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An in-depth study on solar photovoltaic: Design, operation, and maintenance

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Abstract

The constant increase in greenhouse gas emissions in the world degrades the ozone layer and jeopardize the future of the planet. In order to respond to this major challenge, governments and organism (example industries) are mobilizing to reduce the use of fossil energies and increase the use of renewable energies. Solar energy is free and inexhaustible. It is one of the main energies renewable.

This paper discusses pros and cons about design, maintenance and performance monitoring and management on solar panel. Innovation in this field is also reviewed.

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Introduction

This article contains all specifications that can be formulated for the procurement of small to mid-sized (50 – 500 kW) solar PV systems, as seen in figure 1, across the world. These specifications constitute a framework to deploy the technology in a standardized and cost-efficient manner.

Specifications will be available for the system's key components, panels, and the electric balance of system. This section also prescribes the minimum requirements surrounding insurance and warranties.

One of the most important considerations to choose a solar panel is its quality through the system's projected lifecycle and the manufacturer's reliability. The performance should be guaranteed by a manufacturer's warranty, and the manufacturer must be a financially stable organization to back the warranty throughout its effect.

This paper discusses about design (type of panels, inverters….), main technologies and maintenance. It also includes performance monitoring and management.

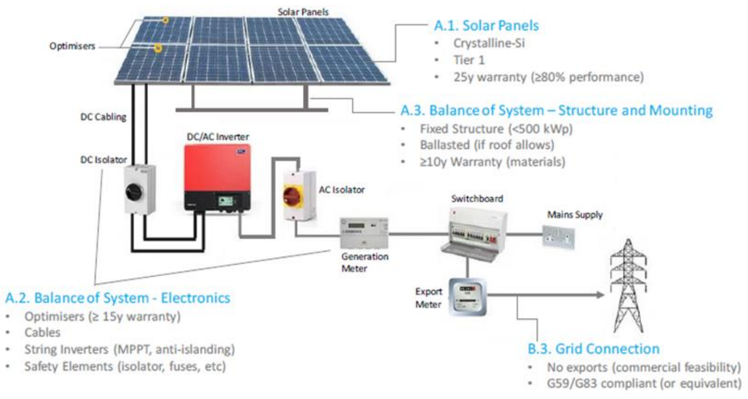

Fig 1: Solar PV systems schematic

Main technologies of panels

Crystalline Silicon (c-Si) panels have been prescribed due to their superior long-term efficiency and commercial availability (Battaglia *et al*., 2016) [7].

Monocrystalline (mono-Si) panels are the most efficient type of c-Si panels (Kahoul *et al*., 2021) [13], but these tend to be more expensive than polycrystalline (poly-Si). Other key differences are the speed at which efficiency degrades over the years, and the amount of square footage needed on the location per MW_p installed capacity, both of which are better for mono-Si (Arissetyadhi *et al*., 2020) [5].

Both technologies are easily recognizable from their appearance as shown in figure 2. Mono-Si panels are made of uniformly looking cells that tend to be darker with a visible cut-out corner profile from the cutting of ingot. Poly-Si panels are usually made into square wafers that are usually lighter in color with an uneven visual appearance.

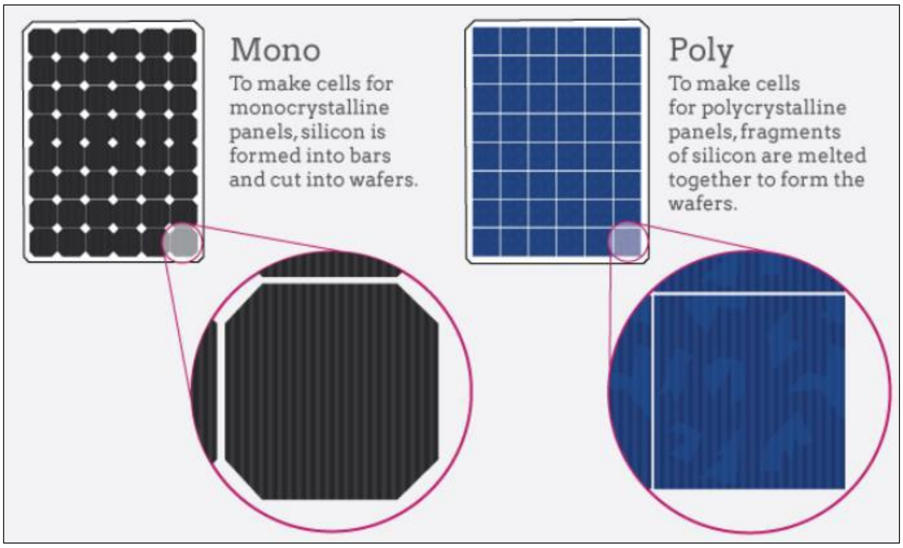

Fig 2: Mono and Poly Silicon appearance

Consequently, install monocrystalline panels as a first preference, especially on location where conditions for solar PV are favorable. Favorable conditions are a combination of:

