

Introduction to Solar Photovoltaic Energy Systems

Abstract

This introductory session presents the overall structure and purpose of a solar photovoltaic energy system. It provides learners with a system-level view of how sunlight is received by PV modules, converted into direct-current electricity, collected through electrical circuits, conditioned by power-electronic equipment, and delivered to electrical loads or the utility grid. The session introduces the main physical and functional parts of a PV installation without entering into detailed calculations or component-design procedures. Students will examine the relationship between the solar resource, PV modules, mounting structures, electrical connections, protection devices, inverters, monitoring equipment, and the final point of energy use. Common PV system configurations will also be introduced, including rooftop and ground-mounted installations, fixed and tracking systems, and stand-alone and grid-connected applications.

The session will also describe the main stages in the life of a PV project. These include site assessment, preliminary system planning, component coordination, installation, inspection, commissioning, monitoring, maintenance, and long-term operation. Particular attention will be given to the need for coordination between solar-resource assessment, mechanical design, electrical design, power-electronic equipment, installation practices, and safety procedures. This session is intentionally descriptive. It establishes the terminology, system relationships, and learning framework required for the following sessions. It does not include equations, design formulations, or detailed sizing calculations.

1 Solar Photovoltaic Energy Systems Overview

1.1 Solar Energy as an Energy Resource

This subsection will introduce solar energy as the primary input to every photovoltaic system. Learners will become familiar with the idea that the amount of solar energy available to a PV installation changes according to location, season, time of day, weather conditions, surrounding obstacles, and the orientation of the receiving surface.

The discussion will explain why solar energy must be treated as a variable natural resource rather than as a constant source of power. Trainees will recognize that clouds, atmospheric conditions, shading, dust, temperature, and changes in the position of the sun can affect the energy received by a PV array.

This introduction will prepare learners to understand why solar-resource information is essential when selecting a site, arranging modules, estimating plant performance, and comparing different PV system configurations.

1.2 From Sunlight to Electrical Energy

Learners will follow the complete energy pathway through a photovoltaic system. The pathway begins with sunlight reaching the module surface and continues through the production of direct-current electricity by the PV cells.

The session will explain how individual cells are assembled into modules, how modules are grouped into strings, and how strings form a complete PV array. They will then follow the electrical energy as it passes through cables, connectors, collection equipment, protective devices, power converters, and inverters.

The final stage of the pathway will show how the converted electrical energy is supplied to local loads, stored for later use, or delivered to the utility grid. Learners will also recognize that losses and operating limitations may occur at several stages of this pathway, including at the module surface, within the electrical connections, and during power conversion.

1.3 Applications and System Scales

This subsection will introduce the main applications of photovoltaic technology. They will compare small systems used for individual devices or remote loads with residential, commercial, industrial, and utility-scale installations.

Residential systems will be presented as installations commonly mounted on houses or small buildings and designed to support local electricity consumption. Commercial and industrial systems will be introduced as larger installations serving offices, schools, factories, warehouses, and other facilities. Utility-scale plants will be described as

extensive ground-mounted systems developed primarily to supply electricity to the power network.

Learners will also examine remote and stand-alone applications in which PV systems provide electricity where a utility connection is unavailable or impractical. These examples will help learners recognize that the same fundamental PV principles are used across a wide range of system sizes, while the arrangement of components, protection, control, and maintenance requirements may differ.

2 Main Subsystems of a Solar PV Installation

2.1 Solar Resource, PV Modules, and Arrays

This subsection will introduce the solar resource and the PV array as the starting points of the energy-conversion process. Students will identify the PV cell as the basic energy-conversion element and will understand how cells are assembled into modules for practical use.

They will then examine the progression from modules to strings and from strings to arrays. The purpose of this arrangement will be described in terms of obtaining the voltage, current, and power levels needed by the connected system.

Trainees will become familiar with the information normally associated with a PV module, including its electrical ratings, physical dimensions, technology type, environmental limitations, and installation requirements. They will also recognize that module output depends on actual operating conditions and does not remain equal to its rated value throughout the day.

This overview will prepare learners for the later study of solar radiation, photovoltaic conversion, environmental effects, module characteristics, and array configuration.

2.2 Mechanical Support and Mounting

The mechanical subsystem will be introduced as the part of the PV installation that supports the modules, maintains their required position, and transfers loads to a roof, building structure, foundation, or soil.

Learners will identify the principal mechanical components, including module frames, clamps, rails, brackets, beams, posts, braces, roof attachments, fasteners, and foundations. The discussion will emphasize that these components form a continuous supporting path rather than a collection of independent parts.

The session will describe how the mechanical arrangement maintains module orientation while responding to wind, gravity, temperature changes, handling, and other environmental or operational conditions. They will also become familiar with the importance of alignment, approved clamping locations, corrosion resistance, drainage, access, and safe installation practices.

This introductory treatment will prepare learners for the separate mechanical session, where rooftop structures, ground-mounted systems, tracking arrangements, support components, foundations, durability, and installation safety will be examined in greater depth.

2.3 Electrical Collection, Connection, and Protection

This subsection will introduce the electrical structure that carries the direct-current electricity produced by the PV modules toward the power-conversion equipment.

Learners will identify the main electrical components used between the PV array and the inverter. These include module cables, connectors, string conductors, combiner boxes, disconnect switches, grounding conductors, fuses, circuit breakers, surge-protection devices, and monitoring equipment.

The purpose of electrical collection will be described as the safe combination and transfer of power from many modules and strings. Learners will recognize that proper electrical arrangement is required to maintain correct polarity, limit unwanted voltage drop, protect equipment during faults, isolate circuits for maintenance, and reduce the risk of electric shock or fire.

The session will also introduce the distinction between the direct-current side and the alternating-current side of a PV installation. This will prepare learners for the later electrical session covering cells, modules, strings, arrays, series and parallel connections, cables, protection, grounding, insulation, electrical characteristics, and inverter matching.

2.4 Power Conversion and Energy Delivery

Power electronics will be introduced as the subsystem that controls and conditions the electrical energy produced by the PV array. Learners will become familiar with the need to adapt the variable direct-current output of the array to the requirements of electrical loads, energy-storage equipment, or the utility grid.

The session will describe the general roles of DC/DC converters, DC-link components, inverters, output filters, controllers, and monitoring systems. Learners will understand that these devices regulate voltage and current, control the operating point of the array, convert direct current into alternating current, and support safe and stable energy delivery.

The inverter will be introduced as the main interface between the PV array and most alternating-current loads or grid connections. Learners will also encounter the basic purpose of maximum power point tracking, which enables the system to respond to changing solar and temperature conditions and make more effective use of the available PV power.

This overview will provide the foundation for the later power-electronics session covering semiconductor devices, converter types, inverter operation, voltage and frequency control, grid interaction, maximum power point tracking, conversion losses, thermal conditions, protection, and reliability.

3 Common Solar PV System Configurations

3.1 Rooftop and Building-Mounted Systems

This subsection will introduce photovoltaic systems installed on residential, commercial, and industrial buildings. Learners will examine the general differences between systems mounted on sloped roofs, flat roofs, façades, and other building surfaces.

The session will describe how rooftop systems may be attached directly to structural roof members or supported using ballasted arrangements. Learners will recognize that the building becomes part of the PV support system and must therefore be considered when evaluating available space, structural capacity, waterproofing, drainage, access, wind exposure, and maintenance routes.

Attention will also be given to the coordination required between module layout, roof penetrations, electrical cable routes, inverter locations, fire access, shading obstacles, and existing building services. The aim is to help learners understand that a rooftop PV system must be integrated with the building rather than treated as equipment placed independently on the roof.

3.2 Ground-Mounted Solar Plants

Ground-mounted systems will be introduced as installations supported by dedicated structures and foundations placed directly in or on the ground. Learners will identify the typical arrangement of modules, rails, beams, posts, braces, foundations, electrical routes, inverter stations, access roads, and monitoring equipment.

The session will describe how ground-mounted systems provide greater flexibility in array orientation, row length, spacing, maintenance access, and overall plant capacity. Learners will also recognize the additional importance of terrain, soil conditions, drainage, vegetation, erosion, foundation installation, cable routing, security, and environmental exposure.

The relationship between individual module rows and the complete plant layout will be introduced. Learners will understand that decisions about row direction, spacing, height, access, and equipment placement influence energy production, mechanical loading, construction, electrical losses, maintenance, and land use.

3.3 Fixed-Tilt and Tracking Systems

This subsection will compare systems that maintain a constant module orientation with systems that change their orientation during operation.

Learners will examine fixed-tilt systems as mechanically simple arrangements in which modules remain at a selected orientation throughout the year. They will recognize

the importance of choosing an arrangement that considers the solar resource, available area, shading, wind exposure, maintenance, and project objectives.

Tracking systems will be introduced as arrangements that rotate the module structure to follow changes in the apparent position of the sun. Learners will distinguish between basic single-axis and dual-axis concepts and will identify the additional mechanical and control components associated with moving systems.

The discussion will emphasize that tracking may improve solar-energy collection but introduces additional requirements for drives, bearings, sensors, moving cables, clearances, alignment, wind response, control, inspection, and maintenance.

3.4 Stand-Alone and Grid-Connected Systems

Learners will compare photovoltaic systems that operate independently from the utility network with systems that are connected to it.

Stand-alone systems will be introduced as systems designed to supply local loads without relying on a continuous grid connection. Learners will become familiar with the possible roles of batteries, charge controllers, stand-alone inverters, backup sources, and energy-management equipment. They will recognize that these systems must balance available solar generation, stored energy, and load demand.

Grid-connected systems will be described as systems that operate in coordination with an electrical network. Learners will understand that the inverter must deliver alternating-current electricity with characteristics compatible with the grid and must include suitable monitoring and protection functions.

The session will also explain that the grid may receive surplus PV generation and supply electricity when local PV production is insufficient. This comparison will prepare learners to understand why inverter responsibilities, protection arrangements, control methods, and operating priorities differ between stand-alone and grid-connected applications.

4 From Project Concept to Operating PV System

4.1 Site Assessment and Project Requirements

This subsection will introduce the information that must be understood before a PV system is planned. Students will examine the importance of defining the purpose of the system, the expected energy use, the available site, the type of electrical connection, the project scale, and the intended operating conditions.

Site assessment will be described as a coordinated review of solar access, shading obstacles, roof or ground conditions, terrain, drainage, environmental exposure, access, available electrical infrastructure, equipment locations, and maintenance requirements.

Learners will recognize that different sites create different technical opportunities and limitations. A roof may provide convenient access to an existing electrical system but impose restrictions related to space, loading, waterproofing, and shading. A ground-mounted site may provide greater layout flexibility but require foundations, roads, fencing, drainage, vegetation management, and longer electrical routes.

The aim of this subsection is to help trainees understand that successful PV design begins with reliable site information and clearly defined project requirements.

4.2 Preliminary Layout and Subsystem Coordination

Students will be introduced to the way the main PV subsystems are brought together during preliminary planning. The session will describe how module arrangement, orientation, row spacing, supporting structure, electrical grouping, cable routes, inverter placement, access, drainage, and monitoring locations must be considered as parts of one coordinated system.

The mechanical arrangement affects module orientation, spacing, cable support, and maintenance access. The electrical arrangement affects string grouping, conductor routes, collection equipment, protection, and inverter locations. Power-electronic equipment affects the required array configuration, operating conditions, heat management, communication, and grid connection.

They will recognize that improving one aspect of a design may create consequences elsewhere. A compact layout may use land efficiently but reduce access or increase shading. Longer rows may simplify the visual arrangement but affect cable routes and structural movement. Equipment placed close to the array may reduce electrical distance but require additional environmental protection.

This subsection will establish the importance of interdisciplinary coordination before detailed design begins.

4.3 Installation, Inspection, and Commissioning

This subsection will introduce the sequence through which a planned PV system becomes an operating installation.

Learners will review the general progression from site preparation and setting-out to the installation of foundations or roof attachments, supporting structures, modules, electrical cables, collection equipment, inverters, protection devices, monitoring systems, and grid or load connections.

The importance of inspection during each stage will be emphasized. Learners will understand that installation quality includes correct positioning, alignment, fastening, module handling, cable support, connector compatibility, polarity, grounding, labeling, weather sealing, equipment clearance, and protection against damage.

Commissioning will be introduced as the controlled process used to confirm that the completed system has been assembled correctly and is ready for safe operation. Students will become familiar with the purpose of visual inspections, electrical checks, mechanical checks, functional tests, equipment settings, communication checks, documentation, and initial operating observations.

4.4 Monitoring, Operation, and Maintenance

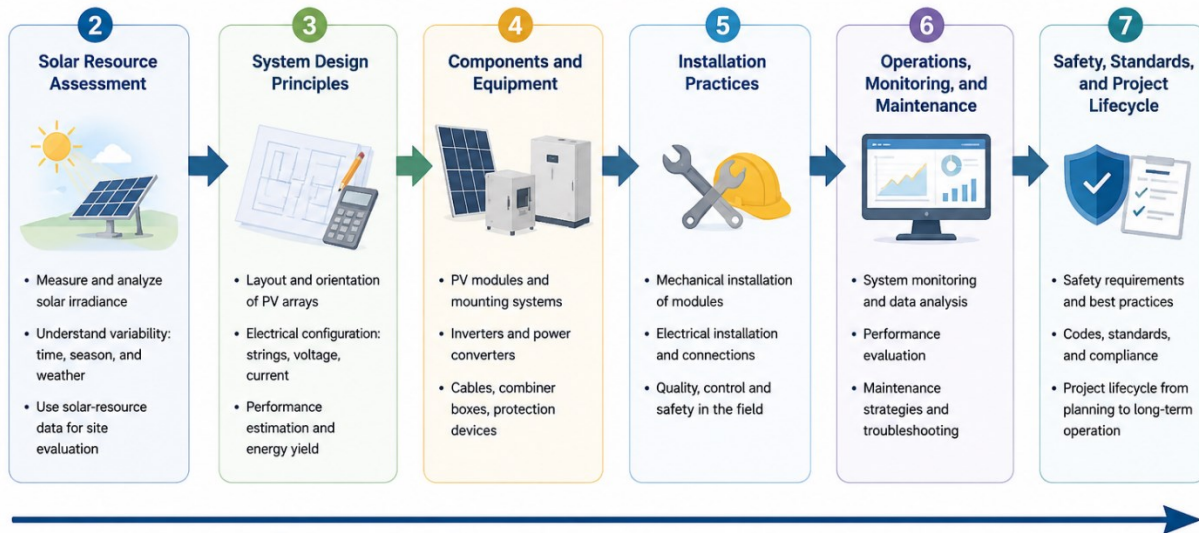
Trainees will be introduced to the activities required after a PV system begins operation. The session will describe how monitoring systems provide information about solar conditions, array production, inverter operation, exported energy, equipment status, and possible faults.

The discussion will explain how performance information can be used to identify unexpected changes caused by shading, soiling, high temperature, equipment outages, electrical faults, communication problems, module damage, loose connections, or mechanical deterioration.

Routine maintenance will be described as a combination of visual inspection, cleaning when required, vegetation control, cable and connector inspection, fastener checks, drainage review, inverter and enclosure inspection, protection-device checks, and monitoring-data assessment.

Learners will recognize that long-term performance depends not only on the original equipment selection but also on installation quality, documentation, inspection, fault response, environmental management, and continued maintenance throughout the operating life of the system.

The following figure, represents the procedure of the basics course.



5 Session Summary

This introductory session has presented a solar photovoltaic installation as an integrated energy system. Learners have been introduced to the pathway beginning with the available solar resource and continuing through the PV cells, modules, strings, arrays, mounting structures, electrical collection circuits, protection devices, converters, inverters, loads, and utility grid.

The session has described the principal PV system configurations, including rooftop and ground-mounted systems, fixed-tilt and tracking arrangements, and stand-alone and grid-connected applications. Learners have also been introduced to the main stages of a PV project, beginning with site assessment and project requirements and continuing through preliminary planning, subsystem coordination, installation, inspection, commissioning, monitoring, operation, and maintenance.

The discussion has emphasized that PV system performance is influenced by the complete chain of environmental conditions, physical components, electrical connections, power-conversion equipment, installation quality, and operational practices. Safety and coordination between solar-resource, mechanical, electrical, and power-electronic disciplines are required throughout the life of the system.

This system-level foundation prepares learners to study each technical area separately while continuing to understand its role within the complete photovoltaic installation.

Basic Solar Radiation Rules in PV Energy Conversion and Plant Design

Learning Objectives

- Distinguish irradiance from irradiation and explain the direct, diffuse, reflected, global horizontal, and plane-of-array components of solar radiation.
- Describe the apparent motion of the sun using solar declination, hour angle, zenith angle, solar altitude, azimuth, and incidence angle.
- Explain the photovoltaic conversion process and interpret the principal electrical quantities of a PV cell, module, string, and array.
- Quantify the first-order effects of irradiance, cell temperature, shading, soiling, and weather conditions on PV power and energy production.
- Apply basic orientation, tilt, row-spacing, loss-budget, performance-ratio, and energy-yield relationships in preliminary PV plant design.

Abstract

The useful output of a photovoltaic plant is determined by a chain of physical processes. Solar radiation first passes through the atmosphere, reaches the site as direct and diffuse radiation, and is then intercepted by the inclined PV surface. Part of this incident energy is converted into direct-current electricity, while the remainder is lost through optical reflection, sub-bandgap transmission, thermalization, recombination, resistance, temperature effects, mismatch, shading, soiling, cabling, conversion equipment, and plant unavailability. Consequently, PV plant design cannot be based only on module nameplate power or module efficiency. It must be based on time-dependent solar geometry, plane-of-array irradiance, operating temperature, electrical behavior, layout, and system losses.

The course plan identifies S1-02 as a four-hour basic session covering solar-resource principles, irradiance, temperature effects, PV conversion fundamentals, and their influence on plant design. It organizes the session into solar-radiation fundamentals, PV energy-conversion principles, environmental effects, basic plant-design rules, and performance and design trade-offs. The technical treatment below expands that structure using standard first-order PV engineering relationships while leaving detailed structural, electrical-protection, and inverter design to later sessions.

1 Solar Radiation Fundamentals

1.1 Solar radiation as an energy resource

Solar radiation is electromagnetic energy emitted by the sun and received at the Earth's surface after atmospheric absorption, scattering, and reflection. For PV engineering, the most important quantity is not the total solar energy outside the atmosphere, but the radiation that reaches the module surface at each instant.

The atmosphere modifies solar radiation in two main ways. A portion travels approximately along a straight path from the solar disk and is called direct or beam radiation. Another portion is scattered by molecules, aerosols, water vapor, and clouds and reaches the surface from different parts of the sky; this is diffuse radiation. Radiation reflected from the ground and surrounding surfaces may also reach an inclined PV module.

The distinction between irradiance and irradiation is fundamental, which are presented in Table 1.1.

Table 1.1: The parameters and definitions within solar energy conversion context.

Quantity	Typical symbol and unit	Engineering meaning
Irradiance	G , W/m ²	Instantaneous solar power incident per unit area
Irradiation	H , Wh/m ² or kWh/m ²	Solar energy received per unit area over a time interval
Direct normal irradiance	DNI , W/m ²	Direct-beam irradiance measured on a surface normal to the sun's rays
Diffuse horizontal irradiance	DHI , W/m ²	Diffuse-sky irradiance received by a horizontal surface
Global horizontal irradiance	GHI , W/m ²	Total direct-horizontal and diffuse irradiance on a horizontal surface
Plane-of-array irradiance	G_{POA} , W/m ²	Total irradiance incident on the actual PV module plane
Ground reflectance	ρ_g , dimensionless	Fraction of radiation reflected by the ground or surrounding surface

Irradiation is the time integral of irradiance:

$$H(t_1, t_2) = \int_{t_1}^{t_2} G(t) dt \quad (1.1)$$

Therefore, irradiance describes the instantaneous operating condition of a PV module, whereas irradiation is used to estimate daily, monthly, or annual energy production. For

example, a daily irradiation of 6 kWh/m^2 does not mean that the irradiance remained at 6 kW/m^2 . It means that the time-integrated radiation is equivalent to six hours at 1 kW/m^2 . Using the reference irradiance $G_{\text{ref}} = 1 \text{ kW/m}^2$, the equivalent peak-sun-hours or reference yield is

$$Y_r = \frac{H}{G_{\text{ref}}}. \quad (1.2)$$

When H is expressed in kWh/m^2 , Y_r is numerically expressed in hours.

1.2 Direct, diffuse, and global radiation

For an unobstructed horizontal surface, the basic radiation balance is

$$GHI = DNI \cos \theta_z + DHI \quad (1.3)$$

where θ_z is the solar zenith angle. The term $DNI \cos \theta_z$ is the direct-beam component projected onto the horizontal plane. This relationship illustrates why DNI , DHI , and GHI should not be treated as interchangeable (see Figure 1.1). Under a clear sky, DNI is usually a major component, while under an overcast sky the direct component may become small and most of the available radiation may be diffuse. A fixed-tilt PV array can use both direct and diffuse radiation, but its orientation has a stronger effect on the direct component.

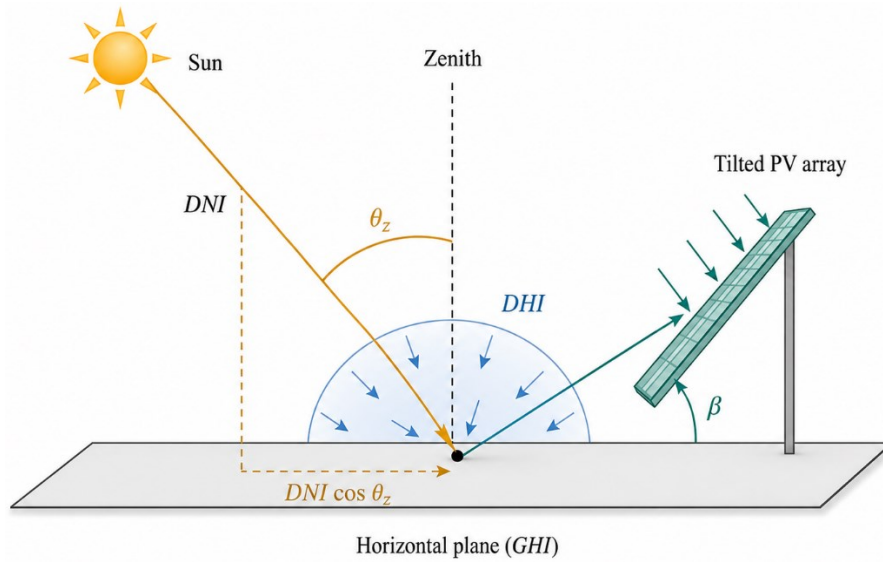


Figure 1.1: Solar radiation geometry with PV panel.

A radiation measurement or database value must always be associated with its measurement plane. A value reported as GHI is not the same as the irradiance incident on a tilted PV array. Conversion from horizontal radiation to plane-of-array radiation is therefore an essential design step.

1.3 Sun path and basic solar angles

The apparent position of the sun depends on latitude, day of the year, and local solar time. The principal angles are:

- Latitude, ϕ , which defines the site's angular position north or south of the equator.
- Solar declination, δ , which describes the seasonal angular position of the sun relative to the Earth's equatorial plane.
- Hour angle, ω , which describes time relative to solar noon.
- Solar zenith angle, θ_z , measured between the sun's direction and the local vertical.
- Solar altitude angle, α_s , measured above the horizon.
- Solar azimuth, which gives the sun's compass direction.
- Incidence angle, θ_i , measured between the incoming solar beam and the normal to the module surface.

A useful approximation for solar declination can be expressed as:

$$\delta \approx 23.45^\circ \sin \left[\frac{360^\circ}{365} (284 + n) \right] \quad (1.4)$$

where n is the day number, with $n = 1$ on 1 January. The hour angle is $\omega = 15^\circ(t_s - 12)$, where t_s is local solar time in hours. The hour angle is zero at solar noon, negative in the morning, and positive in the afternoon. Civil clock time must be corrected for longitude, time-zone meridian, equation of time, and daylight-saving adjustments before it is used as solar time.

