



Solar Energy Systems

Complete study notes — from how sunlight becomes electricity to designing, installing and maintaining a real rooftop solar system.

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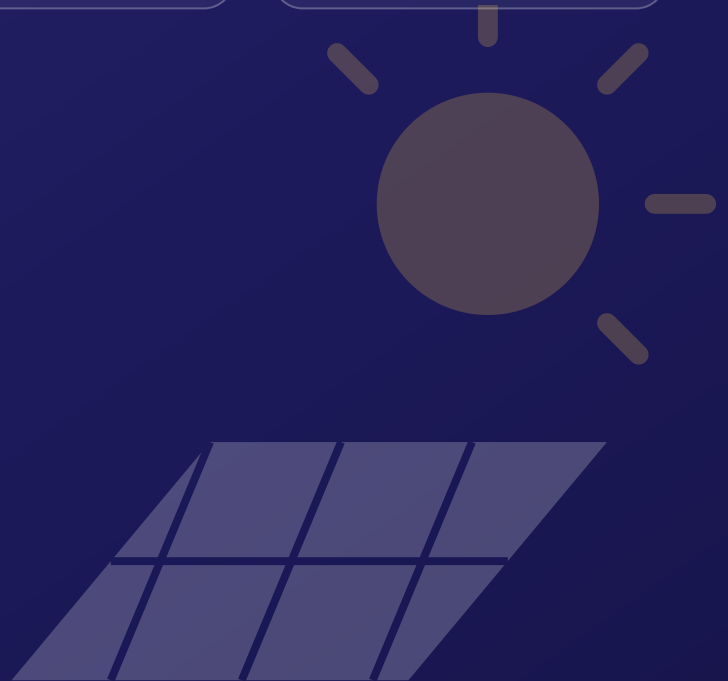
Modules

50+

Diagrams & tables

200+

Questions & MCQs



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How to use these notes

Read one module at a time and do its practice questions before moving on. Module 6 (sizing) is the heart of the course — master its worked examples before the project in Module 10.

Blue box — Key idea. The one thing to remember from that part.

Yellow box — Formula. Learn these; they come up in every sizing problem.

Green box — Practical tip. What installers actually do on site.

Orange box — Caution. Safety points and common mistakes.

Worked example. Read the steps, then cover them and try it yourself.

Practice.
Short questions at the end of every module.

Introduction to Renewable Energy and Solar Power

Where solar fits among the energy sources that power the world, and why it has become the fastest-growing source of electricity in history.

1.1 What is energy, and why does the source matter?

Energy is the ability to do work — to lift, heat, light, move or compute. Every appliance in your home is simply a device that converts one form of energy into another: a fan converts electrical energy into motion, a bulb converts it into light, and a heater converts it into heat. The electricity that reaches your socket, however, has to be produced somewhere first, and **how** it is produced decides its cost, its pollution, and whether it will still be available fifty years from now.

For most of the twentieth century, electricity came from burning fuels. Coal, oil and natural gas are burned to boil water; the steam spins a turbine; the turbine spins a generator. This works well, but the fuel is used up forever once it is burned, it has to be dug up and transported continuously, and burning it releases carbon dioxide (CO₂) and other pollutants into the air. These are called **non-renewable** or **fossil** sources, because they formed from plants and animals buried millions of years ago and cannot be replaced on any human timescale.

Renewable sources are those that are naturally replenished — the sun rises again tomorrow, the wind blows again, rivers keep flowing. Using them today does not reduce what is available tomorrow. They also produce little or no pollution while generating electricity.

Key idea

A renewable source is one that nature refills faster than we use it. Solar energy is the ultimate renewable: the sunlight reaching the Earth in about one and a half hours carries more energy than the whole world uses in a year.

1.2 The main renewable energy sources

Almost all renewable energy is, directly or indirectly, energy from the sun. Sunlight heats the air unevenly, which creates wind. Sunlight evaporates water, which falls as rain in the hills and flows back down as rivers — hydro power. Plants capture sunlight through photosynthesis —

biomass. Only geothermal (heat from inside the Earth) and tidal energy (from the Moon's gravity) come from elsewhere.

Source	How electricity is produced	Strengths	Limitations
Solar PV	Sunlight falls on semiconductor cells that directly produce DC electricity	No moving parts, works on any rooftop, very low running cost, modular (1 kW to 1,000 MW)	Only during daylight; output falls with clouds and dust
Solar thermal	Mirrors concentrate sunlight to heat a fluid, which drives a steam turbine; or panels heat water directly	Heat can be stored for a few hours; solar water heaters are cheap	Large plants need strong direct sunlight and big land areas
Wind	Moving air turns large blades connected to a generator	Works day and night; cheap at good sites	Needs windy locations; output varies with weather; tall towers
Hydro	Water falling from a height spins a turbine	Reliable, can be switched on quickly, can store energy (pumped hydro)	Dams affect rivers, villages and ecology; limited suitable sites
Biomass / biogas	Crop waste, wood or dung is burned or digested to produce gas	Uses waste; can run any time	Needs a steady supply of fuel; some air pollution
Geothermal	Heat from hot rocks underground produces steam	Constant output	Only in a few geological regions

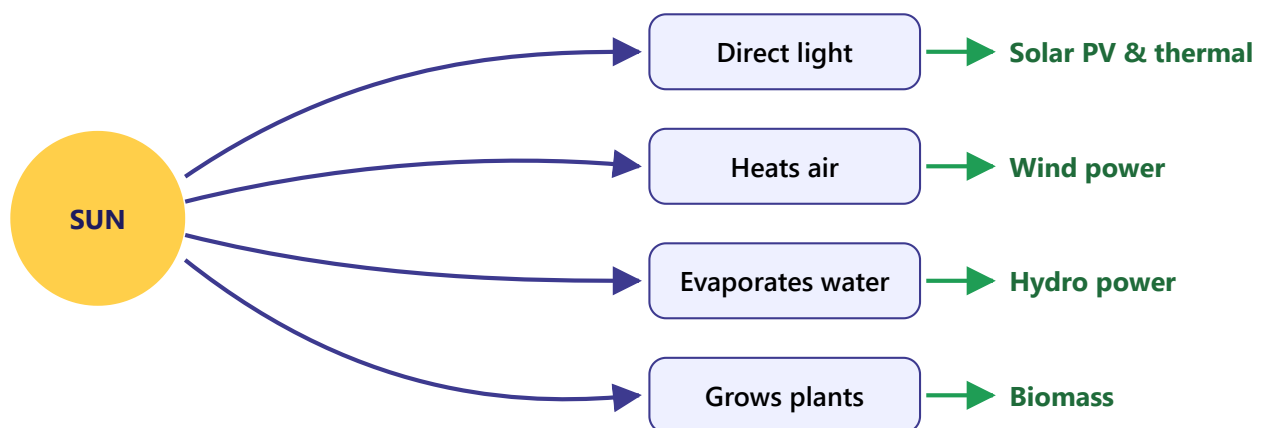


Figure 1.1 — Most renewable energy is solar energy in disguise.

1.3 A short history of solar electricity

The ability of light to produce electricity was first observed in **1839** by the French physicist **Edmond Becquerel**, who noticed that certain materials produced a small current when exposed to light. This is called the **photovoltaic effect** — "photo" meaning light, "voltaic" meaning electricity (after Alessandro Volta). In 1905, Albert Einstein explained the related photoelectric effect by proposing that light arrives in packets of energy called **photons**, work for which he later received the Nobel Prize.

The first practical silicon solar cell was built at **Bell Laboratories, USA, in 1954**. It converted about 6% of sunlight into electricity. The cells were extremely expensive, so their first real use was in space: from 1958 onwards, satellites were powered by solar panels because there was no other way to generate electricity in orbit for years at a time.

For decades solar stayed expensive. What changed everything was mass manufacturing. As factories grew larger — especially in China from the late 2000s — the price of solar modules dropped by around 90% between 2010 and 2020. Today, in sunny countries like India, electricity from a new large solar plant is among the cheapest electricity from any new power station of any kind.

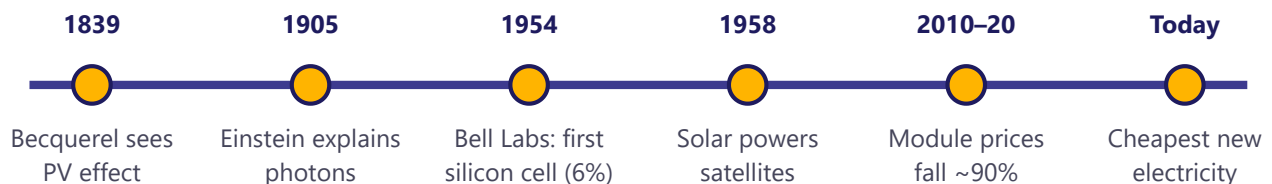


Figure 1.2 — Key milestones in the history of solar photovoltaics.

1.4 Why solar has grown so fast

Solar power has grown faster than any other source of electricity for several reasons working together:

1. **Falling cost.** Every time the world's total installed solar capacity doubles, the price of modules has historically fallen by roughly 20–25%. This "learning curve" has made solar cheaper year after year.
2. **Modularity.** A solar system is built from identical panels. The same technology powers a 10-watt lantern, a 3-kW home rooftop and a 2,000-MW solar park. No other power source scales so smoothly.

3. **Speed of installation.** A home rooftop system can be installed in one or two days; a large solar park can be built in months, whereas a coal or hydro plant takes many years.
4. **Low running cost.** Sunlight is free. There is no fuel to buy, and with no moving parts, maintenance is mostly cleaning and inspection.
5. **Long life.** Good-quality panels come with 25-year performance warranties and often keep working for 30 years or more.
6. **Clean and quiet.** No smoke, no noise and no emissions while generating electricity.
7. **Government support.** Subsidies, net-metering rules and national targets have encouraged homes and businesses to install solar.

1.5 Solar energy in India

India is one of the best places in the world for solar energy. Most of the country receives **4 to 7 kWh of solar energy per square metre per day**, with about 250–300 clear sunny days a year. Rajasthan, Gujarat, Maharashtra, Karnataka and Andhra Pradesh are especially sunny, but even eastern states such as Odisha receive around 4.5–5 kWh/m²/day, which is more than enough for rooftop solar to pay for itself.

India has set very ambitious clean-energy targets, including 500 GW of non-fossil electricity capacity by 2030, with solar as the largest part. National programmes such as the **PM Surya Ghar: Muft Bijli Yojana** (rooftop solar subsidy for homes) and **PM-KUSUM** (solar pumps and plants for farmers) make it cheaper for ordinary families and farmers to go solar. The Ministry of New and Renewable Energy (**MNRE**) sets the rules and maintains lists of approved equipment and vendors.

Practical tip

Subsidy amounts, eligibility rules and approved-vendor lists change from time to time. Before advising a customer, always check the current details on the official national rooftop portal and with the local electricity distribution company (DISCOM).

1.6 Advantages and disadvantages of solar power

Advantages

- Free, unlimited fuel (sunlight)
- No pollution or noise during operation
- Very low maintenance
- Long life — 25+ years
- Can be installed close to where power is used, reducing transmission losses
- Reduces electricity bills; payback often 4–6 years for homes
- Works in remote places with no grid

Disadvantages

- No output at night; less on cloudy days
- Needs storage (batteries) or the grid for 24-hour supply
- Upfront cost is higher than the monthly bill it replaces
- Needs shade-free roof or land area (about 6–8 m² per kW)
- Output falls with dust and high temperature
- Batteries add cost and need replacement every 5–10 years

1.7 Important units: power versus energy

The single most common confusion for beginners is the difference between **power** and **energy**. Getting this right is essential for every calculation in the rest of the course.

Power is the *rate* at which energy is produced or used — how fast. It is measured in **watts (W)** or kilowatts (kW; 1 kW = 1,000 W). A 100-W bulb uses energy at a rate of 100 watts while it is on.

Energy is the *total amount* produced or used over a period of time. It is power multiplied by time, measured in **watt-hours (Wh)** or **kilowatt-hours (kWh)**. One kWh is the "unit" on your electricity bill.

Formula — energy from power

$$\text{Energy (Wh)} = \text{Power (W)} \times \text{Time (h)}$$

$$1 \text{ kWh} = 1,000 \text{ Wh} = 1 \text{ unit of electricity}$$

Worked example 1.1

A 1.5-ton air conditioner draws about 1,500 W. It runs for 6 hours a day. How many units does it use in a 30-day month?

Step 1: Daily energy = $1,500 \text{ W} \times 6 \text{ h} = 9,000 \text{ Wh} = 9 \text{ kWh}$.

Step 2: Monthly energy = $9 \text{ kWh} \times 30 = \mathbf{270 \text{ kWh (270 units)}}$.

Step 3: At ₹7 per unit, this costs about $270 \times 7 = \mathbf{₹1,890 \text{ per month}}$.

Solar panels are rated in **watt-peak (Wp)** — the power they produce under standard test conditions (bright sunlight of $1,000 \text{ W/m}^2$ at 25°C cell temperature). A "3 kW system" means 3 kWp of panels. How many units it actually produces depends on the sunlight at your site, which is the subject of Module 2. As a first rule of thumb, in most of India **1 kWp of panels produces about 4 units a day**, or roughly 1,200–1,500 units a year.

Worked example 1.2

A family's bill shows an average of 300 units a month. Roughly what size of solar system would cover it?

Daily need = $300 \div 30 = 10 \text{ kWh/day}$. Each kWp gives about 4 kWh/day, so the system size $\approx 10 \div 4 = \mathbf{2.5 \text{ kWp}}$. In practice we would choose a 3-kWp system to allow for losses and future growth. (Module 6 does this properly.)

1.8 Types of solar energy use

It helps to separate the ways sunlight can be used:

- **Solar photovoltaic (PV):** converts light directly into electricity. This course focuses on PV.
- **Solar thermal (low temperature):** flat-plate or evacuated-tube collectors heat water for bathing or industry. A 100-litre home solar water heater is one of the fastest-paying investments in any home.
- **Concentrated solar power (CSP):** fields of mirrors focus sunlight to produce very high temperatures that drive steam turbines. Used only in very large plants.
- **Passive solar design:** designing buildings with windows, shading and materials that use sunlight for daylight and warmth — and avoid unwanted heat.
- **Solar cooking and drying:** solar cookers, and dryers for crops, fish and spices.

1.9 Solar and the environment

A solar panel does produce some emissions while it is being manufactured — mining, purifying silicon and making glass and aluminium all use energy. However, a panel installed in a sunny location typically "pays back" the energy used to make it within about 1–3 years, and then produces clean electricity for another 25 years or more. Over its whole life, rooftop solar electricity has only a small fraction of the carbon footprint of coal electricity.

Each kWh of coal-based electricity in India releases roughly 0.7–0.8 kg of CO₂. A 3-kWp rooftop system producing about 4,000 kWh a year therefore avoids roughly **3 tonnes of CO₂ every year** — similar to what around 100–150 trees absorb.

At the end of its life, a panel should be recycled: the glass, aluminium frame and copper can be recovered. India's e-waste rules now include solar panels, and responsible installers take back old panels rather than dumping them.

Module 1 — Summary

- Renewable sources are refilled by nature; fossil fuels are used up and pollute.
- Solar, wind, hydro and biomass are all ultimately powered by the sun.
- Photovoltaic effect: discovered 1839; first silicon cell 1954; prices fell ~90% in 2010–2020.
- Power (W, kW) is a rate; energy (Wh, kWh) is power × time. 1 kWh = 1 unit.
- Panels are rated in watt-peak (Wp). Rule of thumb in India: 1 kWp ≈ 4 units/day.
- India receives 4–7 kWh/m²/day — excellent for solar.

Practice questions — Module 1

1. Define renewable energy and give four examples.
2. Explain why wind and hydro power are said to be "indirect" forms of solar energy.
3. What is the difference between power and energy? Give the unit of each.
4. A 60-W fan runs for 10 hours a day. How many units does it use in 30 days? (*Ans: 18 kWh*)
5. List four reasons why solar power has grown so quickly in the last 15 years.
6. What does "Wp" mean on a solar panel label? What conditions is it measured under?
7. A house uses 450 units a month. Estimate the solar system size needed using the rule of thumb. (*Ans: about 3.75 → choose 4 kWp*)
8. Give three disadvantages of solar power and suggest how each can be reduced.

Solar Radiation and Site Assessment

How much sunlight a site really receives, how the sun moves across the sky, and how to judge whether a roof or plot is a good place for solar panels.

2.1 Sunlight as energy: irradiance and irradiation

The sun radiates an enormous amount of energy into space. At the top of the Earth's atmosphere, a surface facing the sun directly receives about **1,361 watts per square metre**. This value is called the **solar constant**. As sunlight passes through the atmosphere, some of it is absorbed by gases and water vapour and some is scattered by dust and air molecules, so on a clear day at noon the ground receives about **1,000 W/m²**. This round figure is used as the standard for testing solar panels.

Two words sound similar but mean different things, exactly like power and energy in Module 1:

- **Irradiance (G)** is the *power* of sunlight falling on a surface at a given moment, measured in **W/m²**. It changes every minute as the sun moves and clouds pass.
- **Irradiation (H)**, also called **insolation**, is the total *energy* received over a period — usually a day — measured in **kWh/m²/day**. It is the area under the irradiance curve.

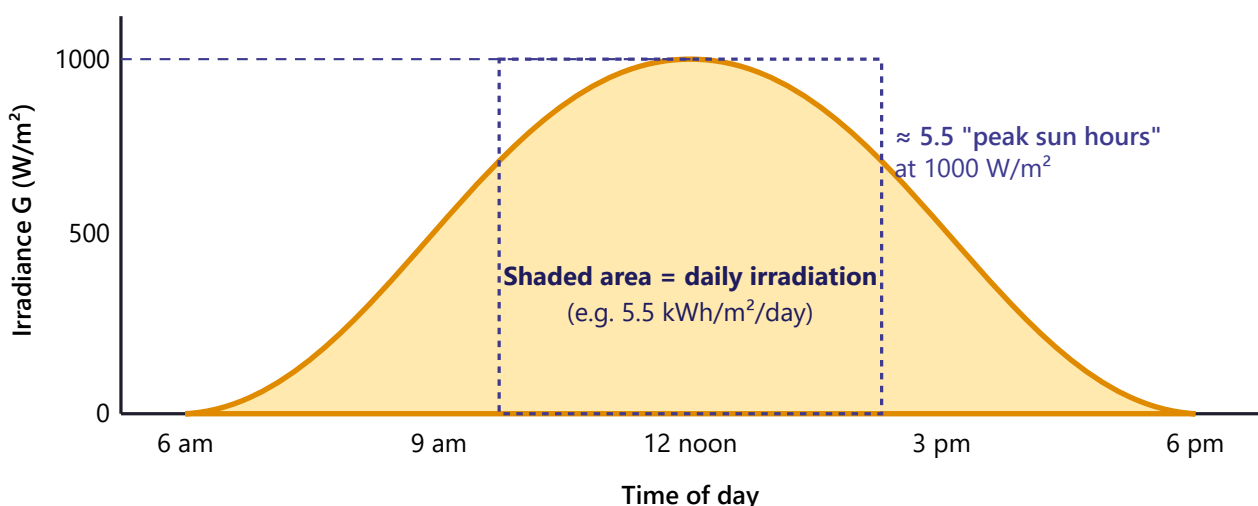


Figure 2.1 — Irradiance rises and falls through a clear day. The area under the curve is the day's irradiation; squeezing it into a rectangle 1,000 W/m² high gives the peak sun hours.

2.2 Peak sun hours (PSH)

Because irradiance keeps changing, it is awkward to calculate with directly. Instead, designers use a clever simplification called **peak sun hours**. We imagine squeezing the whole day's sunlight into a block of time during which the irradiance is exactly $1,000 \text{ W/m}^2$. The number of hours in that block is the peak sun hours.

Formula — peak sun hours

$$\text{PSH (hours)} = \text{Daily irradiation (kWh/m}^2\text{/day)} \div 1 \text{ kW/m}^2$$

So numerically, **PSH equals the irradiation in kWh/m²/day**. A site receiving $5.2 \text{ kWh/m}^2\text{/day}$ has 5.2 peak sun hours.