- High irradiation
- High power prices
- Good policy incentives / tax breaks

If the location is considered to have unfavorable Solar PV conditions, poly-Si panels can be explored, particularly if there is a large additional cost required for mono-Si panels. The better yield of mono-Si panels, and the subsequent better revenue (kWh generated multiplied by the kWh price) might still provide a worse Net Present value (NPV) as compared to poly-Si.

Mono-Si panels have better electrical properties and perform better with time and unfavorable conditions. Their main characteristics of both technologies are described in the table 1.

Table 1

	Monocrystalline	**Polycrystalline**
Cost	~$0.38/W	~$0.36/W
Lab Achieved Efficiency	~26%	~21%
Commercial Efficiency	15% - 22%	13% - 20%
Space-efficiency (power density)	55 - 115 Wp/m2	50 - 100 Wp/m2
High-temperature tolerance	Higher	Lower
Low-light performance	Higher	Lower
Degradation	Lower (~0.4%/y)	Higher (~0.5%/y)

The map in figure 3 shows climatic conditions across the world and provides an indication whether mono-Si is the best solution or whether poly-Si should also be considered.

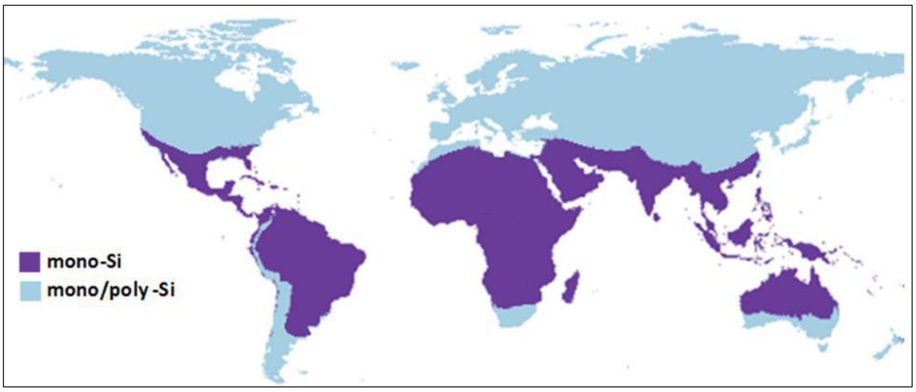

Fig 3: Regions with climatic conditions that favor mono-Si over poly-Si

Mono-Si panels are recommended in environments with high radiation and temperatures. Mono-Si Panels have a higher efficiency, in general, and cope better with rises in temperature. Also, mono-Si panels efficiency degradation is slower compared to poly-Si panels. In these regions, the yield difference between a typical mono-Si panel and a poly-Si panel is amplified. Increased capital costs associated with mono-Si are more likely to be recovered through increased savings, provided power prices are substantial.

Both mono-Si/poly-Si panels could be appropriate in the regions with low or medium high radiation and temperatures. Whilst mono-Si panels would provide the highest year-round efficiencies, a lower irradiation would mean this increase in efficiency results in marginally higher yields. In other words, the increase in yield might not justify the increased capital expense in this case. The higher sensitivity of poly-Si panels to temperature increases will also be less relevant in the blue-highlighted areas.

Inverter

The sizing of the inverter will affect both the capital expenditure and the yield of the system (Dogga & Pathak, 2019). It is necessary to do a thorough sizing exercise considering all other design parameters was done to determine the optimal equipment. Consider the following characteristic in inverters: DC/AC ratio.

The DC/AC ratio is determined by dividing the rated power of the solar panels by the rated power of the inverter.

Solar inverters can change the operating point of the panels to curtail DC power and keep the AC power within limits. This is denoted as "clipping". This opens the possibility to install inverters with smaller ratings than the panels.