The solar zenith angle is calculated from

$$\cos \theta_z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \quad (1.5)$$

Solar altitude and zenith angle are complementary $\alpha_s = 90^\circ - \theta_z$. The sunrise or sunset hour angle on a horizontal horizon is approximately $\omega_s = \cos^{-1}(-\tan \phi \tan \delta)$, and the approximate astronomical day length is

$$N = \frac{2\omega_s}{15^\circ} \quad (1.6)$$

in hours, provided that ω_s is expressed in degrees. High-latitude polar-day and polar-night conditions require separate treatment. The incidence angle can be expressed compactly using vectors:

$$\cos \theta_i = \hat{s} \cdot \hat{n} \quad (1.7)$$

where $\hat{s}$ is the unit vector directed toward the sun and $\hat{n}$ is the outward normal vector of the front side of the PV module. When $\cos \theta_i = 1$, the solar beam is perpendicular to the module and the intercepted direct radiation is maximized. When $\cos \theta_i \leq 0$, the front surface does not receive direct-beam radiation. The above formulation is illustrated in Figure 1.2.

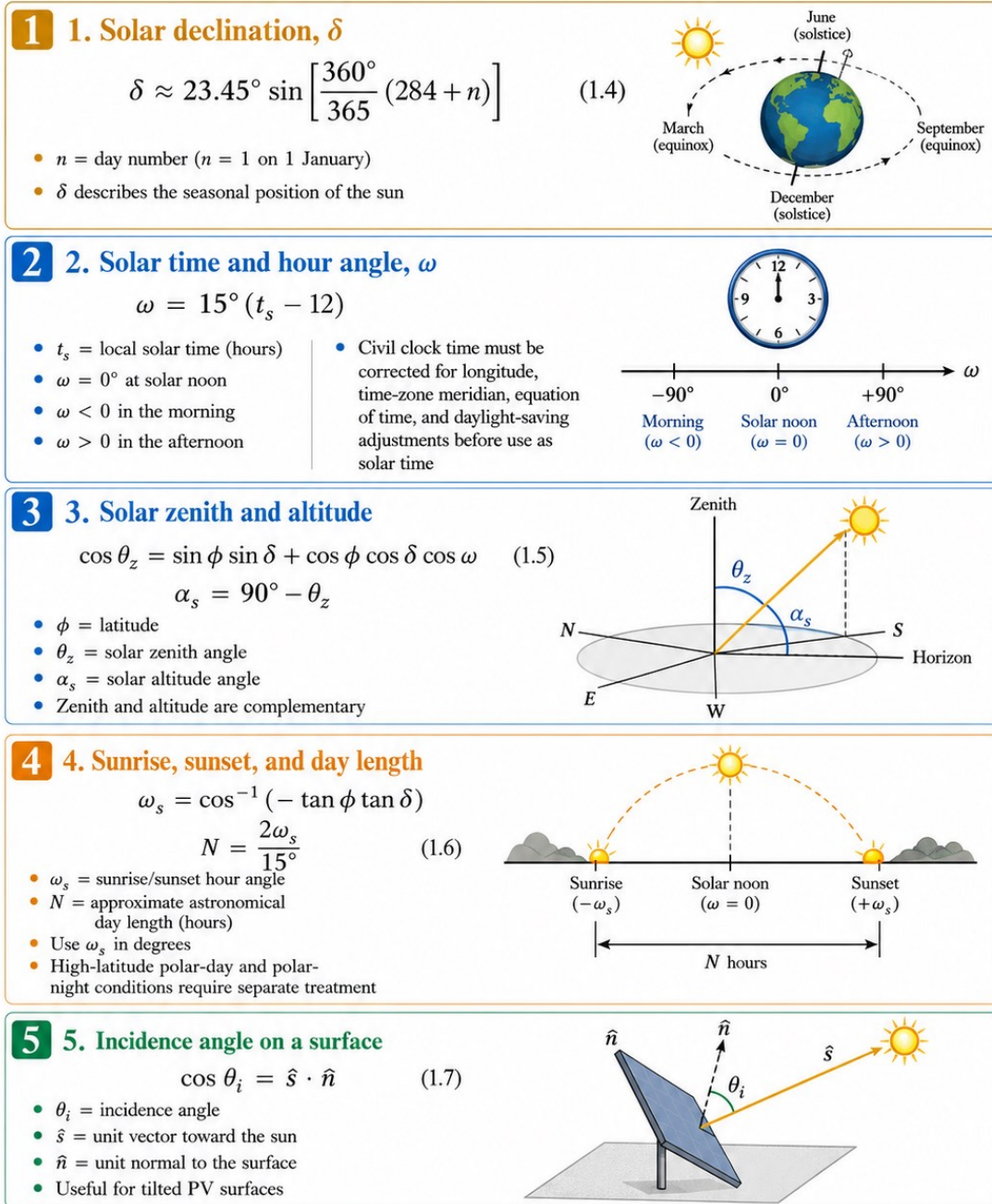


Figure 1.2: Solar geometry and time relations.

1.4 Plane-of-array irradiance

For a tilted module, plane-of-array irradiance is divided into beam, sky-diffuse, and ground-reflected components:

$$G_{\text{POA}} = G_{\text{b,POA}} + G_{\text{d,POA}} + G_{\text{r,POA}} \quad (1.8)$$

For a first-order isotropic-sky model, one can write:

$$G_{\text{POA}} = DNI[\cos \theta_i]_+ + DHI \left(\frac{1 + \cos \beta}{2} \right) + \rho_g GHI \left(\frac{1 - \cos \beta}{2} \right) \quad (1.9)$$

Where $[x]_+ = \max(0, x)$, β is the module tilt from horizontal, and ρ_g is ground reflectance.

The beam term is controlled by the sun-module incidence angle. The diffuse term uses the fraction of the sky hemisphere visible to the inclined surface. The reflected term uses the fraction of the ground hemisphere visible to that surface. A horizontal module has $\beta = 0^\circ$, so it sees the full sky and essentially no ground-reflected radiation in this simple model. A vertical surface has $\beta = 90^\circ$, so it sees half of the sky hemisphere and half of the ground hemisphere.

The isotropic model is appropriate for introductory calculations, but real sky diffuse radiation is not perfectly uniform. More detailed transposition models separately treat circumsolar diffuse radiation, horizon brightening, cloud conditions, and angle-of-incidence effects. For preliminary design, the important rule is that plant energy calculations should be based on G_{POA} , not directly on GHI .

Technical Note 1:

In industrial PV development, solar-radiation data are treated as design inputs with defined measurement planes, time resolution, uncertainty, and quality-control requirements. Resource datasets should distinguish GHI, DNI, and DHI, because utility-scale energy models calculate plane-of-array irradiance by transposing these components according to module tilt, azimuth, tracker position, horizon profile, ground reflectance, and solar geometry. Ground measurements are commonly obtained from pyranometers, reference cells, and complete meteorological stations, while satellite or reanalysis datasets are used to establish long-term climatic behavior. The measured resource must be checked for sensor fouling, shading, calibration drift, timestamp errors, missing data, and inconsistency between radiation components. In operating plants, irradiance sensors should be installed in representative array planes rather than only horizontally, because performance ratio, inverter efficiency, clipping, and underperformance investigations

depend on the irradiance actually received by the modules. Industrial energy assessment therefore separates short-term measured conditions from long-term expected conditions and applies data correction, gap filling, interannual variability, and uncertainty analysis before the resource is used for contractual yield guarantees or financial modelling.

2 PV Energy Conversion Principles

2.1 The photovoltaic effect

A photovoltaic cell is a semiconductor device, normally based on a p-n junction, that converts part of the incident photon energy into electrical energy. The energy of an individual photon is

$$E_\gamma = h\nu = \frac{hc}{\lambda} \quad (1.10)$$

where h is Planck's constant, ν is frequency, c is the speed of light, and λ is wavelength.

A photon can generate an electron-hole pair when its energy is at least equal to the semiconductor bandgap E_g . Photons with energy below E_g are not effectively absorbed for electrical conversion. For photons with energy above E_g , the energy in excess of the bandgap is primarily converted to heat through thermalization. Additional losses arise from reflection, carrier recombination, electrical resistance, inactive module area, and optical absorption in encapsulation materials.

The electric field of the semiconductor junction separates the photogenerated charge carriers. When the cell is connected to an external circuit, this charge separation produces direct current. The resulting current is strongly related to photon flux and therefore irradiance, while the cell voltage depends on junction properties, irradiance, and temperature.

2.2 Electrical model of a PV cell or module

A widely used physical representation is the single-diode model:

$$I = I_{\text{ph}} - I_0 \left[\exp \left(\frac{V + IR_s}{nN_c V_T} \right) - 1 \right] - \frac{V + IR_s}{R_{\text{sh}}} \quad (1.11)$$

With $V_T = \frac{kT_c}{q}$.

In this relationship, I_{ph} is the photogenerated current, I_0 is diode saturation current, R_s is series resistance, R_{sh} is shunt resistance, n is the diode ideality factor, N_c is the number of series-connected cells represented by the model, k is Boltzmann's constant, q is the elementary charge, and T_c is absolute cell temperature.

The model explains several basic PV characteristics (see Figure 1.3). Photogenerated current increases approximately in proportion to effective irradiance. Diode current increases exponentially with voltage. A high series resistance produces voltage losses at high current, while a low shunt resistance allows leakage current and reduces performance, especially at low irradiance.

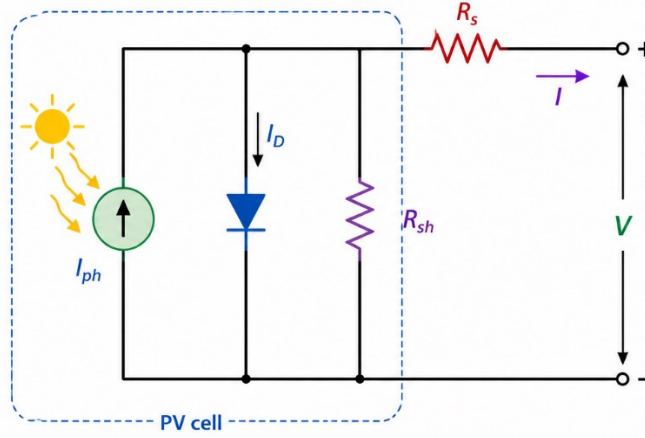


Figure 1.3: Equivalent electrical model of a PV cell.

The current-voltage curve contains three principal operating points. Short-circuit current I_{sc} occurs at $V = 0$. Open-circuit voltage V_{oc} occurs at $I = 0$. Between these points lies the maximum-power point, defined by V_{mpp} and I_{mpp} . Electrical power at the maximum-power point is $P_{mpp} = V_{mpp}I_{mpp}$, and mathematically,

$$\frac{dP}{dV} = I + V \frac{dI}{dV} = 0 \quad (1.12)$$

The fill factor indicates how closely the usable maximum-power rectangle approaches the rectangle formed by V_{oc} and I_{sc} :

$$FF = \frac{V_{mpp}I_{mpp}}{V_{oc}I_{sc}} \quad (1.13)$$

The instantaneous conversion efficiency is $\eta = \frac{P_{mpp}}{G_{eff}A}$, where A is the active or defined module area and G_{eff} is effective irradiance after relevant optical effects.

Module nameplate quantities are commonly reported at standard test conditions, generally corresponding to 1000 W/m^2 irradiance, 25°C cell temperature, and a standard terrestrial solar spectrum. Standard-test-condition power is a rating point, not a prediction of actual field output.

2.3 DC power and energy generation

PV power is time-dependent because irradiance and cell temperature continuously change. The operating DC power can be represented as

$$P_{DC}(t) = P_{mpp}[G_{eff}'(t)T_c(t)] \quad (1.14)$$

The DC energy over a period is

$$E_{\text{DC}} = \int_{t_1}^{t_2} P_{\text{DC}}(t) dt \quad (1.15)$$

In a grid-connected plant, AC power is obtained after DC cabling, power conversion, transformer, auxiliary, and collection losses:

$$P_{\text{AC}}(t) = P_{\text{DC}}(t)\eta_{\text{conv}}(t) - P_{\text{aux}}(t) \quad (1.16)$$

where η_{conv} represents the combined conversion efficiency over the relevant operating path and P_{aux} is plant auxiliary consumption. Detailed inverter operation is outside the present session, but its efficiency must be included in energy-yield calculations.

Technical Note 2:

At plant scale, the photovoltaic conversion process is managed through electrical grouping and operating-point control rather than at individual-cell level. Module current is primarily governed by effective irradiance, while module voltage is strongly affected by cell temperature; therefore, series-connected modules should have similar orientation, irradiance exposure, technology, and thermal conditions. String voltage must remain inside the inverter's permissible DC and maximum-power-point tracking range under both the lowest expected module temperature and the highest expected operating temperature, while parallel-string currents determine combiner, conductor, protection, and inverter-input requirements. Module datasheet parameters such as P_{mpp} , V_{oc} , I_{sc} , V_{mpp} , I_{mpp} , temperature coefficients, bifaciality, and power tolerance are converted into plant-level string and array models. Industrial design also accounts for module binning, manufacturing tolerance, degradation, series resistance, connector resistance, cable voltage drop, bypass-diode behavior, and inverter MPPT efficiency. The plant nameplate rating represents DC power at standard test conditions, not continuously deliverable field power, so contractual and operational assessments must distinguish installed DC capacity, available DC power, inverter AC rating, exported grid power, and net delivered energy.

3 Environmental Effects on PV Output

3.1 Irradiance influence

At approximately constant cell temperature, short-circuit current is nearly proportional to effective irradiance:

$$I_{sc} \approx I_{sc,ref} \frac{G_{eff}}{G_{ref}} \quad (1.17)$$

Open-circuit voltage varies approximately logarithmically with irradiance:

$$V_{oc} \approx V_{oc,ref} + nN_c V_T \ln \left(\frac{G_{eff}}{G_{ref}} \right) \quad (1.18)$$

for a simplified comparison at constant temperature. The plot of the equations can be found in Figure 1.4.

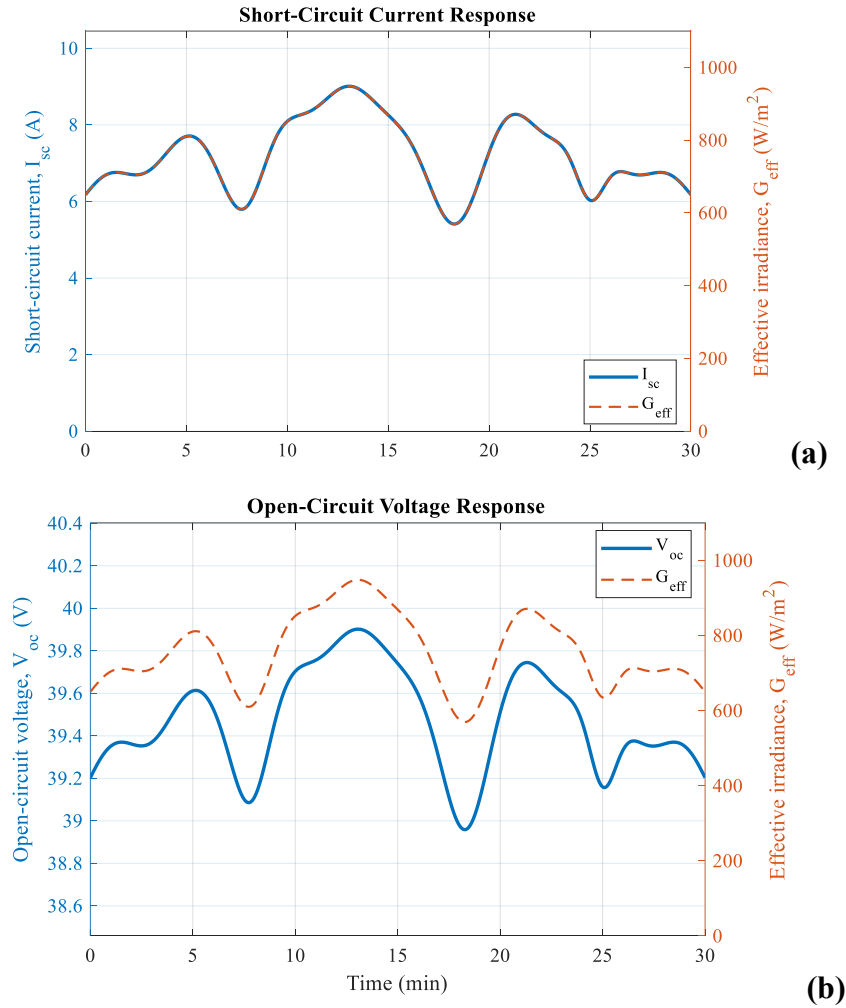


Figure 1.4: PV Response at Constant Cell Temperature.

Consequently, PV maximum power is approximately proportional to irradiance over much of the normal operating range, but the relationship is not perfectly linear. At low irradiance, diode, leakage, conversion, and fixed auxiliary effects become more significant. At high irradiance, increased cell temperature can offset part of the irradiance gain. A reduction in irradiance primarily reduces current. A rise in temperature primarily reduces voltage. This distinction is important when interpreting measured I-V curves or plant-monitoring data.

3.2 Cell temperature influence

PV cell temperature is normally higher than ambient air temperature because much of the absorbed solar energy becomes heat. A basic open-rack approximation based on nominal operating cell temperature is

$$T_c \approx T_a + \left(\frac{NOCT - 20^\circ\text{C}}{800 \text{ W/m}^2} \right) G_{\text{POA}} \quad (1.19)$$

where T_a is ambient temperature and G_{POA} is in W/m^2 . This relationship is only a first-order estimate. Actual cell temperature also depends on wind speed, mounting configuration, rear ventilation, thermal mass, module construction, roof temperature, and long-wave thermal exchange. What's more, the first-order combined irradiance and temperature correction for maximum power can be written as:

$$P_{\text{mpp}}(G, T_c) \approx P_{\text{STC}} \frac{G_{\text{eff}}}{G_{\text{ref}}} [1 + \gamma_P (T_c - T_{\text{ref}})] \quad (1.20)$$

where $T_{\text{ref}} = 25^\circ\text{C}$ and γ_P is the module maximum-power temperature coefficient expressed as a fractional change per degree Celsius. For conventional crystalline-silicon modules, γ_P is negative. Therefore, a cell temperature above the reference temperature reduces maximum power as can be seen in Figure 1.5.

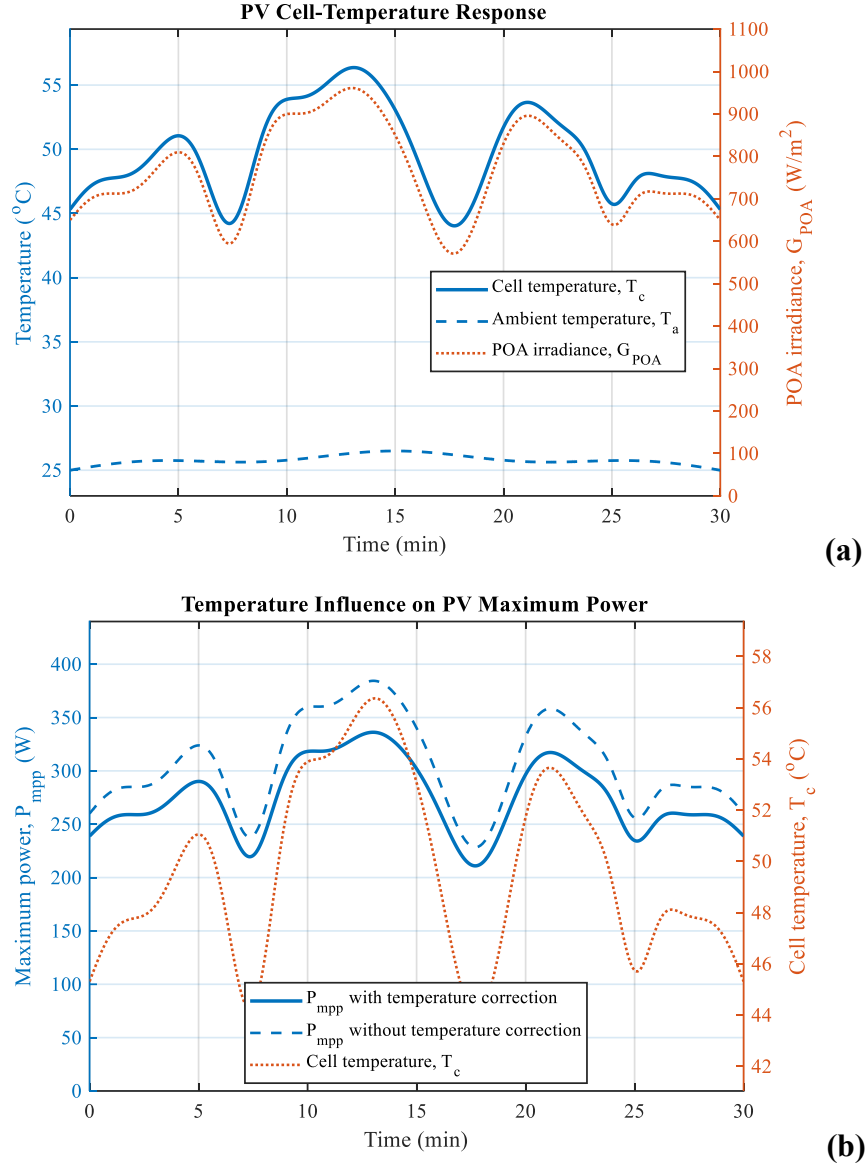


Figure 1.5: PV Cell Temperature and Maximum-Power Profile over 30 Minutes.

The temperature effect on current is generally positive and relatively small, while the temperature effect on voltage is negative and dominant. This is why cold conditions can produce high string voltages even when irradiance is moderate, whereas hot sunny conditions may produce high current but lower module voltage and efficiency.

3.3 Shading and electrical mismatch

Shading may originate from terrain, adjacent rows, buildings, vegetation, utility poles, fences, trackers, module frames, dust accumulation, or other plant equipment. The electrical loss caused by shading is not necessarily proportional to the shaded area. The different types of the shadings are shown in Figure 1.6.

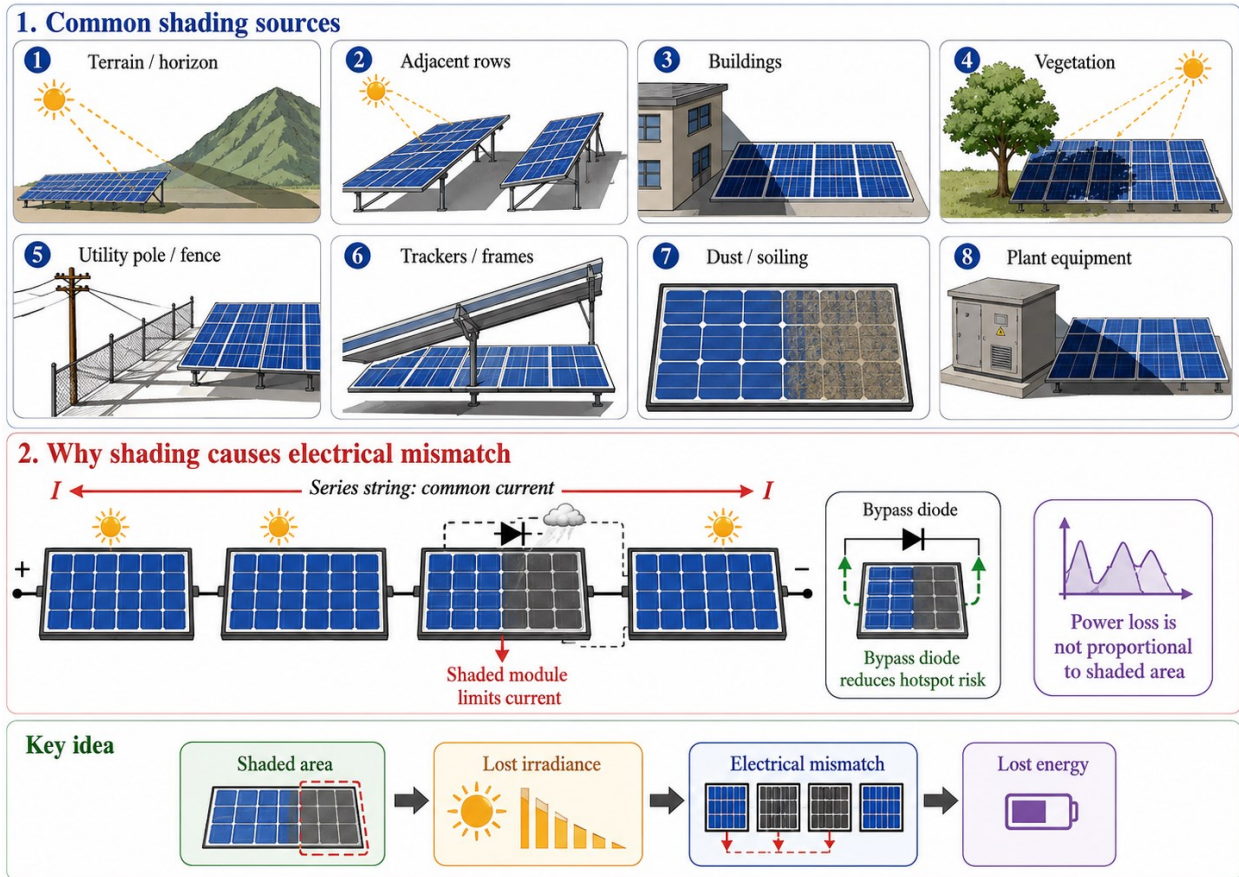


Figure 1.6: Shading effects in solar energy systems and the effects.

