience with DC and AC wiring Inverter manufacturers have low design hours per model, as there are various models required, hence more design related failures	If the inverter fails the solar system stops generating electricity until a replacement is sourced and installed. An inverter designed to work with the particular model DC optimiser at the site must be selected for replacement. This can be challenging to source. The inverter needs to be installed by an accredited installer with experience with DC and AC wiring and DC Optimisers Inverter manufacturers have low design hours per model, as there are various models required, hence more design related failures	If an inverter fails only one solar module is affected. The remaining solar modules produce power while the replacement inverter is sourced and installed The latest model micro inverter can be used as replacement. There is no need to source the same model as the existing microinverter. They are all connected in AC and operate independently. The replacement of the microinverter is "plug and play". There is no wiring required and hence can be installed by wide variety of solar installers Inverter manufacturers have high design hours, as there is only one inverter size. Hence high reliability. Microinverters have remote monitoring capability for fault finding
Flexibility	To add more solar modules complete new strings are required Cannot add individual solar modules Need to use the same make and model of solar modules already installed which can be very difficult to source Need to upgrade the inverter to meet capacity Need to install all of the solar modules in the same tilt angle and orientation	To add more solar modules complete new strings are required Cannot add individual solar modules Need to use the same make and model of solar modules and power optimisers already installed which can be very difficult to source Need to upgrade the inverter to meet capacity Can install on multiple tilt angles and orientation	Can add individual solar modules as they operate independently Can use the latest model solar modules. There is no requirement to use the same solar modules with the same voltage as they are connected via 240V AC not DC No need to upgrade any of the existing inverters Can install on multiple tilt angles and orientation
Cost	Various inverter sizes required: • Hard to purchase in bulk quantities • Require high variety of stock	Various inverter sizes required: • Hard to purchase in bulk quantities • Require high variety of stock	One inverter for all systems sizes: • Can purchase in bulk quantities • Only require one or 2 inverters in stock

	• Manufacturers need to produce a variety of inverters designs • Need to use an inverter to the nearest design size • Need to install DC cabling	• Manufacturers need to produce a variety of inverter designs • Need to use an inverter to the nearest design size • Need to install DC cabling	• Can size inverters to the exact size of the solar system • No need to install DC cabling • Fast and consistent install for all system sizes (domestic and commercial)
Battery Compatible	Need to replace string inverter with an interactive inverter/charger for DC battery There is dangerous DC voltage cabling required for a DC battery Installer is responsible for ensuring the inverter/charger and battery are perfectly matched Can use AC battery without changing inverter and adding more dangerous DC voltage wiring	Some string inverters designed to work with DC optimisers have charging capability. You would need to check whether the charging voltage and charge protection is suitable for the DC battery being used. Installer is responsible for ensuring the inverter/charger and battery are perfectly matched Can use AC battery without changing inverter and adding more dangerous DC voltage wiring	Can use AC battery No dangerous DC voltage cabling required. Manufacturer is responsible for ensuring the inverter/charger and battery are perfectly matched. Inverter/charger has been designed for the battery

About the Author

David is a qualified electrician with a Bachelor of Engineering in Electrical and Electronics with Honours. David is a Registered Professional Engineer of Queensland, a Member of Engineers Australia and Clean Energy Council and accredited for design and installation.

David has been working with solar technologies since 1996; firstly designing remote area power supplies for western cattle properties and National Park ranger stations through to domestic and commercial solar grid connected systems. David was Principal Engineer Generation at Ergon Energy for over 7 years where he was responsible for the management of 33 power stations, including wind, biomass, geothermal and solar farms. David was involved with the design and installation of the first grid connected solar system in Queensland and developing the first grid connection guidelines. David has used string inverters for many years for domestic and commercial designs and became interested in microinverters when he was involved with designing and delivering a project using microinverters for the Townsville Solar cities in 2008. This involved spending time in the US working with inverter manufacturers where microinverters are widely used. David co-established AC Solar Warehouse with Grant Behrendorff in 2012 to help people in Australia access the benefits of microinverter technology for use in domestic and commercial solar applications.

About AC Solar Warehouse

AC Solar Warehouse is a 100% Australian owned and operated company that wholesales microinverters, AC and DC Solar panels, energy storage equipment and related components required for domestic and commercial solar systems.

We are the only specialist wholesaler of AC Solar equipment in Australia and have built our business through relationships based on honesty, transparency and integrity.

AC Solar Warehouse has a team of professional engineers with Clean Energy Council design and installation accreditation, and years of practical experience in the solar industry. Our engineers provide professional advice on optimum domestic and commercial solar design, technology selection and installation.