Since the solar panels are rarely operating at their rated power, the clipping losses can be negligible for ~1.1 DC/AC ratios (which is common practice). A smaller inverter will be less expensive, and the yield losses might be justified by the smaller capital. The optimal DC/AC ratio for a system might be bigger than 1.1, and the only way to determine it is by doing a detailed modelling. Losses under 1% are obtainable for DC/AC ratios of up to 1.3 in some situations.

The optimal sizing of the inverter is influenced by its efficiency curve. As seen in the figure 4, the peak efficiency is obtained around ~30% of the load. For bigger loads the efficiency remains high, but for lower loads the efficiency drops very quickly.

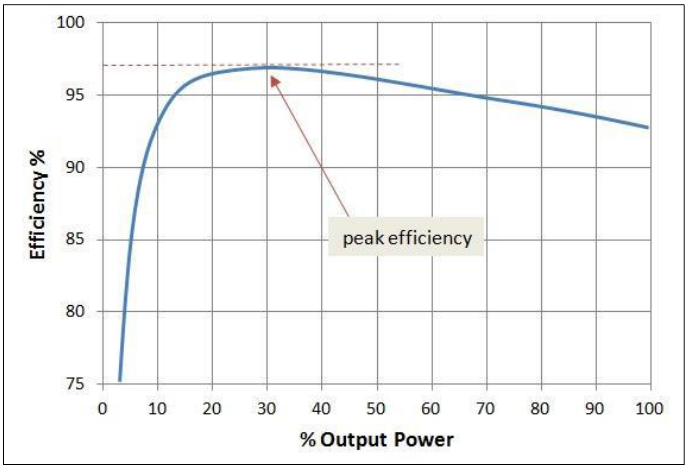

Fig 4: Typical efficiency curve of an inverter

The loading of the inverter will be determined by the DC power that the panels are producing in each instant, which means that most of the time it will be lower than a 100%. As seen in figure 5, if an inverter is undersized the clipping losses increase, but overall operation might be more efficient – both in yield and capital expenses. An oversized inverter is not only more expensive but depending on site conditions the average efficiency might be lower for low light conditions.

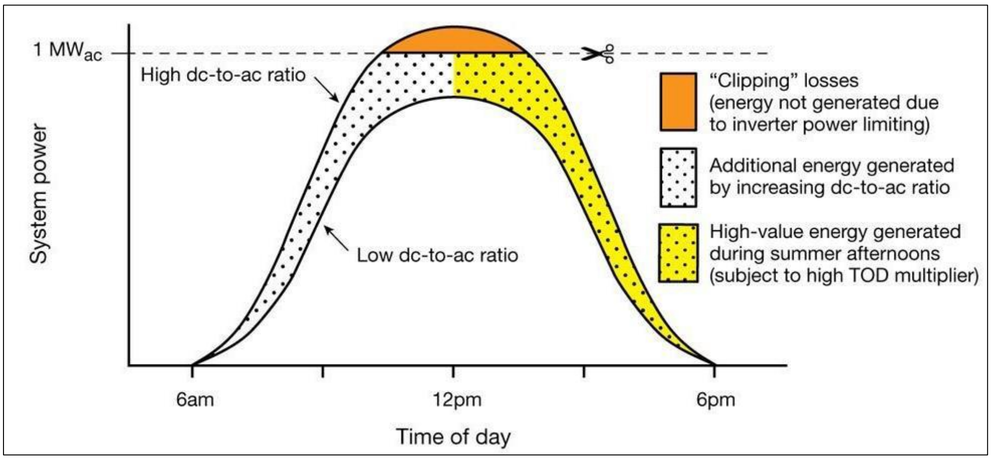

Fig 5: Effects of DC/AC ratio

The California Energy Commission (CEC) has proposed a weighted average efficiency, typical for high irradiation locations:

$$\eta CEC=0.04\eta 10\%+0.05\eta 20\%+0.12\eta 30\%+0.21\eta 50\%+0.53\eta 75\%+0.05\eta 100\% \quad (1)$$

This efficiency is meant to match the average operation in a radiation regime like that of California. There is a European standard for locations for less radiation. Use European standard for higher latitudes.

CEC efficiency will allow to compare inverters for real operating conditions, keeping in mind the DC/AC ratio will affect the average efficiency. All other parameters help determine the operational limits of the inverter and must be kept in mind for inverter design. Also use temperature coefficients to estimate Voc, Isc under 1250 W/m^2 and extreme recorded temperatures at site.