Modules in a series string must operate at a common current. A weakly illuminated cell or module can therefore limit the current of the entire series path. Bypass diodes provide an alternate current path around groups of cells under severe current mismatch, reducing reverse-bias stress and hotspot risk. However, diode activation removes part of the module voltage and can create multiple local maxima in the array power-voltage curve.

Shading analysis must therefore consider four related but different quantities: geometric shaded area, lost irradiance, electrical mismatch, and lost energy. A geometric shade fraction of 10% does not automatically mean a 10% power loss. The result depends on cell interconnection, bypass-diode grouping, string layout, shade location, operating voltage, and maximum-power-point tracking.

3.4 Soiling, dust, and optical losses

Soiling reduces the radiation transmitted through the module glass. Dust, pollen, industrial deposits, salt, bird droppings, and mud can produce either uniform attenuation or highly nonuniform shading. Uniform soiling behaves approximately as an optical transmission loss, whereas nonuniform soiling can also cause mismatch and local heating.

3.5 Weather effects

Weather affects both the available solar radiation and the operating condition of the PV modules that are summarized in Table 1.2.

Table 1.2: Weather effects on PV generation from different aspects.

Environmental factor	Radiation or thermal effect	Principal PV consequence
Clouds	Reduce direct radiation and alter diffuse fraction	Rapid power variation and lower total irradiance
Aerosols and humidity	Scatter and absorb radiation; modify spectrum	Reduced direct radiation and possible spectral mismatch
Wind	Increases convective cooling	Lower cell temperature and potentially higher efficiency
Rain	Temporarily reduces radiation but may remove loose soiling	Short-term generation loss followed by possible optical recovery
Snow or frost	May cover modules; can also increase ground reflectance	Severe coverage loss or increased reflected radiation after clearing
High ambient temperature	Raises cell operating temperature	Lower module voltage and maximum power
Dust storms	Increase atmospheric attenuation and surface deposition	Simultaneous resource loss and soiling accumulation
Uneven weather across the site	Creates irradiance and temperature differences	Array mismatch and spatially variable output

4 Basic PV Plant Design Rules

4.1 Module orientation and tilt

Module orientation is described by tilt angle β and surface azimuth γ . Tilt is measured from horizontal: $\beta = 0^\circ$ is horizontal and $\beta = 90^\circ$ is vertical (See Figure 1.1). Azimuth specifies the compass direction faced by the module. For annual energy production, an equator-facing orientation is usually the first design candidate: south-facing in the Northern Hemisphere and north-facing in the Southern Hemisphere. However, this is not an absolute design rule. Site boundaries, terrain, shading, wind, electrical interconnection, desired production profile, land density, and market value of energy can justify a different azimuth.

A tilt angle near the site latitude is a useful preliminary annual-energy starting point, but it is not a final optimization method. The optimum tilt depends on the temporal radiation distribution, diffuse fraction, ground reflectance, temperature, soiling, row spacing, seasonal energy requirements, and site constraints. A resource-only orientation optimization may be expressed as

$$(\beta^*, \gamma^*) = \sum_t G_{\text{POA}}(t; \beta; \gamma) \Delta t \quad (1.21)$$

A more complete plant-level optimization uses energy rather than irradiance:

$$(\beta^*, \gamma^*) = \sum_t P_{\text{AC}} [G_{\text{POA}}'(t; \beta; \gamma) T_c(t)] \Delta t \quad (1.22)$$

The second expression is more appropriate because two orientations with similar annual irradiation may have different temperature, shading, clipping, conversion-efficiency, or availability behavior.

4.2 Basic row-spacing geometry

Rows must be separated sufficiently to control inter-row shading. Consider identical fixed-tilt rows on level terrain. Let L be the module-table chord length measured along the inclined surface in the direction of tilt. The vertical height difference between the lower and upper edges is

$$h = L \sin \beta \quad (1.23)$$

and the horizontal ground projection is

$$w = L \cos \beta \quad (1.24)$$

Let α_p be the solar profile angle, meaning the solar altitude projected onto the vertical plane perpendicular to the row direction. The shadow length beyond the upper-edge ground projection is approximately

$$s = \frac{h}{\tan \alpha_p} \quad (1.25)$$

The minimum front-to-front row pitch for zero geometric shading at that selected solar position is therefore

$$D_{\min} = w + s = L \cos \beta + \frac{L \sin \beta}{\tan \alpha_p} \quad (1.26)$$

This relationship demonstrates why low solar angles require large spacing. As α_p approaches zero, the theoretical shadow length becomes very large. Designing for zero inter-row shading during every daylight hour is therefore normally impractical. The designer selects a critical date and time window, a maximum acceptable annual shading loss, or an energy-economic optimum. For the projected-width convention used here, a basic ground-coverage ratio is

$$GCR_p = \frac{w}{D} = \frac{L \cos \beta}{D} \quad (1.27)$$

A larger GCR_p places more module area within a given land area but increases the probability and duration of inter-row shading. A smaller GCR_p reduces shading but uses more land and may increase road, trench, cable, and collection-system lengths. Because industry definitions of ground-coverage ratio are not completely uniform, every design document should state whether the numerator is module chord, horizontal projection, aperture width, or tracker width.

Terrain slope modifies the row-to-row height relationship and must be included in the shading geometry. East-west terrain slope may shift shadow timing, while north-south slope may significantly alter effective row pitch and apparent tilt. A general example for the row-spacing geometry is shown in Figure 1.7.

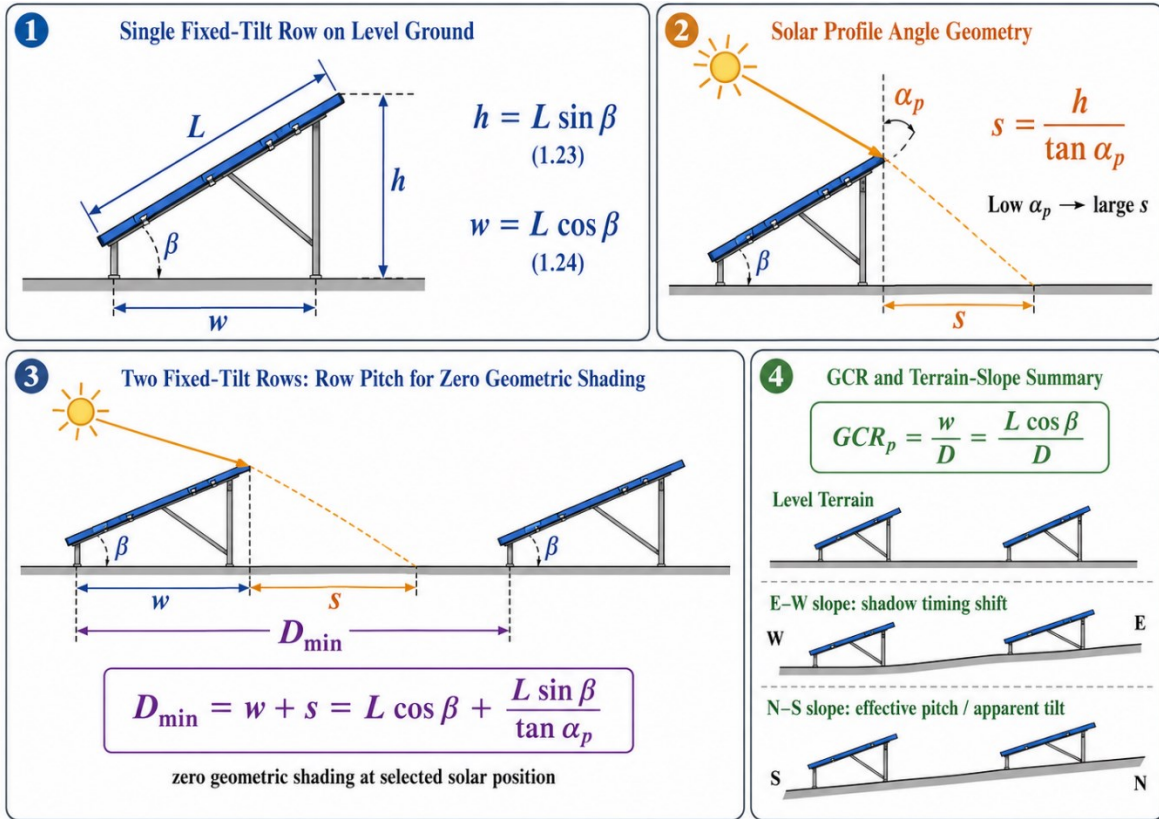


Figure 1.7: Basic row-spacing geometry overview.

Technical Note 3:

Environmental effects are treated industrially as time-dependent loss mechanisms that influence energy production, equipment loading, reliability, and maintenance requirements. High irradiance increases current and thermal loading, while high cell temperature reduces module voltage and maximum power; consequently, modules in hot, low-wind locations may operate substantially below their standard-test-condition rating despite strong sunlight. Shading from adjacent rows, terrain, vegetation, buildings, transmission structures, weather stations, and electrical equipment must be assessed geometrically and electrically because partial shading can activate bypass diodes, distort the array P-V curve, increase mismatch, and create localized heating. Soiling is evaluated through site-specific deposition rates, rainfall patterns, module tilt, soil type, agricultural activity, industrial emissions, and cleaning economics; uniform soiling reduces transmitted irradiance, whereas nonuniform contamination can cause disproportionate electrical losses. Industrial monitoring may include soiling stations, module-temperature sensors, rear-side irradiance sensors for bifacial systems, wind sensors, string-current monitoring, infrared inspection, and I-V curve testing. Cleaning intervals and vegetation-control plans

should therefore be based on recoverable energy, water availability, labor cost, module-access risk, and seasonal conditions rather than on a fixed universal schedule.

Session Summary

Solar-resource analysis begins by distinguishing instantaneous irradiance from time-integrated irradiation. The radiation reaching a PV plant consists of direct, diffuse, and reflected components. On a horizontal plane, GHI is the sum of the projected direct-normal component and diffuse-horizontal irradiance. For an inclined PV surface, these components must be transposed to plane-of-array irradiance using the sun's position, module tilt, module azimuth, incidence angle, sky view, and ground reflectance. Solar declination controls seasonal sun position, hour angle controls the time relative to solar noon, and zenith, altitude, and incidence angles determine the geometric projection of direct radiation.

PV conversion is governed by photon absorption and charge separation in a semiconductor junction. Photogenerated current is primarily controlled by effective irradiance, while voltage is strongly affected by junction temperature. The I-V curve extends from short-circuit current to open-circuit voltage and contains a unique maximum-power point under uniform conditions. The fill factor describes the shape of this curve, while conversion efficiency relates maximum electrical power to incident solar power. Cells are assembled into modules, modules into series strings, and strings into parallel arrays. Series connections add voltage, parallel connections add current, and the time integral of operating power gives electrical energy.

Environmental conditions modify both the radiation available to the module and the module's electrical behavior. Increasing irradiance generally raises current and power, while increasing cell temperature mainly reduces voltage and maximum power. Cell temperature must not be assumed equal to ambient temperature. Shading can create disproportionate losses because series-connected cells and modules must operate at a common current; bypass diodes reduce reverse stress but create voltage loss and multiple power maxima. Soiling, snow, angle-of-incidence effects, clouds, wind, humidity, and spatially variable weather must also be represented in an energy estimate.

Basic plant design requires simultaneous selection of orientation, tilt, row pitch, module quantity, and land allocation. Equator-facing orientation and a tilt near latitude are useful starting points, not universal optima. Row spacing is governed by table height, horizontal projection, and the selected critical solar profile angle. Wider spacing reduces shading but lowers land-use density. The final design should be evaluated using plane-of-array irradiation, effective irradiance, cell temperature, DC output, conversion losses, final yield, performance ratio, specific yield, capacity factor, and energy per unit land area.

Mechanical Structure and Mechanisms in Solar PV Systems – Part I

Learning Objectives

- Identify the principal mechanical components of a photovoltaic system and describe the structural function of modules, frames, rails, clamps, fasteners, posts, brackets, and foundations.
- Distinguish between rooftop, ground-mounted, fixed-tilt, and basic tracking configurations according to their mechanical arrangement and load-transfer path.
- Explain how gravity, wind, thermal movement, and other environmental actions are transferred from a PV module to the supporting roof or soil.
- Apply fundamental mechanical formulations for equilibrium, stress, wind pressure, foundation stability, thermal expansion, and connection preload.
- Describe the basic requirements for material durability, module handling, structural alignment, fastening, inspection, and safe mechanical installation.

Abstract

The mechanical subsystem of a solar photovoltaic installation maintains the modules at the required orientation while safely transferring environmental and operational loads to a roof, supporting structure, foundation, or soil. Although the PV module is primarily an energy-conversion device, it also behaves as a structural panel subjected to pressure, uplift, bending, vibration, thermal movement, and handling loads. The mounting structure must therefore provide adequate strength, stiffness, stability, durability, accessibility, and installation accuracy throughout the operating life of the system.

The uploaded course plan defines S1-03 as a basic four-hour introduction covering PV modules, mounting structures, fixed-tilt systems, tracking basics, foundations, and structural support components. Its detailed organization includes main mechanical components, mounting-system types, structural support and foundations, basic mechanical design conditions, and installation and safety considerations. The technical explanations and equations below expand this syllabus at a fundamental level. Detailed structural loading analysis, fatigue, tracker actuation, wind-stow operation, mechanical wear, calibration, and advanced reliability are reserved for Part II.

1 Main Mechanical Components of PV Systems

1.1 Mechanical Function of a PV System

The main mechanical purpose of a photovoltaic structure is to support the active PV surface at a defined tilt and orientation while maintaining structural integrity under all expected conditions. The mechanical system must resist downward gravity loads, upward wind suction, lateral wind forces, thermal expansion, installation forces, and site-specific actions such as snow, seismic movement, or maintenance loads. A useful way to understand the complete structure is through its load path, as shown in Figure 3.1.

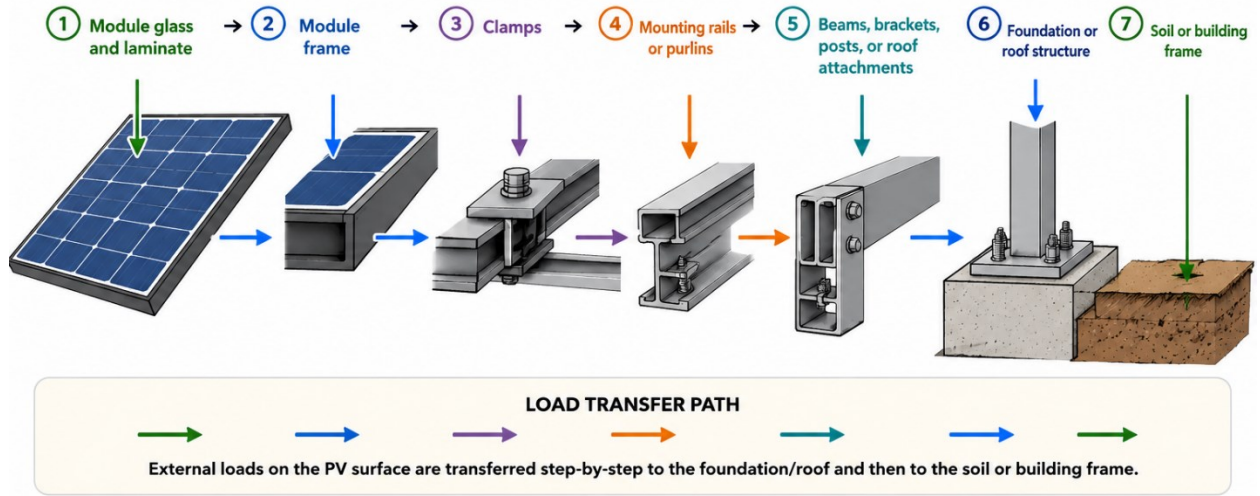


Figure 3.1: PV structure load path diagram.

Every interface in this chain must transfer force without excessive deformation, slipping, loosening, fracture, pullout, or local crushing. A strong rail, for example, does not make a system safe when the rail-to-post bolt or the roof attachment is inadequate. Structural performance is governed by the complete load path rather than by a single component.

To discuss mathematically, for a stationary structure, the basic equilibrium conditions are:

$$\sum F_x = 0, \sum F_y = 0, \sum F_z = 0 \quad (3.1)$$

And

$$\sum M = 0 \quad (3.2)$$

where F_x , F_y , and F_z are the forces in the three principal directions, and M represents moment about a selected point or axis. These equations are used to calculate the reactions at clamps, rail supports, posts, roof anchors, and foundations.

1.2 PV Modules as Physical Components

A PV module is a laminated panel that protects electrically active solar cells while transmitting mechanical loads to the mounting structure. A conventional framed module normally contains front glass, encapsulation material, interconnected PV cells, a rear encapsulation layer, a backsheet or second glass layer, edge sealing, a junction box, and an external frame. Figure 3.2 illustrates the components.

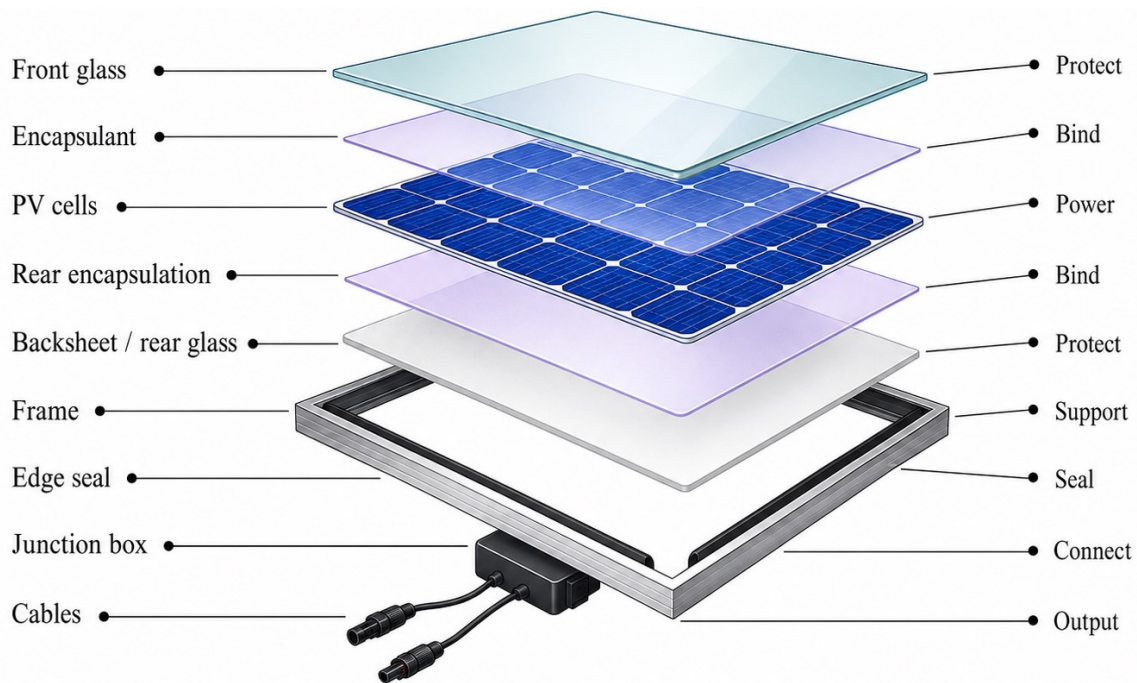


Figure 3.2: Solar panel components diagram.

The front glass provides environmental protection and contributes substantially to the stiffness of the module. Glass performs well under distributed loading but is sensitive to concentrated impact, edge damage, twisting, and local point loads. The module should therefore be supported only at locations permitted by the manufacturer. The encapsulation system holds the cells in position and protects them from moisture and mechanical contact. Solar cells are thin and brittle. Excessive module deflection, torsion, vibration, or improper handling can create microcracks even when the external glass remains visually undamaged. The backsheet or rear glass protects the rear surface. Glass-glass modules use a second glass sheet instead of a polymer backsheet. Their weight, stiffness, clamping method, and edge-support requirements may differ from those of conventional framed modules.

The junction box and cables are electrical components, but they also require mechanical protection. The junction box must not be used as a lifting point, and cables should not be allowed to carry module weight or rub against sharp structural edges.

1.3 Rails, Clamps, Brackets, and Fasteners

Mounting rails support one or more modules and behave primarily as beams between brackets, posts, or roof attachments. The rail must resist bending, shear, local bearing at fasteners, and sometimes torsion. Rail span is therefore controlled not only by material strength but also by deflection. Excessive rail deflection may not immediately cause structural failure, but it can change module alignment, place additional stress on the glass, loosen clamps, reduce drainage clearance, and create uneven rows. This illustrates the difference between:

- **Strength**, meaning resistance to yielding, fracture, pullout, or collapse.
- **Serviceability**, meaning acceptable deflection, movement, vibration, and alignment during normal operation.

Mid-clamps connect two adjacent module frames to a rail, while end-clamps secure the outer modules of a row. Their purpose is to create sufficient normal force and friction to prevent slipping while also transferring uplift and downward loads. Clamp geometry must match the module-frame height and shape. Brackets and standoffs connect the rails to a roof, beam, purlin, or other primary support. Ground-mounted structures may also contain posts, rafters, cross-beams, diagonal braces, and purlins. These components establish the array geometry and transfer the reactions to the foundations. Fasteners include bolts, nuts, washers, screws, rivets, and anchors. Their mechanical performance depends on diameter, grade, material, preload, edge distance, hole geometry, thread engagement, corrosion protection, and installation quality.

Table 3.1: Summary for the components and their main mechanical role.

Component	Primary mechanical function	Main mechanical concern
Module laminate	Protects cells and carries distributed surface pressure	Glass bending, cell cracking, impact and torsion
Module frame	Stiffens and protects the laminate; provides a mounting interface	Local deformation, incorrect clamp position, corner damage
Mid-clamp and end-clamp	Transfers module load to the rail	Slip, insufficient overlap, excessive tightening, uplift
Rail or purlin	Supports modules between structural attachment points	Bending, shear, deflection, local fastener bearing
Bracket or standoff	Transfers rail reactions to the primary structure	Eccentric loading, local bending, pullout, waterproofing
Beam, rafter, post, or brace	Forms the primary load-carrying structure	Bending, axial force, buckling, connection failure
Bolts and anchors	Join components and maintain connection preload	Loosening, corrosion, shear, tension, pullout
Foundation or roof attachment	Transfers the complete array load to soil or building structure	Bearing, uplift, sliding, overturning, settlement

2 Mounting System Types

2.1 Rooftop Mounting Systems

Rooftop PV structures are supported by an existing building. The building roof is therefore part of the PV load path. The roof covering or membrane itself should not normally be treated as the principal structural support unless the roof system has been specifically designed and verified for that purpose. Rooftop systems can be divided broadly into mechanically attached and ballasted systems, shown in Figure 3.3.