This is very useful because panels are rated at $1,000 \text{ W/m}^2$. A 1-kWp panel array in full $1,000 \text{ W/m}^2$ sunlight produces about 1 kW. If a site has 5 PSH, the ideal daily energy from 1 kWp is $1 \text{ kW} \times 5 \text{ h} = 5 \text{ kWh}$. After real-world losses (heat, dust, wiring, inverter — usually 20–25% in total) we get about 4 kWh. This is where the Module 1 rule of thumb comes from.

Formula — daily energy from an array

$$E (\text{kWh/day}) = P_{\text{array}} (\text{kWp}) \times \text{PSH} \times \text{PR}$$

PR is the **performance ratio** — the fraction of ideal energy actually delivered after losses. Typical values: 0.75–0.80 for a well-built rooftop system.

Worked example 2.1

A 5-kWp rooftop system in Bhubaneswar receives an annual average of 4.9 PSH. The performance ratio is 0.77. Estimate its daily and yearly energy.

Daily: $E = 5 \times 4.9 \times 0.77 = \mathbf{18.9 \text{ kWh/day}}$.

Yearly: $18.9 \times 365 \approx \mathbf{6,890 \text{ kWh/year}}$ (about 574 units a month).

2.3 Components of sunlight: direct, diffuse and reflected

Sunlight reaching a panel arrives in three parts:

- **Direct (beam) radiation** travels in a straight line from the sun. It casts sharp shadows. On a clear day it is the largest component.
- **Diffuse radiation** has been scattered by air, dust and clouds, so it comes from the whole sky. On a cloudy day almost all the light is diffuse — which is why panels still produce

some power (typically 10–30% of rated output) under clouds.

- **Reflected (albedo) radiation** bounces off the ground or nearby surfaces. White roofs, sand or snow reflect much more than grass or dark soil. Bifacial panels, which collect light on their back side too, benefit from this.

The total on a tilted surface is called **global tilted irradiance (GTI)**. On a horizontal surface it is called **global horizontal irradiance (GHI)**. Solar maps usually give GHI; design software converts it to GTI for your panel's tilt.

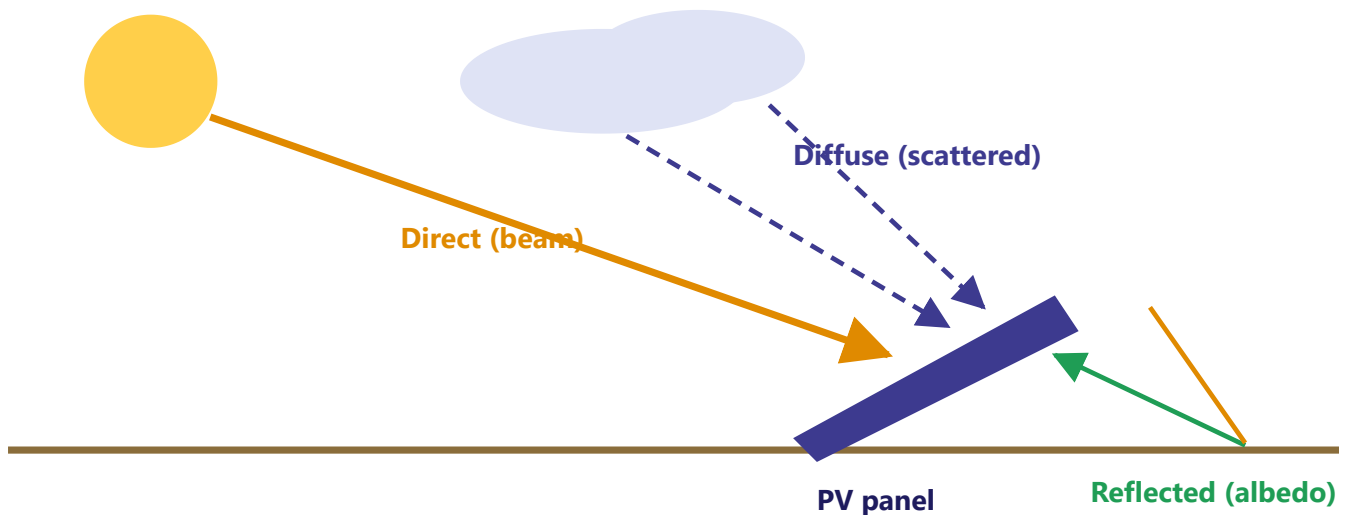


Figure 2.2 — The three components of sunlight reaching a tilted panel.

2.4 Air mass and the path of sunlight through the atmosphere

When the sun is directly overhead, its light takes the shortest path through the atmosphere. When the sun is low — early morning, late evening or in winter — the light travels through much more air, so more is absorbed and scattered. The relative path length is called **air mass (AM)**. AM1 means the sun is directly overhead; AM2 means the light passes through twice as much air (sun about 30° above the horizon). Panels are tested at **AM1.5**, which represents a typical mid-latitude condition. This is part of the **Standard Test Conditions (STC)**: 1,000 W/m², AM1.5 spectrum, 25 °C cell temperature.

2.5 The sun's movement across the sky

To place panels well, we need to understand where the sun is at different times of day and year. Two angles describe the sun's position:

- **Solar altitude (elevation) angle** — how high the sun is above the horizon, from 0° at sunrise to its maximum at solar noon.

- **Solar azimuth angle** — the compass direction of the sun, measured from north (or from south in some books). The sun rises in the east, is due south at noon (for places north of the Tropic of Cancer), and sets in the west.

The Earth's axis is tilted by **23.45°**. As the Earth orbits the sun, this tilt makes the sun's noon height change through the year. The angle between the sun's rays and the equator's plane is called the **declination (δ)**. It varies from +23.45° at the summer solstice (around 21 June) to -23.45° at the winter solstice (around 22 December), and is 0° at the equinoxes (around 21 March and 23 September).

Formula — noon altitude of the sun

$$\alpha_{\text{noon}} = 90^\circ - \varphi + \delta$$

φ = latitude of the site; δ = declination on that day.

Worked example 2.2

Bhubaneswar is at latitude about 20.3° N. Find the noon sun altitude on 21 June and 22 December.

21 June ($\delta = +23.45^\circ$): $\alpha = 90 - 20.3 + 23.45 = \mathbf{93.15^\circ}$. More than 90° means the sun is slightly to the *north* of overhead at noon — this happens in summer at places south of the Tropic of Cancer (23.45° N).

22 December ($\delta = -23.45^\circ$): $\alpha = 90 - 20.3 - 23.45 = \mathbf{46.25^\circ}$ — the sun is much lower, in the southern sky.

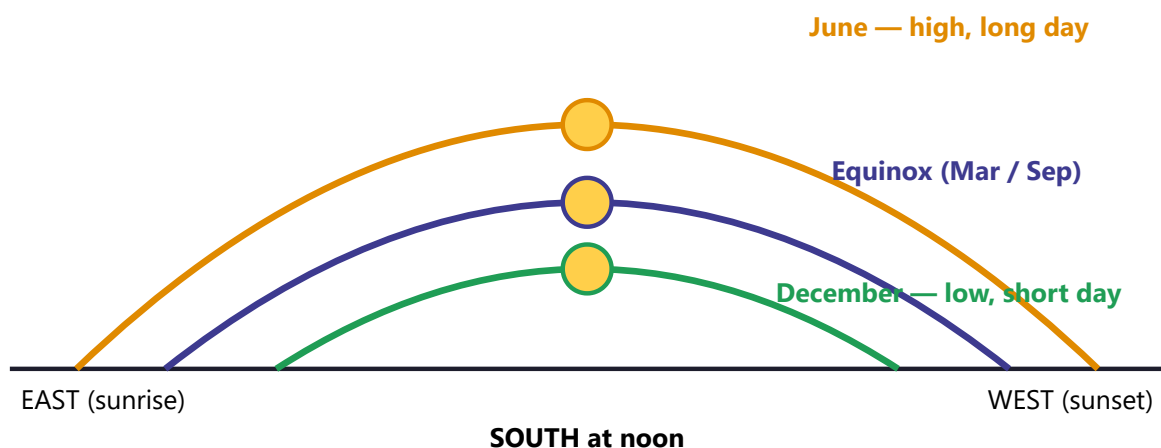


Figure 2.3 — The sun's daily path is highest in June and lowest in December (northern hemisphere).

2.6 Choosing orientation and tilt

A panel produces the most energy when sunlight hits it at right angles (perpendicular). Since the sun moves, a fixed panel is a compromise. For locations in the northern hemisphere, including all of India:

- **Orientation (azimuth):** panels should face **true south**. Facing south-east or south-west loses only a few percent; facing east or west loses around 10–20%; facing north loses much more and should be avoided at Indian latitudes unless the tilt is very small.
- **Tilt angle:** for maximum yearly energy, the tilt from horizontal should be roughly equal to the **site latitude**. In practice, a tilt of latitude minus a few degrees often works slightly better because of stronger summer generation. Delhi (28.6° N) → about $25\text{--}28^\circ$; Bhubaneswar (20.3° N) → about $18\text{--}20^\circ$; Chennai (13° N) → about $12\text{--}13^\circ$.
- **Seasonal tilt:** if the structure allows adjustment, use a steeper tilt (latitude + 15°) in winter and a flatter tilt (latitude – 15°) in summer. This can add a few percent, but most rooftop systems use a fixed tilt for simplicity.
- **Minimum tilt:** never go below about 10° , so that rain can wash off dust and water does not stand on the glass.

Caution — magnetic vs. true south

A phone compass shows *magnetic* south. In India, the difference from true (geographic) south — the magnetic declination — is small (usually within about $1\text{--}2^\circ$), so it rarely matters. But in other parts of the world it can be 10° or more. Satellite maps and solar design apps give true south directly.

2.7 Shading — the biggest enemy of a solar system

Shading harms solar panels far more than most people expect. Because the cells in a panel are connected in series, a shadow on even a small part of a panel can reduce the current of the whole string. A shadow covering just one cell can reduce a panel's output by a third or more. This is explained in detail in Module 3 (bypass diodes) — for now, remember that **a shade-free location between about 9 am and 4 pm is essential**.

Common sources of shade on rooftops include water tanks, staircase rooms (mumty), parapet walls, neighbouring buildings, trees, mobile towers, overhead cables and dish antennas. Remember that shadows are much longer in winter, when the sun is low.

Formula — minimum distance to avoid shade

$$\text{Shadow length } L = h \div \tan(\alpha)$$

h = height of the obstacle above the panel's lower edge; α = the lowest sun altitude you design for (commonly the altitude at 9 am on 22 December).

Worked example 2.3

A water tank stands 1.5 m above the roof. The design winter sun altitude is 30° . How far north of the tank should the panels start?

$L = 1.5 \div \tan 30^\circ = 1.5 \div 0.577 = \mathbf{2.6 \text{ m}}$. The first row of panels should start at least 2.6 m north of the tank (the shadow falls northwards because the winter sun is in the southern sky).

The same formula sets the **row spacing** between rows of tilted panels on a flat roof — the back of one row must not shade the front of the next row in winter. If a panel of slant length 2 m is tilted at 20° , its top edge is $2 \times \sin 20^\circ = 0.68 \text{ m}$ high. With $\alpha = 30^\circ$, the gap needed is $0.68 \div \tan 30^\circ \approx 1.2 \text{ m}$.

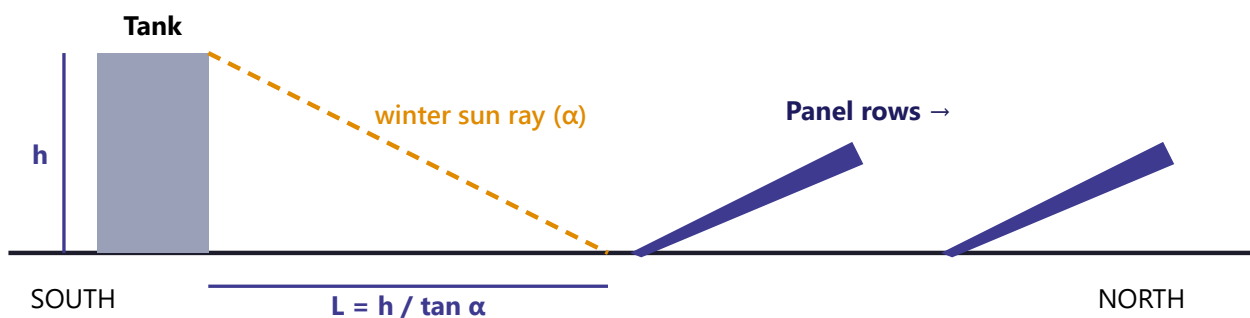


Figure 2.4 — Keep panels beyond the winter shadow length of any obstacle.

2.8 Site assessment step by step

A professional site survey collects everything needed to design the system and quote a price. A typical checklist:

1. **Customer's needs:** collect 12 months of electricity bills; note sanctioned load, connection type (single/three phase), tariff category and any power-cut problems.

2. **Solar resource:** find the site's average PSH from a reliable source (for example NASA POWER, the Global Solar Atlas, or NREL/NIWE data) — design software also includes this.
3. **Roof details:** type (RCC concrete, metal sheet, tiled), age and condition, usable shade-free area, orientation, load-bearing capacity, access for installation and cleaning.
4. **Shading analysis:** note all obstacles with their height and direction; use a sun-path app or a solar pathfinder; take photos facing south, east and west.
5. **Electrical details:** location of the main meter and distribution board, earthing condition, distance from roof to inverter and to meter (for cable sizing).
6. **Inverter and battery location:** a shaded, ventilated, dry place close to the distribution board.
7. **Safety and access:** ladder or staircase access, parapet height, fragile roof areas, overhead lines nearby.
8. **Local rules:** DISCOM net-metering limits, building permissions, housing society approval.

Site factor	Good	Acceptable	Poor
Orientation	South, SE, SW	East or West	North-facing at steep tilt
Shade (9 am–4 pm)	None	Brief morning/evening shade	Midday shade on panels
Area per kWp	$\geq 8 \text{ m}^2$	6–8 m^2	< 6 m^2 (tight layout)
Roof condition	New RCC, strong	Older but sound	Leaking, cracked, weak sheet
Dust / pollution	Low, easy cleaning	Moderate	Heavy dust, no water access

Practical tip — area needed

A modern 540–580 Wp panel measures about $2.28 \text{ m} \times 1.13 \text{ m} \approx 2.6 \text{ m}^2$. About two of them make 1 kWp. Allowing for walkways and spacing, plan roughly **6–8 m^2 of shade-free roof per kWp** (about 65–85 sq ft).

2.9 Other things that affect the yield

- **Temperature:** panels lose efficiency when hot — roughly 0.3–0.4% of power for every °C above 25 °C cell temperature. On a hot Indian summer day, cells can reach 60–65 °C, losing 12–15% of power. Good airflow behind the panels helps.
- **Dust and soiling:** a dusty panel can lose 5–25% of its output. Regular cleaning is the cheapest way to raise yield (Module 9).

- **Monsoon and clouds:** generation drops during July–September in much of India; annual averages account for this.
- **Altitude and pollution:** clean air at high altitude gives more sunlight; smog reduces it.

Module 2 — Summary

- Irradiance (W/m^2) is instantaneous power; irradiation ($\text{kWh/m}^2/\text{day}$) is daily energy.
- Peak sun hours = daily irradiation in $\text{kWh/m}^2/\text{day}$. India: typically 4–6 PSH.
- $E (\text{kWh/day}) = \text{kWp} \times \text{PSH} \times \text{PR}$, with $\text{PR} \approx 0.75\text{--}0.80$.
- $\text{STC} = 1,000 \text{ W/m}^2$, AM1.5, 25°C .
- In India, face panels true south, tilt $\approx$ latitude (never below $\sim 10^\circ$).
- Shading is the biggest yield killer; clear distance $L = h / \tan \alpha$.
- Allow 6–8 m^2 shade-free roof per kWp.

Practice questions — Module 2

1. Distinguish between irradiance and irradiation, giving units.
2. What are peak sun hours? A site receives $5.6 \text{ kWh/m}^2/\text{day}$. What is its PSH?
3. Estimate the yearly energy of a 3-kWp system with 5.1 PSH and $\text{PR} = 0.78$. (*Ans: $\approx 4,356 \text{ kWh}$*)
4. List the three components of solar radiation. Which one lets panels work on cloudy days?
5. State the Standard Test Conditions for solar panels.
6. Find the noon sun altitude at Jaipur (26.9° N) on 22 December. (*Ans: 39.65°*)
7. A parapet wall is 0.9 m high. Using $\alpha = 28^\circ$, how far from the wall should panels be placed? (*Ans: $\approx 1.7 \text{ m}$*)
8. Prepare a ten-point site-survey checklist for a rooftop solar installation.

Photovoltaic (PV) Cell and Panel Technology

How a thin slice of silicon turns light into electricity, how cells are built into panels, and how to read every line of a panel datasheet.

3.1 Semiconductors — the material behind solar cells

Materials can be grouped by how easily electricity flows through them. **Conductors** such as copper have many free electrons and let current flow easily. **Insulators** such as glass or rubber have almost none. **Semiconductors** such as silicon sit in between: in the dark and when cold they conduct poorly, but when given energy — by heat or by light — some of their electrons break free and they can conduct.

Silicon atoms have four outer (valence) electrons. In a pure silicon crystal, each atom shares these four electrons with four neighbours, forming strong **covalent bonds**. When a photon of light with enough energy strikes the crystal, it can knock an electron out of its bond. This creates two charge carriers: a free **electron** (negative) and the empty place it left behind, called a **hole** (which behaves like a positive charge). The minimum energy needed to free an electron is called the **band gap**; for silicon it is about **1.1 electron-volts (eV)**, which matches the energy of near-infrared and visible light very well.

3.2 Doping: making n-type and p-type silicon

Pure silicon alone cannot make a solar cell, because the freed electrons and holes would simply wander around and recombine. We need a built-in "push" that separates them. This is created by **doping** — adding tiny, controlled amounts of other elements:

- **n-type silicon:** doped with **phosphorus**, which has five outer electrons. Four bond with silicon and the fifth is free to move. n-type silicon has extra free electrons (negative carriers).
- **p-type silicon:** doped with **boron** (or gallium), which has only three outer electrons. This leaves a missing bond — a hole. p-type silicon has extra holes (positive carriers).

3.3 The p-n junction and the photovoltaic effect

When a layer of n-type silicon is formed on top of p-type silicon, electrons near the boundary flow from the n-side into the p-side and fill holes there. This leaves the n-side near the boundary slightly positive and the p-side slightly negative. A thin region called the **depletion region** forms, containing a built-in **electric field**. This field is the "push" we needed.

Now, when sunlight creates an electron–hole pair near the junction, the electric field sweeps the electron towards the n-side (front) and the hole towards the p-side (back). Electrons collect at the front contact and holes at the back contact, creating a voltage between them. If we connect a wire and a load between the front and back contacts, electrons flow through the external circuit — a **direct current (DC)** — do useful work, and return to the back of the cell to recombine with holes. As long as light keeps arriving, current keeps flowing. This is the **photovoltaic effect**.