Balance of System (BoS)

Electronic Components

The electronic components used in the system can account for up to ~15% of total losses. Using the right and optimally sized equipment can have a major impact on overall performance. Below, some specification to meet to ensure efficient operation of the PV system:

1. **Inverter Manufacturer**
    a. Inverter CEC Efficiency ➔ ≥ 96%
    b. DC/AC Ratio ➔ 1.1 – 1.3 (optimize)

2. **Cables DC Cable**
    a. DC cable Type ➔ Specially Designed “PV Cables”
    b. Cable Sizing ➔ Applicable Standard
    c. DC and AC Cables Max Voltage Drop ➔ 3%
    d. DC String and Main Cable Voltage Rating ➔ ≥ M x Voc x 1.2* *
    e. DC String Cables Current Rating ➔ ≥ (N-1)x Isc x 1.35**
    f. DC Main Cable Rating ➔ ≥ N x Isc x 1.35 Cable tray and enclosure Required

3. **System**
    a. DC Elements’ ‘Max Voltage Rating’ ➔ ≥ Voc x 1.2
    b. DC Elements’ ‘Max Current Rating’ ➔ ≥ Isc x 1.35

* M stands for the number of panels connected in series in each string and N for the number of strings connected in parallel per inverter. * Multiplication factor (1.2) is based on extreme low temperature conditions. Warmer sites could use lower multiplication factors, provided calculations are done by developers.

** Multiplication factor (1.35) is based on extreme warm temperature.

Structure and Mounting

The optimal mounting system should be determined after carrying a sub-surface investigation for ground-mounted systems and a structural survey for roof mounted systems.

Roof-Mounted Systems

The main consideration for roof mounted systems will be protecting the existent waterproofing. This is done ideally by avoiding penetration, which might damage or make the waterproofing’s warranty void. This can be achieved by using ballasted systems, which will weigh the mounting to the roof without any anchoring. This can only be implemented on flat roofs able to withstand the additional load. Tilted roofs will require other types of anchoring and fixing.

Ground-Mounted Systems

Ballasted systems can be cost-competitive and quickly deployed in ground-mounted applications, provided the conditions are adequate. These include a levelled ground with no flooding risk and no invasive vegetation - weed control membranes might be needed. Plastic applications underperform in high temperatures, due to a higher heat absorption which reduces yield of the system.

Driven beams (usually steel posts rammed into the soil) are another good alternative for ground mounted installations. These will work in any type of soil unless subterranean conditions render them unpractical or more expensive.

In those cases, anchoring mechanisms like ground screws or expanding anchors should be considered. These are typically more expensive and take longer to install but allow for shallower soil perforation. In some cases, the soil penetration will not be allowed, or the system will need relocation before decommissioning. The only alternative for those cases is a ballasted system. For their convenience and lower cost, plastic ballasts can be considered before concrete ballasts. However, these systems will not work in land with high slopes or risk of flooding, and in most cases levelling works will be necessary.

Optimizers and Micro-inverters

When some panels or even part of a panel is shaded or affected, this can reduce the yield of all the string. This effect, denoted mismatch, can be very significant on systems with considerable shading, soiling or even sections with different tilts and orientations.

To address these losses, optimizers or micro-inverters can be used. Fixing mismatch can increase yield in over 2%, depending on shading conditions. Both optimizers and micro-inverters are mutually exclusive.

Optimizers

- Reduces the mismatch in DC allowing for string inverter to optimize all string.
- Efficiencies above 99% (96% when combined with string inverter efficiency).
- Increases Operations and Maintenance (O&M) and failure rates (less than micro-inverters).

Micro-inverters

- Carries DC to AC conversion for a single panel, having local MPP (Maximum Power Point Tracking) tracking.
- Efficiencies ~96%.
- Perform MPP tracking individually for each panel.
- Increases O&M and failure rates.

Due to panel integration and reduced failures and costs, it is recommended to consider optimizers over micro-inverters. Both technologies are being actively developed, so this balance might change in the future.

Optimizers make more sense with shading and high Ground Coverage Ratio (GCR). Hence, they are recommended in all roof-top applications. Optimizers also improve performance with panel degradation.

New electricity standards (2017 NEC in the US) require PV systems to have isolation on the panel level, which will require optimizers. This will allow to monitor and even turn down panels individually in a remote manner.

Design Standards

Array design is essentially an optimization process that is specific to each site. This section provides some background on key considerations; orientation and tilt; soiling and shading; land roof system considerations and fixed versus tracking systems.