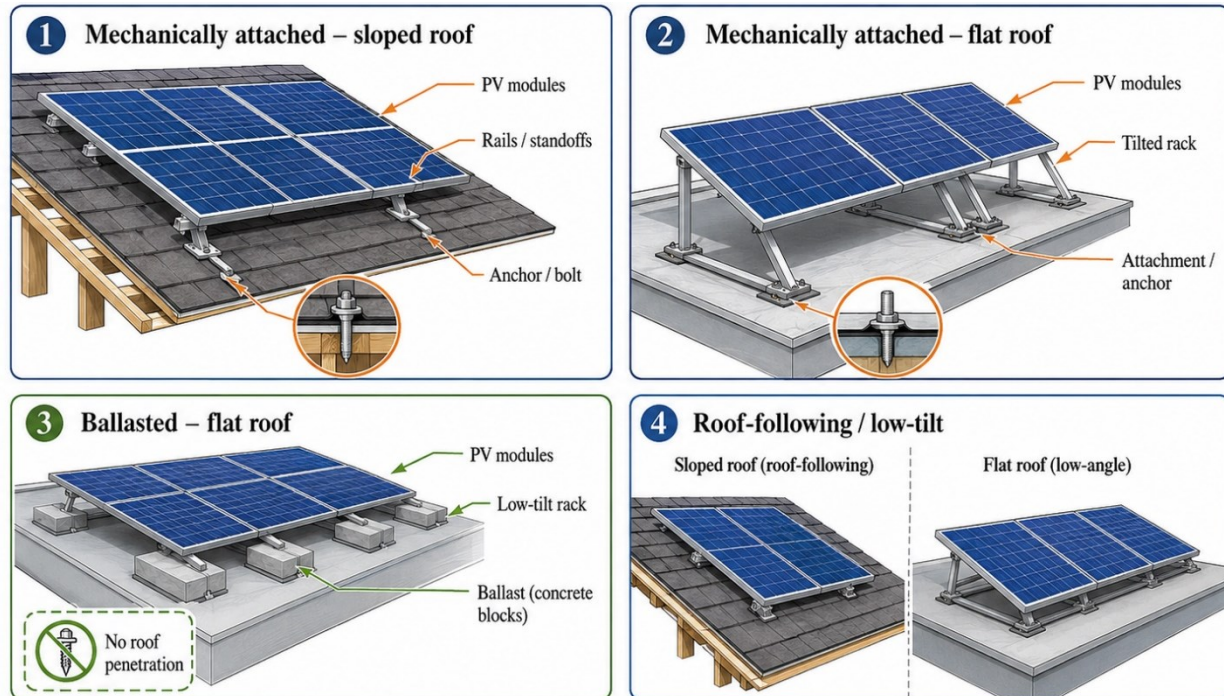


Figure 3.3: Rooftop PV mounting system types.

A mechanically attached system uses anchors, screws, bolts, standoffs, or brackets connected to structural roof members such as rafters, trusses, beams, or purlins. The attachment must resist downward force, uplift, shear, and moment. The connection must also maintain roof waterproofing. Flashing and sealing are therefore functional parts of the mounting system, not merely construction details. A ballasted system uses concrete blocks or other masses to resist uplift and sliding without extensive roof penetration. The array force is transferred to the ballast and then to the roof surface. Ballasted systems reduce the number of penetrations but increase roof dead load. They also require checks for friction, sliding, roof-membrane protection, local pressure, drainage, and ballast movement. Sloped-roof systems usually follow the roof plane or use a small additional tilt. Flat-roof systems often use low-angle triangular frames to limit wind exposure and avoid excessive row-to-row shading. In both cases, the existing roof capacity must be assessed because the PV system introduces permanent weight and concentrated attachment reactions.

Important rooftop considerations include the location of structural members, roof condition, local load capacity, drainage paths, waterproofing, edge and corner wind zones, maintenance access, and compatibility between the mounting materials and roof membrane.

2.2 Ground-Mounted Structures

A ground-mounted PV structure transfers loads directly to foundations installed in the soil. It commonly consists of modules, rails or purlins, transverse beams or rafters, posts, braces, and foundations (see Figure 3.4).



Figure 3.4: Ground-mounted PV structure components breakdown.

Ground-mounted systems provide greater freedom in tilt, row length, orientation, and maintenance access than rooftop systems. However, they are often more exposed to wind and require direct consideration of soil properties, terrain, drainage, corrosion, foundation installation, settlement, and vegetation control. The structural arrangement may use a single central post, two or more support posts, or a continuous frame. A single-post structure may reduce foundation quantity but can produce larger bending moments and torsional demands in the post. A multi-post structure can distribute the reactions but requires tighter alignment of the foundation locations.

A ground-mounted array should accommodate reasonable terrain variation without forcing the modules or rails into a twisted shape. Significant changes in elevation may require stepped rows, adjustable brackets, variable post lengths, or local grading.

2.3 Basic Tracking-System Concept

A tracking system changes the module orientation during the day or year. At this introductory level, tracking systems can be classified as single-axis and dual-axis systems, demonstrated in Figure 3.5.

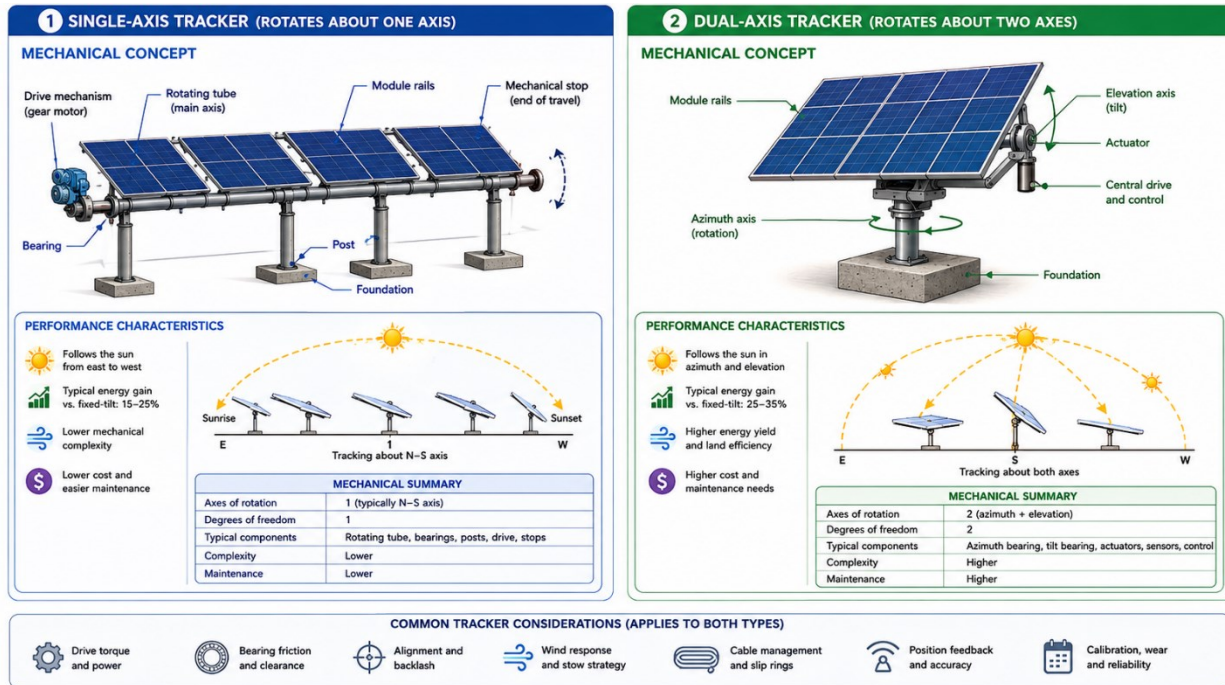


Figure 3.5: Solar tracker system comparison infographic.

A single-axis tracker rotates the module table around one main axis. The mechanical assembly typically includes a rotating tube or beam, bearings, posts, module rails, a drive mechanism, and mechanical stops. Several tracker rows may be moved individually or through linked drive arrangements. A dual-axis tracker rotates about two axes and can control both azimuth and elevation. It requires more bearings, joints, actuators, sensors, and structural degrees of freedom than a single-axis tracker. It is therefore mechanically more complex.

Tracking introduces additional mechanical requirements, including rotational clearances, drive torque, bearing friction, alignment, backlash, dynamic wind response, cable movement, and position accuracy. Part I is limited to the basic arrangement. Actuators, gear drives, linkages, position feedback, wind-stow behavior, calibration, wear, and tracker reliability are developed in Part II.

3 Structural Support and Foundations

3.1 Load Transfer Principles

Structural analysis begins by identifying all relevant actions on the PV system. The most fundamental actions are dead load and wind load. Depending on the site, snow, seismic forces, maintenance loads, thermal movement, rain accumulation, construction loads, or accidental impacts may also need to be considered. The dead load is the permanent weight of the modules, rails, frames, fasteners, cables, ballast, and other supported components. For a component of mass m , $W = mg$, where W is its weight and g is gravitational acceleration. Also, wind can create downward pressure, upward suction, horizontal force, and overturning moment. The direction of the resulting reaction may change with wind direction. A connection that is mainly in compression under gravity may therefore be in tension during uplift.

Structural members may experience axial force, shear, bending, and torsion. The fundamental normal stress under a centered axial force is

$$\sigma = \frac{N}{A} \quad (3.3)$$

where N is axial force and A is the cross-sectional area. The average shear stress can be represented in simplified form as

$$\tau_{\text{avg}} = \frac{V}{A} \quad (3.4)$$

where V is shear force. Actual shear distribution depends on the cross-sectional shape and connection geometry. For a beam subjected to bending, the elastic bending stress is

$$\sigma_b = \frac{My}{I} \quad (3.5)$$

The maximum bending stress occurs at the greatest distance c from the neutral axis:

$$\sigma_{b,\text{max}} = \frac{Mc}{I} \quad (3.6)$$

where M is bending moment and I is the second moment of area. The second moment of area represents the geometric resistance of a section to bending. Increasing section depth is generally more effective for bending stiffness than simply increasing material thickness near the neutral axis. A simplified utilization ratio may be written as

$$U = \frac{\text{design demand}}{\text{design capacity}} \quad (3.7)$$

Ans a basic acceptance condition is $U \leq 1$.

The load factors, resistance factors, allowable stresses, and load combinations used to calculate demand and capacity must come from the applicable structural design method. Arbitrary safety factors should not be mixed with code-based factored-load procedures. Strength alone is not sufficient. Deflection, rotation, vibration, and differential settlement must also be controlled. Excessive movement can damage module glass, create cell microcracks, loosen clamps, alter tracker alignment, or change drainage behavior even when the metal structure remains below its yield strength.

3.2 Connections as Part of the Load Path

Connections often control the structural capacity of PV mounting systems because loads pass through many relatively small fasteners and contact surfaces.

A bolted connection may be subjected to bolt tension, bolt shear, bearing of the bolt against the hole, plate tear-out, net-section fracture, slip, or combined tension and shear. An anchor may fail through steel fracture, concrete breakout, pullout, local crushing, or loss of bond. A screw in a thin roof purlin may be limited by thread pullout rather than by screw strength. Eccentric connections create additional moment. For example, when a rail is offset from a roof attachment, the attachment may experience both shear and bending rather than simple direct shear. Brackets should therefore be evaluated according to their actual geometry. Long slotted holes may be provided for installation tolerance or thermal movement. A slot can permit controlled movement, but it also changes bearing behavior and must be oriented correctly. Installation workers should not assume that every slot should be tightened in a way that prevents all movement.

3.3 Foundation Types

Foundations transfer structural reactions to the soil. The selected foundation depends on soil conditions, groundwater, terrain, corrosion environment, installation equipment, required pullout resistance, project scale, and whether removal at the end of life is required. Table 3.2 summarizes the details about the different types of foundations.

Table 3.2: Summary for the components and their main mechanical role.

Foundation type	Basic description	Main advantages	Main limitations or checks
Driven steel pile	Steel post or pile driven directly into the soil	Rapid installation; limited excavation; little concrete	Refusal on rock or obstructions, alignment, corrosion, pullout
Helical pile or ground screw	Screw-shaped foundation installed by rotation	Useful uplift resistance; removable; installation feedback possible	Installation torque, soil disturbance, underground obstructions
Cast-in-place concrete pier	Reinforced or unreinforced concrete placed in an excavation	Adaptable to many geometries and post types	Excavation, curing time, groundwater, quality control

Concrete spread footing	Broad footing distributes load over a larger soil area	Good bearing and overturning resistance	More excavation and concrete; settlement and drainage
Precast or surface ballast	Heavy block placed on or near the ground surface	Minimal penetration; useful where excavation is restricted	Sliding, overturning, transport weight, surface stability

3.4 Soil Support Considerations

Soil is not a uniform rigid support. Its capacity and deformation depend on density, moisture, layering, particle size, groundwater, compaction, and previous disturbance.

Unequal soil conditions along a long PV row can cause differential settlement. Differential settlement may distort rails, change module gaps, alter tracker alignment, or increase connection forces. Foundations should therefore be installed to the required position, depth, verticality, and elevation. Water management is also important. Surface runoff should not erode soil around foundations or expose embedded sections. Poor drainage can soften soil, increase corrosion, create frost-related movement in cold regions, or reduce access for maintenance.

A geotechnical assessment provides information such as allowable bearing pressure, pile capacity, groundwater level, soil aggressiveness, settlement behavior, and potential construction difficulties. Mechanical design should not assign foundation capacity based only on visual inspection of the ground.

3.5 Roof Support Considerations

For rooftop systems, the existing building replaces the soil and ground foundation. The design must trace the PV reactions through roof attachments into roof decking, purlins, rafters, trusses, beams, columns, and the building foundation. A roof attachment introduces a concentrated reaction. Even when the total PV weight is small relative to the complete roof area, local reactions may be significant. The roof deck, insulation, membrane, and structural member should not be treated as a single material with one capacity.

Ballast also creates local pressure. Protective pads or spreader plates may be needed to prevent damage to the membrane. Drainage paths should remain open, and ballast should not be placed where it causes water accumulation. The existing condition of the building is part of the assessment. Corroded purlins, damaged timber, deteriorated concrete, loose fasteners, or aged waterproofing may reduce the available capacity. A rooftop PV system should not be used to conceal an existing structural problem.

4 Basic Mechanical Design Conditions

4.1 Wind Loads

Wind is often one of the most important mechanical actions on a PV structure because it can produce large uplift forces and overturning moments. The basic dynamic pressure of moving air is

$$q = \frac{1}{2} \rho V^2 \quad (3.9)$$

where:

- q is dynamic pressure,
- ρ is air density,
- V is wind speed.

The quadratic relationship is important: pressure varies approximately with the square of wind speed. A moderate increase in wind speed can therefore produce a much larger increase in wind force. A simplified surface pressure can be represented as $p = Cq$, where C represents the combined influence of shape, orientation, exposure, gust effects, pressure coefficients, and other design factors. The coefficient is not universal and must be taken from an applicable wind-loading method or verified analysis. The resultant force on an effective area is

$$F = pA_{\text{eff}} \quad (3.10)$$

where A_{eff} is the area associated with the pressure. The resulting overturning moment may be approximated as $M = Fz$, where z is the perpendicular distance from the resultant force to the point of rotation or foundation reference point.

Wind acts on both the upper and lower module surfaces. The net structural pressure is related to the difference between these pressures. Gaps beneath an array, module tilt, edge distance, row spacing, surrounding buildings, terrain, parapets, and neighboring rows can all influence the net load. Uplift may be more severe near roof edges and corners or at the end of an exposed ground-mounted row. The pressure should not automatically be assumed uniform over the entire array.

Wind also affects partially completed structures. A row with modules installed on only one side, missing braces, or incomplete fasteners may have a load path different from that of the finished system. Temporary stability must therefore be considered during construction. Detailed wind coefficients, dynamic response, aeroelastic effects, tracker stow angles, and advanced wind-load combinations belong to the later structural study.

4.2 Thermal Expansion

PV structures experience daily and seasonal temperature variation. Modules, rails, steel supports, concrete, roof materials, and fasteners may heat and cool at different rates. For a uniform temperature change, free thermal expansion is

$$\Delta L = \alpha L \Delta T \quad (3.11)$$

where:

- ΔL is the change in length,
- α is the coefficient of thermal expansion,
- L is the original length,
- ΔT is the temperature change.

Thermal movement becomes important in long continuous rails or module rows. If movement is completely restrained, an idealized thermal stress is

$$\sigma_{th} = E \alpha \Delta T \quad (3.12)$$

where E is the elastic modulus of the material. This equation represents a fully restrained condition. Real structures usually contain joint slip, bolt-hole clearance, bracket flexibility, module gaps, and foundation movement, so the actual stress may be lower.

Thermal movement is managed by providing suitable rail joints, module gaps, slotted connections, sliding interfaces, and defined fixed and free points. The objective is not to make every connection loose, but to control where movement is allowed and where load is positively restrained. Dissimilar materials require special attention because their thermal expansion coefficients may differ. A long aluminum rail connected rigidly to a steel frame, for example, may develop internal force or connection slip when temperature changes.

4.3 Corrosion and Material Durability

PV structures operate outdoors for long periods and are exposed to water, humidity, airborne salts, dust, industrial pollutants, temperature cycling, and ultraviolet radiation. Material selection must therefore consider durability as well as initial strength. Common structural materials include aluminum alloys, galvanized carbon steel, stainless steel, concrete, and engineering polymers (See Figure 3.6 and Table 3.3). Each material has different stiffness, mass, corrosion behavior, fabrication method, and cost.

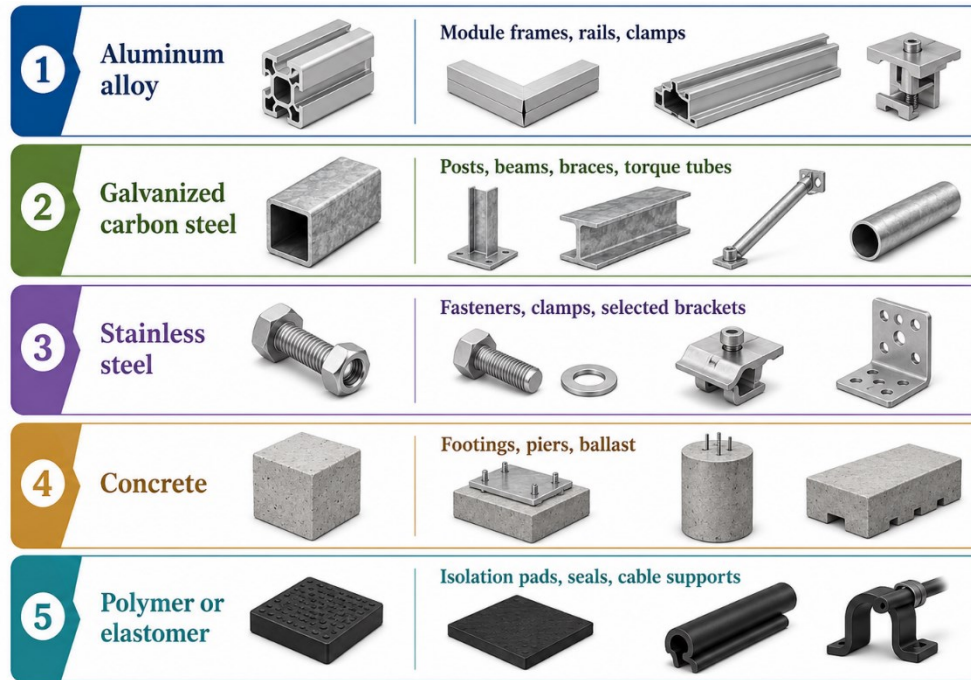


Figure 3.6: Common materials in PV structures chart.

Table 3.3: Summary for the materials and their specifications in PV plants.

Material	Common PV application	Main advantage	Main durability consideration
Aluminum alloy	Module frames, rails, clamps	Low mass, easy extrusion, natural protective oxide layer	Galvanic contact, local deformation, coating damage
Galvanized carbon steel	Posts, beams, braces, torque tubes	High stiffness and strength; economical for primary structures	Damage to zinc coating, cut edges, buried corrosion
Stainless steel	Fasteners, clamps, selected brackets	Good corrosion resistance in many environments	Material grade selection, galling, galvanic interaction
Concrete	Footings, piers, ballast	High mass and compressive capacity	Cracking, poor curing, anchor-zone deterioration
Polymer or elastomer	Isolation pads, seals, cable supports	Electrical and mechanical separation; flexibility	UV exposure, temperature aging, creep

Galvanic corrosion may occur when dissimilar metals are electrically connected in the presence of an electrolyte such as rainwater or saltwater. This risk can be reduced by selecting compatible materials, using nonconductive isolation pads or washers, applying suitable coatings, controlling drainage, and avoiding persistent moisture traps. Cutting or

drilling galvanized steel removes part of the protective coating. Damaged areas should be treated using an approved repair method. Similarly, stainless-steel fasteners do not automatically protect an entire connection if the surrounding carbon steel or aluminum is not compatible with the environment.

Water should be able to drain from rails, hollow sections, clamp recesses, and foundation details. Closed cavities and horizontal ledges can collect water and dirt, increasing crevice corrosion and freeze-related damage. Durability also requires access for inspection. A connection that cannot be viewed or reached may be difficult to maintain even when it is structurally adequate at the time of installation.

5 Installation and Safety Considerations

5.1 Module Handling

PV modules must be handled as fragile structural panels. Their frames can resist properly distributed loads but may be damaged by twisting, dropping, edge impact, or concentrated pressure. Modules should remain in their protective packaging until they are required for installation. They should be lifted using the approved frame locations and should not be carried by the cables or junction box. Workers should not stand, sit, kneel, or place tools on the glass.

Dragging a module across another module or across a metal rail can damage the frame, glass, coating, backsheet, or connector. Modules should also be protected from sudden wind during lifting because their large surface area can produce significant force. A module with a damaged frame, cracked glass, loose junction box, damaged backsheet, or distorted corner should be separated for inspection rather than forced into the mounting row.

5.2 Mechanical Alignment

Alignment starts with survey and setting-out. Ground foundations must be installed at the correct position, spacing, elevation, and verticality. Roof attachments must correspond to actual structural members and the approved layout. Posts should be checked for plumbness, beams for level or specified slope, and rails for straightness. Module gaps, row spacing, tilt angle, azimuth, and edge alignment should be consistent with the design drawings.

Mechanical misalignment is not only an appearance issue. A misaligned rail can twist a module when clamps are tightened. Unequal support heights can create concentrated frame contact. Incorrect tracker-post alignment can increase bearing friction and drive load. Even in fixed-tilt systems, poor alignment can create residual stresses and uneven load distribution.

Adjustable brackets are useful for compensating for reasonable installation tolerance, but they should not be used to conceal major foundation-position errors. All adjustment bolts must remain within their permitted range and retain sufficient edge distance and engagement.

5.3 Fastener Tightening and Preload

Bolted joints depend on controlled tightening. Tightening creates preload in the bolt and clamping force between the connected parts. Adequate preload helps prevent slip, separation, vibration loosening, and water penetration at some interfaces. A simplified relationship between applied torque and bolt preload is described as

$$T \approx KF_p d \quad (3.13)$$

where:

- T is tightening torque,
- K is a torque coefficient influenced mainly by friction,
- F_p is the desired bolt preload,
- d is the nominal bolt diameter.

This expression is approximate because most applied torque is consumed by friction in the threads and under the bolt head or nut. Surface coating, lubrication, contamination, reuse, and material pairing can significantly change the relationship between torque and preload.

Manufacturer-specified torque values therefore take precedence over calculations based on a general torque coefficient. Installation should use the specified fastener, washer, thread condition, tightening sequence, and calibrated tool. Under-tightening may permit slip or loosening. Over-tightening can strip threads, deform module frames, crush polymer pads, damage rails, or fracture fasteners. Torque values should not be transferred from one connection type to another merely because the bolts have the same diameter.

5.4 Typical Mechanical Installation Sequence

A controlled installation sequence helps maintain alignment and prevents unstable intermediate conditions (see Table 3.4).

Table 3.4: Summary for the materials and their specifications in PV plants.