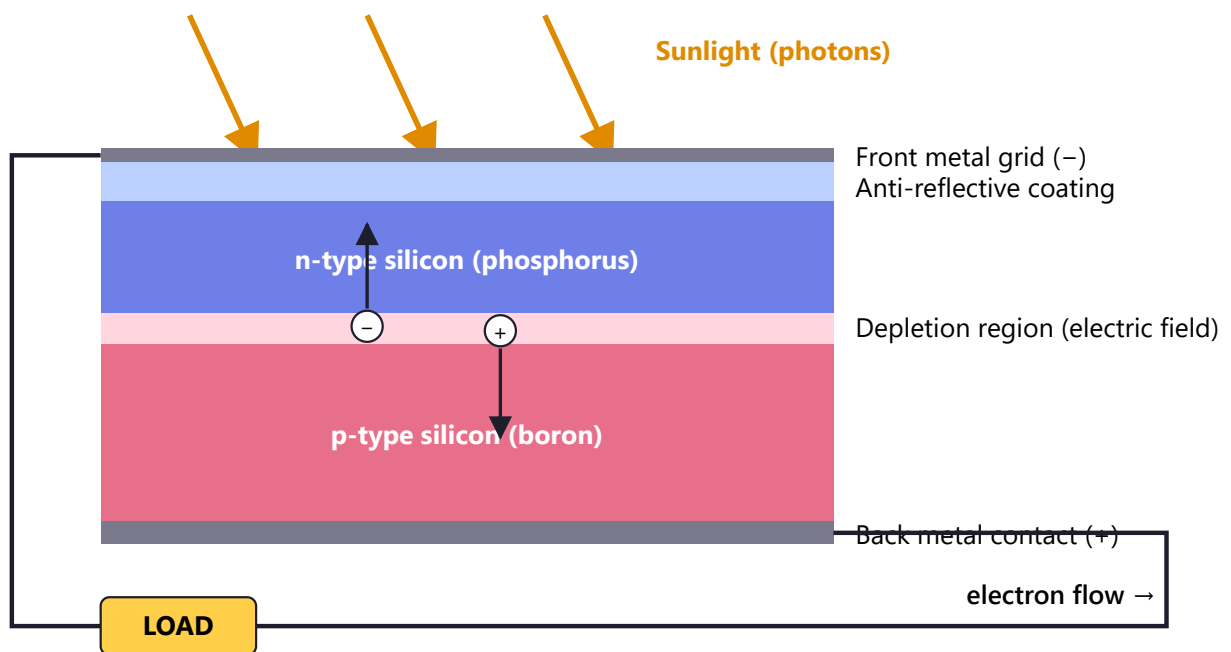


Figure 3.1 — Cross-section of a crystalline silicon solar cell. The junction's electric field separates electron–hole pairs created by light.

Key idea

A solar cell is a large, flat p–n junction diode. Light creates electron–hole pairs; the junction's built-in field separates them; the separated charges drive current through an external circuit.

3.4 Why a cell is not 100% efficient

The **efficiency** of a cell is the percentage of the sunlight's power falling on it that comes out as electrical power. Commercial silicon cells today reach about 21–25%, and whole panels about 20–23%. The theoretical maximum for a single silicon junction is about 33% (the Shockley–Queisser limit). Losses happen because:

- Photons with energy **below** the band gap (deep infrared) pass straight through without freeing an electron.

- Photons with energy **above** the band gap (blue and ultraviolet) free an electron but the extra energy is wasted as heat.
- Some light is **reflected** from the surface or **blocked** by the front metal grid lines.
- Some electrons and holes **recombine** before they are collected.
- Current meets **resistance** in the silicon, contacts and wires.

Formula — efficiency

$$\eta = P_{\max} \div (G \times A) \times 100\%$$

$P_{\max}$ = maximum electrical output (W); G = irradiance (W/m²); A = area (m²).

Worked example 3.1

A panel measures 2.278 m × 1.134 m and is rated at 550 Wp. Find its efficiency.

$A = 2.278 \times 1.134 = 2.583 \text{ m}^2$. Power in at STC = $1,000 \times 2.583 = 2,583 \text{ W}$.

$\eta = 550 \div 2,583 \times 100 = \mathbf{21.3\%}$.

3.5 From cell to module to array

A single silicon cell produces only about **0.5–0.6 V**, regardless of its size. Its current depends on its area and on the light — a standard cell gives around 10–13 A in full sun. To get useful voltages, cells are connected in **series** (voltages add):

- **Cell:** the basic unit (about 0.5–0.6 V).
- **Module (panel):** typically 60, 72, 120 or 144 cells in series, sealed in a weatherproof package. A 72-cell (or 144 half-cell) module has an open-circuit voltage of about 45–50 V.
- **String:** several modules connected in series to reach the inverter's operating voltage.
- **Array:** one or more strings connected together — the whole generator.

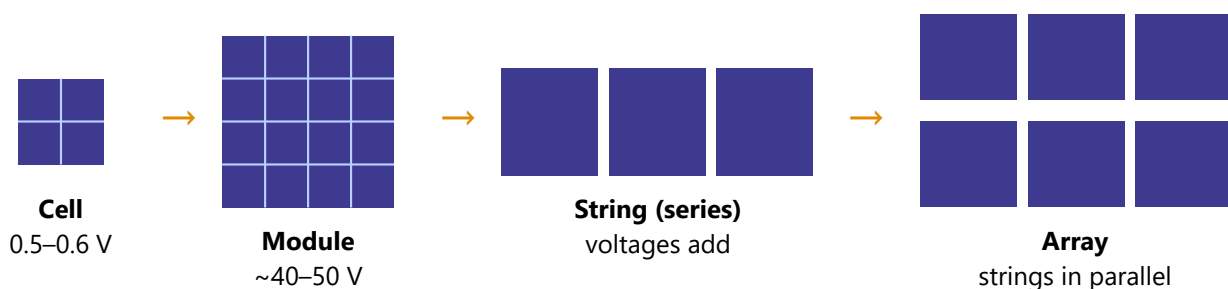


Figure 3.2 — Cells build modules; modules build strings; strings build the array.

3.6 Construction of a solar module

A standard module is a carefully engineered sandwich designed to last 25–30 years outdoors:

1. **Tempered glass (front):** 3.2 mm, low-iron for high clarity, often with an anti-reflective coating. It must withstand hail and wind loads.
2. **EVA encapsulant:** a clear plastic sheet (ethylene vinyl acetate) melted around the cells to glue the layers together and keep moisture out.
3. **Solar cells:** connected by thin tinned-copper ribbons (busbars).
4. **Second encapsulant layer.**
5. **Backsheet or back glass:** a multilayer plastic sheet (or a second glass in "glass-glass" and bifacial modules) that insulates and protects the back.
6. **Aluminium frame:** gives strength and allows mounting; it must be earthed.
7. **Junction box:** on the back, containing the **bypass diodes** and the output cables with MC4-type connectors.

3.7 Types of solar cell technology

Technology	Appearance	Module efficiency	Notes
Monocrystalline (mono-PERC)	Uniform black, cells with cut corners	20–22%	Made from a single crystal; the mainstream choice for rooftops for many years
TOPCon / n-type mono	Black	21.5–23%	Newer n-type cells with better temperature behaviour and less degradation; now very common
Heterojunction (HJT)	Black	22–23.5%	Combines crystalline and thin amorphous silicon; excellent in heat
Polycrystalline	Blue, speckled "crystal" pattern	15–18%	Cheaper, older technology; now largely phased out
Thin-film (CdTe, CIGS, a-Si)	Uniform dark, no visible cells	10–19%	Used mainly in large utility plants; better in diffuse light and heat, needs more area
Bifacial	Glass on both sides	+5–20% energy gain	Collects reflected light on the back; best on white roofs or raised structures

Other terms you will see: **half-cut cells** (each cell cut in two, halving the current in each half, reducing resistive losses and shading impact), and **multi-busbar (MBB)** designs (more, thinner ribbons for lower resistance). Most modern modules combine these features.

3.8 The I–V curve: how a panel behaves electrically

A panel's current (I) and voltage (V) depend on the load connected to it. Plotting current against voltage gives the **I–V curve**, the most important graph in PV:

- **Short-circuit current (I_{sc})**: the current when the terminals are shorted ($V = 0$). It is the maximum current.
- **Open-circuit voltage (V_{oc})**: the voltage with nothing connected ($I = 0$). It is the maximum voltage.
- **Maximum power point (MPP)**: the one point on the curve where $V \times I$ is greatest. The voltage and current there are V_{mp} and I_{mp} . The panel's rated power is $P_{max} = V_{mp} \times I_{mp}$.

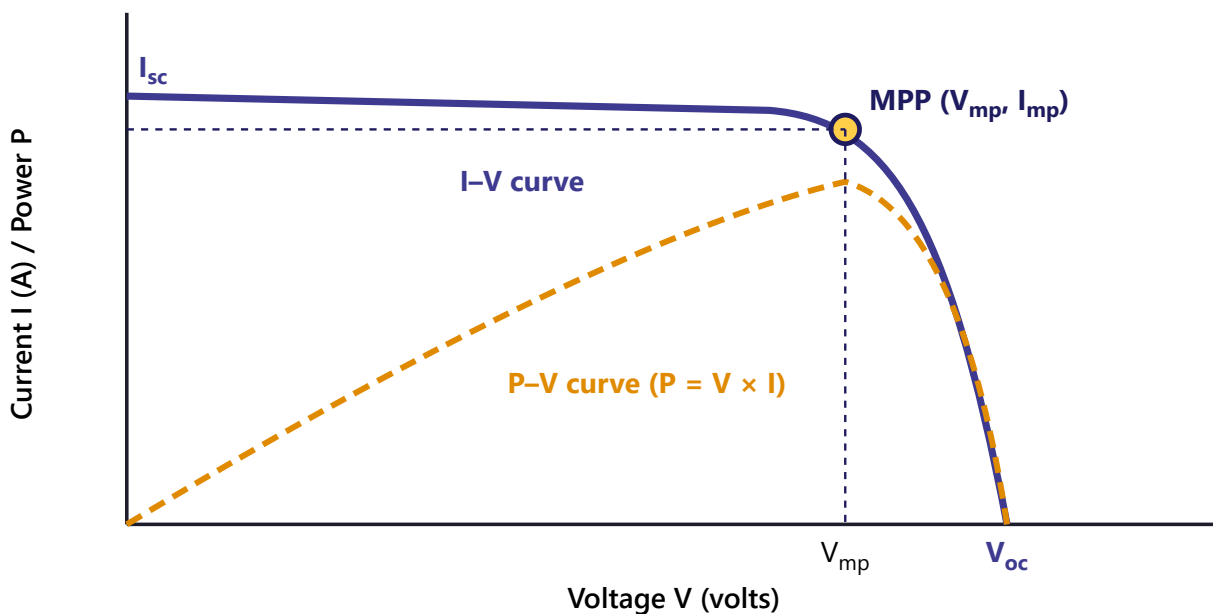


Figure 3.3 — I–V and P–V curves of a PV module. The inverter's MPPT keeps the panel at the maximum power point.

Because the MPP moves as sunlight and temperature change, modern charge controllers and inverters contain a **maximum power point tracker (MPPT)** that continuously adjusts the operating voltage to stay at the peak.

Formula — fill factor

$$FF = (V_{mp} \times I_{mp}) \div (V_{oc} \times I_{sc})$$

The fill factor measures how "square" the I–V curve is. Good modules have FF of about 0.78–0.82.

3.9 Effect of irradiance and temperature

Irradiance mainly changes current. Current is almost directly proportional to irradiance: at 500 W/m², I_{sc} is about half its value at 1,000 W/m². Voltage falls only slightly.

Temperature mainly changes voltage. As a cell gets hotter, its voltage falls noticeably while current rises very slightly, so overall power falls. Datasheets give temperature coefficients, for example:

- Temperature coefficient of P_{max} : about **–0.29% to –0.40% per °C**
- Temperature coefficient of V_{oc} : about **–0.25% to –0.30% per °C**
- Temperature coefficient of I_{sc} : about **+0.04% to +0.05% per °C**

Formula — temperature correction

$$X_T = X_{STC} \times [1 + \gamma \times (T_{cell} - 25)]$$

γ = temperature coefficient (as a decimal, e.g. –0.0035 per °C); $X = P_{max}, V_{oc}$ or I_{sc} .

Worked example 3.2

A 550-Wp panel has a P_{max} coefficient of –0.35%/°C. On a summer afternoon the cell temperature is 63 °C. Estimate its power at 1,000 W/m².

$\Delta T = 63 - 25 = 38$ °C. Power = $550 \times [1 + (-0.0035 \times 38)] = 550 \times 0.867 = \mathbf{476.9\ W}$ — a loss of about 13%.

Worked example 3.3 — cold-morning voltage

A panel has $V_{oc} = 49.6 \text{ V}$ and a V_{oc} coefficient of $-0.27\%/^{\circ}\text{C}$. The coldest expected cell temperature is 5°C . Find the maximum V_{oc} .

$\Delta T = 5 - 25 = -20^{\circ}\text{C}$. $V_{oc} = 49.6 \times [1 + (-0.0027 \times -20)] = 49.6 \times 1.054 = \mathbf{52.3 \text{ V}}$. This higher cold voltage must be used when checking the inverter's maximum input voltage (Module 8).

3.10 Shading, hot spots and bypass diodes

Because cells in a panel are in series, the same current must flow through all of them. If one cell is shaded, it can only pass a small current, and it limits the whole series chain — like a narrow section in a water pipe. Worse, the shaded cell can become reverse-biased by its neighbours and start to dissipate power as heat. This creates a **hot spot** that can crack the cell, brown the encapsulant or even burn the backsheet.

To prevent this, modules contain **bypass diodes**, usually three in the junction box, each across one-third of the cells. When part of a panel is shaded, the diode for that section conducts and current flows around the shaded group. The panel loses that section's voltage (about a third) but the rest keeps producing, and hot spots are avoided.

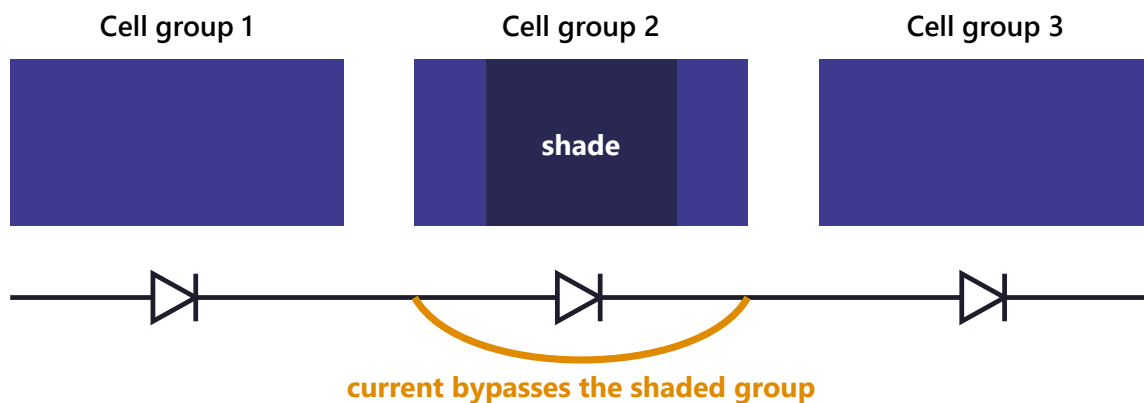


Figure 3.4 — A bypass diode lets current flow around a shaded section of the module.

3.11 Reading a module datasheet

Every module comes with a datasheet. Below is a typical example for a 550-Wp mono module. Learn what each line means — you will use these values in Modules 6 and 8.

Parameter (at STC)	Symbol	Typical value	What it tells you
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Maximum power	$P_{\max}$	550 W	Rated power at STC
Power tolerance	—	0 to +5 W	Actual power will not be below rating
Voltage at max power	V_{mp}	41.9 V	Normal operating voltage
Current at max power	I_{mp}	13.13 A	Normal operating current
Open-circuit voltage	V_{oc}	49.6 V	Maximum voltage (use cold correction)
Short-circuit current	I_{sc}	13.93 A	Maximum current (use for fuse/cable sizing)
Module efficiency	η	21.3%	Power per unit area
NOCT / NMOT	—	43–45 °C	Cell temperature in typical real operation
Max system voltage	—	1,500 V DC	Upper limit for the string voltage
Max series fuse rating	—	25 A	Largest fuse allowed in series
Temp. coeff. $P_{\max}$ / V_{oc} / I_{sc}	γ	–0.35 / –0.27 / +0.048 %/°C	How output changes with heat
Dimensions / weight	—	2278 × 1134 × 35 mm, 28 kg	Layout and roof-load planning
Warranty	—	12 yr product, 25–30 yr power	E.g. ≥ 80–87% of power after 25–30 years

Practical tip — quality marks

In India, modules for subsidised and government projects must be BIS-certified and appear on MNRE's Approved List of Models and Manufacturers (ALMM). International test standards include IEC 61215 (design and durability) and IEC 61730 (safety). Always check the datasheet and nameplate for these.

3.12 Degradation

All panels slowly lose output. There is usually a slightly larger drop in the first year (light-induced degradation, about 1–2%), followed by a steady yearly decline of around 0.4–0.55%. A typical warranty guarantees at least about 80–87% of original power after 25–30 years. When estimating lifetime energy, reduce the yearly yield accordingly.

Module 3 — Summary

- A solar cell is a p-n junction; light creates electron-hole pairs, the junction field separates them.
- One silicon cell $\approx 0.5\text{--}0.6\text{ V}$; cells in series make a module; modules make strings and arrays.
- Efficiency $\eta = P_{\text{max}} / (G \times A)$. Modern modules: 20–23%.
- Key datasheet values: P_{max} , V_{mp} , I_{mp} , V_{oc} , I_{sc} , temperature coefficients.
- Irradiance changes current; temperature changes voltage. Heat reduces power by $\sim 0.3\text{--}0.4\%/^{\circ}\text{C}$.
- Bypass diodes limit shading loss and prevent hot spots.
- Panels degrade $\sim 0.5\%$ per year; warranties cover 25–30 years.

Practice questions — Module 3

1. Explain the difference between n-type and p-type silicon.
2. Describe, with a labelled sketch, how a p-n junction produces current when light falls on it.
3. Give four reasons why a solar cell cannot convert all sunlight into electricity.
4. A $1.7\text{ m} \times 1.0\text{ m}$ panel is rated at 340 Wp. Find its efficiency. (Ans: 20%)
5. Sketch an I–V curve and mark I_{sc} , V_{oc} and the MPP.
6. A panel has $V_{\text{mp}} = 41.9\text{ V}$, $I_{\text{mp}} = 13.13\text{ A}$, $V_{\text{oc}} = 49.6\text{ V}$, $I_{\text{sc}} = 13.93\text{ A}$. Find the fill factor. (Ans: ≈ 0.80)
7. A 400-Wp panel ($-0.34\%/^{\circ}\text{C}$) operates at 58°C . Find its power at STC irradiance. (Ans: $\approx 355\text{ W}$)
8. What is a hot spot? How do bypass diodes prevent it?

Solar System Components

Inverters, charge controllers, batteries and the balance-of-system parts — what each one does, how it is rated, and how to choose it.

4.1 The building blocks of a solar power system

Solar panels produce DC electricity whenever light falls on them. But most homes use AC appliances, the sun does not shine at night, and electricity must be delivered safely. So a complete system needs several other parts. Everything apart from the panels is called the **balance of system (BOS)**.

Energy flow in a typical rooftop system

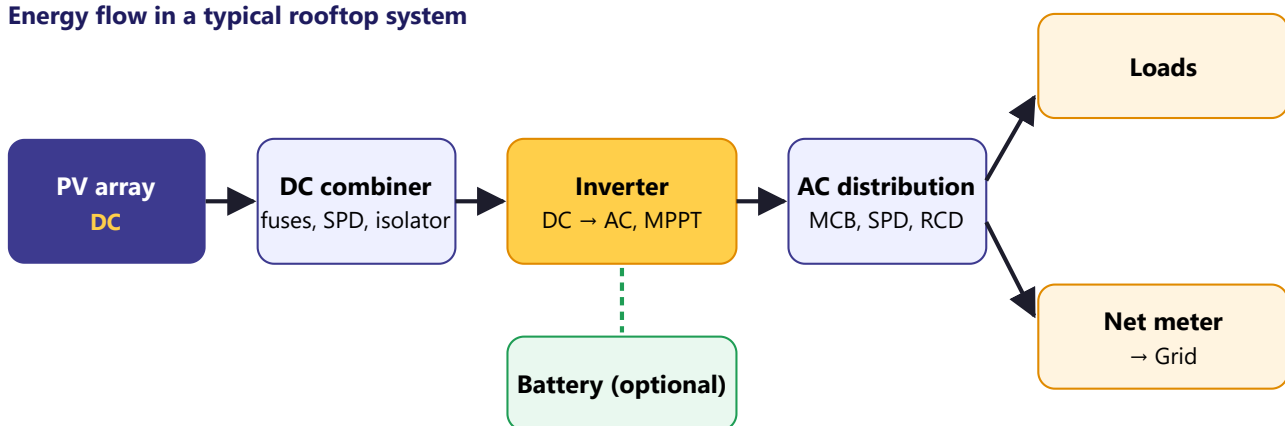


Figure 4.1 — The main components and how energy flows between them.