Soiling and Shading

Efficiency of solar panels over the lifetime of the asset will depend in large parts to soiling and shading issues. Soiling losses refer to the loss in capacity due to dirt, dust, snow, sand, or any other particles that cover the surface of the model (Mustafa *et al*., 2020; Kleissl & Mejia, 2013) [18, 14]. Shading results from other items, whether fixed or temporary, prohibiting the panels from catching sunlight directly.

Consequently, it is necessary to avoid

- Using areas with shading from trees, neighboring buildings, or other objects such as chimneys and satellites,
- Self-shading, by modelling the distance between rows of models correctly,
- Places with high dusting potential.

Orientation and Tilt

The optimal tilt will depend on the latitude and other local considerations, which should be determined by the developer using modelling software.

The optimal tilt proposed by a developer might deviate slightly from the range, as shading, space constraints, optimizer use and climatological considerations from each site will determine the tilt that maximizes NPV or yield. The fixed tilt that maximizes yield per panel is related to the site's latitude and ranges between the angles shown in the figure 6.

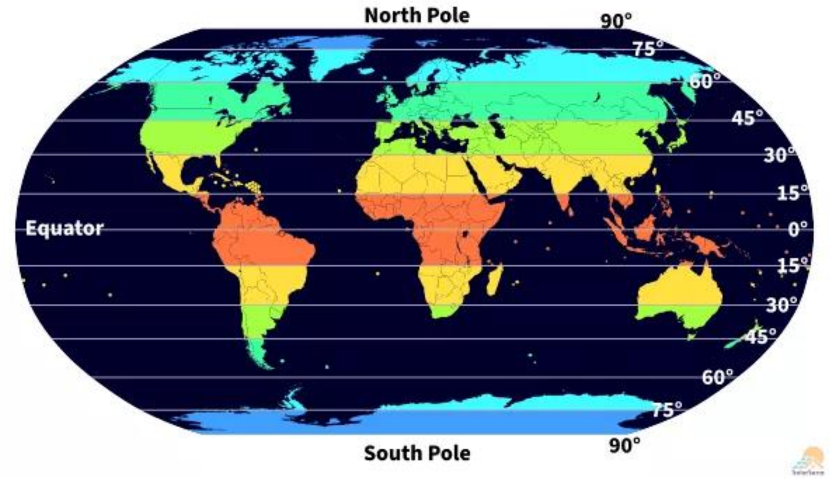

Fig 6: World map with optimal tilt by latitude (Solar Sena, 2021)

Spacing and Ground Coverage Ratio (GRC)

The optimization of spacing should also be done. Where space is very limited, it may be preferable to optimize for yield rather than NPV. This means that a system with less space between rows can increase the number of panels, hence the system's rated power and yield. However, that may lead to more shading and an overall smaller NPV or higher paybacks.

Determine ideal spacing between rows to maximize input. If optimizers are used, higher GCR (less spacing) can be achieved. Minimum spacing for no shading is latitude dependent:

- Higher latitudes will require more spacing to avoid shading.
- Required spacing increases with tilt of the panels.
- Tracking systems will require more spacing to avoid shading.

The Ground Coverage Ratio (GRC) is the ratio between the surface area of the panels and the total ground area. The optimal GRC will be higher for sites closer to the equator and ranges from 0.3 to 0.6 typically. Lower ratios will reduce shading between panels but reduce the system's rating (Wp/m^2). A strategy to maximize yield in reduced areas can be using a high GCR and optimizers on the panels.

An alternative to maximize yield in space constrained roof-mounted systems located at high latitudes (shading between panels require spacing between rows) is to use an East/West mounting. In such configuration, the panels are placed facing east and west with a tilt ~10°. This will minimize shading between panels allowing for a higher GCR and power density (kW/m2). The yields per panel can be up to 20% lower compared to the optimally oriented, but some developers are achieving lower costs ($/kW) compared to the optimal configuration, which allows for similar paybacks and NPV.

Ground & Roof Mounted Installations

Ground mounted installations should be considered if available lands can be committed for a period of over 15 years to a PV system at low or no or cost. Otherwise, roof mounted installations are expected to be the best and most common solution. Both options are not mutually exclusive, and most locations are expected to have large enough daytime electrical baseload to consume the generation of considerably sized systems.

For roof-mounted systems, do ensure roof coverage and the structural integrity of the roof are assessed by a qualified structural engineer and take into account the additional ballast provided by the panels and the balance of system (BoS). Maintenance could potentially be more difficult as well, so the complications that come with providing access to the developer's maintenance personnel are to be reviewed (Bódis *et al*., 2019) [8]. It is recommended to use ballasted systems whenever structurally possible to protect waterproofing of the building.