Installation stage	Main mechanical checks
Survey and setting-out	Coordinates, row direction, elevations, clearances, underground and rooftop constraints
Foundations or roof attachments	Position, depth, pullout condition, verticality, waterproofing, anchor engagement
Primary structure	Post plumbness, beam level, bracing, temporary stability, connection fit
Rails and secondary members	Span, straightness, thermal joints, splice position, support spacing
Module installation	Correct orientation, approved clamp zones, clamp overlap, module gap, cable clearance
Fastener completion	Correct fastener grade, washer arrangement, torque, locking feature, torque marking
Final mechanical inspection	Alignment, coating damage, loose components, drainage, sharp edges, access routes

Temporary bracing may be required until all permanent braces, rails, and modules are installed. The structure should not be assumed stable merely because the foundations and posts are in place. Splices should be installed at their intended locations. A rail splice placed at a region of high bending moment may behave differently from one located near a support. Thermal-expansion splices should not be installed as rigid structural splices unless the design specifically requires this.

5.5 Basic Installation Safety

Mechanical installation presents risks from lifting, falling objects, sharp edges, work at height, excavations, rotating equipment, unstable structures, and pinch points. A lifting plan should consider module size, wind, access, lifting equipment, worker coordination, and exclusion zones. Large modules can be difficult to control even when their mass is manageable because they behave as broad aerodynamic surfaces.

Workers on roofs require suitable fall protection and safe access. Materials should not be stored in concentrated piles without confirmation that the roof can support them. Tools and components should be secured to prevent falling. Ground work may involve pile-driving equipment, augers, cranes, excavations, and underground services. The work area should be controlled so that workers are not positioned beneath suspended loads or between moving equipment and fixed structures. Hands should be kept clear of clamp interfaces, folding frames, tracker bearings, linkages, and other pinch points. Sharp rail ends and cut steel sections should be treated or covered.

The structure must be stable during every construction stage. Wind limits for lifting and module installation should be established as part of the work procedure. Installation should stop when modules cannot be controlled safely. Although this session focuses on mechanical safety, PV modules produce electrical voltage when exposed to light. Cable and connector handling must therefore also follow the electrical-safety requirements developed in the electrical-structure session.

Session Summary

This session introduced the mechanical structure of a solar PV system as a continuous load path extending from the module glass and frame to the clamps, rails, brackets, primary supports, foundations, roof structure, and ultimately the soil or building frame. The PV module was treated as both an energy-conversion device and a structural panel. Its glass, laminate, frame, clamp zones, and mounting instructions directly influence how pressure and uplift are transferred to the supporting structure.

The main mounting arrangements were examined at a fundamental level. Rooftop systems may be mechanically attached or ballasted, with roof capacity, waterproofing, concentrated reactions, uplift, and membrane protection as primary concerns. Ground-mounted systems use posts, beams, braces, and soil foundations and require attention to terrain, alignment, pullout, settlement, drainage, and corrosion. Fixed-tilt systems provide a simple and stationary geometry, while tracking systems introduce rotation, bearings, torque tubes, drives, clearances, and additional mechanical complexity.

Basic structural behavior was described using static equilibrium, axial stress, shear stress, bending stress, stiffness, and utilization. Structural adequacy requires both strength and acceptable serviceability. Rails and beams must not only avoid yielding but must also limit deflection. Connections require checks for tension, shear, bearing, slip, pullout, and eccentricity. Foundations require consideration of bearing, uplift, sliding, overturning, lateral resistance, and settlement, while rooftop systems require the same reactions to be traced through the existing building structure.

Wind loading was introduced through dynamic pressure, effective surface pressure, resultant force, and overturning moment. Wind can produce both pressure and suction, and its force increases approximately with the square of wind speed. Thermal movement was described through free expansion and fully restrained thermal stress. Long rails and dissimilar materials require planned movement joints, slots, gaps, and fixed or sliding connection points. Material durability depends on corrosion protection, drainage, compatible material combinations, coating integrity, environmental exposure, and access for inspection. Aluminum, galvanized steel, stainless steel, concrete, and polymers each provide useful properties but also introduce specific design and maintenance considerations.

Finally, the session covered module handling, structural alignment, controlled fastener tightening, installation sequencing, inspection, temporary stability, lifting safety, work at height, and mechanical hazards. These fundamentals form the basis for Part II, in which the mechanical analysis can be expanded to detailed load combinations, member sizing, fatigue, tracker drives, bearings, wind-stow operation, thermal interaction, wear, calibration, reliability, and failure prevention.

Electrical structure in solar PV systems- Part I

Learning Objectives

- Explain the fundamental electrical principles governing photovoltaic (PV) energy generation and describing the electrical behavior of PV cells, modules, strings, and arrays under different operating conditions.
- Analyze the effects of series and parallel connections on PV system voltage, current, and power output.
- Identify the main electrical components of a PV system, including DC cables, connectors, combiner boxes, disconnect switches, and protective devices.
- Apply basic electrical protection and safety principles, including grounding, overcurrent protection, polarity verification, and insulation requirements.
- Interpret the electrical characteristics of PV modules using I–V and P–V curves and understand the influence of environmental conditions on system performance.
- Perform basic PV array sizing and configure PV strings to meet inverter operating requirements.
- Match PV array electrical characteristics with inverter specifications to ensure safe, efficient, and reliable system operation.

Abstract

This course, “*Electrical structure in solar PV systems- Part I*”, introduces the fundamental electrical concepts of PV systems, beginning with the electrical behavior of photovoltaic cells and the characteristics of direct current (DC) generation. It then examines how individual PV modules are interconnected into strings and arrays to achieve the required voltage, current, and power levels. The course also presents the primary electrical components of PV installations, including DC wiring, connectors, combiner boxes, disconnect switches, and protective devices. Essential safety concepts, such as grounding, overcurrent protection, insulation, and polarity verification, are discussed to ensure safe installation and operation. Finally, the course explains PV electrical output characteristics through I–V and P–V curves and demonstrates how PV arrays are electrically matched with inverters to maximize energy production while maintaining compatibility with system operating limits. By understanding these fundamental electrical principles, learners will establish the knowledge required for PV system design, installation, protection, and performance evaluation, providing a strong foundation for more advanced topics in photovoltaic engineering.

1 Electrical Generation Basics in PV System

Photovoltaic technology converts solar energy directly into electrical energy through the photovoltaic effect. When sunlight strikes the semiconductor material inside a photovoltaic cell, photons transfer their energy to electrons, allowing them to move freely and generate an electric current. Unlike conventional generators, PV cells produce electricity without moving parts, combustion, or mechanical energy conversion, making them a clean and reliable source of renewable electricity.

The electricity generated by a PV cell is direct current, whose magnitude depends primarily on the available solar irradiance and the operating temperature of the cell. Since an individual PV cell produces only a small voltage and limited power, many cells are interconnected to form modules, and modules are further combined into strings and arrays to satisfy the voltage and power requirements of practical PV systems. Understanding the electrical characteristics of the PV cell is therefore the first step toward understanding the design and operation of complete photovoltaic systems.

1.1 PV cell electrical behavior and equivalent circuit

A photovoltaic cell is essentially a semiconductor device that converts solar radiation directly into electrical energy. Its operation is based on the photovoltaic effect, where photons from sunlight excite electrons within the semiconductor material. If the photon energy exceeds the semiconductor bandgap energy, electrons gain sufficient energy to move from the valence band into the conduction band, leaving behind holes. The built-in electric field of the p–n junction separates these electrons and holes, producing an electric current when an external load is connected. Unlike an ideal voltage source or current source, a PV cell exhibits nonlinear electrical behavior. The output current and voltage vary continuously with irradiance, temperature, and load conditions. As solar irradiance increases, more photons are absorbed by the semiconductor, producing more free charge carriers and consequently increasing the output current. Conversely, increasing the cell temperature mainly reduces the output voltage because the semiconductor junction characteristics change with temperature. Therefore, both environmental conditions and electrical loading determine the operating point of the PV cell. In this regard, a single diode equivalent circuit is used to analyze and predict this behavior as shown in Fig. 4.1.

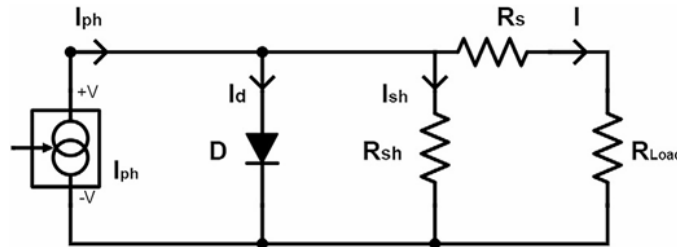


Figure 4.1: Single diode model of a solar cell

Which I_{ph} represents the current generated by incident solar radiation, R_s is internal resistive losses in the semiconductor material, metallic contacts, and electrical interconnections and R_{sh} indicates leakage current paths caused by manufacturing imperfections or material defects. Applying Kirchhoff's Current Law (KCL) to the equivalent circuit gives the generated current based on Eq. (1).

$$I = I_{ph} - I_D - I_{sh} \quad (1)$$

Where I_D is the diode current. Considering current passing through the diode by the Shockley diode equation, the Eq. (2) is derived.

$$I = I_{ph} - I_0 \left[\left(e^{\frac{V_{sh} \cdot q}{n \cdot k \cdot T}} \right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \quad (2)$$

Where q , n , k and T are charge on an electron, the ideality factor of solar material, the Boltzmann's constant and cell temperature, respectively.

Since the photocurrent I_{ph} is approximately proportional to the incident solar irradiance, an increase in sunlight directly increases the output current and the electrical power produced by the PV cell. In contrast, increasing the cell temperature increases the diode saturation current I_0 , which causes a reduction in the output voltage and consequently lowers the maximum power that the PV cell can deliver. The equation also highlights the influence of the internal resistances; a higher series resistance increases the internal voltage drop, while a lower shunt resistance increases leakage current, both of which reduce the cell efficiency and maximum power output. Therefore, the electrical characteristics of a PV cell are determined not only by solar irradiance but also by temperature and the internal electrical parameters represented in the equivalent circuit.

Technical Note 1

For more detailed analyses, particularly under low irradiance or varying temperature conditions, the two-diode model is often employed. This model introduces an additional diode to represent carrier recombination losses within the semiconductor material, resulting in more accurate prediction of the current and voltage characteristics. Although the two-diode model improves modeling accuracy, it requires additional parameters and greater computational effort. Consequently, the single-diode model remains the preferred choice for most practical PV engineering applications, while the two-diode model is mainly used in advanced research and detailed performance studies.

1.2 DC voltage and current generation

The electrical energy produced by a photovoltaic cell is in the form of direct current, meaning that the current flows continuously in one direction with constant polarity. This differs from alternating current (AC), where both the current direction and voltage polarity change periodically.

The electrical output of a PV cell is described by two fundamental electrical quantities:

- Voltage: the electrical potential difference generated by the cell.
- Current: the flow of electric charge supplied to the external circuit.

The generated current depends mainly on the available solar irradiance. As sunlight intensity increases, more electron-hole pairs are generated, producing higher current. The output voltage is influenced by the semiconductor properties and varies relatively little with irradiance, but decreases as the cell temperature rises. A single crystalline silicon solar cell typically produces only about 0.5–0.6 V, which is insufficient for practical electrical applications. Therefore, multiple cells are electrically interconnected inside a PV module to obtain usable voltage levels.

1.3 Series and parallel connection of PV cells

A single PV cell generates a relatively low DC voltage under standard operating conditions. Although the current produced by a single cell depends on its surface area and irradiance, the electrical output of one cell is insufficient for most practical applications. Therefore, multiple PV cells are electrically interconnected to produce a module with the required voltage, current, and power ratings. The electrical connection of PV cells can be made in series, parallel, or a combination of both, depending on the desired output characteristics. These interconnections determine the electrical rating of the PV module and directly influence its performance.

1.3.1 Series connection

In a series connection, the positive terminal of one PV cell is connected to the negative terminal of the next cell. This arrangement increases the output voltage while maintaining the same current as that produced by a single cell. This configuration is widely used because higher DC voltage reduces transmission losses and satisfies the input voltage requirements of PV inverters.

An important characteristic of a series connection is that the same current flows through every cell. Consequently, if one cell is shaded, damaged, or produces less current than the others, the current of the entire series string is reduced. For this reason, PV modules commonly incorporate bypass diodes to minimize power losses and protect shaded cells from overheating.

1.3.2 Parallel connection

In a parallel connection, all positive terminals are connected together, and all negative terminals are connected together. In this arrangement, the output current increases while the voltage remains equal to that of a single cell.

Parallel connections are used when a higher current output is required without increasing the voltage. Since each branch contributes independently to the total current, partial shading of one branch has a smaller effect on the remaining branches compared with a purely series-connected circuit. However, parallel connections require larger conductors because of the increased current and are therefore less common inside conventional PV modules. The series and parallel connection of two PV cell is described in Fig. 4.2.

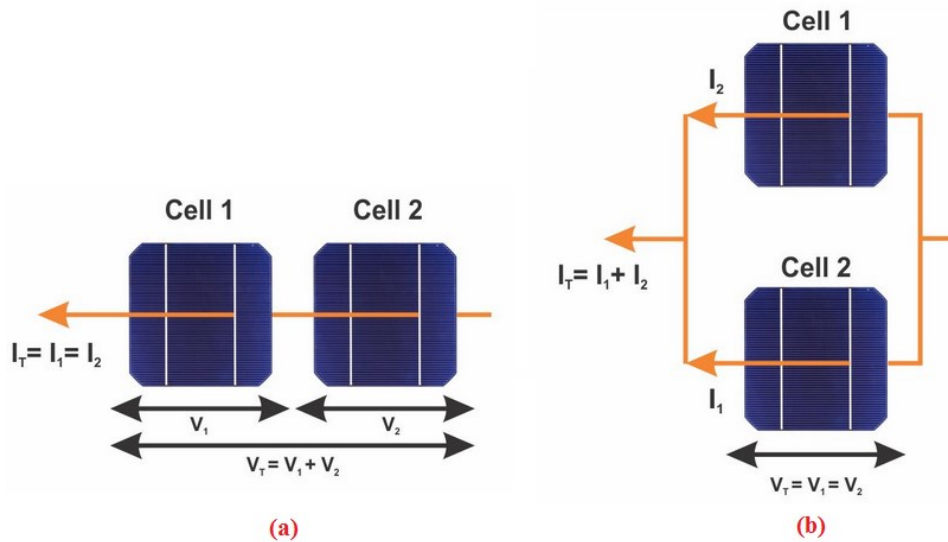


Figure 4.2: Connection of PV cells, a) series b) parallel.

1.3.3 Series-parallel connection

Most commercial PV modules employ a series-parallel arrangement, combining both types of electrical connections to achieve the desired voltage, current, and power output. In this configuration, several cells are first connected in series to obtain the required voltage, while multiple series-connected groups may then be connected in parallel to increase the available current.

This arrangement allows module manufacturers to optimize electrical performance, improve power capability, and satisfy different application requirements. For example, modules designed for high-power applications may incorporate several parallel cell paths to reduce resistive losses and improve tolerance to partial shading. The series-parallel configuration represents the fundamental building block of a PV module. Once individual modules are manufactured, they are later interconnected into strings and arrays, which will be discussed in the next section.

2 PV module, string and array

Individual PV cells generate only a small amount of electrical power. To supply practical electrical loads, cells are first interconnected to form a PV module. Multiple modules are then connected together to form a string, and several strings are combined to create a PV array capable of delivering the voltage, current, and power required by residential, commercial, or utility-scale PV systems, as depicted in Fig. 4.3. The electrical configuration of modules, strings, and arrays is determined according to the required system voltage, current rating, inverter specifications, and desired power capacity.

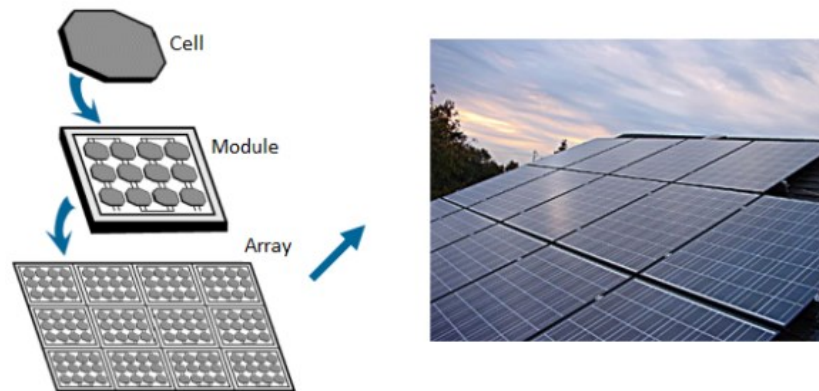


Figure 4.3: PV cell, module and array

2.1 PV Modules and electrical ratings

A PV module consists of several solar cells electrically connected and encapsulated within a protective structure made of tempered glass, encapsulant material, and an aluminum frame. Although each individual cell produces only small voltage, connecting many cells together enables the module to provide useful voltage and power levels suitable for practical applications.

The electrical performance of a PV module is specified by several standard ratings measured under Standard Test Conditions (STC). The most important ratings include the open-circuit voltage, short-circuit current, voltage at maximum power, current at maximum power, maximum output power, and module efficiency. These parameters are provided by the manufacturer and are used when designing strings and selecting compatible inverters. To obtain higher voltage or current than a single module can provide, PV modules are interconnected in series, parallel, or series-parallel configurations.

In a series connection, the positive terminal of one module is connected to the negative terminal of the next module. The module voltages add together while the current remains unchanged. Considering the V_{cell} and I_{cell} as the cell generated voltage and

current, if N identical cells connected in series, the voltage and current of module would be as:

$$\begin{aligned} V_{module} &= N \times V_{cell} \\ I_{module} &= I_{cell} \end{aligned} \quad (3)$$

Similarly, in parallel connection the Equation rewrite as Eq. (4).

$$\begin{aligned} V_{module} &= V_{cell} \\ I_{module} &= N \times I_{cell} \end{aligned} \quad (4)$$

In large PV installations, both series and parallel connections are combined. Series connections provide the required operating voltage, while parallel connections increase the available current and total power delivered by the system.

2.2 PV strings and array Configuration

When several PV modules are connected in series, they form a PV string. The string voltage is equal to the sum of the individual module voltages, while the current is determined by the current rating of one module. The string voltage is selected to satisfy the input voltage requirements of the inverter while remaining within its allowable operating range under all environmental conditions.

Multiple PV strings are then connected in parallel to form a PV array. Since the strings are connected in parallel, the array voltage remains equal to the voltage of one string, whereas the total output current becomes the sum of the currents produced by all parallel strings. Figure 4.4 illustrates a PV array having two parallel strings of PV modules, each having two PV modules in series.

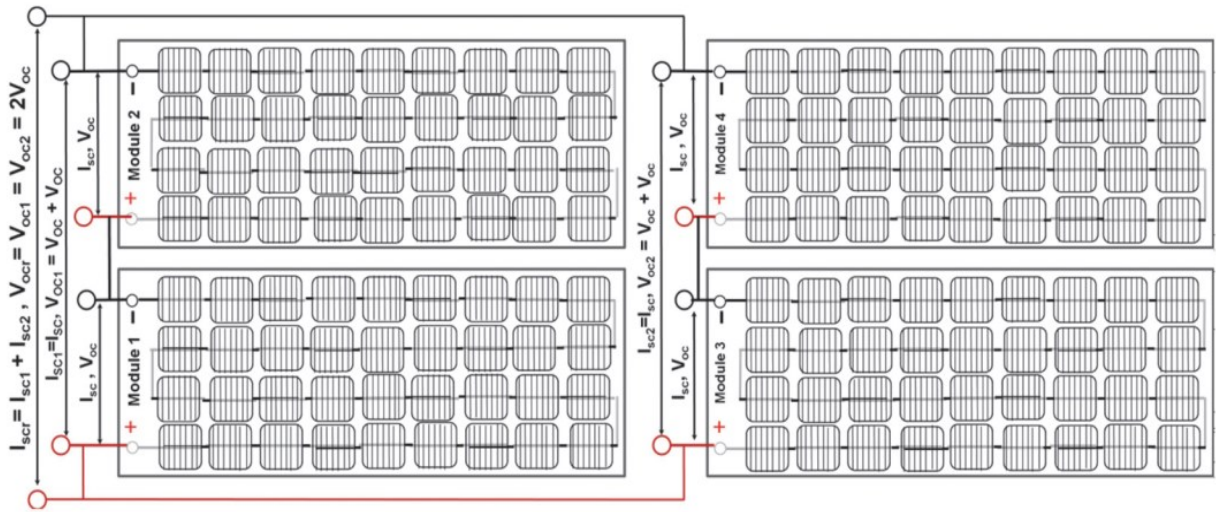


Figure 4.4: A typical PV array

This hierarchical arrangement allows PV systems to be designed over a wide power range, from a few hundred watts for residential systems to several megawatts for utility-scale solar power plants. Most modern PV arrays are connected to an inverter, which converts the generated DC electricity into AC electricity suitable for supplying electrical loads or feeding power into the utility grid.

2.3 PV array sizing basics

The purpose of PV array sizing is to determine the number of modules and strings required to satisfy the desired electrical load while operating safely within the voltage and current limits of the inverter. The array size depends on the daily energy demand, available solar irradiation, system efficiency, module electrical characteristics, and environmental conditions such as temperature.

A simple estimation of the required PV array capacity can be obtained using Eq. (5).

$$W_{PV} = \frac{E}{PSH \times \eta_{sys}} \quad (5)$$

Where E is the daily energy demand (Wh/day), PSH indicates the average daily Peak Sun Hours and η_{sys} is the overall system efficiency.

Once the required array power has been determined, the designer selects the appropriate number of modules connected in series to satisfy the inverter voltage requirements, and then determines the number of parallel strings needed to achieve the required current and total power output. The final design should also account for wiring losses, module temperature variations, dust accumulation, aging effects, and local solar irradiation conditions to ensure reliable long-term operation.

Technical Note 2

In practical PV system design, selecting the number of modules in each string involves more than simply achieving the desired voltage. The string voltage must remain above the inverter's minimum operating voltage during hot weather, when module voltage decreases, while also remaining below the inverter's maximum allowable input voltage during cold conditions, when module voltage increases. Similarly, the number of parallel strings is selected according to the inverter's maximum DC input current rating. For this reason, inverter manufacturers specify the recommended operating voltage range, maximum input voltage, and maximum input current in their datasheets, which serve as the primary reference when designing PV strings and arrays. This ensures reliable operation, maximizes energy production, and prevents inverter shutdown due to voltage or current limits.

3 Main Electrical Components in Solar PV System

In addition to photovoltaic modules and inverters, every PV installation requires a set of electrical components that safely transfer, combine, protect, and isolate electrical power throughout the system. These components are collectively known as the Balance of System (BOS). Although they do not generate electricity, BOS components have a direct influence on system reliability, efficiency, maintenance, and operational safety.

The electrical BOS includes DC cables and connectors, combiner boxes, disconnect switches, protective devices, grounding conductors, and monitoring equipment. Their primary purpose is to provide a secure electrical path between the PV array and the inverter while protecting the system against faults such as short circuits, overcurrent, and accidental contact. Proper selection and installation of these components are essential for ensuring long-term operation and compliance with electrical standards.

3.1 DC cable and connectors

DC cables carry the electrical energy generated by the photovoltaic modules to the combiner box and subsequently to the inverter. Since the output of a PV array is direct current, these cables are specifically designed to withstand continuous DC voltage, outdoor environmental conditions, ultraviolet radiation, and temperature variations throughout the lifetime of the system.

A typical PV cable consists of a stranded copper conductor surrounded by multiple layers of insulation and protective jackets. Copper is widely used because of its high electrical conductivity, flexibility, and excellent corrosion resistance. Proper cable sizing is essential because undersized conductors increase electrical resistance, resulting in voltage drop and power loss, whereas oversized cables unnecessarily increase installation cost. Since resistance increases with cable length and decreases with conductor cross-sectional area, shorter cable routes and larger conductors help minimize power losses.

Modern PV systems commonly use connectors to establish reliable plug-and-play electrical connections between modules. These weatherproof connectors provide secure locking mechanisms, low contact resistance, and protection against dust and water ingress, making them suitable for long-term outdoor operation. The connectors in a PV module is represented in Fig. 4.5.



Figure 4.5: Connectors and DC cables

3.2 Combiner box

Combiner boxes are electrical enclosures used to collect power from multiple circuits into a single output circuit while providing protection and simplifying system wiring. Depending on their location within the PV system, combiner boxes are classified as DC combiner boxes and AC combiner boxes.