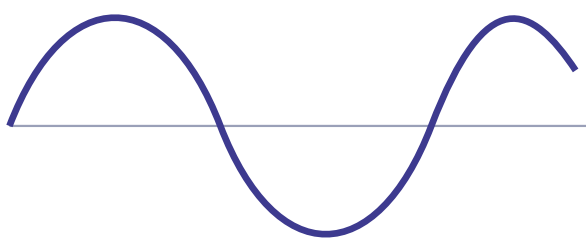
4.2 The inverter — the brain of the system

The **inverter** converts the DC from the panels (or battery) into AC at the voltage and frequency used by homes and the grid — in India, **230 V single-phase or 415 V three-phase, at 50 Hz**. A modern solar inverter does much more than convert:

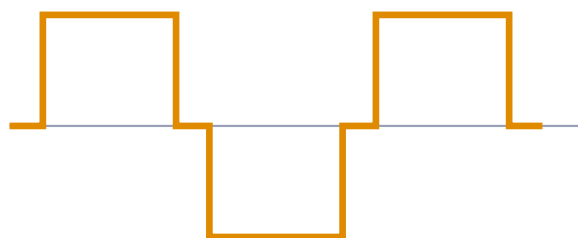
- **MPPT:** keeps the panels at their maximum power point (Module 3).
- **Grid synchronisation:** matches the grid's voltage, frequency and phase exactly before connecting.
- **Anti-islanding protection:** shuts down within a fraction of a second if the grid fails, so that linemen repairing the lines are not electrocuted by solar power fed back into them.
- **Monitoring:** records generation and faults, often sending data to a phone app via Wi-Fi or GSM.
- **Protection:** against over-voltage, over-current, earth faults and over-temperature.

How an inverter makes AC

Inside the inverter, fast electronic switches (MOSFETs or IGBTs) turn on and off thousands of times a second. By varying how long each pulse stays on — a technique called **pulse-width modulation (PWM)** — and then smoothing the result with filters, the inverter produces a clean **pure sine wave**. Cheap inverters sometimes produce a **modified (quasi) sine wave**, which is a stepped approximation; this can make motors and fans hum and run hot, and can damage some electronics. For solar systems, always use pure sine wave inverters.



Pure sine wave — use this



Modified sine wave — avoid

Figure 4.2 — Pure versus modified sine-wave output.

Types of solar inverter

Type	Description	Typical use
String inverter (on-grid)	One inverter handles one or more strings of panels; has 1–4 MPPT inputs	Most home and commercial rooftops, 1–100 kW
Central inverter	Very large units (hundreds of kW to MW)	Utility-scale solar parks
Microinverter	A small inverter behind each panel; AC is produced at the panel	Roofs with shading or multiple orientations; panel-level monitoring
String inverter + optimisers	DC optimisers at each panel do MPPT; a central inverter converts to AC	Partially shaded or complex roofs
Off-grid inverter / PCU	Works with batteries, no grid export; often includes a charge controller (PCU = power conditioning unit)	Remote homes, backup systems
Hybrid inverter	Handles panels, batteries and grid together; can export and give backup	Homes wanting net metering plus power-cut backup

Key inverter specifications

- **Rated AC output power** (kW) — the continuous AC power it can deliver.

- **Maximum DC input power** — many inverters allow 110–150% DC oversizing (more panel kWp than inverter kW). This is called the **DC/AC ratio**.
- **Maximum DC input voltage** — the string's cold-weather V_{oc} must never exceed this.
- **MPPT voltage range** — the string's V_{mp} in hot and cold conditions must stay inside this window.
- **Start-up voltage** — the minimum string voltage needed for the inverter to switch on in the morning.
- **Maximum input current per MPPT** — must be at least the string's I_{sc} (or parallel strings' total).
- **Efficiency** — peak and "European/weighted" efficiency; good inverters reach 97–98.5%.
- **Number of MPPTs** — separate trackers allow two roof faces or different strings.
- **Protection rating (IP65/IP66)** — for outdoor installation.

4.3 Charge controllers

In battery-based systems, a **charge controller** sits between the panels and the battery. It prevents overcharging (which damages batteries and can cause gassing or fire), prevents over-discharge in many designs (low-voltage disconnect), and stops battery current flowing back into the panels at night.

Feature	PWM controller	MPPT controller
How it works	Connects panels to the battery through a fast switch; panel voltage is pulled down to battery voltage	A DC-DC converter runs panels at their MPP and converts the extra voltage into extra current
Efficiency gain	None — energy above battery voltage is wasted	Typically 15–30% more energy, more in cold weather
Panel voltage	Must closely match battery voltage (e.g. "12 V" panels for a 12 V battery)	Can use high-voltage strings — fewer, thinner cables
Cost	Cheap	Higher
Best for	Very small systems (< 200 W), lanterns, street lights	Anything above a few hundred watts

Worked example 4.1 — why MPPT gains energy

A panel has $V_{mp} = 30\text{ V}$ and $I_{mp} = 10\text{ A}$ (300 W). It charges a 12 V battery at 13 V.

PWM: the panel is forced to about 13 V, where its current is close to I_{sc} , say 10.5 A.

Power into battery $\approx 13 \times 10.5 = \mathbf{136.5\text{ W}}$.

MPPT (96% efficient): power = $300 \times 0.96 = 288\text{ W}$; current into battery = $288 \div 13 = \mathbf{22.2\text{ A}}$.

The MPPT controller delivers more than twice the energy in this badly matched case.

Battery charging stages

Controllers charge lead-acid batteries in stages: **bulk** (maximum current until the voltage rises to the absorption level), **absorption** (hold the voltage constant while current tapers off), and **float** (lower maintenance voltage once full). Lithium batteries typically use constant-current then constant-voltage (CC/CV) charging with no float, controlled together with the battery's own management system.

4.4 Batteries

Batteries store energy for use at night or during power cuts. They are the most expensive part of an off-grid system to own over its lifetime, because they wear out and need replacement.

Key battery terms

- **Nominal voltage:** 12 V, 24 V, 48 V (or higher for high-voltage lithium packs).
- **Capacity (Ah):** ampere-hours, at a stated discharge rate — e.g. 150 Ah at C10 means 15 A for 10 hours.
- **Energy (Wh or kWh):** voltage $\times$ capacity. A 12 V 150 Ah battery stores $12 \times 150 = 1,800\text{ Wh} = 1.8\text{ kWh}$.
- **Depth of discharge (DoD):** the percentage of capacity used. Using only 50% of a lead-acid battery each day makes it last much longer than using 80%.
- **State of charge (SoC):** how full the battery is ($100\% - \text{DoD}$).
- **Cycle life:** how many charge–discharge cycles before capacity falls to about 80%; depends strongly on DoD and temperature.
- **C-rate:** charge or discharge current relative to capacity. 0.5C for a 100 Ah battery is 50 A.
- **Round-trip efficiency:** energy out $\div$ energy in. Lead-acid $\approx 75\text{--}85\%$; lithium $\approx 92\text{--}96\%$.

Formula — usable battery energy

$$\text{Usable energy (Wh)} = V \times \text{Ah} \times \text{DoD} \times \eta_{\text{battery}}$$

Battery types compared

Type	Usable DoD	Cycle life (approx.)	Maintenance	Comments
Flooded lead-acid (tubular)	50–70%	1,200–1,800 at 50–80% DoD	Top up distilled water, ventilate	Cheapest per kWh upfront; common in Indian home inverters
Sealed lead-acid (VRLA: AGM / gel)	50%	500–1,200	Maintenance-free	No water topping; sensitive to heat
Lithium iron phosphate (LiFePO ₄ / LFP)	80–95%	3,000–6,000+	None; needs BMS	Light, efficient, long life; lowest cost per cycle; now the preferred choice
Lithium NMC	80–90%	1,500–3,000	None; needs BMS	High energy density (EVs); less thermally stable than LFP

Caution — battery safety

- Lead-acid batteries release hydrogen while charging — keep them in a ventilated space, away from sparks and flames.
- Battery short circuits deliver thousands of amps and can melt tools and cause burns. Use insulated tools and always install a **DC fuse or DC breaker** close to the battery.
- Lithium batteries must have a **battery management system (BMS)** that protects against over-charge, over-discharge, over-current and temperature extremes.
- Heat shortens every battery's life. Every 10 °C above 25 °C roughly halves lead-acid life.

Series and parallel battery connections

Connecting batteries in **series** adds their voltages (two 12 V 150 Ah → 24 V 150 Ah). Connecting in **parallel** adds their capacities (two 12 V 150 Ah → 12 V 300 Ah). Both give the same total energy (3.6 kWh). Always use identical batteries of the same age in a bank, and avoid many parallel strings, which tend to share current unequally.

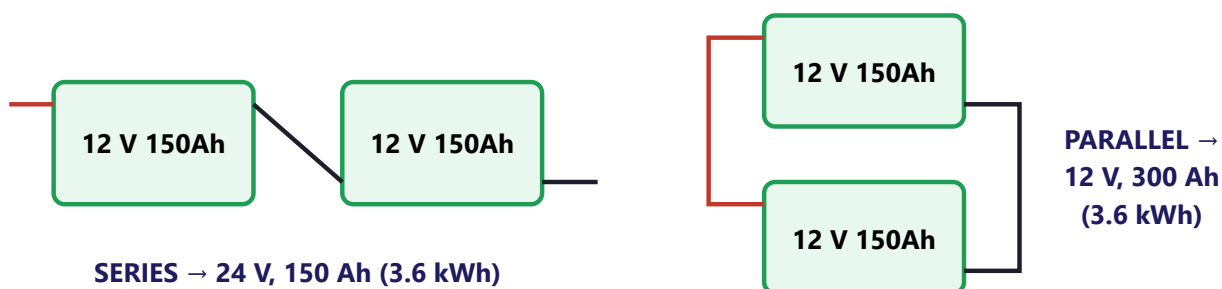


Figure 4.3 — Series connection adds voltage; parallel connection adds capacity.

4.5 Balance-of-system (BOS) components

Component	Purpose	Key points
Mounting structure	Holds panels at the right tilt and orientation	Hot-dip galvanised steel ($\geq 80 \mu\text{m}$ zinc) or anodised aluminium; designed for local wind speed (up to $\sim 150\text{--}170 \text{ km/h}$ in cyclone zones)
DC cables	Carry DC from panels to inverter	Solar-grade, UV-resistant, double-insulated copper, typically $4\text{--}6 \text{ mm}^2$, rated $1.1\text{--}1.5 \text{ kV DC}$
MC4 connectors	Weatherproof plug-and-socket connection between panels	Must be the same brand/type on both sides; crimp with the correct tool
DC combiner box / ACDB–DCDB	Combines strings; houses protection devices	String fuses, DC isolator, surge protection device (SPD); IP65 enclosure
DC isolator	Safely disconnects the array for maintenance	Rated for DC voltage and current (AC switches are not safe on DC)
SPD (surge protection)	Diverts voltage surges from lightning to earth	Type 2 on DC and AC sides; separate DC and AC ratings
AC distribution box	Connects inverter output to the building	MCB, RCD/RCCB, SPD, and sometimes an energy meter
Earthing system	Safety path for fault currents and lightning	Separate pits for DC, AC and lightning arrester; earth resistance ideally below 5Ω
Lightning arrester	Protects against direct strikes	Mounted above the highest point of the array, with its own earth pit
Net / bidirectional meter	Measures import and export of energy	Installed by the DISCOM for grid-tied systems

Practical tip — do not skimp on BOS

Most real-world solar failures are not panel failures. They are loose MC4 connectors, undersized cables, rusting structures, water inside junction boxes, and poor earthing. Quality BOS work is what makes a system last 25 years.

4.6 Choosing components — a quick guide

1. **Panels:** BIS/ALMM listed, reputable brand, good temperature coefficient, 25–30-year warranty.
2. **Inverter:** match type (on-grid / off-grid / hybrid) to the need; size by AC load or DISCOM limit; check voltage window against string design; warranty 5–10 years.
3. **Battery:** LFP for long life and deep daily cycling; tubular lead-acid if budget is tight and use is mostly backup.
4. **Charge controller:** MPPT for anything above a few hundred watts.
5. **BOS:** solar-grade cables, genuine MC4 connectors, DC-rated isolators and SPDs, proper earthing.

Module 4 — Summary

- BOS = everything except the panels.
- Inverters convert DC to 230/415 V AC at 50 Hz, perform MPPT and anti-islanding. Use pure sine wave.
- Inverter types: string, central, micro, optimiser-based, off-grid (PCU), hybrid.
- MPPT controllers harvest 15–30% more energy than PWM controllers.
- Battery energy = $V \times Ah$; usable = $\times DoD \times efficiency$. LFP: long life, 80–95% DoD.
- Series adds voltage; parallel adds capacity.
- Protection: DC fuses, DC isolators, SPDs, RCD, earthing, lightning arrester.

Practice questions — Module 4

1. List five functions of a grid-tied solar inverter.
2. What is anti-islanding, and why is it essential?
3. Compare PWM and MPPT charge controllers in a table.
4. How much energy is stored in a 24 V, 200 Ah battery bank? How much is usable at 50% DoD and 85% efficiency? (*Ans: 4.8 kWh; 2.04 kWh*)
5. Four 12 V 100 Ah batteries are connected as two series pairs in parallel. What are the bank voltage, capacity and energy? (*Ans: 24 V, 200 Ah, 4.8 kWh*)
6. Why is LFP preferred over lead-acid for daily cycling?
7. Name six balance-of-system components and state the purpose of each.
8. Why must an isolator used on the DC side be DC-rated?

On-Grid vs. Off-Grid vs. Hybrid Systems

The three ways to build a solar system, how energy flows in each, and how to pick the right one for a customer.

5.1 Why there are three system types

Every solar system must answer one question: **what happens when the panels are not producing enough?** At night, on cloudy days, or when the load is larger than the solar output, energy must come from somewhere else. And when the panels produce more than the load needs, the extra energy must go somewhere. The three system types answer these questions differently:

- **On-grid (grid-tied):** the utility grid acts like a giant battery — surplus goes to the grid; shortfall comes from the grid.
- **Off-grid (stand-alone):** batteries store surplus and supply shortfall; there is no grid connection.
- **Hybrid:** both batteries and the grid are used, giving the benefits of each.

5.2 On-grid (grid-tied) systems

An on-grid system consists of panels, a grid-tied inverter, protection devices and a bidirectional (net) meter. It has no batteries. During the day, solar energy supplies the building's loads first. If there is extra, it flows out through the meter into the grid. At night, or when solar is not enough, the building draws from the grid as usual.

ON-GRID SYSTEM

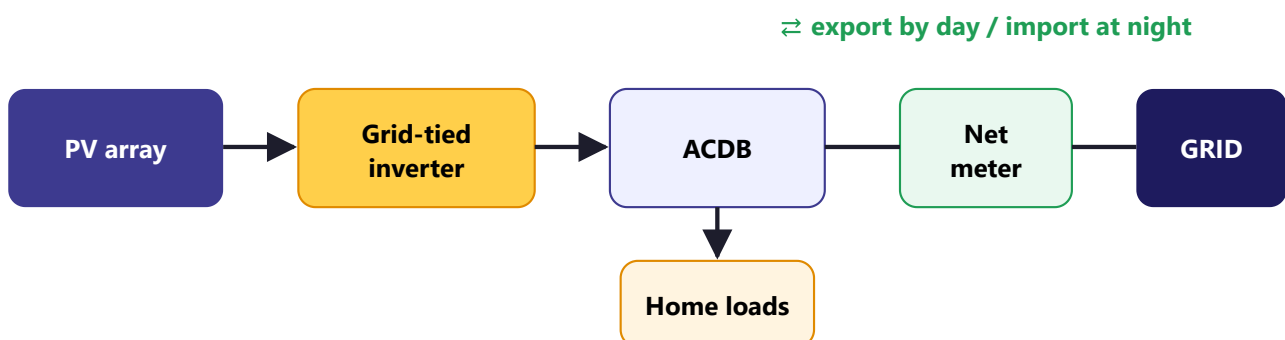


Figure 5.1 — On-grid system: the grid absorbs surplus solar energy and supplies any shortfall.

Net metering and gross metering

Under **net metering**, the bidirectional meter records both the units imported from the grid and the units exported to it. At the end of the billing cycle, the consumer pays only for the **net** units (import – export). If exports exceed imports, the surplus is carried forward or, at the end of the settlement year, paid for at a rate set by the state regulator. Net metering is the most common arrangement for Indian homes.

Under **gross metering**, all solar generation is sold to the DISCOM at a fixed tariff, and all consumption is bought at the normal tariff. Some states also use **net billing**, where exports and imports are valued at different rates. The exact rules — including maximum system size (often limited to the sanctioned load) — are set by each State Electricity Regulatory Commission.

Worked example 5.1 — a net-metering bill

In one month, a home imports 220 units from the grid at night and exports 310 units during the day. Under net metering:

Net = $220 - 310 = -90$ units. The home pays only the fixed charges, and **90 units are carried forward** as credit to the next month.

If instead it imported 350 units and exported 310, it would pay for only $350 - 310 = 40$ units.

Advantages and limitations of on-grid systems

Advantages

- Lowest cost — no batteries (₹45,000–65,000 per kW range for homes, before subsidy; varies)
- Highest efficiency; all solar energy is used or exported
- Very little maintenance
- Eligible for government rooftop subsidies
- Fastest payback (often 4–6 years)

Limitations

- **No power during a grid failure** — anti-islanding shuts the inverter off, even in bright sun
- Depends on DISCOM approval and net-meter installation
- Size may be capped by sanctioned load or transformer capacity
- Grid voltage problems can trip the inverter

Key idea — the most common customer surprise

"I have solar, so why did my lights go off in the power cut?" An on-grid inverter **must** shut down when the grid fails, to protect line workers. If the customer needs backup, they need a hybrid or off-grid system.

5.3 Off-grid (stand-alone) systems

An off-grid system has no connection to the utility grid. It includes panels, a charge controller, a battery bank and an off-grid inverter (often combined into one power conditioning unit). During the day, solar energy runs the loads and charges the batteries. At night, the batteries supply everything. A diesel generator is sometimes added as a backup for long cloudy spells.

OFF-GRID SYSTEM

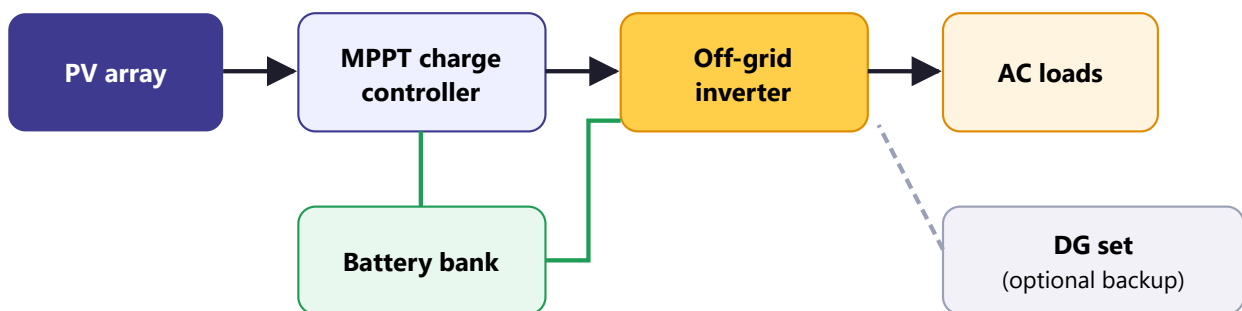


Figure 5.2 — Off-grid system: batteries store daytime surplus for night-time use.

Designing for "days of autonomy"

Because an off-grid system has nowhere else to get energy, it must be designed for bad weather. **Days of autonomy** is the number of days the battery can supply the load with no sun at all. Homes typically use 1–2 days; critical loads such as telecom towers or medical fridges may use 3–5 days. More autonomy means a bigger, more expensive battery. Module 6 shows the calculation.