For ground mounted installations, consider rocks, trees and stumps that would need to be removed. Flooding risk are to be identified as well. Security concerns with ground mounted installations, particularly if placed directly adjacent to the location, could bring additional capital and/or operational requirements as well.

Fixed vs Single/double Axis & Efficiency

Tracking Solar PV systems have historically been installed using fixed panels, whether mounted on the ground or the roof. Today, panels that track the sun are becoming the norm. This minimizes the angle between the sunlight and the solar panel and capture more solar energy than it would otherwise. If the selected location is on the roof, or a sloped field, fixed panels are likely the best option. If the site is constrained by space, fixed panels are likely the best option. If a quick payback is required, single axis tracking systems could be the better option provided sizing it at the very least 500kWp

Various studies estimate that tracking systems can yield up to 50% more than fixed panels, although there is additional capital expenditure associated with tracking systems (Awasthi *et al*, 2020; Amelia *et al*., 2020) [6, 3]. There are also additional aspects to consider when it comes to Operation & Maintenance, the required space on site, all of which will be touched upon in this section.

A represented in figure 7

- Single axis tracking systems have one degree of freedom and tend to tilt from East to West so that the panels move with the sun from dawn until sunset (Racharla *et al*., 2015) [19].
- Single-axis tracking systems can also rotate along the horizontal axis.
- Double axis tracking systems have two degrees of freedom, rotating around a vertical axis and adjusting the modules to the altitude of the sun.

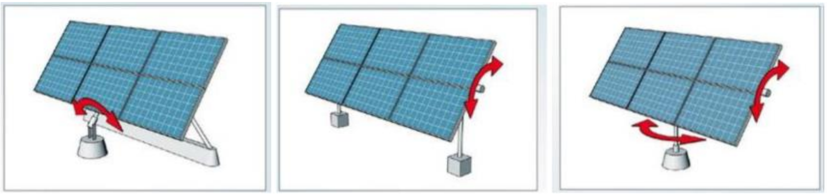

Fig 7: A tilted (left) and a horizontal single axis tracking (middle) and a double axis tracking (right) Solar PV panel

In recent years, the majority of Solar PV that is being deployed was utility scale and ground mounted, most of which was built with single-axes tracking models. In most instances, the additional yield generated by the single axis tracking system thus outweighs any additional capital or operational expenditure. Installation size, local weather, degree of latitude and specific site conditions however all play a role in determining what set-up is most appropriate. Table 2 below provides an overview of some of the key pros and cons between fixed single axis tracking systems. The additional yield provided by double axis systems is not considered commensurate with the additional costs, whether in the form of capital or land usage.

Table 2

	Fixed	Single-axis Tracking
Yield	Lower	Higher (10-50% depending on geographic location*)
Capital Expenditure	Lower	Higher (~10%)
Annual Savings (kWh)	Lower	Higher (10-50%)
Annual Savings ($)	Lower	Higher (10-70%)**
Space intensity (m2/W)	Lower (25%-100%)	Higher
Roof / Field suitability	Better for most roofs or sloped fields (>10%)	-
Climate	Better for harsh winter (snowfall)	-

* Single-axis tracking has a bigger impact on sites with latitudes closer to the equator.

** The monetary savings are affected negatively by larger O&M costs associated with the tracking mechanism. However, tracking panels provide a flatter generation profile, which primarily means that more energy is generated in the mornings and evenings, which includes the more valuable peak hours.

Maintenance

Maintenance is to be undertaken at least annually to keep an efficient and safe operating PV system (Hernández-Callejo *et al*., 2019; Abubakar *et al*., 2021) [11, 1]. A typical O&M contract includes some or all of the following activities:

For Solar Panels

- Cleaning is most needed after prolonged dry periods, where natural cleaning is reduced.
- Dry cleaning to reduce water consumption (avoid detergents) in cool conditions.
- Visual inspection cleaning for cracks or discoloration
- Infrared scan of 2% of panels (30 as minimum) for solar cells and junction box circuits.

For Low Voltage Rooms and DC connections

- All cabling and earthing connections to be checked for mechanical damage and loose elements.
- Thermal inspection to identify hot areas (high losses).
- Inventory central components.

For Inverters

- All inspections to be done on a working inverter without removing seals or covers.
- Check AC and DC voltage and current and confirm within manufacturer parameters.
- Clean and remove dust and vermin interference. Special attention to exhaust fan.
- Change air filters if any according to manufacturer specifications.
- Check for torque in cables in agreement to manufacturer's specifications.
- Compare power output between inverters connected to strings of the same size (benchmarking).