A DC combiner box is installed between the PV array and the inverter. It combines the outputs of several PV strings connected in parallel into a single DC output that is delivered to the inverter. In addition to reducing the number of cables, the DC combiner box typically houses string fuses, DC circuit breakers or disconnect switches, surge protection devices (SPDs), busbars, and, in large installations, string monitoring equipment.

An AC combiner box, sometimes referred to as an AC distribution box, is installed on the output side of the inverter. It combines the AC outputs from one or more inverters before connecting them to the building distribution board or the utility grid. The AC combiner box generally contains AC circuit breakers, surge protection devices, protective relays, metering equipment, and disconnect switches to ensure safe operation and facilitate maintenance.

Both DC and AC combiner boxes improve the organization, safety, and reliability of photovoltaic systems by centralizing electrical connections and integrating the necessary protection devices required for system operation. Figure 4.6 demonstrates a DC combiner box, which three PV string are connected to increase output current.

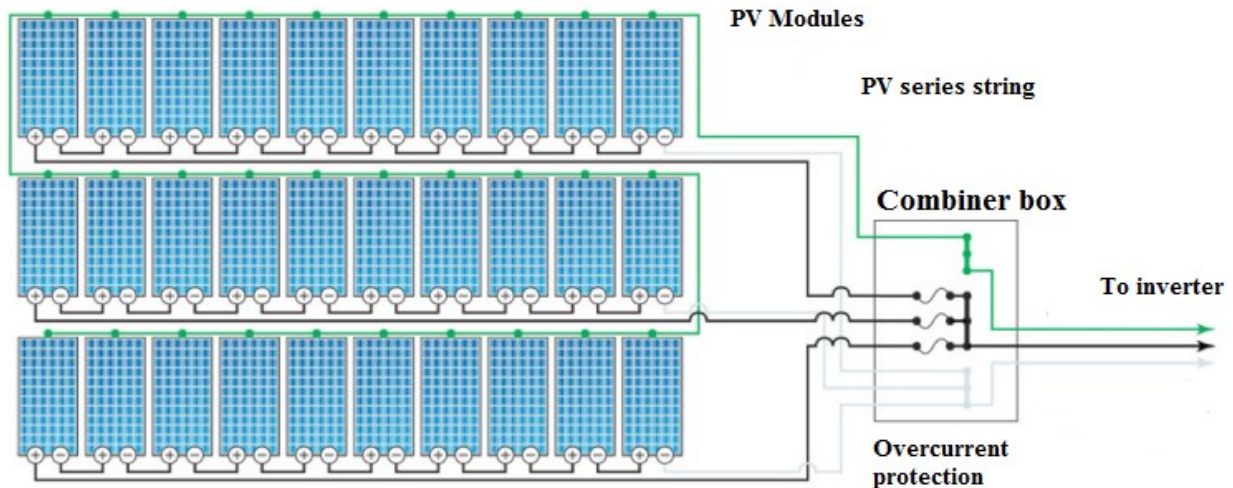


Figure 4.6: DC combiner box

3.3 Disconnect switches and fuses

Electrical protection devices allow PV systems to operate safely during normal conditions while protecting equipment and personnel during faults or maintenance activities.

A DC disconnect switch is installed between the PV array and the inverter. Its primary function is to isolate the photovoltaic array from the inverter, allowing maintenance personnel to safely service the inverter without exposure to energized DC conductors. During emergency situations such as equipment failure or fire, the DC disconnect quickly interrupts the power supplied by the PV array. Similarly, an AC disconnect switch is installed between the inverter output and the electrical distribution panel or utility grid. This switch enables the inverter to be isolated from the AC network for maintenance, inspection, or emergency shutdown. Many utilities require an externally accessible AC disconnect for grid-connected installations. Figure 4.7 illustrates a typical DC disconnect switch.



Figure 4.6: DC disconnect switch

Overcurrent protection is provided using fuses and circuit breakers. String fuses protect individual PV strings against reverse currents that may occur when one string becomes faulted while adjacent healthy strings continue producing current. Circuit breakers provide both manual switching and automatic interruption when excessive current caused by overloads or short circuits is detected. Molded Case Circuit Breakers (MCCBs) are commonly used in larger PV installations because they can safely interrupt high fault currents while allowing repeated operation after faults are cleared.

A comparison between fuse and MCCB provided in Table 4.1.

Table 4.1: Comparison between operating characteristic of fuse and MCCB

Scheme	Advantage	Disadvantage
Fuse	Very fast response to short-circuit faults; Excellent current-limiting capability; Simple construction with high reliability; Low initial cost and minimal maintenance during normal operation; Suited for PV string protection in combiner boxes.	Must be replaced after every fault operation; Cannot be reset or reused; Fixed operating characteristics with no adjustment; Provides limited protection against overloads; Replacement requires spare fuses and maintenance intervention.
MCCB	Can be reset and reused after clearing the fault; Protects against both overloads and short circuits using thermal and magnetic trip mechanisms; Adjustable trip settings available in many models; Can be used as both a protective device and an isolation switch; Suitable for main DC feeders, inverter outputs, and AC distribution systems.	Higher initial cost than fuses; Larger physical size; Slower response to severe short-circuit currents compared with fuses; Requires periodic inspection and testing to ensure reliable operation; Lower current-limiting capability than high-speed fuses.

Together, disconnect switches and protective devices ensure that electrical faults are isolated quickly, equipment damage is minimized, and maintenance can be performed safely without interrupting the operation of the entire PV installation.

4 Basic Protection and Safety

Electrical protection is one of the most important aspects of photovoltaic system design because PV installations continuously generate electrical energy whenever sunlight is available. Unlike conventional electrical systems, the DC side of a PV system remains energized during daylight, making proper protection essential for both personnel safety and equipment reliability. Protection systems are therefore designed to prevent electric shock, minimize equipment damage during electrical faults, reduce fire hazards, and ensure compliance with electrical standards. The fundamental protection measures include grounding, overcurrent protection, correct polarity, and adequate insulation of all electrical components.

4.1 Grounding concepts

Grounding provides a low-resistance path for fault currents to safely dissipate into the earth. Its primary purpose is to protect both people and equipment from dangerous voltages caused by insulation failures, lightning strikes, or accidental contact between energized conductors and metallic structures. By establishing a reference potential of approximately zero volts, grounding stabilizes system voltages and significantly reduces the risk of electric shock.

In PV systems, grounding consists of two complementary practices: system grounding and equipment grounding. System grounding connects one conductor of the electrical system—typically the negative conductor on the DC side or the neutral conductor on the AC side—to earth. This establishes a stable voltage reference and limits excessive voltages caused by transient events. Equipment grounding, on the other hand, connects all exposed conductive parts, such as module frames, inverter enclosures, combiner boxes, and mounting structures, to the grounding electrode. Under normal operating conditions this conductor carries no current, but during a fault it provides a safe path for fault current, allowing protective devices to operate rapidly. Figure 4.7 describes the PV system grounding configuration, consisting system grounding, equipment grounding, and grounding electrode.

A proper grounding system normally consists of a grounding electrode, such as a copper rod driven into moist soil, interconnected through grounding conductors to all metallic equipment. To avoid circulating ground currents and potential differences, PV installations are generally designed with a single grounding point. When multiple grounding electrodes are required in large installations, they should be electrically bonded together to maintain the same ground potential throughout the system.

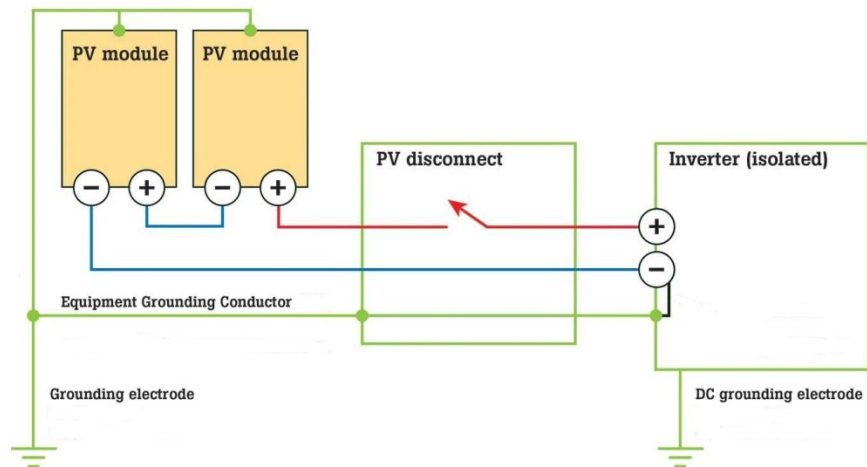


Figure 4.7: PV system grounding architecture

Technical Note 3

Although the terms earthing and grounding are often used interchangeably, they refer to two related but distinct concepts in electrical engineering. Earthing is the physical connection of exposed conductive parts, such as equipment enclosures, PV module frames, and mounting structures, directly to the earth through a grounding electrode. Its primary purpose is personnel safety, providing a low-resistance path for fault currents so that dangerous touch voltages are minimized and protective devices can operate quickly. Under normal operating conditions, the earthing conductor carries no current. Grounding refers to establishing a common electrical reference point for the power system. In photovoltaic systems, grounding is typically achieved by connecting one current-carrying conductor—such as the negative conductor of the DC system or the neutral conductor of the AC system—to earth. This stabilizes system voltage, improves protection against lightning and transient overvoltages, reduces electrical noise, and enables the proper operation of protection devices during fault conditions.

4.2 Overcurrent protection

Overcurrent protection prevents excessive current from damaging cables, inverters, batteries, and other electrical equipment during overload or short-circuit conditions. Since PV systems contain both DC and AC circuits, protection devices are required on both sides of the inverter. Properly selected overcurrent protection devices (OCPDs) isolate faulty circuits while allowing the remainder of the system to continue operating safely.

4.2.1 DC side overcurrent protection

The DC side of a photovoltaic system includes the PV modules, strings, combiner boxes, batteries (if present), and the DC input of the inverter. Because photovoltaic modules continue producing current whenever sunlight is available, interrupting DC current is considerably more difficult than interrupting AC current due to the absence of

natural current zero crossings. Consequently, specialized DC-rated fuses, circuit breakers, and disconnect switches are required.

DC overcurrent protection devices are commonly installed inside combiner boxes, where each PV string is individually protected by a fuse or DC circuit breaker before being connected in parallel. This arrangement prevents reverse currents from healthy strings flowing into a faulted string and protects cables from excessive heating. Additional DC disconnect switches are installed between the PV array and the inverter to safely isolate the array during maintenance or emergency conditions. Modern grid-connected inverters often integrate DC disconnects within the inverter enclosure, simplifying installation while maintaining safety. The current rating of DC protection devices is typically selected above the maximum continuous operating current while remaining low enough to interrupt fault currents effectively. This ensures reliable operation without nuisance tripping during normal power production.

Figure 4.8 illustrates a typical fault scenario on the DC side of a photovoltaic system. When multiple PV strings are connected in parallel through a combiner box, a short circuit occurring in one string can cause back-feeding currents from the remaining healthy strings. Instead of flowing toward the inverter, the current produced by the unaffected strings is diverted through the faulted string because it provides a low-resistance path. As the number of parallel strings increases, the reverse current can become sufficiently large to overheat conductors, damage PV modules, and create a potential fire hazard. To prevent this condition, each PV string is protected by a DC fuse or a DC-rated circuit breaker installed inside the combiner box. Under normal operation, the fuse allows the generated current to pass without interruption. However, when a fault causes the reverse current to exceed the fuse rating, the fuse rapidly opens the circuit and isolates the faulty string from the healthy strings. This prevents excessive back-feeding currents, limits equipment damage, and allows the remaining PV strings to continue operating safely.

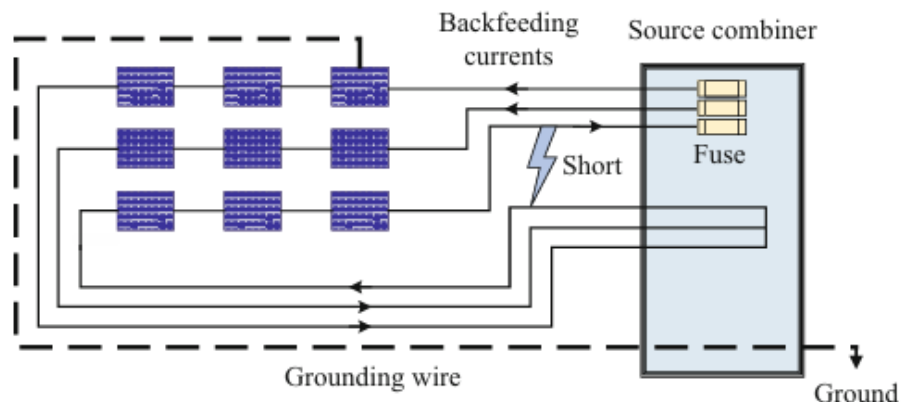


Figure 4.8: PV source back-feeding short circuit current

4.2.2 AC side overcurrent protection

After the inverter converts DC power into AC power, conventional AC protection methods are employed. AC overcurrent protection safeguards the inverter output, building distribution system, and utility connection against overloads and short circuits.

AC protection devices typically include MCCB, fuses, and AC disconnect switches. These devices isolate faults on the AC side and provide safe disconnection during maintenance. Because AC current naturally passes through zero twice during each cycle, interrupting AC faults is generally simpler than interrupting DC faults, allowing AC breakers to extinguish arcs more effectively. The AC overcurrent protection device is usually installed immediately after the inverter and before the distribution board or utility interconnection point. According to common design practice, its current rating is selected at approximately 125% of the inverter's rated output current, ensuring continuous operation while maintaining adequate protection against abnormal operating conditions.

4.3 Polarity and insulation safety

Correct conductor polarity and adequate insulation are fundamental requirements for safe PV system installation. Every DC conductor is permanently identified as positive or negative, and reversing these connections may result in equipment damage, malfunction of protection devices, or inverter failure. Therefore, polarity should always be verified before energizing the system.

Insulation protects conductors from accidental contact and prevents leakage currents between energized components and grounded structures. PV cables are specially designed with UV-resistant, and high-temperature insulation suitable for outdoor environments. Proper insulation not only reduces the risk of electric shock but also minimizes the possibility of short circuits and ground faults caused by damaged cable jackets or deteriorated connectors. Before commissioning a PV installation, insulation resistance testing is commonly performed to verify that conductors are properly insulated from each other and from ground. Maintaining correct polarity together with high insulation integrity significantly improves system reliability, reduces fire hazards, and ensures long-term safe operation.

Technical Note 4

Reverse polarity protection is incorporated to detect or prevent incorrect wiring before serious damage occurs. Reverse polarity faults may occur on either the PV side or the DC bus side of the system. PV-side protection safeguards the connection between PV strings and the inverter or DC/DC converter. In parallel PV strings, a reversed string can receive current from the healthy strings, creating high fault currents capable of damaging modules and cables. Protection is commonly provided using DC fuses, blocking or bypass diodes, MOSFET-based electronic protection, or software-based monitoring that

disconnects the faulty string when abnormal voltage or current is detected. DC bus-side protection protects the common DC link connecting multiple converters. Reverse polarity at this location may cause fault current to flow through converter power devices, damaging semiconductor components. Protection methods include diode bypass circuits, voltage-polarity detection, and controller-based monitoring, which isolate the faulty converter when abnormal current conditions are identified. Modern PV systems often combine hardware protection devices with intelligent inverter monitoring to provide fast, reliable, and efficient reverse polarity protection while minimizing maintenance requirements and power losses.

5 Electrical Output and System Matching

5.1 Voltage–Current characteristics

The electrical performance of a PV cell is described by the relationship between its output voltage and output current. This relationship is governed by the PV cell current equation presented previously in Eq. (2), which accounts for the photocurrent generated by solar irradiance, the diode characteristics, and the internal losses represented by the series and shunt resistances.

According to Eq. (2), the output current is not constant but varies with the terminal voltage and operating conditions. Two characteristic operating points define the limits of PV cell operation.

When the PV cell is disconnected from any external load, no current flows through the external circuit. This condition is referred to as the open-circuit condition, and the corresponding voltage is known as the open-circuit voltage (V_{OC}). It represents the maximum voltage that the PV cell or module can produce. The open-circuit voltage is mainly influenced by cell temperature and increases slightly with increasing solar irradiance.

Conversely, when the output terminals are directly connected together, the terminal voltage becomes zero and the PV cell delivers its maximum current. This operating condition is known as the short-circuit condition, and the resulting current is called the short-circuit current (I_{SC}). The short-circuit current is primarily determined by the photocurrent generated within the cell and therefore varies almost linearly with solar irradiance while being only slightly affected by temperature.

Between these two operating extremes, the PV cell can operate at any combination of voltage and current depending on the connected electrical load. The relationship between these quantities is represented by the current–voltage (I–V) characteristic, while the corresponding output power is represented by the power–voltage (P–V) characteristic.

5.2 Basic concepts of curves

The current–voltage (I–V) curve illustrates the variation of the output current with terminal voltage under specified operating conditions. It provides a complete electrical description of the PV module and is one of the most important tools for evaluating module performance. The curve begins at the short-circuit current, where the voltage is zero, and ends at the open-circuit voltage, where the current becomes zero. Figure 4.9 represents the I–V curve of PV module.

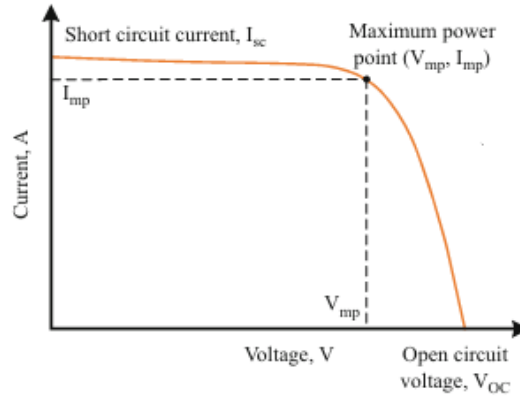


Figure 4.9: I-V characteristic curve of a solar module

For every operating point on the I–V curve, the corresponding output power is obtained by multiplying the voltage and current. Plotting the calculated power against voltage produces the power–voltage (P–V) curve, as shown in Fig. 4.10.

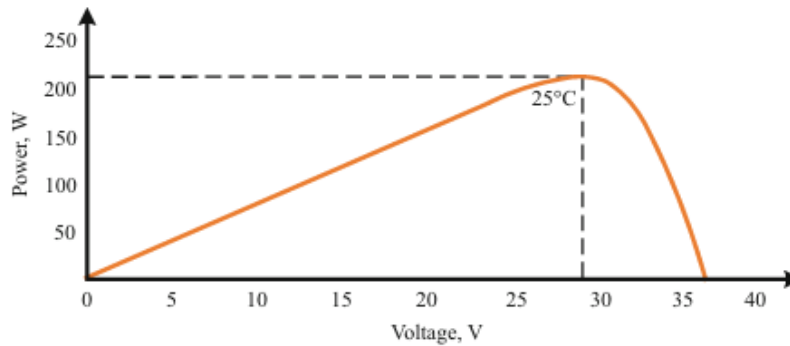


Figure 4.10: P-V curve of a solar module

Unlike the I–V curve, the P–V characteristic exhibits a single maximum point known as the Maximum Power Point (MPP). This operating point, defined by the voltage V_{MP} and current I_{MP} , corresponds to the maximum electrical power that the PV module can deliver under the prevailing environmental conditions.

Since solar irradiance and cell temperature continuously vary during operation, the location of the MPP also changes. Modern grid-connected and stand-alone inverters therefore employ MMPPT algorithms to continuously adjust the operating point of the PV array and maximize the harvested energy. There are several factors which have the influence on I-V curve.

5.2.1 Effect of series resistance

The series resistance represents the internal electrical resistance of the PV cell, including the semiconductor material, metallic contacts, interconnections, and conductors. An increase in series resistance causes a larger internal voltage drop,

reducing the terminal voltage delivered to the load. Consequently, the slope of the I–V curve near the open-circuit voltage becomes steeper, the fill factor decreases, and the maximum output power is reduced. The I–V curve for different resistance is depicted in Fig. 4.11.

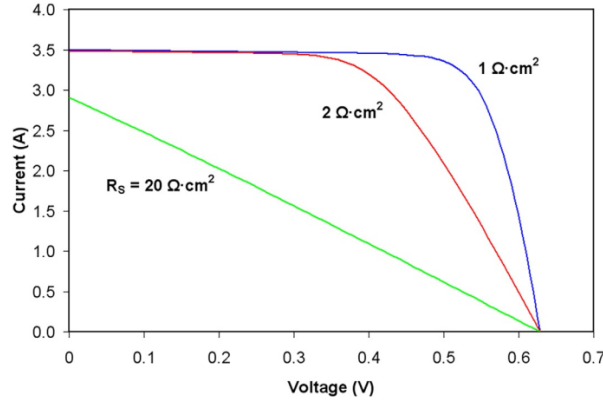


Figure 4.11: Effect of series resistance on the I–V curve of a solar cell

5.2.2 Effect of shunt resistance

The shunt (parallel) resistance represents leakage current paths inside the PV cell caused by material imperfections or manufacturing defects. A decrease in shunt resistance allows part of the generated current to bypass the external circuit, reducing the useful output current. This effect mainly influences the low-voltage region of the I–V curve, lowering the fill factor and decreasing the maximum power output. An ideal PV cell has a very high shunt resistance to minimize leakage losses.

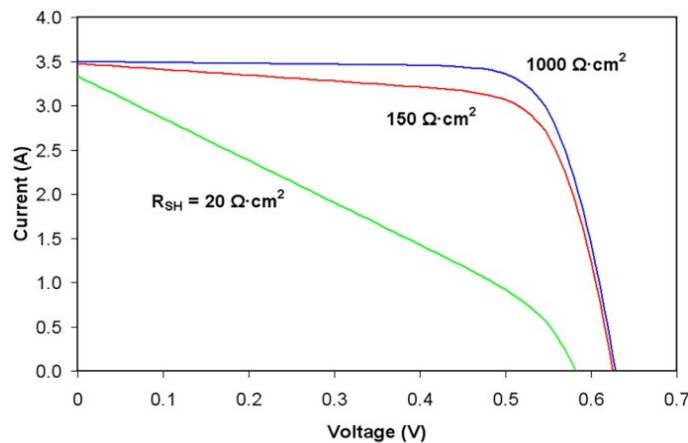


Figure 4.12: Effect of shunt resistance on the I–V curve

5.2.3 Effect of temperature

Cell temperature has a significant influence on PV performance. As temperature increases, the open-circuit voltage decreases considerably, whereas the short-circuit current increases only slightly. Consequently, both the I–V and P–V curves shift toward

lower voltage values, reducing the maximum power output and the overall efficiency of the PV module. Conversely, lower operating temperatures increase the open-circuit voltage and improve the maximum available power.

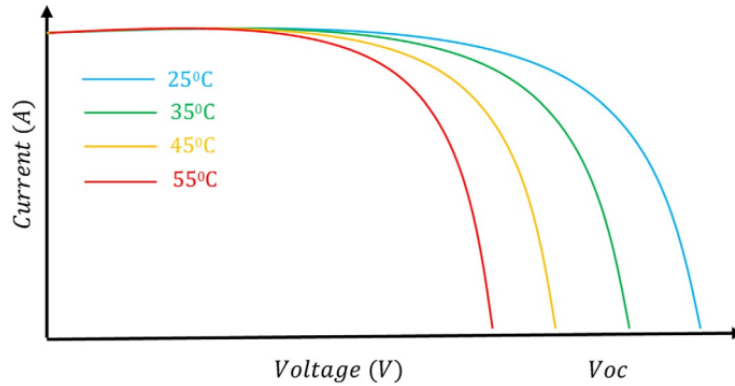


Figure 4.12: Effect of temperature on the I-V curve

5.2.4 Effect of solar irradiance

Solar irradiance directly determines the amount of photocurrent generated within the PV cell. As irradiance increases, the short-circuit current increases almost proportionally, while the open-circuit voltage increases only slightly. Consequently, the I–V curve shifts upward and the P–V curve exhibits a higher maximum power output. Under reduced irradiance conditions, the output current decreases significantly, resulting in a corresponding reduction in power generation.