Advantages

- Works where there is no grid — villages, farms, islands, hilltop sites
- Complete independence from power cuts
- No DISCOM paperwork

Limitations

- Most expensive per unit of energy (batteries)
- Batteries need replacement (lead-acid: 3–5 years; LFP: 8–12+ years)
- Surplus solar is wasted once batteries are full
- Careful load management needed in cloudy weather

5.4 Hybrid systems

A hybrid system connects panels, batteries and the grid through a **hybrid inverter**. It can work in several modes, which the user or installer can set:

- **Self-consumption mode:** solar supplies loads first, then charges the battery, then exports any surplus. At night, the battery supplies loads before the grid is used.
- **Backup (UPS) priority:** the battery is kept full and used only during power cuts. When the grid fails, the inverter isolates the house from the grid and runs the **backup loads** from solar and battery — safely, without back-feeding the grid.
- **Time-of-use mode:** the battery is charged when electricity is cheap and discharged during expensive peak hours (useful where time-of-day tariffs apply).

HYBRID SYSTEM

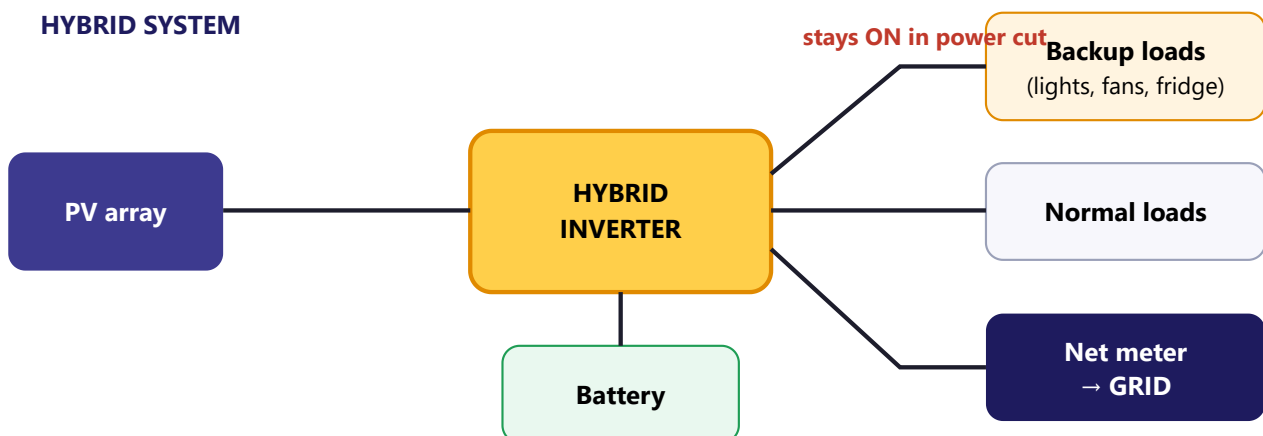


Figure 5.3 — Hybrid system: grid export plus battery backup for selected loads.

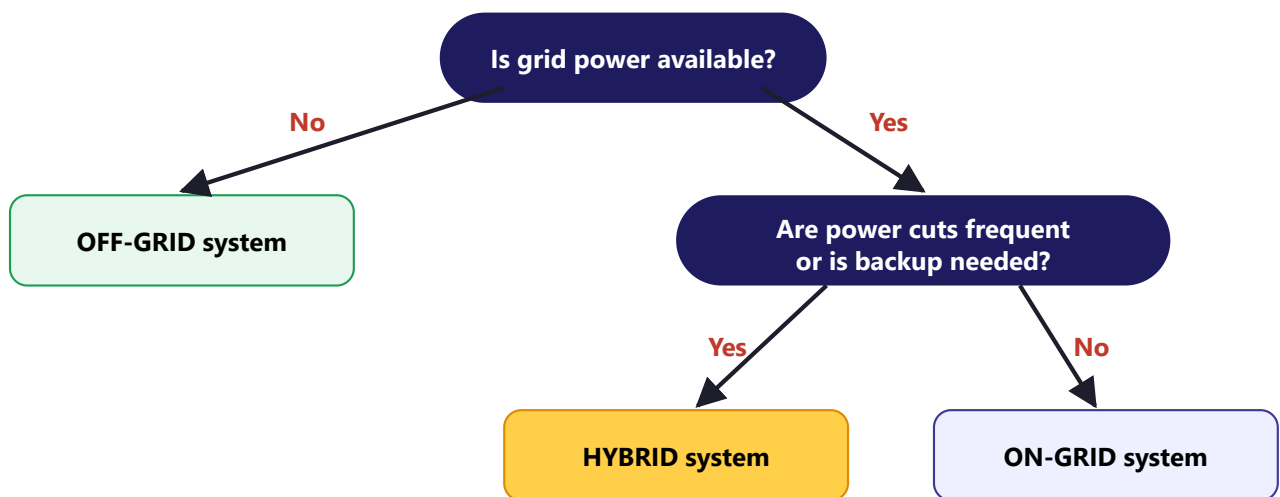
Practical tip — backup loads

Most hybrid systems do not back up the whole house. The installer creates a separate "backup" distribution board for essential loads (lights, fans, fridge, Wi-Fi, a few sockets). Heavy loads such as ACs, geysers and water pumps stay on the normal board and switch off in a power cut unless the battery and inverter are sized for them.

5.5 Side-by-side comparison

Feature	On-grid	Off-grid	Hybrid
Grid connection	Yes	No	Yes
Batteries	No	Yes (essential)	Yes
Power during grid failure	No	Yes	Yes (backup loads)
Surplus energy	Exported to grid	Wasted once battery is full	Stored, then exported
Relative cost per kW	Lowest	Highest	Medium-high
Maintenance	Very low	Battery care needed	Battery care needed
Subsidy / net metering	Usually eligible	Not for net metering	Usually eligible (check local rules)
Best for	Cities with reliable grid; bill saving	No grid; remote sites	Frequent power cuts + bill saving

5.6 Choosing the right system — decision guide



Then check: budget, roof area, DISCOM rules, and which loads need backup.

Figure 5.4 — A simple decision tree for choosing a system type.

5.7 Case studies

Case A — city apartment owner, Bengaluru

Reliable grid, bill ₹4,000/month, sanctioned load 5 kW, rooftop available. Goal: reduce bill. **Choice: 4-kW on-grid system with net metering.** Lowest cost and fastest payback; the rare power cut is handled by the existing small inverter-battery.

Case B — farmhouse in a forest area, no grid within 3 km

Needs lights, fans, a fridge and a TV. **Choice: off-grid system with LFP battery and 2 days' autonomy.** Extending the grid would cost far more.

Case C — small clinic in a town with 3–4 hours of daily power cuts

Needs uninterrupted power for a vaccine fridge, lights and a computer, and wants lower bills. **Choice: hybrid system** with backup board for critical loads and net metering for surplus.

Case D — farmer needing irrigation

Pump needed only in daytime. **Choice: solar water pump with a VFD/pump controller** (a special off-grid system without batteries — water is "stored" in a tank or field instead). Supported under PM-KUSUM.

5.8 Special system types

- **Solar water pumping:** panels drive a DC or AC pump through a pump controller with MPPT. No battery; the pump runs faster in stronger sun.
- **Solar street lights:** a small panel, battery (usually LFP), LED lamp and controller on one pole; dusk-to-dawn operation with motion sensing.
- **Mini-grids and micro-grids:** a shared solar-plus-battery plant supplying a whole village through its own local network.
- **Floating solar:** panels on floats on reservoirs; water cooling improves efficiency and reduces evaporation.
- **Agrivoltaics:** raised panels over crops, sharing land between farming and power generation.

Module 5 — Summary

- On-grid: no batteries; net metering; cheapest; **no power in grid failure.**
- Off-grid: batteries essential; designed with days of autonomy; most expensive per unit.
- Hybrid: grid + battery; backup for selected loads; export surplus.
- Net metering bills only (import – export); rules vary by state.
- Choose by grid availability, need for backup, budget and local rules.

Practice questions — Module 5

1. Draw block diagrams of on-grid, off-grid and hybrid systems.
2. Explain why an on-grid system does not supply power during a power cut.
3. Differentiate between net metering and gross metering.
4. A home imports 180 units and exports 240 units in a month under net metering.
What does it pay for? (*Ans: only fixed charges; 60 units credit*)
5. What is meant by "days of autonomy"? Why is it important in off-grid design?
6. List three operating modes of a hybrid inverter.
7. Recommend a system type for: (a) a hostel in a city with reliable power; (b) a mobile tower on a hill; (c) a shop with daily 2-hour power cuts. Justify each.
8. Why don't most solar pumps need batteries?

System Sizing and Load Calculation

Step-by-step methods to work out energy demand and size the panels, inverter, battery and charge controller — with fully worked examples for on-grid, off-grid and hybrid systems.

6.1 The sizing process at a glance

Sizing means choosing the capacity of every component so that the system meets the customer's needs reliably, without wasting money on oversized equipment. The process always follows the same order:

1. **Load assessment** — how much power (W) and energy (Wh/day) is needed?
2. **Solar resource** — how many peak sun hours at the site?
3. **Array sizing** — how many kWp of panels?
4. **Inverter sizing** — what AC power rating?
5. **Battery sizing** (off-grid/hybrid) — how many kWh / Ah?
6. **Charge controller sizing** (off-grid) — what current rating?
7. **String design, cables and protection** — covered in Module 8.



Figure 6.1 — The sizing sequence.

6.2 Step 1 — Load assessment

For grid-connected homes, the simplest and most accurate method is to read the **electricity bills for the last 12 months**. For off-grid systems (and to plan backup loads), we build a **load table** listing every appliance, its power, quantity and hours of use.

Typical appliance ratings

Appliance	Typical power (W)	Appliance	Typical power (W)
LED bulb	9–12	Refrigerator (190–250 L)	100–150 (runs ~8–10 h/day)

LED tube light	18–22	Washing machine	400–500
Ceiling fan (normal / BLDC)	70 / 28–35	Water pump (1 HP)	750 (motor) — surge 3×
LED TV (32–43 inch)	40–80	1.5-ton inverter AC	1,200–1,600
Laptop / desktop PC	45 / 150	Electric iron	1,000
Wi-Fi router	10	Microwave oven	1,200
Mobile charger	10	Geyser (water heater)	2,000

Caution — surge (starting) power

Motors in pumps, fridges, ACs and washing machines draw a **starting current** of 3–7 times their running current for a fraction of a second. The inverter must be able to supply this surge. Always check the inverter's surge rating when motors are on its output.

Worked example 6.1 — building a load table (off-grid home)

Appliance	Qty	Power (W)	Total W	Hours/day	Wh/day
LED bulb	6	10	60	6	360
BLDC fan	3	30	90	10	900
LED TV	1	60	60	4	240
Refrigerator	1	120	120	9 (compressor running)	1,080
Wi-Fi router	1	10	10	24	240
Mobile charging	3	10	30	2	60
Laptop	1	50	50	4	200
Totals			420 W		3,080 Wh/day

Connected load = 420 W. Daily energy = **3.08 kWh/day**.

6.3 Step 2 — Solar resource

Take the site's average peak sun hours (Module 2). For grid-tied systems, use the **annual average**. For off-grid systems that must work every day of the year, designers often use the value for the **worst month** (usually a monsoon or winter month), or the annual average with extra days of autonomy.

6.4 Step 3 — Sizing the PV array

Formula — array size

$$P_{\text{array}} (\text{kWp}) = E_{\text{daily}} (\text{kWh/day}) \div (\text{PSH} \times \text{PR})$$

For off-grid systems, divide E_{daily} also by the battery round-trip efficiency, because energy passing through the battery loses some on the way.

Understanding the performance ratio

Loss source	Typical loss
Temperature (hot climate)	7–12%
Dust / soiling	2–5%
DC cable losses	1–2%
Module mismatch and tolerance	1–2%
Inverter losses	2–4%
AC cable and transformer losses	1–2%
Shading / low-light / availability	1–3%
Overall PR	≈ 0.75–0.80

Worked example 6.2 — on-grid home from bills

A home in Bhubaneswar uses 4,380 units a year. PSH = 4.8, PR = 0.77. Find the system size and number of 550-Wp panels.

Daily energy: $4,380 \div 365 = 12$ kWh/day.

Array: $12 \div (4.8 \times 0.77) = 12 \div 3.696 = \mathbf{3.25 \text{ kWp}}$.

Panels: $3,250 \div 550 = 5.9 \rightarrow \mathbf{6 \text{ panels}}$ (3.3 kWp).

Check: $3.3 \times 4.8 \times 0.77 \times 365 = \mathbf{4,452 \text{ kWh/year}}$ ✓ (covers the need).

Practical tip — check the limits

Before finalising, check: (1) shade-free roof area ($3.3 \text{ kWp} \times \sim 7 \text{ m}^2 \approx 23 \text{ m}^2$); (2) DISCOM limit (often $\leq$ sanctioned load); (3) subsidy slabs; (4) budget.

6.5 Step 4 — Sizing the inverter

On-grid inverter

The inverter is sized to the array. Because panels rarely produce their full STC power in real conditions (heat, dust, angle), the inverter's AC rating is usually a little smaller than the array's DC rating. A **DC/AC ratio** of about **1.0 to 1.25** is typical.

Formula — DC/AC ratio

$$\text{DC/AC ratio} = \text{Array kWp} \div \text{Inverter AC kW}$$

For the 3.3-kWp array in Example 6.2, a 3-kW inverter gives a ratio of 1.1 — a good match.

Off-grid / hybrid inverter

Here the inverter must supply all the loads that may run **at the same time**, plus a safety margin, plus the surge of motors.

Formula — off-grid inverter rating

$$\text{Inverter (VA)} \geq (\text{Simultaneous load W} \div \text{power factor}) \times 1.25$$

Use a power factor of about 0.8 when the load includes motors and electronics. Also check: surge rating $\geq$ largest motor's starting power + other running loads.

Worked example 6.3 — off-grid inverter

For the home in Example 6.1, all loads (420 W) might run together.

Inverter VA $\geq (420 \div 0.8) \times 1.25 = \mathbf{656 \text{ VA}}$. The fridge compressor can surge to ~600 W for an instant, so choose an inverter of **1 kVA** with a good surge rating. A 24 V or 48 V system is preferred over 12 V at this size to keep battery currents manageable.

6.6 Step 5 — Sizing the battery

Formula — battery capacity

$$\text{Battery energy (Wh)} = (E_{\text{daily}} \times \text{Days of autonomy}) \div (\text{DoD} \times \eta_{\text{inverter}} \times \eta_{\text{temp}})$$

$$\text{Battery capacity (Ah)} = \text{Battery energy (Wh)} \div \text{System voltage (V)}$$

$\eta_{\text{inverter}} \approx 0.90\text{--}0.95$. η_{temp} (temperature derating) ≈ 0.9 for lead-acid in heat; ≈ 1.0 for LFP in normal conditions.

Worked example 6.4 — lead-acid battery bank

Load = 3,080 Wh/day, 2 days of autonomy, tubular lead-acid at 50% DoD, inverter efficiency 0.9, temperature factor 0.9, system voltage 24 V.

$$\text{Energy} = (3,080 \times 2) \div (0.5 \times 0.9 \times 0.9) = 6,160 \div 0.405 = \mathbf{15,210 \text{ Wh.}}$$

$$\text{Capacity} = 15,210 \div 24 = \mathbf{634 \text{ Ah at 24 V.}}$$

Selection: 12 V 150 Ah batteries $\rightarrow$ need $634 \div 150 = 4.2 \rightarrow$ round up. Two in series make 24 V 150 Ah; we need about 4 such pairs in parallel (600 Ah) — slightly short — or better, use **2 V cells**: twelve 2 V 650 Ah tubular cells in series = 24 V 650 Ah ✓ (one string, no parallel issues).

Worked example 6.5 — the same home with LFP

LFP at 90% DoD, inverter 0.93, temperature factor 1.0, 48 V system.

$$\text{Energy} = 6,160 \div (0.9 \times 0.93 \times 1.0) = 6,160 \div 0.837 = \mathbf{7,360 \text{ Wh.}}$$

$$\text{Capacity} = 7,360 \div 48 = \mathbf{153 \text{ Ah at 48 V}} \rightarrow \text{a standard } \mathbf{48 \text{ V } 150\text{--}160 \text{ Ah } (\approx 7.5 \text{ kWh})}$$

LFP pack. Less than half the nominal capacity of the lead-acid bank, much lighter, and it will last many more cycles.

6.7 Off-grid array size including battery losses

Worked example 6.6 — off-grid array

Load 3,080 Wh/day; worst-month PSH = 4.2; PR (for array and controller) = 0.75; battery efficiency (lead-acid) = 0.85.

Energy needed from array = $3,080 \div 0.85 = 3,624$ Wh/day.

Array = $3,624 \div (4.2 \times 0.75) = 3,624 \div 3.15 = \mathbf{1,150\text{ Wp}}$.

With 550-Wp panels: $1,150 \div 550 = 2.1 \rightarrow \mathbf{3\text{ panels}}$ (1,650 Wp). The extra margin helps recharge the battery after cloudy days. (With LFP at 0.95 efficiency the array would be about 1,030 Wp — two 550-Wp panels would be just enough, but three give a healthier margin.)

6.8 Step 6 — Sizing the charge controller

Formula — charge controller current

$$\text{PWM: } I_{\text{controller}} \geq 1.25 \times I_{\text{sc}} \times N_{\text{parallel strings}}$$

$$\text{MPPT: } I_{\text{output}} \geq (P_{\text{array}} \div V_{\text{battery}}) \times 1.25$$

For MPPT also check that the array's cold V_{oc} is below the controller's maximum PV input voltage.

Worked example 6.7 — MPPT controller

Array = 1,650 Wp, battery = 24 V.

$I = (1,650 \div 24) \times 1.25 = 68.75 \times 1.25 = \mathbf{86\text{ A}} \rightarrow$ choose a **24 V, 100 A MPPT controller** (or an off-grid PCU with a built-in MPPT of that rating).

Voltage check: three 550-Wp panels in series have $V_{\text{oc}} \approx 3 \times 49.6 = 148.8$ V at STC; at 5 °C $\approx 3 \times 52.3 = 157$ V. The controller's max PV input must exceed this (e.g. 200 V or 250 V models).

6.9 Hybrid system sizing

A hybrid system is sized in two parts: the **array** like an on-grid system (to cover the bill) and the **battery and inverter** like an off-grid system — but only for the backup loads and the backup duration needed.

Worked example 6.8 — hybrid system for a clinic

Annual use: 5,475 kWh (15 kWh/day). PSH = 5.0; PR = 0.77. Backup loads: vaccine fridge 150 W, lights 100 W, fans 150 W, computer 150 W = 550 W for up to 4 hours of power cut per day.

Array: $15 \div (5.0 \times 0.77) = 3.9 \text{ kWp}$ → eight 550-Wp panels = 4.4 kWp.

Backup energy: $550 \text{ W} \times 4 \text{ h} = 2,200 \text{ Wh}$.

Battery (LFP, 90% DoD, inverter 0.93): $2,200 \div (0.9 \times 0.93) = 2,628 \text{ Wh}$ → a **5 kWh LFP battery** (gives margin and room to grow).

Hybrid inverter: must handle 4.4 kWp of PV, and backup output of $(550 \div 0.8) \times 1.25 = 860 \text{ VA}$ — so a **5-kW hybrid inverter** suits the PV side comfortably.

6.10 Financial sizing — payback and savings

Customers usually ask, "How soon will I recover my money?" A simple payback estimate:

Formula — simple payback

$$\text{Payback (years)} = \text{Net system cost} \div \text{Annual savings}$$

$$\text{Annual savings} = \text{Annual solar energy used or credited (kWh)} \times \text{Tariff (₹/kWh)}$$

Worked example 6.9 — payback

A 3-kWp on-grid system costs ₹1,80,000. After a subsidy of ₹78,000 the net cost is ₹1,02,000. It produces 4,000 kWh/year, all credited under net metering, at an average tariff of ₹6.5/kWh.