For Distribution Boards

- Visual inspection for rust or damage
- Clean dust and vermin interference
- Should be kept locked or isolated, check for any security breaches
- All breakers should be on and labelling in perfect condition
- All fuses to be examined and replaced if necessary
- Check for water leak evidence and correct if necessary
- All cabling to be firmly fixed and terminals free from rust and dust
- Inspect all AC cabling for any mechanical damages
- Test all switches

For Structure and Mounting

- Random water tightness testing on 2% (or elements corresponding to 30 panels at least)
- Inspect the visible underside part of mounting

o Seam, side and middle clamps for signs of rust or damage
o End caps to check for any missing
o Waterproofing conditions (if applicable)
o Any other visible damage on structures, foundations, or ballasting

For Meters and Sensors

- Check data monitoring is working correctly.
- Check meter display for correct reporting (kWh, kW) • Turn on/off to ensure all sensors are pyranometers and anemometers are working.

Performance Management and Key Metrics

Performance management is necessary to ensure value over the long term (Andrei *et al*., 2022; M'Baye 2022a) [4, 15]. Below, do take note of the minimum requirements for several key metrics.

Standard Testing Conditions

The electrical output of a solar panel depends on operational conditions. An industry standard to measure and compare performance of different panels was created, denoted "**Standard Testing Conditions**" (STC) (Hohl-Ebinger *et al*., 2016) [12].

The STC are reproduced in laboratories by providing the solar cells/panels a radiation of 1000 W/m^2 with a standard 1.5 AM solar spectrum whilst maintaining the solar cell temperature at 25°C. All datasheets for solar panels provide information measured under STC, unless specified differently.

Most of the operating hours of a solar panel will be under very different conditions to STC. Consequently, choosing a panel for a project based only on efficiency or power output under STC should be avoided. The operational conditions on the locations will deviate from STC in:

- **Irradiation:** Throughout the day and the seasons, the irradiation will rarely reach 1000 W/m^2. Most of the time, radiation will be lower.
- **Cell Temperature:** The operating temperature of the cell will be different to 25°C (usually higher).

Ensure to use a database with the site's climatological conditions (for at least one full year) to account for the deviations when providing yield estimations.

Nominal Operating Cell Temperature

The Nominal Operating Cell Temperature (NOCT) refers to the measured operational temperature of the panel under a predetermined ambient temperature, irradiation, and wind speed. A lowed NOCT is favored, the cell temperature being lower under these standardized conditions. Panel performance drops at higher cell temperatures, however, different panels will operate at different temperatures under the exact same conditions.

NOCT is a value reported by the manufacturer in the datasheet. The NOCT testing conditions are reproduced in laboratories by providing the solar panels with a radiation of 800 W/m^2 with a standard 1.5 AM solar spectrum whilst maintaining the panel exposed to a 1 m/s wind at 20°C and mounted with an open back side.

The International Electrochemical Commission has recently drafted a replacement for NOCT testing aiming to improve panel characterization. It is called "Nominal Module Operating Temperature" (NMOT). Not all manufacturers have migrated to NMOT, so at the moment of writing NOCT and NMOT are to be compared directly.

Smaller NOCT/NMOT values are desired, especially for warmer climates.

Typical NOCT/NMOT for solar panels are:
Mono-Si: *39°C – 50°C*
Poly-Si: *41°C – 51°C*

The operational conditions on location will deviate from NOCT in:

- Irradiation: Throughout the day and the seasons, the irradiation will differ from 800 W/m^2 most of the time.
- Temperature: The ambient temperature will be different to 20°C most of the time.
- Wind speed: A wind speed of 1 m/s will not be present at site most of the time.
- Mounting: Not all systems will be mounted with an open back at 45°. For example, roof-mounted installations, which have no air flow on the back of the panel will have NOCT between 17°C and 35°C higher.

Temperature Coefficient

The Temperature Coefficient refers to the reduction in efficiency with each degree Celsius increase in cell temperature (not ambient temperature), as compared to STC. Efficiency and power output of PV materials decline linearly with temperature. Solar panels will usually operate with cell temperatures above 25°C (STC), however, in colder climates the temperature could be below 25°C and in the same sense the efficiency of the panel will increase compared to STC.