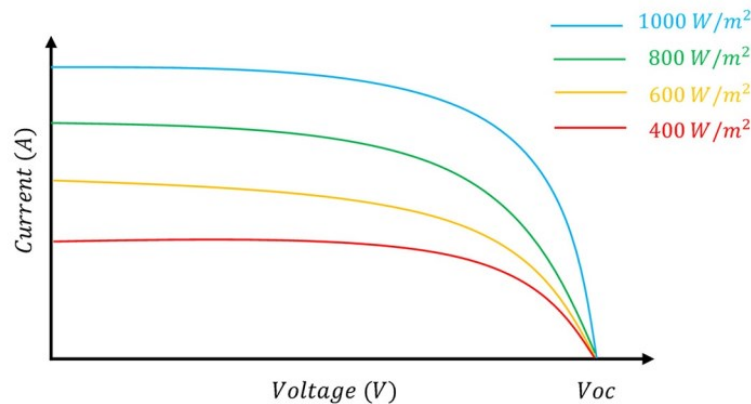


Figure 4.13: Effect of irradiance on the I-V curve

5.3 Matching PV arrays with inverters

Proper electrical matching between the PV array and the inverter is essential to ensure safe operation, maximize energy production, and prevent equipment damage. The PV array should be designed so that its electrical characteristics remain within the inverter operating limits under all expected environmental conditions.

The array maximum open-circuit voltage at the minimum expected cell temperature must always remain below the inverter's maximum allowable DC input voltage. Exceeding this limit may permanently damage the inverter input stage. Similarly, the operating voltage at the Maximum Power Point should remain within the inverter's MPPT voltage range throughout the expected temperature variations. Operating outside this range prevents the inverter from tracking the maximum power point efficiently, leading to energy losses. The array maximum short-circuit current and maximum operating current must also remain below the inverter's maximum DC input current rating. If multiple strings are connected in parallel, their combined current must be considered during system design.

Finally, the installed DC array power should be appropriately matched with the inverter AC rated power. In practice, PV arrays are commonly sized slightly larger than the inverter rating to improve annual energy production, provided that the inverter manufacturer permits the selected DC/AC ratio. Proper voltage, current, and power matching ensures reliable operation, maximizes energy harvest, and extends the service life of both the PV array and the inverter.

Session Summary

This section introduced the fundamental principles of electrical generation in PV systems. It explained how photovoltaic cells convert solar radiation directly into (DC) electricity through the photovoltaic effect and described the electrical behavior of a PV cell using the single-diode equivalent circuit. The influence of solar irradiance, temperature, and internal electrical parameters on the output current and voltage was discussed based on the PV cell current equation. The section also presented the methods of connecting PV cells into modules, modules into strings, and strings into arrays to achieve the required voltage, current, and power levels for practical applications. Basic PV array sizing principles and the role of key electrical components, including cables, combiner boxes, disconnect switches, and protective devices, were reviewed together with essential grounding and overcurrent protection concepts. Finally, the electrical output characteristics of PV modules were examined through the I–V and P–V curves, highlighting the effects of series resistance, shunt resistance, temperature, and irradiance on system performance, as well as the importance of properly matching PV arrays with inverter voltage, current, and power ratings to ensure safe operation and maximum energy production.

Power electronics in solar energy generation-Basic

Learning Objectives

- Explain the fundamental role of power electronics in photovoltaic (PV) energy systems and understand its function in electrical energy conversion, power conditioning, and grid integration.
- Identify the main power electronic components used in solar PV systems, including diodes, switching devices, DC/DC converters, inverters, and DC-link components, and explain their roles in solar energy conversion.
- Describe the basic operation of stand-alone and grid-connected inverters and understand how power electronic systems regulate output voltage and frequency.
- Explain the concept of Maximum Power Point Tracking (MPPT), understand the characteristics of the PV power curve, and describe how MPPT improves the energy harvesting capability of photovoltaic systems.
- Understand the practical performance considerations of power electronic systems in solar energy applications, including conversion efficiency, thermal effects, system reliability, and basic protection requirements.

Abstract

This session, *“Power electronics in solar energy generation”* introduces the fundamental power electronic technologies used in modern photovoltaic energy systems. Learners will explore how the direct current (DC) electricity generated by photovoltaic modules is converted, regulated, and delivered to electrical loads or the utility grid. The course discusses the main power electronic components used in PV systems, including semiconductor switching devices, DC/DC converters, inverters, and DC-link circuits, and explains their roles in efficient energy conversion and power management. The operation of stand-alone and grid-connected inverter systems is also introduced to demonstrate how power electronics enables reliable electricity supply under different operating conditions. In addition, the session presents the basic principles of Maximum Power Point Tracking (MPPT), highlighting its importance in maximizing the energy extracted from photovoltaic arrays. Finally, practical aspects such as conversion losses, thermal management, reliability, and protection requirements are discussed to provide a comprehensive understanding of the role of power electronics in improving the efficiency, performance, and long-term operation of modern solar energy systems.

1 Role of Power Electronic in PV Systems

Power electronics (PE) is a branch of electrical engineering that focuses on the conversion, control, and conditioning of electrical energy using semiconductor-based electronic devices. It enables efficient conversion between different forms of electrical power, such as direct current (DC) and alternating current (AC), while regulating voltage, current, and power flow to meet the requirements of various applications. Over the past few decades, power electronics has experienced remarkable technological progress, driven by advances in semiconductor switching devices, digital control techniques, and microprocessor technology. These developments have significantly improved the efficiency, reliability, and controllability of power conversion systems while reducing their size, complexity, and cost. Consequently, power electronics has become a key enabling technology in numerous applications, including renewable energy systems, electric vehicles, motor drives, industrial automation, and modern power networks.

In photovoltaic energy systems, power electronics plays a particularly important role by converting the variable DC electricity generated by solar modules into high-quality electrical power suitable for supplying loads or connecting to the utility grid. As solar energy continues to expand as a major renewable energy source, the importance of efficient and reliable power electronic systems continues to grow.

1.1 Energy conversion in PV system

Power electronics has become an essential technology in modern PV energy systems. Unlike conventional power plants that generate alternating current, photovoltaic modules produce direct current, and their electrical output continuously varies with solar irradiance and cell temperature. Consequently, the electricity generated by a PV array cannot usually be supplied directly to the utility grid or most AC loads. Power electronic converters are therefore required to regulate, condition, and convert the generated electrical power into a form suitable for practical applications.

Figure 5.1 illustrates the typical energy conversion process in a grid-connected PV system. The PV array converts solar radiation into DC electrical power, which is first processed by a DC/DC converter. This converter regulates the operating point of the PV array and adjusts the DC voltage to an appropriate level for subsequent conversion. The processed DC power is then transferred to a DC-link, where capacitors provide temporary energy storage and maintain a stable DC voltage. Finally, a DC/AC inverter converts the DC power into AC electricity with the required voltage and frequency before it is delivered to the utility grid through an output filter.

The output power of a photovoltaic array changes continuously because environmental conditions are naturally variable throughout the day. Therefore, power electronic converters not only perform electrical energy conversion but also ensure efficient energy extraction, stable operation, and high-quality power delivery. In modern PV systems, they form the interface between the solar array, electrical loads, and the utility network, enabling reliable operation under varying operating conditions.

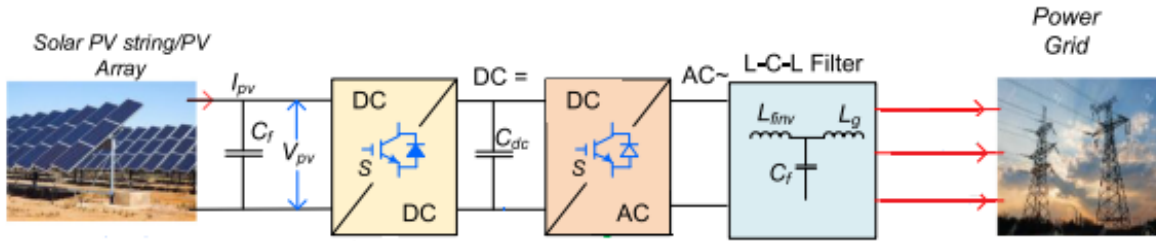


Figure 5.1: Typical power electronic configuration of a grid-connected PV system

Technical Note 1

It should be mentioned that not all PV systems include a separate DC/DC converter. In many residential string inverter systems, the photovoltaic array is directly connected to the inverter, which performs both maximum power point tracking and DC-to-AC conversion. A separate DC/DC converter is generally employed in larger or more advanced PV systems when additional voltage regulation, wider operating ranges, or enhanced control flexibility are required. Therefore, the choice between single-stage and two-stage converter architectures depends on the system design, PV array characteristics, and application requirements.

1.2 Inverter function in system

Among all power electronic devices used in photovoltaic systems, the inverter is the most important component because it enables the utilization of the electricity generated by the PV array. Its primary function is to convert the direct current produced by solar panels into alternating current suitable for residential loads or the electrical grid. Without an inverter, the electricity generated by conventional photovoltaic modules could only be supplied to DC loads or stored in batteries, significantly limiting the practical application of solar energy.

Modern PV inverters perform many functions beyond simple DC-to-AC conversion. They continuously regulate the output voltage and frequency, synchronize the generated AC voltage with the utility grid, and maintain stable power delivery despite variations in solar irradiance. In addition, inverter control systems improve power quality by reducing harmonic distortion and ensuring that the generated electricity satisfies grid requirements. Many inverters also incorporate monitoring, protection, and communication functions,

allowing safe system operation and effective fault detection. As photovoltaic installations continue to increase worldwide, inverters have evolved into intelligent power electronic devices that actively support the operation of electrical networks. Their advanced control capabilities improve conversion efficiency, enhance system reliability, and facilitate the integration of renewable energy into modern power systems.

1.3 PV system, load and grid interface

Power electronic converters act as the electrical interface between the photovoltaic array, the electrical load, and the utility grid, as illustrated in Fig 5.1. They manage the flow of energy while ensuring compatibility between the characteristics of the PV source and the requirements of the connected system.

In stand-alone PV systems, the generated electricity is supplied directly to local loads or stored in batteries for later use. In contrast, grid-connected systems deliver surplus electrical energy to the utility grid while receiving power from the grid whenever solar generation is insufficient. In both configurations, the inverter serves as the central interface that controls power flow and maintains stable system operation. Depending on the operating conditions, the inverter regulates the amount of electrical power delivered to the load or injected into the grid while maintaining the required voltage and frequency characteristics. The coordinated operation of the PV array, power electronic converters, and utility grid enables photovoltaic systems to operate efficiently under continuously changing environmental conditions. Consequently, power electronics has become one of the key enabling technologies for the widespread deployment of modern solar energy systems.

2 Main Power Electronic Components in Solar Energy System

Power electronic converters consist of several components that work together to control, convert, and deliver electrical energy efficiently. In PV systems, these components regulate the variable electrical output produced by solar modules and ensure that the generated power can be supplied to electrical loads or integrated into the utility grid. The main components include semiconductor devices, DC/DC converters, inverters, and DC-link elements. Each component performs a specific function in the overall energy conversion process and contributes to the efficiency, reliability, and controllability of the PV system.

2.1 Diodes and power switching devices

Semiconductor devices form the foundation of all power electronic converters. Unlike conventional electronic components used for signal processing, power semiconductor devices are designed to control the flow of relatively large amounts of electrical energy with high efficiency. They operate primarily as electronic switches, rapidly turning ON and OFF to regulate voltage, current, and power flow within the converter.

The simplest power semiconductor device is the diode, which permits current to flow in only one direction while blocking current in the opposite direction. In photovoltaic systems, diodes are commonly used as blocking diodes to prevent reverse current flow toward the PV array and as bypass diodes to protect solar modules from overheating and power loss caused by partial shading. More advanced semiconductor devices provide controllable switching operation. Among these, the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) is widely used in low- and medium-power DC/DC converters because of its high switching speed and simple voltage-controlled gate. For higher-power photovoltaic applications, the Insulated Gate Bipolar Transistor (IGBT) is one of the most common switching devices. The IGBT combines the simple gate control of a MOSFET with the high current-handling capability of bipolar devices, making it particularly suitable for grid-connected inverters. Another important family of semiconductor devices is the thyristor, also known as the Silicon Controlled Rectifier (SCR). Unlike MOSFETs and IGBTs, thyristors remain in the conducting state after receiving a gate signal and continue conducting until the current naturally falls below a specified level. This characteristic makes them suitable for controlled rectifiers and high-power industrial converters. A modified version, known as the Gate Turn-Off Thyristor (GTO), can be switched both ON and OFF through gate control and is used in certain high-power converter applications.

The selection of semiconductor devices depends on the converter topology, switching frequency, efficiency requirements, and operating conditions. Modern photovoltaic systems increasingly employ advanced semiconductor technologies that improve

conversion efficiency while reducing converter size and power losses. The characteristics of these power devices and their application are summarized in Table 5.1.

Table 5.1: Applications and characteristics of switching devices used in PV system

Switch Type	Basic characteristic	Application in PV generation
Diode	Allows current flow in one direction only	Blocking diodes, bypass diodes, rectifier circuits
MOSFET	Voltage-controlled semiconductor switch with high switching speed	DC/DC converters and low- to medium-power inverters
IGBT	Combines MOSFET gate control with bipolar current conduction	Grid-connected inverters and medium- to high-power converters
SCR (Thyristor)	Latching semiconductor switch activated by a gate signal	Controlled rectifiers and industrial power converters
GTO	Gate-controlled thyristor that can be turned ON and OFF by sending a pulse to its gate terminal	High-power inverter applications

2.2 DC-DC converters

The electrical output of a photovoltaic array varies continuously with solar irradiance. Consequently, the generated DC voltage may not always match the voltage required by the inverter or the connected electrical system. A DC/DC converter is therefore used to regulate the PV output voltage and provide a stable operating condition for the subsequent stages of power conversion.

In addition to voltage regulation, DC/DC converters perform several important functions in photovoltaic systems. They adjust the operating point of the PV array to maximize energy production, reduce voltage fluctuations, improve power quality, and provide an appropriate DC voltage level for the inverter. Modern DC/DC converters operate using high-frequency semiconductor switching devices, which significantly improves conversion efficiency while reducing the size of passive components such as inductors and capacitors. High-frequency operation also enhances the dynamic response of the converter, allowing rapid adaptation to changes in solar irradiance or electrical loading.

Several converter topologies are available for photovoltaic applications. The most commonly used configurations include the Buck converter, Boost converter, and Buck–Boost converter, each providing different voltage conversion characteristics depending on system requirements. Fig 5.2 illustrates the basic converter topologies used in PV energy generation system.

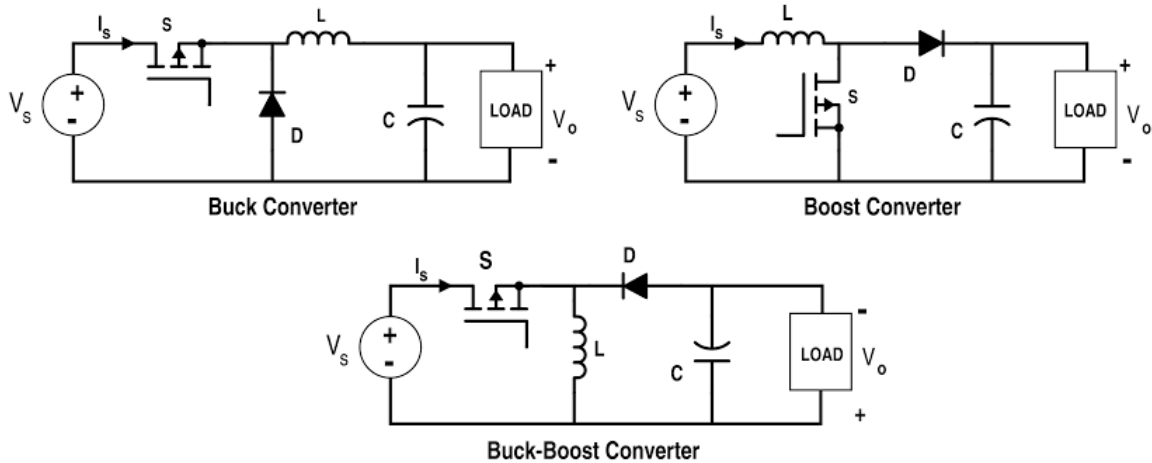


Figure 5.2: Common DC/DC converter topologies

Technical Note 2

Different DC/DC converter topologies provide different voltage conversion functions. Buck converter produces an output voltage lower than the input voltage and is used when the PV array voltage exceeds the required DC bus voltage. In contrast, Boost converter produces an output voltage higher than the input voltage and is widely employed in photovoltaic systems to raise the relatively low PV voltage to the required DC-link voltage. Buck–Boost converter can either increase or decrease the output voltage depending on the operating conditions, making it suitable for PV systems experiencing wide voltage variations. The selection of a converter topology depends on the photovoltaic array configuration, desired DC-link voltage, system efficiency, and converter control strategy.

2.3 Inverter

An inverter is the principal power electronic device responsible for converting the direct current generated by photovoltaic modules into alternating current suitable for supplying electrical loads or connecting to the utility grid. Since most electrical appliances and power networks operate with AC power, the inverter is an essential component of almost every grid-connected photovoltaic system.

Modern photovoltaic inverters perform considerably more than simple DC-to-AC conversion. They regulate the magnitude and frequency of the output voltage, synchronize the generated electrical power with the utility grid, and ensure that the delivered electricity satisfies power quality requirements. Inverter operation is achieved through the high-speed switching of semiconductor devices, producing a controlled output waveform that closely approximates a sinusoidal AC voltage. Most photovoltaic systems employ Voltage Source Inverters (VSIs), in which the input DC voltage is maintained relatively constant while the inverter synthesizes an AC output through pulse-width modulation. Although the inverter initially generates a series of high-frequency switching pulses, output filters remove

unwanted harmonics, producing a smooth sinusoidal waveform suitable for practical applications.

2.4 DC-link components

The DC-link forms the intermediate stage between the DC/DC converter and the inverter in a PV power conversion system. Its primary purpose is to maintain a stable DC voltage and temporarily store electrical energy during the conversion process. By acting as an energy buffer, the DC-link reduces voltage fluctuations caused by variations in solar irradiance, switching operations, and load changes.

The most important DC-link component is the capacitor, which stores electrical energy and smooths the DC voltage supplied to the inverter. A stable DC-link voltage enables the inverter to generate a high-quality AC output with reduced voltage ripple and improved control performance. In addition to capacitors, inductors are often incorporated into converter circuits and output filters to reduce current ripple, and suppress switching harmonics. Proper design of DC-link components contributes significantly to converter efficiency and long-term operating performance. Consequently, capacitors and inductors are considered essential passive elements in modern photovoltaic power electronic systems.

3 Basic PV System Inverter Operation and Frequency and Voltage Control

The inverter is the central component of a photovoltaic power conversion system because it transforms the direct current generated by solar modules into alternating current suitable for electrical loads and utility networks. Beyond energy conversion, modern inverters regulate power flow, maintain stable output voltage and frequency, and ensure that the generated electricity satisfies the operating requirements of the connected system. Depending on the application, PV inverters operate either as **stand-alone inverters**, supplying isolated loads without connection to the utility grid, or as **grid-connected inverters**, which synchronize with the electrical grid and inject the generated power into the distribution or transmission network based on the plant capacity. Although both inverter types perform DC-to-AC conversion, their operating principles and control objectives differ according to the system configuration.

3.1 Stand-alone inverter operation

Stand-alone photovoltaic systems are designed to supply electrical energy to locations where access to the utility grid is unavailable or impractical. Typical applications include remote houses, telecommunication stations, rural electrification projects, water pumping systems, and isolated industrial facilities. Since solar energy is only available during daylight hours and varies with weather conditions, stand-alone systems generally include an energy storage unit, most commonly a rechargeable battery bank, to provide continuous electricity during nighttime or periods of low solar irradiance.

In a stand-alone PV system, the inverter receives DC power either directly from the photovoltaic array or from the battery storage system and converts it into AC power for local electrical loads, as depicted in Fig 5.3. Unlike grid-connected inverters, the stand-alone inverter operates independently and must generate its own output voltage and frequency. Consequently, it acts as the voltage source for the entire electrical system and is responsible for maintaining a stable sinusoidal output under changing load conditions.

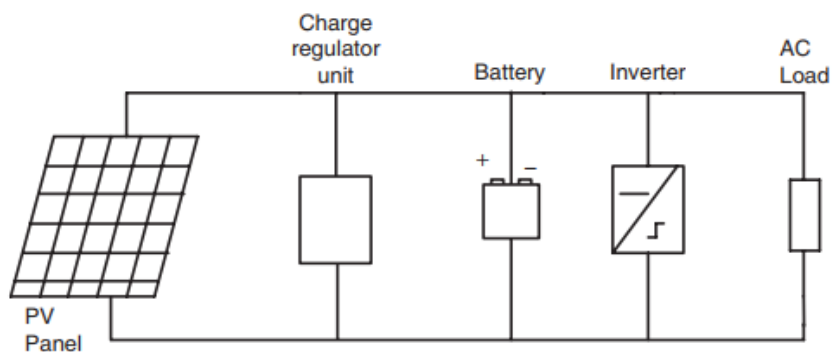


Figure 5.3: Stand-alone PV system

Modern stand-alone inverters employ semiconductor switching devices, such as MOSFETs or IGBTs, together with pulse-width modulation techniques to synthesize a high-quality AC waveform. Output filters are incorporated to reduce switching harmonics and improve power quality before supplying electricity to connected loads. In addition, stand-alone inverters incorporate several protection functions, including over-voltage, under-voltage, overload, short-circuit, and battery protection, to ensure reliable and safe operation.

Technical Note 3

To ensure reliable battery operation, stand-alone PV systems employ charge controllers that regulate the charging and discharging process while preventing battery overcharging and excessive discharge. The most common charge controller types are series charge, shunt charge and DC/DC converter charge controllers. In series charge controller, the PV array is disconnected when the battery reaches its maximum charging voltage. When the voltage reduces below the discharge limit, the load is disconnected from the battery to avoid deep discharge beyond the limit. The main problem associated with this type of controller is the losses associated with the switches. Shunt charge controller, which diverts excess photovoltaic power away from the battery once full charge is achieved and is commonly used in small PV systems. DC/DC converter charge controller, which regulates battery charging through high-frequency switching while enabling functions such as voltage regulation and MPPT. This approach is widely adopted in modern photovoltaic installations because of its higher efficiency and improved control capability.

3.2 Grid-connected inverter operation

3.2.1 Grid-connection system

Grid-connected photovoltaic systems are the most common configuration used in residential, commercial, and utility-scale solar power plants. Unlike stand-alone systems, these installations are directly connected to the electrical distribution network and generally do not require battery storage. During periods of high solar generation, surplus electrical energy can be exported to the utility grid, whereas electricity is imported from the grid whenever the PV array cannot satisfy the local demand.

The grid-connected inverter serves as the interface between the photovoltaic array and the utility network. Its primary function is to convert the DC power generated by the PV array into AC power while ensuring complete synchronization with the grid voltage, frequency, and phase angle. This synchronization enables smooth power exchange without disturbing the operation of the electrical network. Grid-connected photovoltaic inverters can be classified according to the characteristics of their DC input stage into Voltage Source Inverters (VSIs) and Current Source Inverters (CSIs). The distinction is based on the electrical behavior of the DC side rather than on the type of energy source itself.

- VSI maintains a nearly constant DC input voltage by means of a capacitor connected across the DC-link. The inverter converts this regulated DC voltage into a controlled AC output using high-frequency switching techniques. Because of their simple structure, excellent controllability, and ability to produce high-quality sinusoidal output waveforms, VSIs have become the predominant topology in modern grid-connected photovoltaic systems.
- CSI is supplied by a nearly constant DC current, which is maintained using a series-connected inductor at the inverter input. Although photovoltaic arrays naturally exhibit current-source characteristics, CSI topologies are less common in PV applications. Instead, they are primarily employed in certain high-power industrial systems, such as large motor drives, where current control is advantageous. The objective of this scheme is to control active and reactive components of the current fed into the grid.

In addition to power conversion, the inverter continuously monitors grid conditions and adjusts its output accordingly. Modern grid-connected inverters also incorporate safety functions such as anti-islanding protection, which automatically disconnects the PV system if the utility supply is interrupted. This protection prevents unintentional energization of disconnected distribution lines and enhances the safety of maintenance personnel and electrical equipment.