Annual savings = $4,000 \times 6.5 = ₹26,000$. Payback = $1,02,000 \div 26,000 = 3.9 \text{ years}$. Over 25 years (allowing for ~0.5%/year degradation and rising tariffs), total savings typically exceed ₹6–7 lakh.

(Prices and subsidy values here are only illustrative — always use current local figures.)

6.11 Common sizing mistakes

- Confusing kW (power) and kWh (energy) — e.g. sizing a battery in kW.
- Using STC panel power without the performance ratio — overestimating generation by 20–25%.

- Forgetting motor surge currents — inverter trips when the pump or fridge starts.
- Sizing lead-acid batteries at 100% DoD — batteries die within a year.
- Choosing a 12 V system for kilowatt loads — huge currents, thick cables, big losses.
- Ignoring the worst month for off-grid systems — blackouts in the monsoon.
- Not checking cold-morning V_{oc} against the inverter/controller maximum voltage.

Module 6 — Summary

- Array kWp = Daily kWh $\div$ (PSH $\times$ PR); off-grid: also $\div$ battery efficiency.
- On-grid inverter: DC/AC ratio $\approx$ 1.0–1.25.
- Off-grid inverter VA $\geq$ (simultaneous W $\div$ 0.8) $\times$ 1.25, plus surge check.
- Battery Wh = (Daily Wh $\times$ autonomy) $\div$ (DoD $\times \eta_{inv} \times \eta_{temp}$); Ah = Wh $\div$ V.
- MPPT current $\geq$ (Array W $\div$ Battery V) $\times$ 1.25.
- Payback = Net cost $\div$ Annual savings.

Practice questions — Module 6

1. A home uses 360 units/month. PSH = 5.2, PR = 0.78. Find the array size. (Ans: $\approx$ 2.96 kWp $\rightarrow$ 3 kWp)
2. How many 540-Wp panels are needed for a 5-kWp system? (Ans: 10 panels = 5.4 kWp)
3. A 6.6-kWp array is connected to a 6-kW inverter. What is the DC/AC ratio? (Ans: 1.1)
4. Loads of 800 W can run together. Size an off-grid inverter. (Ans: $\geq$ 1,250 VA $\rightarrow$ 1.5 kVA)
5. Daily load = 2,000 Wh, autonomy = 1.5 days, LFP DoD = 0.9, η_{inv} = 0.93, 24 V. Find battery Ah. (Ans: $\approx$ 149 Ah $\rightarrow$ 24 V 150 Ah)
6. A 2-kWp array charges a 48 V battery. Size the MPPT controller current. (Ans: $\approx$ 52 A $\rightarrow$ 60 A)
7. A system costs ₹1,20,000 net and saves ₹24,000 a year. Find the simple payback. (Ans: 5 years)
8. Prepare a load table for your own home and estimate the daily energy use.

Solar Installation Practices and Safety

How a rooftop system is installed from start to finish — structure, mounting, orientation and tilt — and the safety rules that must never be broken on site.

7.1 The installation workflow

A professional installation follows a planned sequence. Skipping steps or doing them out of order causes most of the problems that appear later — leaks, loose panels, wiring faults and safety hazards.

1. **Final design and approvals** — layout drawing, single-line diagram (SLD), DISCOM application for net metering, society/landlord permission.
2. **Material check** — verify every item against the bill of materials; check panel serial numbers, datasheets and inverter model.
3. **Safety briefing** — hazards on this site, PPE, fall protection, emergency contacts.
4. **Marking out** — mark the array outline, leg positions and cable routes on the roof.
5. **Structure installation** — foundations or anchors, columns, rafters and purlins; check level, tilt and alignment.
6. **Module mounting** — fix panels with the correct clamps and torque.
7. **DC wiring** — string connections with MC4 connectors; cable management; route to the DCDB.
8. **Earthing and lightning protection** — earth pits, earthing conductors, lightning arrester.
9. **Inverter and AC wiring** — mount inverter, connect ACDB and main distribution board.
10. **Testing and commissioning** — polarity, V_{OC} , I_{SC} , insulation resistance, earth resistance, inverter start-up.
11. **Handover** — explain operation to the customer, provide documents, warranty cards and maintenance schedule.

7.2 Types of mounting structure

Roof / site type	Mounting method	Key points
Flat RCC roof	Tilted structure with legs fixed by anchor bolts or on concrete blocks (ballast)	Most common in India; elevated structures (2–3 m) allow roof use below; waterproof around anchors

Metal sheet roof (industrial)	Short rails clamped to the sheet seams (standing seam) or fixed to purlins	Check purlin strength; use EPDM washers to prevent leaks; avoid drilling where possible
Sloped tiled roof	Roof hooks under tiles, attached to rafters, with rails on top	Follow roof slope; replace broken tiles
Ground mount	Piles or concrete foundations with fixed-tilt tables	Soil test for large plants; fencing and drainage
Single-axis tracker	Tables rotate east–west following the sun	10–20% more energy; more cost and maintenance; used in large plants
Carport / elevated	Tall structure over parking or terraces	Provides shade and power; needs careful wind design

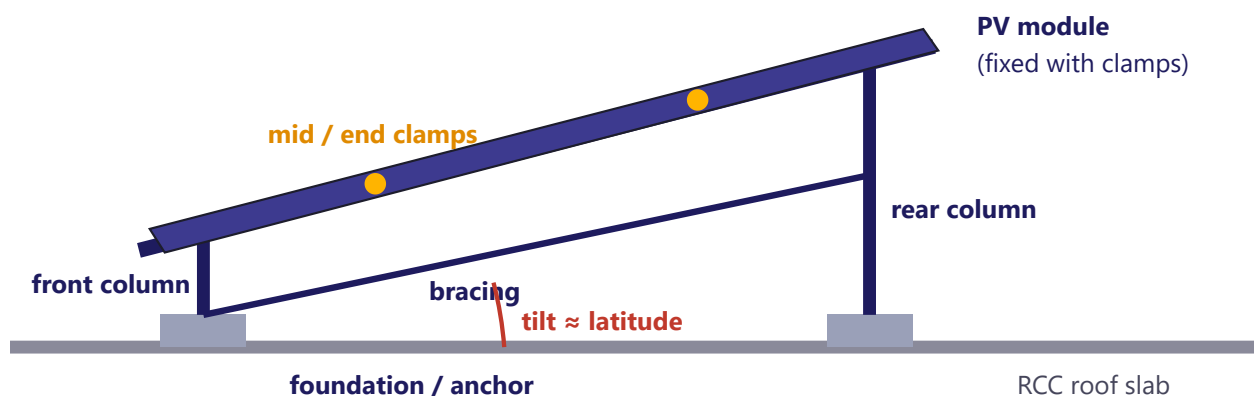


Figure 7.1 — Typical fixed-tilt structure on a flat RCC roof (side view, south to the left).

7.3 Structural design basics

A rooftop array behaves like a sail. During storms, wind pushes on the panels and, more dangerously, tries to **lift** them (uplift). In coastal Odisha, Andhra Pradesh, Gujarat and Tamil Nadu, cyclone winds can exceed 150–200 km/h. The structure must be designed for the **basic wind speed** of the area given in the Indian wind-load standard (IS 875 Part 3).

- **Material:** hot-dip galvanised (HDG) mild steel with adequate zinc coating, or anodised aluminium. Use stainless steel (SS 304) fasteners to avoid rust.
- **Dead load:** modules plus structure weigh about 15–25 kg/m². Check that old roofs can carry this.
- **Anchoring:** chemical or mechanical anchor bolts into sound concrete; or ballast blocks heavy enough to resist uplift. Never anchor into a thin screed layer only.

- **Waterproofing:** seal every roof penetration; apply waterproof coating around anchor points.
- **Ground clearance:** keep the lower edge at least 300–500 mm above the roof for airflow (cooler panels) and cleaning; higher for walkable elevated structures.
- **Access paths:** leave walkways (about 600 mm) for cleaning and maintenance, and clear edges for fire-fighter access.

7.4 Mounting modules correctly

- Handle modules by the frame with two people; never lift by the cables or junction box; never stand, sit or walk on modules.
- Keep modules in their packaging until mounting; store them on edge, not flat under weight.
- Use clamps only in the **clamping zones** shown in the manufacturer's installation manual. Clamping elsewhere voids the warranty and can crack cells under wind load.
- Tighten bolts to the specified **torque** (often 12–20 N·m for clamps) with a torque wrench — too loose and panels fly; too tight and frames deform.
- Leave a small gap (about 10–20 mm) between modules for thermal expansion.
- Keep the array rows straight and level — it also looks professional.
- Check that no module is cracked or scratched; photograph serial numbers for records.

Caution — micro-cracks

Cells are only about 0.15–0.2 mm thick. Dropping, twisting, standing on or over-tightening a panel can create invisible **micro-cracks**. They may not show on day one but grow over months, causing hot spots and power loss. Handle panels like glass — because they are.

7.5 Orientation and tilt on site

Module 2 explained the theory: face true south, tilt close to latitude. On site:

- Use a compass app or satellite map to find south; mark a reference line on the roof.
- Check tilt with a digital inclinometer or angle-finder app on the rafter.
- If the building is not aligned north–south, a deviation of up to about 20–30° from south causes only a small loss; it is often better to follow the building edge for a neater, stronger layout.

- On sloped roofs, panels usually lie flush with the roof slope; accept the roof's orientation and tilt unless the loss is large.
- For east-west layouts (common on industrial sheds), expect a flatter daily generation curve and around 5–15% less energy than south-facing.

7.6 Hazards on a solar installation site

Hazard	Cause	Control measures
Falls from height	Working near roof edges, skylights, fragile sheets, ladders	Guardrails or parapets ≥ 1 m; full-body harness with anchor; never step on fragile roofing; secure ladders at 1:4 angle, extending 1 m above landing
Electric shock (DC)	Panels are live whenever light falls on them — they cannot be "switched off"	Cover panels with opaque sheet or work at dawn/dusk; keep strings open (disconnected) until final connection; use insulated tools and gloves; never disconnect MC4s under load
Electric shock (AC)	Grid and inverter output	Isolate and lock out the supply (LOTO); test before touch
DC arcs and fire	Loose connections, damaged cables, mismatched connectors, pulling connectors under load	Proper crimping; matching MC4 brands; DC-rated isolators; open the DC isolator before disconnecting
Battery hazards	Short circuits, hydrogen gas, acid, heavy weight	Insulated tools; remove metal jewellery; ventilation; eye protection; lifting aids
Heat stress and sunburn	Working all day on hot roofs	Water, shade breaks, early-morning schedules, sun protection
Manual handling	Carrying 25–30 kg panels up stairs	Two-person lifts; rope and pulley; correct posture
Cuts and falling objects	Sharp metal edges, dropped tools	Gloves; helmets; tool lanyards; barricade the area below
Weather	Wind gusts catching panels; lightning; rain making roofs slippery	Stop work in strong wind or lightning; never carry panels in gusty wind

Key idea — PV panels are always live in daylight

A string of 10 panels in sunlight produces about 400–500 V DC — enough to kill. Unlike AC, DC does not pass through zero, so a DC arc keeps burning once struck. Treat every panel and DC cable as live.

7.7 Personal protective equipment (PPE)



Safety helmet



Insulated gloves



Full-body harness



Safety glasses



Safety shoes

Figure 7.2 — Minimum PPE for rooftop solar work. Add arc-rated clothing and face shields for live electrical work.

- **Helmet** with chin strap — against falling objects and head injuries.
- **Electrically insulated gloves** (rated for the working voltage) plus leather gloves for handling metal.
- **Full-body harness with double lanyard** for any work near an unprotected edge.
- **Safety glasses** for drilling, cutting and battery work.
- **Safety shoes** with non-slip, non-conductive soles.
- **Hi-visibility clothing** on large sites; long sleeves against sunburn and cuts.

7.8 Safe electrical work procedure

1. Plan the work; get permission to work on the system.
2. Switch off the AC breaker to the inverter; then open the DC isolator.
3. **Lock out and tag out (LOTO)** — lock switches off and hang a warning tag with your name.
4. **Test before touch** — prove the circuit is dead with a tested voltmeter (test the meter on a known live source first).
5. Remember the array side of the DC isolator is still live in daylight; cover panels or disconnect strings at the panel end (with no current flowing).
6. Work, then remove tools, check connections and insulation, remove locks and tags, and restore power in reverse order: DC isolator ON, then AC breaker ON.

7.9 Fire safety

- Most PV fires start at poor DC connections — loose, badly crimped or mismatched MC4 connectors, or cables rubbing on sharp metal.
- Keep cables clipped and off the roof surface; protect them in UV-resistant conduit or cable trays.
- Install DC isolators accessible to fire-fighters and label them clearly: "*Solar DC — live during daylight*".
- Keep the inverter in a ventilated place, away from flammable materials; keep a CO₂ or dry-powder extinguisher nearby.
- Never use water on live electrical equipment.

7.10 Testing and commissioning

Test	How	Pass criteria
Visual inspection	Check modules, clamps, cable routing, labels, earthing	No damage; everything secure and labelled
Polarity	Multimeter on each string before connecting	Correct + and – at every string
String V_{oc}	Measure each string open-circuit	Within ~5% of expected (adjusted for temperature); all strings similar
String I_{sc}	Clamp meter / PV tester (safely)	Consistent with irradiance at the time
Insulation resistance	Insulation tester between conductors and earth	Above the minimum stated in IEC 62446 (typically $\geq 1\text{ M}\Omega$)
Earth resistance	Earth tester on each pit	Typically $\leq 5\ \Omega$ (lower is better)
Inverter commissioning	Set country grid code, check start-up, anti-islanding	Inverter synchronises and exports; shuts down when grid switched off
Performance check	Compare output with expected at current irradiance	Reasonable agreement

Practical tip — the handover file

Give the customer a folder (or PDF) containing: layout and SLD drawings, datasheets, warranty cards, commissioning test results, serial numbers, monitoring app login, a cleaning and maintenance guide, and your service contact. It prevents disputes and builds trust.

Module 7 — Summary

- Follow a fixed workflow: design → materials → safety → structure → modules → DC → earthing → inverter/AC → testing → handover.
- Structures must resist wind uplift (IS 875 Part 3); use HDG steel or aluminium and SS fasteners.
- Clamp modules only in approved zones at the specified torque; avoid micro-cracks.
- Main hazards: falls, DC shock and arcs, batteries, heat.
- Panels are live whenever light falls on them. Use LOTO and "test before touch".
- Commission with polarity, V_{OC} , I_{SC} , insulation and earth tests.

Practice questions — Module 7

1. List the steps of a rooftop installation in the correct order.
2. Why is wind uplift a major design concern? Which Indian standard gives wind speeds?
3. What are micro-cracks? Give three ways installers cause them.
4. Why can a PV array not be "switched off"? How do installers work safely on it?
5. Explain the lock-out/tag-out procedure.
6. List six items of PPE for rooftop solar work and the purpose of each.
7. Name five commissioning tests and the pass criteria for each.
8. What documents should be included in a customer handover file?

MODULE 08

Wiring, Mounting, and Electrical Codes

Series and parallel wiring, string sizing against the inverter's limits, cable and fuse selection, earthing, and the standards that installers must follow.

8.1 Series and parallel connection of modules

Modules are connected just like batteries (Module 4), and the same two rules apply:

Series connection

Positive of one module to negative of the next.

- **Voltages add**
- Current stays the same (that of one module)
- Used to reach the inverter's operating voltage

Parallel connection

All positives together, all negatives together.

- **Currents add**
- Voltage stays the same (that of one string)
- Used to increase current / power at the same voltage

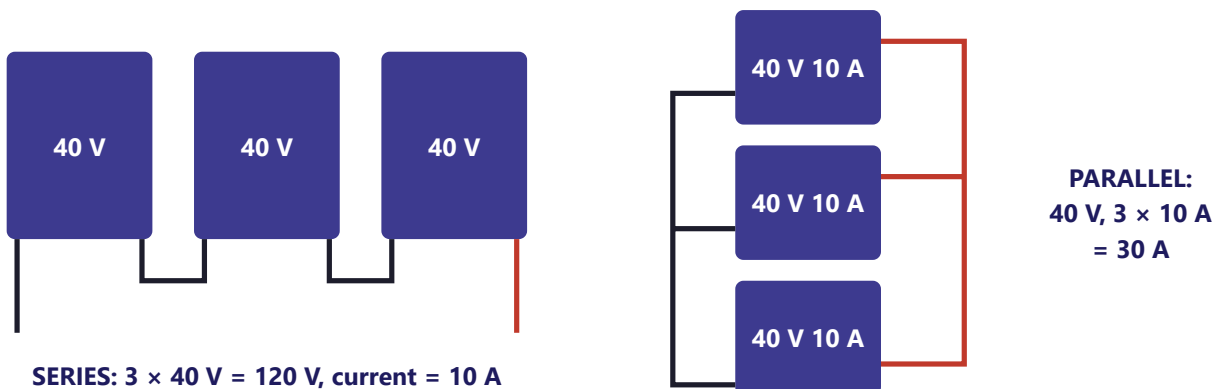


Figure 8.1 — Series wiring adds voltage; parallel wiring adds current. Power is the same (1,200 W) in both.

Caution — mixing modules

Modules in the same string should be identical (same model, power class and orientation). A weaker module limits the current of the whole string. Strings connected in parallel should have the same number of modules so their voltages match.

8.2 Why higher voltage is better

For the same power, higher voltage means lower current ($P = V \times I$). Cable losses depend on the **square of the current** ($P_{\text{loss}} = I^2 R$). Doubling the voltage halves the current and cuts cable losses to one quarter. That is why grid-tied systems use long series strings of 300–1,000 V (up to 1,500 V in large plants), while small battery systems at 12 V need very thick cables.

8.3 String sizing — the most important wiring calculation

The number of modules in each string must satisfy the inverter's limits in **all temperatures** the site will see:

1. **Maximum modules per string:** the string's V_{oc} at the **coldest** cell temperature must stay below the inverter's **maximum DC input voltage**. Exceeding this can permanently destroy the inverter.
2. **Minimum modules per string:** the string's V_{mp} at the **hottest** cell temperature must stay above the inverter's **minimum MPPT voltage** (and start-up voltage), or the inverter stops tracking on hot afternoons.
3. **Current check:** the string's I_{sc} ($\times$ number of parallel strings on one MPPT) must not exceed the MPPT's maximum input current (short-circuit) rating.

Formulas — string limits

$$V_{\text{oc,max}} = V_{\text{oc,STC}} \times [1 + \beta_{V_{\text{oc}}} \times (T_{\text{min}} - 25)]$$

$$N_{\text{max}} = \text{floor}(V_{\text{inverter,max}} \div V_{\text{oc,max}})$$

$$V_{\text{mp,min}} = V_{\text{mp,STC}} \times [1 + \beta_{V_{\text{mp}}} \times (T_{\text{max}} - 25)]$$

$$N_{\text{min}} = \text{ceiling}(V_{\text{MPPT,min}} \div V_{\text{mp,min}})$$

β = temperature coefficient as a decimal (negative). If only $\beta_{V_{\text{oc}}}$ is given, it is commonly used for V_{mp} too (slightly optimistic). T_{max} for cells in Indian summers: 65–70 °C.

Worked example 8.1 — string sizing

Module: $V_{oc} = 49.6 \text{ V}$, $V_{mp} = 41.9 \text{ V}$, $I_{sc} = 13.93 \text{ A}$, $\beta_{Voc} = -0.27\%/^{\circ}\text{C}$, $\beta_{Vmp} \approx -0.35\%/^{\circ}\text{C}$.

Inverter (5 kW): max DC voltage 600 V; MPPT range 120–550 V; max input current 16 A per MPPT (short-circuit 20 A).

Site: $T_{min}(\text{cell}) = 5^{\circ}\text{C}$; $T_{max}(\text{cell}) = 70^{\circ}\text{C}$.

Step 1 — cold V_{oc} : $49.6 \times [1 + (-0.0027)(5 - 25)] = 49.6 \times 1.054 = 52.28 \text{ V}$.

$N_{max} = 600 \div 52.28 = 11.48 \rightarrow$ **11 modules maximum.**

Step 2 — hot V_{mp} : $41.9 \times [1 + (-0.0035)(70 - 25)] = 41.9 \times 0.8425 = 35.30 \text{ V}$.