The slope in the plotted line is a characteristic of the PV material and it is known as the Temperature Coefficient (TC). The higher the magnitude of the TC, the bigger the performance drop suffered by the panel with temperature. As observed in the figure 8, a typical c-Si material (TC ~-0.4%/°C) operating at 60°C will yield ~84% of its rated power.

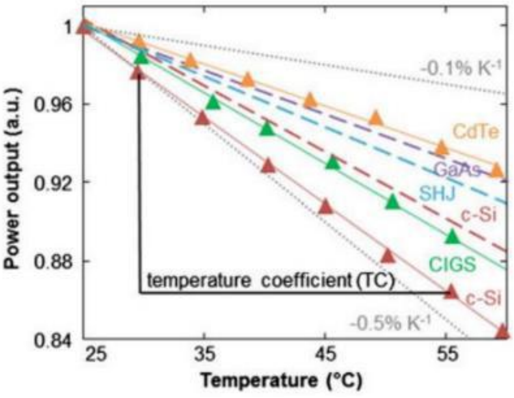

Fig 8: Effect of temperature on PV materials (semi-conductors)

Ambient temperature and cell/module temperature must not be confused. Due to radiation being thermalized in the solar cells, the temperature of these will always be higher than air temperature.

Within c-Si technologies, variations in TC should be expected. For instance, mono-Si technologies typically have TC lower in magnitude than poly-Si. Variations should also be expected between manufacturers and panel models.

Below, typical TC for solar panels (or smaller in magnitude):
Mono-Si: *-0.40%/°C – -0.37%/°C*
Poly-Si: *-0.43%/°C- -0.39%/°C*

The best commercially available temperature coefficients recorded in the California Energy Commission (CEC) database were *-0.227%/°C* among mono-Si panels and *-0.43%/°C* among poly-Si panels.

Maximum Power Point (MPP)

A solar panel tested under STC can produce electricity ranging from zero to its rated power. The power in an electric flow is determined as the product of voltage and current ($P=V x I$). Every panel has an operation point for which the power output is maximized, denominated as the maximum power point (MPP). The STC characteristic curve can be seen in the figure 9.

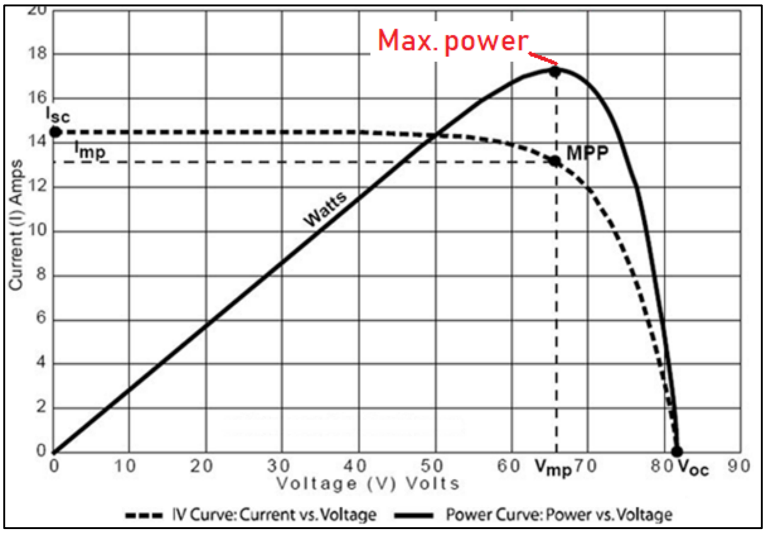

Fig 9: Typical characteristic curve of a solar panel

In operation, the MPP changes dynamically throughout the day, depending mainly on irradiance and cell temperature. Inverters should have tracking mechanisms that will ensure maximum power output.

Energy audit is also powerful tool to verify and improve photovoltaic solar during life cycle (Mbaye, 2022b; Veeraboina & Ratnam, 2012) [16, 21].

Conclusion

In the coming years, it is expected the trend towards tracking mechanisms to continue. Technological development with tracking systems is expected to increase the added value of this mechanism, especially as tracking systems are becoming smarter and connected, allowing it for real time optimization of angle and tilt to ensure optimum efficiency. Additionally, as trackers are becoming more reliable and easier to maintain, the conditions where tracking systems are considered is likely to increase whilst the additional risk associated with the system is likely to decrease.

Recycling and life cycle of solar panel must be continued to study to find solution to significantly reduce impact on the environment (Chowdhury *et al.*, 2020; Alam & Xu, 2022; Maani *et al.*, 2020) [9, 2, 17].

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