3.2.2 Common PV inverter technologies

Grid-connected photovoltaic systems may be implemented using different inverter configurations, including line-commutated inverters, self-commutated inverters, and high-frequency transformer inverters.

- **Line-Commutated Inverters** employ thyristors as the main switching devices. These inverters rely on the utility grid voltage to naturally commute (turn off) the thyristors, making them highly dependent on a strong grid connection. Owing to their simple structure and relatively low cost, line-commutated inverters were widely used in early grid-connected systems. However, they produce considerable harmonic distortion, require additional filtering and reactive power compensation, and have limited control flexibility. Consequently, their application in modern photovoltaic systems is uncommon.
- **Self-Commutated Inverters** utilize controllable semiconductor switches such as MOSFETs, IGBTs, or GTOs that can be turned ON and OFF independently of the grid voltage. By employing PWM, these inverters generate high-quality sinusoidal output voltages with low harmonic distortion while providing accurate control of active and reactive power. Because of their superior performance and flexible control capability, self-commutated voltage source inverters are the standard

topology used in most residential, commercial, and utility-scale photovoltaic systems.

- **High-Frequency Transformer Inverters** replace the conventional low-frequency transformer with a compact high-frequency transformer operating at switching frequencies typically above 20 kHz. The higher operating frequency significantly reduces the size and weight of the transformer while improving power density and overall efficiency. These inverters are widely employed in small and medium-sized PV systems where compact size and galvanic isolation are desirable.

The application, advantages and disadvantages of these three types inverter technology is addressed in Table 5.2.

Table 5.2: Comparison of common grid-connected inverter technologies

Inverter type	Application	Advantages	Disadvantages
LCI	Early grid-connected PV systems and high-power industrial applications.	Simple structure, robust operation, relatively low cost.	High harmonic distortion, poor power factor, requires reactive power compensation and output filters, limited control capability.
SCI	Modern residential, commercial, and utility-scale photovoltaic systems.	High-quality sinusoidal output, excellent voltage and frequency control, low harmonic distortion, flexible active and reactive power control.	More sophisticated control algorithms and switching operation.
High Frequency	Residential rooftop systems, distributed PV generation, and compact inverter designs.	Compact size, reduced weight, improved power density, high efficiency, electrical isolation.	Increased switching complexity and electromagnetic interference considerations.

3.3 Output voltage and frequency control

One of the primary objectives of inverter control is to produce an AC output with stable voltage and frequency despite continuous variations in solar irradiance and load demand. In stand-alone systems, the inverter independently establishes the output voltage magnitude and operating frequency required by the connected loads. In contrast, grid-connected inverters continuously synchronize their output with the utility grid so that both voltage and frequency match those of the electrical network before power is delivered.

Modern photovoltaic inverters achieve this control through pulse-width modulation. In PWM operation, semiconductor switches are turned on and off at high frequency to generate a sequence of voltage pulses whose average value closely approximates a sinusoidal waveform. After passing through output filters, the switching harmonics are significantly reduced, producing high-quality AC power suitable for residential, commercial, and industrial applications.

In addition to voltage and frequency regulation, contemporary grid-connected inverters perform several advanced control functions that improve grid stability and reliability. These functions include frequency regulation through active power adjustment, dynamic voltage support during grid disturbances, reactive power control, and fault ride-through capability. Although these advanced features are increasingly required by modern grid standards, the fundamental objective remains the same: to ensure efficient, stable, and safe transfer of photovoltaic energy to electrical loads and the utility grid.

4 Maximum Power Point Tracking in Solar Energy System

The electrical power produced by a PV module continuously changes with environmental conditions. Unlike conventional generators, the output characteristics of a solar panel are strongly influenced by solar irradiance and cell temperature, causing its voltage, current, and output power to vary throughout the day. Consequently, a PV module operates at different points on its current–voltage (I–V) and power–voltage (P–V) characteristics as weather conditions change.

Among all possible operating points, there is one unique point where the PV module delivers its highest electrical power. This operating condition is known as the Maximum Power Point (MPP). To ensure that the photovoltaic system extracts the maximum available energy under varying environmental conditions, modern PV systems employ a MPPT controller.

4.1 PV power curve concept

The electrical performance of a PV module is commonly described by its current–voltage and power–voltage characteristic curves. These curves illustrate the relationship between the output current, output voltage, and generated power under specific environmental conditions. Understanding these characteristics is essential because the operating point of a PV module determines the amount of electrical power that can be extracted from solar energy. Figure 5.4 demonstrate current and power voltage curve for a PV module.

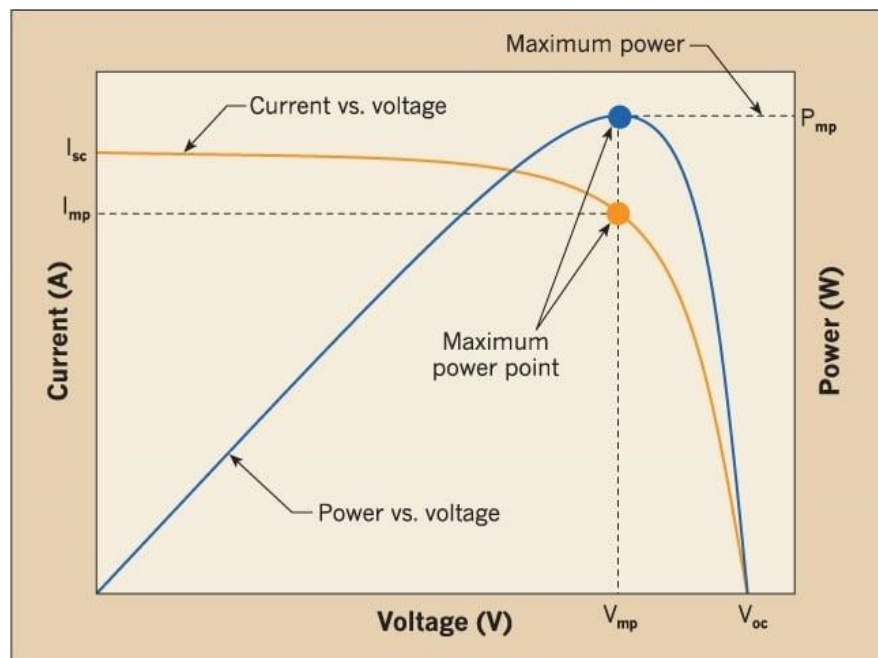


Figure 5.4: I–V and P–V characteristics of a solar cell showing maximum power point

The I–V curve contains several important operating parameters. The short-circuit current (I_{SC}) is the maximum current delivered by the PV module when its output terminals are short-circuited, corresponding to zero output voltage. This parameter mainly depends on the level of solar irradiance, increasing as sunlight intensity increases. At the opposite end of the curve is the open-circuit voltage (V_{OC}), which represents the maximum voltage produced when no external load is connected and the output current is zero. Unlike the short-circuit current, the open-circuit voltage is more sensitive to changes in cell temperature.

Between these two operating limits lies the MPP, which corresponds to the operating condition where the PV module generates its highest electrical power. At this point, the module operates at the maximum power voltage (V_{MP}) and maximum power current (I_{MP}), and the output power reaches its peak value, given by:

$$P_{MP} = V_{MP} \times I_{MP} \quad (1)$$

The P–V curve is obtained by multiplying the current and voltage values along the I–V characteristic. As the operating voltage increases from zero, the output power initially rises because both voltage and current contribute to power generation. The power reaches its maximum value at the MPP and then decreases as the current falls rapidly near the open-circuit voltage. Consequently, operating the PV module at either very low or very high voltages results in lower energy production. The position of the maximum power point continuously changes because photovoltaic modules operate under varying environmental conditions. Therefore, PV systems require a control mechanism capable of tracking this moving operating point to maximize energy extraction.

4.1.1 Effect of solar irradiance on PV characteristic

Solar irradiance and cell temperature are the two most influential environmental factors affecting the electrical characteristics of photovoltaic modules. An increase in solar irradiance causes the output current of the PV module to increase almost proportionally, while the output voltage changes only slightly. As a result, the entire P–V curve shifts upward, and the maximum available power increases significantly. Conversely, during cloudy weather or partial shading, the generated current decreases, causing a substantial reduction in the maximum output power. Therefore, the maximum power point moves to a lower power level under reduced irradiance conditions.

Cell temperature primarily influences the output voltage of the PV module. As the temperature increases, the open-circuit voltage V_{OC} and the maximum power voltage V_{MP} decrease, whereas the current changes only slightly. Consequently, the maximum power point shifts toward lower voltages, leading to a reduction in the maximum electrical power

that can be generated. This explains why photovoltaic modules generally produce less power during very hot operating conditions despite receiving strong solar radiation.

Figure 5.5 demonstrates how variations in solar irradiance modify the P–V characteristic by changing the location and magnitude of the maximum power point.

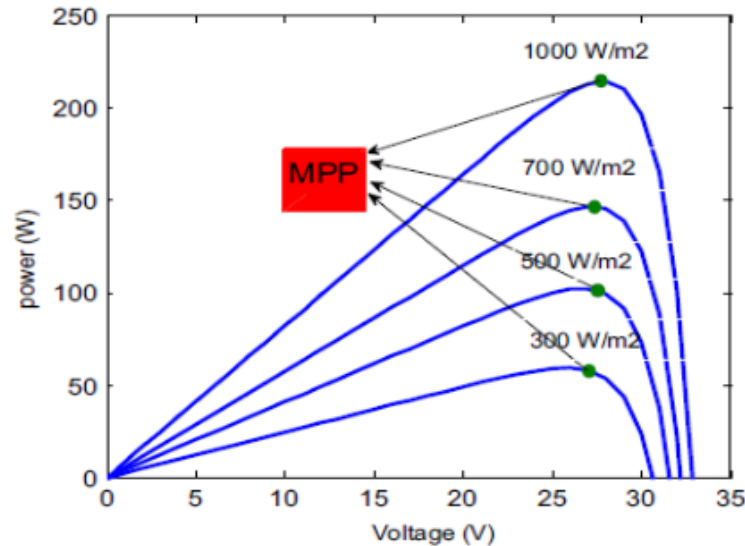


Figure 5.5: Power curve for varying irradiance

4.1.2 Importance of maximum power point tracking

Since the maximum power point continuously changes with weather conditions, a photovoltaic module cannot operate at maximum efficiency using a fixed operating voltage. If the PV array is directly connected to a load, its operating point is determined by the electrical characteristics of the load rather than by the location of the maximum power point. As a result, a considerable portion of the available solar energy may remain unutilized. MPPT overcomes this limitation by continuously adjusting the operating voltage or current of the PV array so that it remains as close as possible to the maximum power point under all operating conditions. This function significantly improves the energy harvested from the photovoltaic system, particularly when irradiance and temperature vary throughout the day. In practical PV systems, the MPPT controller operates together with a DC/DC converter, which modifies the electrical operating point of the PV array while simultaneously providing the voltage required by the inverter, battery, or DC load. Consequently, MPPT improves not only energy production but also the overall efficiency of the power conversion system.

4.2 PV power curve concept

An MPPT system generally consists of three main components:

- Photovoltaic array,

- DC/DC power converter,
- MPPT controller.

The controller continuously measures the PV array voltage and current to determine its operating condition. Using these measurements, it calculates the output power and determines whether the operating point is moving toward or away from the maximum power point. The controller then adjusts the duty cycle of the DC/DC converter, causing the PV operating voltage to increase or decrease until the maximum power point is reached. The control diagram of an MPPT in PV system is depicted in Figure 5.6.

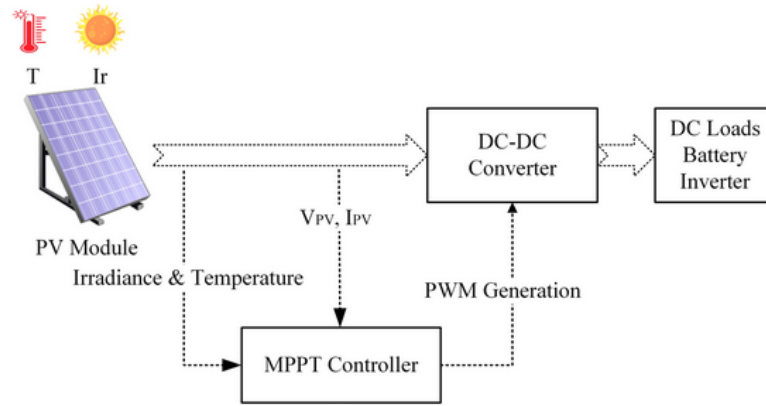


Figure 5.6: Block diagram of a PV system with MPPT.

This tracking process is performed continuously because environmental conditions change throughout the day. Under steady weather conditions, only small adjustments are required. However, rapid changes in solar irradiance, such as those caused by passing clouds, require the controller to quickly identify the new operating point to minimize energy losses. Although different MPPT algorithms employ different decision-making strategies, their common objective is to maintain photovoltaic operation at the maximum power point and maximize the electrical energy delivered to the load or the utility grid.

Technical Note 4

MPPT algorithms allow PV systems to maintain operation at their highest power output under changing environmental conditions. The Perturb and Observe (PAO) method is the most common due to its simplicity; it adjusts the operating voltage or duty cycle and observes power changes, but it can oscillate around the maximum power point and respond slowly to rapid irradiance variations. The Incremental Conductance Technique (ICT) method improves accuracy by comparing incremental and instantaneous conductance to locate the maximum power point, offering better performance during changing weather but requiring more complex control and measurements. The Constant Voltage (CV) method maintains the PV voltage near a fixed reference value, making it simple and low-cost but less accurate. Modern PV systems often use hybrid MPPT techniques that combine multiple algorithms to achieve faster tracking, better stability, and higher efficiency.

5 Practical Performance Considerations

Although modern PV systems achieve high conversion efficiencies, practical limitations such as power losses, thermal stress, and reliability issues directly influence their overall performance and lifetime. Since PV systems are expected to operate for more than 20 years under continuously changing environmental conditions, the design of reliable and efficient power electronic systems is essential. This section discusses the main practical considerations affecting PV power electronic applications, including conversion losses, thermal effects, and protection requirements.

5.1 Conversion losses in PV power electronic systems

In an ideal photovoltaic system, all electrical energy generated by the PV array would be transferred to the load or electrical grid. However, practical power electronic converters cannot achieve 100% efficiency because electrical losses occur during the energy conversion process. These losses mainly appear in DC/DC converters, DC-link components, and DC/AC inverter stages. Even small reductions in efficiency can significantly affect the annual energy production of large-scale PV installations.

The main sources of power losses in PV converters are semiconductor switching losses, conduction losses, and losses in passive components. Semiconductor devices such as MOSFETs, IGBTs, and diodes experience conduction losses because they have internal resistance or voltage drops when current flows through them. Switching losses occur during the transition between the ON and OFF states of semiconductor devices. During these transitions, voltage and current exist simultaneously across the device, resulting in energy dissipation in the form of heat. Increasing the switching frequency can improve the quality of the output waveform and reduce the size of filters; however, it also increases switching losses. Therefore, converter design requires a balance between switching performance and efficiency.

Passive components, including inductors, capacitors, and transformers, also contribute to power losses. Inductors and transformers experience copper losses due to winding resistance and magnetic losses in their cores. Similarly, capacitors used in DC-link circuits have losses caused by their equivalent series resistance. Although each individual loss is relatively small, the combined effect of these losses can reduce the total efficiency of the PV conversion system. The efficiency of a PV power electronic system is commonly evaluated by comparing the output power with the input power from the PV array. Improving converter efficiency is important because it increases the amount of solar energy delivered to the electrical system. Modern PV inverters achieve high efficiency through optimized converter topologies, improved semiconductor technologies, and advanced control methods.

5.2 Thermal effects in power electronic solar system

Thermal performance is one of the most important factors affecting the reliability and lifetime of PV power electronic systems. During operation, semiconductor switches, diodes, magnetic components, and capacitors generate heat due to electrical losses. If this heat is not effectively removed, the temperature of internal components increases, which can reduce efficiency and accelerate component degradation.

Semiconductor devices are particularly sensitive to temperature variations because their electrical characteristics change with temperature. Increased junction temperature can increase conduction losses, reduce switching performance, and accelerate aging mechanisms. In addition, repeated heating and cooling cycles caused by daily variations in solar radiation create thermal stresses inside the components. These thermal cycles can lead to mechanical fatigue, solder joint failures, and degradation of semiconductor packaging. The operating temperature of PV inverters depends on several factors, including ambient temperature, power level, cooling method, and installation location. In outdoor PV systems, inverters are exposed to environmental conditions such as high temperature, humidity, and dust, which can further influence thermal performance. Therefore, effective thermal management is necessary to maintain reliable operation.

Several cooling methods are used in PV power electronic systems. Small residential inverters usually rely on natural air cooling through heat sinks, while larger commercial and utility-scale inverters may use forced air cooling or liquid cooling systems. Proper thermal design includes selecting suitable heat sinks, improving airflow, and maintaining component temperatures within safe operating limits. The inverter cooling system is depicted in Fig 5.7

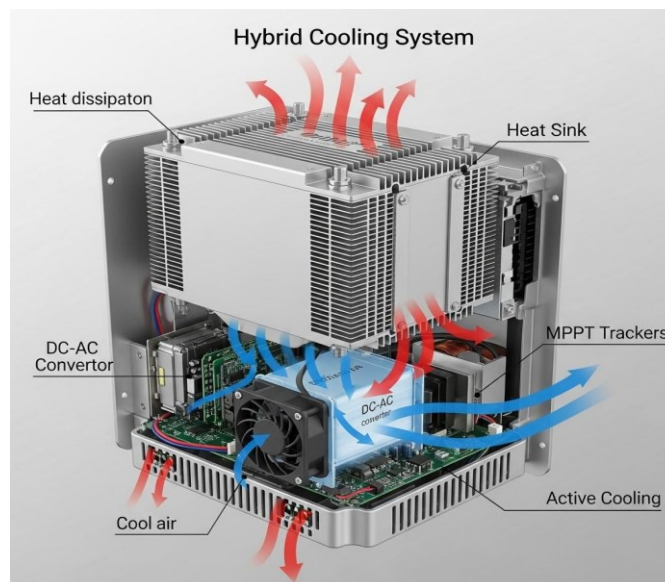


Figure 5.7: Typical PV inverter cooling system.

Thermal management not only improves efficiency but also extends the lifetime of PV converters. Since many failures in power electronic systems are related to excessive temperature and thermal cycling, controlling temperature is a critical requirement for achieving reliable long-term operation.

5.3 Reliability and protection requirements

Reliability is a major consideration in photovoltaic power electronic systems because PV installations are expected to operate continuously for many years with minimum maintenance. Power converters are exposed to electrical, thermal, and environmental stresses that can cause failures if appropriate protection measures are not implemented.

One of the main challenges in PV systems is protecting power electronic components from abnormal electrical conditions. Overcurrent protection is required to prevent excessive current flow caused by short circuits or system faults. Overvoltage protection is also necessary because voltage spikes caused by switching operations or lightning events can damage semiconductor devices and DC-link components. Surge protection devices and appropriate circuit protection elements are commonly used to reduce these risks. For grid-connected PV systems, additional protection functions are required to ensure safe operation during grid disturbances. Inverters must monitor grid voltage, frequency, and phase conditions to maintain synchronization with the electrical network. If abnormal grid conditions occur, such as voltage fluctuations or frequency deviations, the inverter must respond according to grid protection requirements.

So, Failure or in extreme case, destruction can be caused by atmospheric or switching overvoltage. Another potential source of failure is an short-circuit of part of the electrical circuit, which can result in overload of certain parts up to their eventual destruction or possibly even in fire. For this reason, especial attention is paid to devices from a proven manufacturer. The protection diagram for a typical PV system illustrated in Fig 5.8.

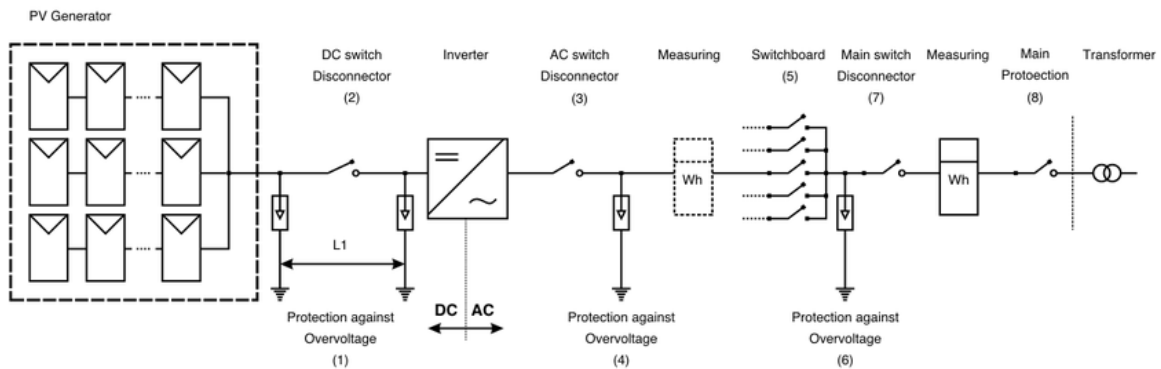


Figure 5.8: PV system protection system

The first level of protection is provided by the surge protection device (1), which protects the PV system from transient overvoltage caused by lightning strikes or switching

operations. When the distance between the PV array and the inverter is relatively long, it is recommended to install additional surge protection devices at both the PV generator and the inverter terminals to minimize the effects of voltage surges along the cable. For maintenance and safety purposes, the inverter must be capable of being electrically isolated from both the DC and AC sides of the system. This is achieved by installing a DC disconnect switch (2) between the PV array and the inverter, and an AC disconnect switch (3) between the inverter and the utility grid. These disconnectors allow maintenance to safely service the inverter by completely isolating it from the power sources. In systems where the DC circuit is switched only after the AC side has been disconnected, and reconnected only after the AC supply is restored, a DC isolator can provide adequate and safe switching.

On the AC side of the inverter, an additional surge protection device (4) is commonly installed, particularly in installations with long cable runs. This device provides further protection against transient overvoltage that may originate from the utility grid. The meter is connected to the main distribution board through an appropriate protective device (5), ensuring safe operation and accurate energy measurement.

For large-scale photovoltaic installations, multiple PV strings or inverter outputs are often connected in parallel before feeding the main distribution board. Each parallel circuit is protected by its own protective device to prevent fault currents from affecting the remaining circuits. In addition, another surge protection device (6) is installed at the point where the PV system connects to the network, providing protection for the switchboard and downstream electrical equipment against overvoltage events.

Finally, the connection between the PV installation and the utility grid includes a main disconnect switch (7), located upstream of the electricity meter. Depending on the system configuration, the meter records either the energy exported to the grid or both the imported and exported electrical energy. To complete the protection scheme, a main protective device (8) is installed to safeguard the distribution board and the grid connection cable against overloads and short-circuit faults. Together, these protection and isolation components ensure safe operation, facilitate maintenance, and improve the reliability of the PV power generation system.

Session Summary

This session presented the fundamental role of power electronics in PV energy generation systems. It explained how power electronic converters enable the efficient conversion of the direct current produced by photovoltaic modules into alternating current suitable for supplying electrical loads and the utility grid. The functions of DC/DC converters, inverters, and DC-link components were discussed, emphasizing their importance in voltage regulation, power conditioning, and grid integration.

The session also introduced the main semiconductor switching devices used in PV applications, including diodes, MOSFETs, IGBTs, and thyristors, together with the basic operating principles of stand-alone and grid-connected inverter systems. Furthermore, the concept of MPPT was presented, highlighting the relationship between the PV power characteristics and environmental conditions, and demonstrating how MPPT techniques maximize the energy harvested from photovoltaic arrays under varying solar irradiance and temperature. Finally, practical aspects affecting the performance of PV power electronic systems were discussed. These included power conversion losses, thermal effects on semiconductor devices, and the importance of proper cooling, protection, and reliability measures. The implementation of surge protection devices, disconnect switches, and protective equipment was also described to illustrate how modern PV systems achieve safe, efficient, and reliable operation. Overall, this session demonstrated that power electronics is an indispensable technology for maximizing the efficiency, stability, and long-term performance of contemporary photovoltaic energy generation systems.