$N_{min} = 120 \div 35.30 = 3.4 \rightarrow$ **4 modules minimum.**

Also check the upper MPPT limit in cold: V_{mp} at $5^{\circ}\text{C} \approx 41.9 \times 1.07 = 44.8 \text{ V}$; $11 \times 44.8 = 493 \text{ V} < 550 \text{ V} \checkmark$.

Step 3 — current: one string $I_{sc} = 13.93 \text{ A} < 20 \text{ A} \checkmark$. Two strings in parallel (27.9 A) would exceed it — so use **one string per MPPT**.

Design: for a 5.5-kWp array ($10 \times 550 \text{ Wp}$), use **one string of 10 modules** ($V_{oc,max} = 523 \text{ V}$) on MPPT 1, or two strings of 5 on MPPT 1 and MPPT 2 if the roof has two faces. $\checkmark$

8.4 DC cable selection

Cables must be chosen for three things: **current-carrying capacity**, **voltage drop**, and **suitability for outdoor use**.

- **Type:** solar DC cable — tinned copper, double-insulated, UV and ozone resistant, rated 1.1–1.5 kV DC and 90–120 $^{\circ}\text{C}$ (to EN 50618 / IEC 62930 type standards). Never use ordinary PVC house wire on the roof.
- **Current rating:** the cable must carry at least **$1.25 \times I_{sc}$** continuously (some codes use $1.56 \times I_{sc}$ to include high irradiance), after derating for temperature and grouping.
- **Voltage drop:** keep total DC voltage drop at or below about **1.5–2%** (and AC side below about 1–2%).

Formula — DC voltage drop

$$V_{\text{drop}} = (2 \times L \times I \times \rho) \div A$$

$$\% \text{ drop} = V_{\text{drop}} \div V_{\text{system}} \times 100$$

L = one-way cable length (m); I = current (A); ρ = resistivity of copper $\approx 0.0178 \Omega \cdot \text{mm}^2/\text{m}$ (use ≈ 0.021 at 70–80 °C); A = cross-section (mm^2). The factor 2 accounts for the go and return conductors.

Worked example 8.2 — voltage drop

A string of 10 modules ($V_{\text{mp}} \approx 419 \text{ V}$, $I_{\text{mp}} = 13.13 \text{ A}$) is 30 m from the inverter. Check a 4 mm^2 cable (use $\rho = 0.021$).

$$V_{\text{drop}} = (2 \times 30 \times 13.13 \times 0.021) \div 4 = 16.54 \div 4 = 4.14 \text{ V}.$$

$$\% \text{ drop} = 4.14 \div 419 \times 100 = \mathbf{0.99\%} \checkmark \text{ (below 1.5\%).}$$

Now a 12 V off-grid system: 600 W at 12 V = 50 A over 8 m with 16 mm^2 : $V_{\text{drop}} = (2 \times 8 \times 50 \times 0.021) \div 16 = 1.05 \text{ V} = \mathbf{8.75\%} \times$ — far too high. Use 35–50 mm^2 or, better, a 24/48 V system. This shows why low-voltage systems need very thick cables.

8.5 Connectors, junctions and cable management

- Use genuine **MC4-compatible** connectors of the **same manufacturer and type** on both halves. Cross-mating different brands is a leading cause of connector burns.
- Crimp with the **correct crimping tool**; a pliers-squashed crimp will heat up and fail.
- Keep connectors off the roof surface (standing water) and out of direct continuous sun where possible.
- Clip cables to the structure with UV-resistant ties or stainless clips; avoid loops that act as antennas for lightning surges — run positive and negative together to minimise loop area.
- Use UV-stabilised conduit or covered cable trays for exposed runs; seal cable entries into boxes with glands.
- Label every string (+/–, string number) at both ends.

8.6 Overcurrent protection — string fuses

If three or more strings are connected in parallel, a fault in one string could allow the others to back-feed large current into it. **String fuses** (gPV type, DC-rated) protect against this. A common rule:

Formula — string fuse rating

$$1.5 \times I_{sc} \leq I_{fuse} \leq 2.4 \times I_{sc}, \text{ and } I_{fuse} \leq \text{module's max series fuse rating}$$

Fuses are usually not required with one or two strings per MPPT, because the fault current cannot exceed what the module can withstand.

Worked example 8.3 — fuse size

$I_{sc} = 13.93 \text{ A}$; module max series fuse = 25 A. Range: $1.5 \times 13.93 = 20.9 \text{ A}$ to $2.4 \times 13.93 = 33.4 \text{ A}$, but also $\leq 25 \text{ A}$. → Choose a **25 A gPV fuse**, rated for the system DC voltage (e.g. 1,000 V DC).

8.7 AC-side wiring and protection

- **AC cable** from inverter to the ACDB and main board: size for the inverter's maximum output current $\times 1.25$ and voltage drop $\leq 1\text{--}2\%$. Example: 5 kW single-phase at 230 V $\rightarrow I = 5,000 \div 230 = 21.7 \text{ A} \rightarrow$ design current $\approx 27 \text{ A} \rightarrow 4 \text{ mm}^2$ or 6 mm^2 copper depending on length.
- **MCB** sized just above the design current (e.g. 32 A for a 5-kW single-phase inverter).
- **RCCB / RCD** (30 mA for personal protection or 100–300 mA as specified; type as recommended by the inverter maker) for earth-leakage protection.
- **AC SPD** (Type 2) at the ACDB.
- Connection to the main board through a dedicated MCB; the DISCOM installs the net meter.

8.8 Earthing and lightning protection

Earthing gives fault currents and lightning surges a safe, low-resistance path into the ground, protecting people and equipment.

- **Equipment (protective) earthing:** all module frames and the mounting structure are bonded together with earthing clips/lugs and a copper or GI earthing conductor, then connected to an earth pit.
- **Separate earth pits:** commonly three — one for DC side/structure, one for the AC side/inverter, and one for the lightning arrester — as specified by the design and local rules. Pits are often bonded together below ground to keep them at the same potential.
- **Earth electrode:** copper-bonded or GI rod/pipe in a pit with earth-enhancing compound; resistance ideally $\leq 5 \Omega$ (Indian practice follows IS 3043).

- **Lightning arrester (LA):** an air terminal (e.g. ESE or conventional rod) mounted above the array's highest point, with a dedicated down conductor to its own earth pit. Its protection zone must cover the whole array.
- **SPDs:** Type 2 SPDs on DC inputs and AC output of the inverter protect against induced surges.

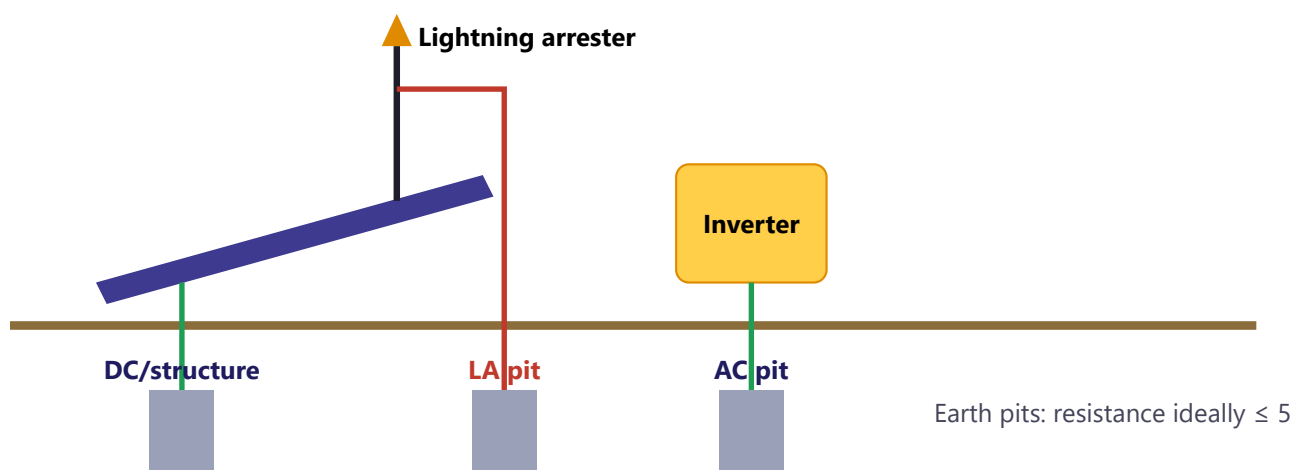


Figure 8.2 — Separate earthing for the structure/DC side, the lightning arrester and the AC side.

8.9 The single-line diagram (SLD)

Every installation must have a **single-line diagram** — a simplified electrical drawing showing each component and protective device from the panels to the grid, with ratings. DISCOMs require it for net-metering approval, and it is invaluable for maintenance. A typical SLD shows: PV strings (number × module) → DC fuses/isolator/SPD (DCDB) → inverter (rating, MPPTs) → AC MCB/RCCB/SPD (ACDB) → main distribution board → net meter → grid, plus the earthing arrangement.

8.10 Standards and codes (overview)

Area	Standard / rule (examples)	What it covers
Modules	IEC 61215, IEC 61730; BIS certification; MNRE ALMM	Design qualification, safety, approved manufacturers
Inverters	IEC 62109 (safety), IEC 61727 & IEC 62116 (grid interface, anti-islanding); BIS	Inverter safety and grid behaviour
PV installation	IEC 60364-7-712; IEC 62548	Design and installation requirements for PV arrays

Commissioning	IEC 62446-1	Tests, documentation and inspection
Wiring (India)	IS 732; Central Electricity Authority (CEA) safety and connectivity regulations	Electrical installation practice and grid connection
Earthing	IS 3043	Earthing practice
Lightning	IS/IEC 62305	Lightning protection
Wind load	IS 875 Part 3	Wind speeds and loads on structures
International reference	NEC Article 690 (USA)	Widely referenced PV electrical code (e.g. rapid shutdown)

Practical tip

Standards are revised regularly and DISCOM technical requirements differ by state. Always check the current tender or DISCOM specification for the project — it overrides general guidance.

Module 8 — Summary

- Series adds voltage; parallel adds current. Keep strings identical.
- $N_{\max}$ from cold V_{oc} vs inverter max voltage; $N_{\min}$ from hot V_{mp} vs MPPT minimum.
- DC cable: solar-grade, $\geq 1.25 \times I_{sc}$, voltage drop $\leq \sim 1.5\text{--}2\%$. $V_{\text{drop}} = 2LI\rho/A$.
- String fuses (gPV) when ≥ 3 strings in parallel: $1.5\text{--}2.4 \times I_{sc} \leq \text{module max fuse}$.
- AC side: MCB, RCCB, SPD; earthing $\leq 5 \Omega$; lightning arrester with its own pit.
- Follow IEC/IS standards, CEA regulations and DISCOM specifications; document with an SLD.

Practice questions — Module 8

1. Twelve modules (V_{mp} 40 V, I_{mp} 10 A) are wired as 3 strings of 4. Find array voltage, current and power. (Ans: 160 V, 30 A, 4.8 kW)
2. Explain why higher string voltage reduces cable losses.
3. $V_{oc} = 45$ V, $\beta = -0.28\%/^{\circ}\text{C}$, $T_{min} = 0$ $^{\circ}\text{C}$, inverter max = 1,000 V. Find N_{max} . (Ans: cold $V_{oc} = 48.15$ V $\rightarrow$ 20 modules)
4. $V_{mp} = 37$ V, $\beta = -0.36\%/^{\circ}\text{C}$, $T_{max} = 70$ $^{\circ}\text{C}$, MPPT min = 200 V. Find N_{min} . (Ans: hot $V_{mp} \approx 31.0$ V $\rightarrow$ 7 modules)
5. Calculate % voltage drop: 25 m, 10 A, 6 mm², 380 V, $\rho = 0.021$. (Ans: $\approx 0.46\%$)
6. When are string fuses required? Size one for $I_{sc} = 11$ A, module max fuse = 20 A. (Ans: 16.5–26.4 A, ≤ 20 A $\rightarrow$ 20 A)
7. Why are separate earth pits used for the lightning arrester?
8. What is an SLD? List the items it should show.

Maintenance, Troubleshooting, and Monitoring

Keeping a system producing at its best for 25 years: cleaning, inspection schedules, finding and fixing faults, and using monitoring data to catch problems early.

9.1 Why maintenance matters

Solar systems are often sold as "maintenance-free". That is only partly true. There are no moving parts, but dust, heat, weather, loose connections and ageing components all reduce output and can create safety risks. A well-maintained system typically delivers **10–20% more energy** over its life than a neglected one, and avoids expensive failures such as burnt connectors, inverter damage or roof leaks.

Maintenance falls into three types:

- **Preventive maintenance:** scheduled cleaning and inspections to prevent problems.
- **Corrective maintenance:** repairing faults after they occur.
- **Condition-based (predictive) maintenance:** using monitoring data and tests (such as thermal imaging) to detect degradation before it becomes a failure.

9.2 Cleaning the panels

In India, dust, bird droppings, pollen, industrial soot and construction dust quickly settle on panels. Soiling losses of 5–25% are common in dry months if panels are not cleaned. Rain helps, but light drizzle often just spreads dust into a muddy film.

Correct cleaning method

1. Clean in the **early morning or evening**, when panels are cool and output is low. Cold water on hot glass can cause thermal shock and micro-cracks.
2. Rinse with **clean, soft water** (low in dissolved salts — hard water leaves white scale).
3. Wipe gently with a **soft sponge, microfibre cloth or soft-bristle brush** on a long handle.
4. For stubborn dirt or bird droppings, soak first; use only mild, non-abrasive, neutral soap if the manufacturer allows.
5. Rinse again and let dry; squeegee if water leaves marks.

Never do this

- Never use high-pressure jets, abrasive powders, steel wool, detergents with solvents or sharp scrapers — they damage the anti-reflective coating and seals.
- Never walk or stand on panels to reach them.
- Never clean with wet cloths near damaged cables or junction boxes — shock risk.

Environment	Suggested cleaning frequency
Clean residential area, regular rain	Every 2–4 weeks
Dusty cities, near roads or construction	Weekly to fortnightly
Deserts, industrial areas, cement plants	2–3 times a week or automatic cleaning systems
Monsoon season	Inspect; clean after dust storms or bird activity

Worked example 9.1 — is cleaning worth it?

A 5-kWp system produces 20 kWh/day when clean. Soiling reduces this by 12% if cleaned only once a month on average, versus 3% with weekly cleaning. Tariff ₹7/kWh.

Extra energy with weekly cleaning = $20 \times (0.12 - 0.03) = 1.8$ kWh/day $\rightarrow 1.8 \times 365 = 657$ kWh/year $\rightarrow$ **₹4,600 per year** — well worth a few hours of cleaning a month.

9.3 Preventive maintenance checklist

Frequency	Component	What to check
Daily / weekly	Monitoring app	Generation compared with previous days and expected output; inverter error messages
	Panels	Visible dirt, bird droppings, new shade (tree growth, new construction)

Monthly	Panels	Cleaning; cracks, discoloration, burn marks, delamination
	Inverter	Display/LEDs normal; vents and fans clear of dust; no unusual noise or heat
	Batteries (lead-acid)	Electrolyte level (top up with distilled water), terminal corrosion, specific gravity
	Site	Vegetation, bird nests under panels, water pooling
Every 6 months	Structure	Rust, loose bolts (re-torque), damaged clamps, anchors and waterproofing
	Cables & connectors	UV damage, rodent bites, loose or discoloured MC4 connectors, cable ties broken
	DCDB / ACDB	Tight terminals, fuses intact, SPD status indicator, water ingress, labels
	Earthing	Continuity of bonding; earth-pit watering where needed
	Performance	String V_{oc} and current comparison; performance ratio
Yearly	Earth resistance	Measure each pit ($\leq 5 \Omega$ target), preferably in dry season
	Insulation resistance	Test DC side to earth
	Thermal imaging	Scan panels and connections for hot spots (larger systems)

9.4 Monitoring systems

Almost all modern inverters include a data logger that sends readings to a cloud portal and phone app through Wi-Fi, Ethernet or a GSM SIM. Monitoring turns problems that would go unnoticed for months into alerts within hours.

What to watch

- **Daily energy (kWh):** compare with the expected value for the season and the weather.
- **Specific yield (kWh/kWp):** daily or annual energy divided by array size — lets you compare systems of different sizes. In India, good systems achieve about 1,300–1,600 kWh/kWp per year.
- **Power curve through the day:** a smooth bell shape on clear days. Dips at the same time daily suggest shading; a flat top suggests inverter clipping (DC/AC ratio high).
- **String currents** (if available): one string lower than others points to a fault in that string.

- **Alarms and event log:** grid over-/under-voltage, isolation faults, over-temperature.

Formulas — performance indicators

$$\text{Specific yield } Y = E_{AC} \text{ (kWh)} \div P_{\text{array}} \text{ (kWp)}$$

$$\text{Performance ratio PR} = E_{AC} \div (P_{\text{array}} \times H_{\text{POA}} \div 1 \text{ kW/m}^2)$$

H_{POA} = irradiation on the plane of the array (kWh/m²) over the same period.

Worked example 9.2 — checking PR from monitoring

A 10-kWp plant produced 1,410 kWh in March. A nearby irradiance sensor recorded 186 kWh/m² on the panel plane that month.

Specific yield = $1,410 \div 10 = 141 \text{ kWh/kWp}$ for the month.

PR = $1,410 \div (10 \times 186) = 1,410 \div 1,860 = \mathbf{0.76}$ — normal. If PR drops to 0.65 the next month with no change in weather, investigate soiling, a failed string or inverter issues.

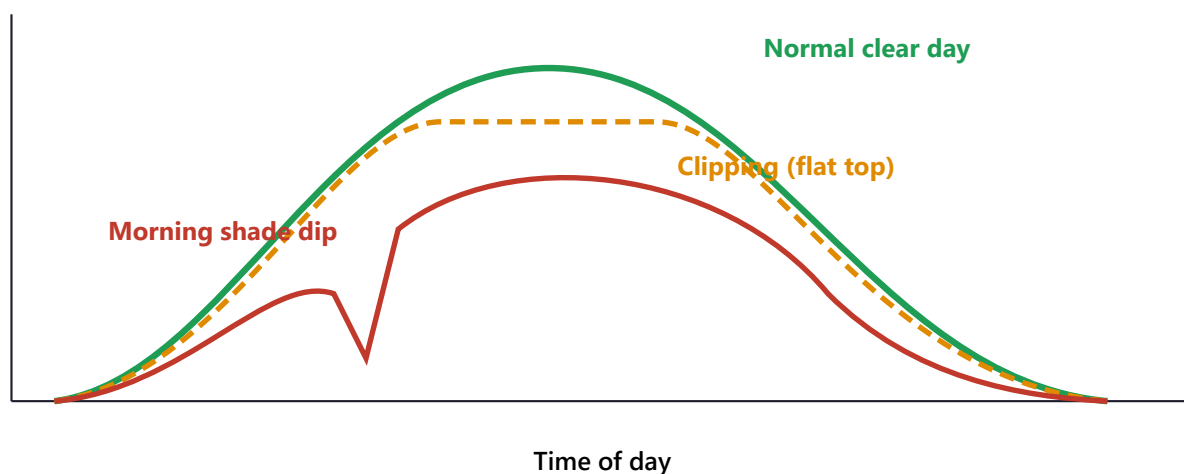


Figure 9.1 — Reading the daily power curve: normal, inverter clipping, and a shading signature.

9.5 Troubleshooting — a systematic approach

When output is low or the system stops, follow a logical sequence rather than guessing:

1. **Gather information:** what changed, when did it start, what does the monitoring show, what error code does the inverter display?
2. **Check the obvious:** is it cloudy? Is the grid present? Are the AC breaker and DC isolator ON? Any tripped MCB or blown fuse?

3. **Look:** visual inspection of panels, cables, connectors, boxes and the inverter for damage, burning smell, water, animals.
4. **Measure:** string V_{OC} and I_{SC} , grid voltage, insulation resistance — and compare with expected values.
5. **Isolate:** narrow down to one string, one panel, one connector.
6. **Repair safely** (LOTO), then **verify** the fix with measurements and monitoring.
7. **Record** the fault, cause and action in the maintenance log.

9.6 Common faults and their fixes

Symptom	Likely cause	Check / fix
Inverter off, no display	No DC input (isolator off, fuse blown), no AC, internal failure	Check isolators, fuses, string voltage at inverter terminals; contact manufacturer if inputs are present
"Grid over-voltage" / "Grid over-frequency" trips, often midday	High local grid voltage (weak grid; many solar systems on one transformer); undersized AC cable	Measure voltage at inverter and at meter; increase AC cable size; ask DISCOM to adjust transformer tap; set grid code correctly
"No grid" / "Islanding"	Power cut; AC breaker off; loose neutral	Normal during outages; otherwise check AC connections
"Isolation fault" / "Low insulation resistance" / "PV earth fault"	Damaged cable insulation, water in connector or junction box, rodent damage	Insulation test string by string; inspect and replace damaged parts; worse in morning dew or rain
One string voltage $\approx$ one module lower	Bypass diode shorted, or a module failed, or wrong module count	Measure individual modules; replace faulty module/junction box
One string voltage zero	Open circuit — disconnected or burnt connector, blown string fuse	Trace string; check connectors; replace fuse after finding cause
All strings low output	Soiling, shading, high temperature, wrong tilt, inverter derating	Clean; check for new shade; check inverter temperature and ventilation
Burnt / melted MC4 connector	Poor crimp, mismatched brands, not fully latched	Replace both halves with matched genuine connectors, crimped properly

Hot spot on panel (thermal image)	Cell crack, shading, soldering fault	Remove shade/dirt; if persistent, warranty claim
Brown lines ("snail trails"), bubbles, yellowing	Micro-cracks, delamination, EVA degradation	Document; measure output; warranty claim if power loss exceeds warranty
Battery not holding charge	Sulphation (lead-acid left discharged), aged cells, BMS protection, controller settings wrong	Check SoC and voltages; equalise lead-acid if allowed; check BMS alarms; verify charge settings
Inverter fan noisy / over-temperature derating	Dust-clogged vents; hot, enclosed location	Clean filters; improve ventilation; shade inverter from direct sun

Worked example 9.3 — diagnosing a string

A system has two strings of 10 modules (V_{oc} each ≈ 49 V at the current temperature). Measured: String 1 = 489 V; String 2 = 440 V.

Expected $\approx 10 \times 49 = 490$ V. String 2 is 50 V lower — about one module's worth. **Likely:** one module in string 2 has failed or has shorted bypass diodes (three shorted diodes $\approx$ one module's voltage). Measure each module in string 2 (safely, disconnected, at low light) to find it.

9.7 Tools of the trade

Tool	Use
Digital multimeter (CAT III 1,000 V DC)	Voltage, continuity, polarity
DC clamp meter	String current without breaking the circuit
Insulation resistance tester	Detects insulation faults
Earth resistance tester	Earth-pit resistance
Irradiance meter (solarimeter)	Measures W/m^2 to compare actual and expected output
I–V curve tracer	Plots the full I–V curve of a string to reveal mismatch, shading, degradation

Thermal (IR) camera / drone	Finds hot spots and hot connectors
MC4 crimping tool and spanner	Correct connector assembly and disconnection
Torque wrench	Re-tightening clamps and terminals to specification

9.8 Battery maintenance

- **Flooded lead-acid:** check electrolyte monthly; top up with distilled water only after charging; keep terminals clean and greased; measure specific gravity (≈ 1.24 – 1.28 when full, depending on type); avoid keeping batteries partly discharged for long; equalise periodically if the manufacturer recommends.
- **VRLA (sealed):** do not open; keep cool; check voltages and terminals.
- **LFP:** almost no routine maintenance; check BMS alarms and cell-voltage balance in the app; keep within temperature limits; avoid storing at 100% or 0% for long periods.
- For all types: keep the battery room ventilated and dry, and never place tools on battery tops.

9.9 Record keeping and warranties

Maintain a **logbook** (paper or digital) with dates of cleaning, inspections, measurements, faults and repairs. It helps spot slow degradation trends and is often required for **warranty claims**. Keep the purchase invoice, serial numbers and commissioning report safely. Typical warranties: modules 10–12 years (product) and 25–30 years (performance); inverters 5–10 years (often extendable); LFP batteries 5–10 years or a stated number of cycles; installation workmanship 1–5 years.

Module 9 — Summary

- Clean panels with soft water and soft tools in cool hours; never use pressure jets or abrasives.
- Follow a schedule: weekly monitoring, monthly cleaning/inspection, 6-monthly structure and wiring checks, yearly earth/insulation tests.
- Monitor daily kWh, specific yield (kWh/kWp) and $PR = E_{AC} \div (kWp \times H_{POA})$.
- Troubleshoot systematically: gather → check obvious → look → measure → isolate → repair → verify → record.
- Common faults: grid over-voltage, isolation faults, burnt connectors, failed modules/diodes, soiling, battery sulphation.
- Keep a logbook and warranty documents.

Practice questions — Module 9

1. Distinguish preventive, corrective and predictive maintenance with examples.
2. Describe the correct procedure and timing for cleaning solar panels.
3. A 3-kWp system loses 15% to dust. It normally produces 12 kWh/day. How much energy is lost in 30 days? (*Ans: 54 kWh*)
4. A 5-kWp system produced 7,250 kWh in a year. Find its specific yield. (*Ans: 1,450 kWh/kWp*)
5. Monthly output 600 kWh; array 4 kWp; plane irradiation 180 kWh/m². Find PR. (*Ans: 0.83*)
6. An inverter shows "Isolation fault" every morning after dew. What is the likely cause and how would you find it?
7. Explain what a flat-topped daily power curve indicates.
8. List six tools used for solar troubleshooting and the purpose of each.

MODULE 10

Practical Project and Final Revision

A complete, worked design of a real rooftop system from bills to handover — followed by the project brief for your own capstone and a one-page formula sheet for revision.

10.1 The capstone project

The best way to prove you understand solar design is to design a complete system yourself. This module first walks through a full example, then gives you a brief to do the same for a site of your choice. Your project should include: a site assessment, load analysis, system type choice, sizing of every component, string design, a layout sketch, a single-line diagram, an energy and payback estimate, and a maintenance plan.

10.2 Worked project — a hybrid rooftop system for a family home

Step 1 — Site and customer information

Item	Details
Location	Cuttack, Odisha — latitude $\approx 20.5^\circ$ N
Building	Two-storey house; flat RCC roof, 9 m $\times$ 7 m; good condition
Obstacles	Staircase room 2.4 m $\times$ 2.4 m, 2.5 m high, at the south-east corner; water tank 1.2 m high on the staircase room
Connection	Single-phase, sanctioned load 5 kW
Consumption (12 bills)	Total 5,110 units/year (min 280 in Jan, max 610 in May)
Power cuts	Frequent in summer and during storms, 1–3 hours
Customer's goals	Cut the bill as much as possible; keep lights, fans, fridge and Wi-Fi running in power cuts

Step 2 — Choose the system type

Grid is available (so export is possible) and the customer wants backup → **hybrid system** (Module 5), with a backup board for essential loads.

Step 3 — Solar resource

Annual average GHI for the area $\approx 4.9 \text{ kWh/m}^2/\text{day}$; on a tilted south-facing plane at about $18\text{--}20^\circ$, PSH ≈ 5.1 . Use PR = **0.77**.

Step 4 — Array size

Daily energy = $5,110 \div 365 = 14.0 \text{ kWh/day}$.

Array = $14.0 \div (5.1 \times 0.77) = 14.0 \div 3.93 = 3.56 \text{ kWp}$.

Using 550-Wp modules: $3,560 \div 550 = 6.5$, so at least 7 modules (3.85 kWp) are needed. Because the family plans to add another AC, and an even number splits neatly into two equal strings, we choose **8 modules = 4.4 kWp** — still below the 5-kW sanctioned load.

Step 5 — Roof layout and shading check

Each module $\approx 2.28 \text{ m} \times 1.13 \text{ m}$. We arrange the eight modules in **two rows of four, in portrait**. Each row is $4 \times 1.13 \text{ m}$ plus small gaps $\approx 4.6 \text{ m}$ wide, and its depth on plan at 20° tilt is $2.28 \times \cos 20^\circ \approx 2.14 \text{ m}$.

Obstacle shadow: the staircase room plus tank is 3.7 m high at the south-east corner. Using a design winter altitude of 30° : $L = 3.7 \div \tan 30^\circ = 6.4 \text{ m}$. That shadow would fall across much of the roof in winter mornings, so we place the array on the **western half** of the roof, where the staircase is not south of the panels, and use an **elevated structure** (lower edge 2.0 m above the roof) so that the parapet (1 m) causes no shading and the roof below stays usable.

Row spacing (if rows are one behind another): row height = $2.28 \times \sin 20^\circ = 0.78 \text{ m}$; gap = $0.78 \div \tan 30^\circ = 1.35 \text{ m}$. Total depth = $2.14 + 1.35 + 2.14 = 5.63 \text{ m}$ — fits in the 7 m roof depth ✓.

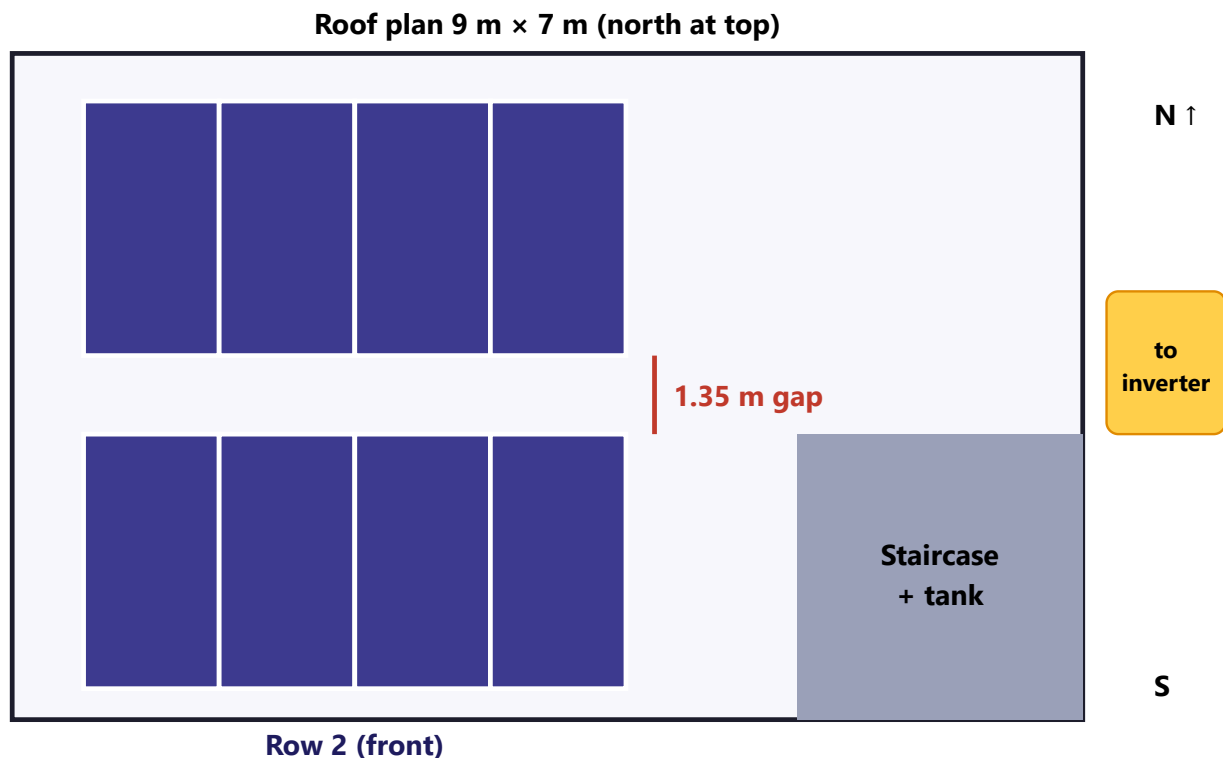


Figure 10.1 — Array layout: two rows of four modules on the western side of the roof, clear of the staircase shadow.

Step 6 — Inverter selection and string design

Chosen: **5-kW single-phase hybrid inverter, 48 V battery**, PV input max 550 V, MPPT range 120–500 V, 2 MPPTs, max 14 A per MPPT (I_{sc} max 18 A). DC/AC ratio = $4.4 \div 5 = 0.88$ — leaves room for expansion.

Module: V_{oc} 49.6 V, V_{mp} 41.9 V, I_{mp} 13.13 A, I_{sc} 13.93 A, β_{Voc} $-0.27\%/^{\circ}\text{C}$, β_{Vmp} $-0.35\%/^{\circ}\text{C}$.
Site cell temperatures: 8 °C min, 70 °C max.

- Cold $V_{oc} = 49.6 \times [1 + 0.0027 \times 17] = 51.9 \text{ V} \rightarrow N_{max} = 550 \div 51.9 = 10.6 \rightarrow 10$.
- Hot $V_{mp} = 41.9 \times [1 - 0.0035 \times 45] = 35.3 \text{ V} \rightarrow N_{min} = 120 \div 35.3 = 3.4 \rightarrow 4$.
- Cold $V_{mp} \approx 41.9 \times 1.06 = 44.4 \text{ V} \rightarrow 8 \times 44.4 = 355 \text{ V} < 500 \text{ V} \checkmark$.
- I_{sc} 13.93 A < 18 A per MPPT $\checkmark$ (one string per MPPT).

Design options: one string of 8 on MPPT 1 ($V_{oc,max} = 415 \text{ V}$), or two strings of 4 (one per row) on MPPT 1 and MPPT 2 ($V_{oc,max} = 208 \text{ V}$; hot $V_{mp} = 141 \text{ V}$, still above 120 V $\checkmark$). We choose **one string per row on separate MPPTs**, so that if the front row gets brief winter shading, the back row keeps working at its own maximum power point.

Step 7 — Backup loads and battery

Backup load	W	Hours in outage	Wh
-------------	---	-----------------	----

LED lights (8 × 10 W)	80	3	240
BLDC fans (4 × 30 W)	120	3	360
Refrigerator (avg. running)	120	3 (duty ~50%)	180
Wi-Fi + phones + laptop	80	3	240
TV	60	2	120
Total per outage			1,140 Wh

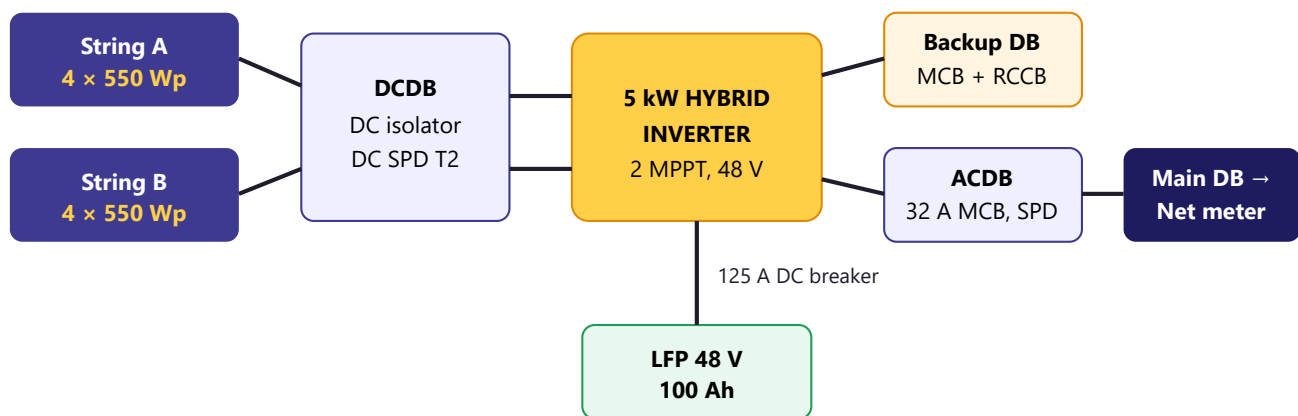
Allow for two outages on a bad day at night (no solar): $2 \times 1,140 = 2,280 \text{ Wh}$.

LFP battery: $2,280 \div (0.9 \times 0.93) = \mathbf{2,724 \text{ Wh}}$ → choose a **48 V 100 Ah LFP battery ($\approx 5.1 \text{ kWh}$)**, which also allows evening self-consumption of stored solar energy.

Step 8 — Cables and protection

- **DC cables:** 4 mm^2 solar cable, one-way length 15 m. Voltage drop = $(2 \times 15 \times 13.13 \times 0.021) \div 4 = 2.07 \text{ V}$; at 4-module string $V_{\text{mp}} \approx 168 \text{ V} \rightarrow 1.2\% \checkmark$.
- **DCDB:** DC isolator 1,000 V / 32 A (two inputs), Type 2 DC SPD; no string fuses needed (one string per MPPT).
- **Battery:** $48 \text{ V} \times 100 \text{ A} \rightarrow$ cables 25–35 mm^2 copper; DC breaker/fuse $\sim 125 \text{ A}$ close to battery.
- **AC output:** $5 \text{ kW} / 230 \text{ V} = 21.7 \text{ A} \rightarrow$ design 27 A $\rightarrow 6 \text{ mm}^2 \text{ Cu}$; **32 A MCB**, 30 mA RCCB (type per inverter manual), AC SPD.
- **Earthing:** three earth pits (DC/structure, AC, lightning arrester), each $\leq 5 \Omega$; LA mounted above the array's highest point.

Step 9 — Single-line diagram



Earthing: Pit 1 structure/DC · Pit 2 AC/inverter · Pit 3 lightning arrester (each $\leq 5 \Omega$)

Figure 10.2 — Single-line diagram of the worked project.

Step 10 — Energy and financial estimate

Annual energy = $4.4 \times 5.1 \times 0.77 \times 365 = \mathbf{6,307 \text{ kWh/year}}$ (first year) — about 123% of current use, leaving room for the planned extra AC.

Assume a total cost of ₹3,20,000 (with battery) and an applicable subsidy of ₹78,000 → net ₹2,42,000 (illustrative figures).

Savings: 5,110 kWh of own use at ₹6.8 = ₹34,748; surplus 1,197 kWh credited at, say, ₹3.5 = ₹4,190 → total $\approx \mathbf{₹38,900/\text{year}}$.

Simple payback = $2,42,000 \div 38,900 \approx \mathbf{6.2 \text{ years}}$, with the battery providing backup value on top.

Step 11 — Maintenance plan

- Weekly: check the app — daily kWh vs. expected; look for alarms.
- Fortnightly: clean modules early morning with soft water (hose reaches the elevated structure via a ladder platform).
- Six-monthly: re-torque bolts; inspect cables, connectors, DCDB/ACDB, SPD indicators; check battery BMS log.
- Yearly (before monsoon): earth-resistance test; insulation test; waterproofing check around anchors.

10.3 Your capstone brief

Project task

Choose a real building — your home, school, a relative's shop or a local clinic. Prepare a design report (8–12 pages) containing:

1. Site description with photos, roof dimensions, orientation and obstacles.
2. 12 months of consumption (from bills) or a load table.
3. Choice of system type with justification.
4. Array, inverter, battery (if any) and controller sizing with all calculations.
5. String design with cold- V_{oc} and hot- V_{mp} checks.
6. Roof layout sketch with shade clearances.
7. Single-line diagram with protection and earthing.
8. Bill of materials and cost estimate.
9. Annual energy, savings, payback and CO₂ avoided.
10. Safety plan and maintenance schedule.

10.4 Formula sheet — revise everything on one page

Quantity	Formula
Energy	$E \text{ (Wh)} = P \text{ (W)} \times t \text{ (h)}$
Peak sun hours	$PSH = \text{daily irradiation (kWh/m}^2\text{/day)}$
Daily PV energy	$E = kWp \times PSH \times PR$
Noon sun altitude	$\alpha = 90^\circ - \varphi + \delta$
Shade distance	$L = h \div \tan \alpha$
Module efficiency	$\eta = P_{\max} \div (G \times A)$
Fill factor	$FF = (V_{mp} I_{mp}) \div (V_{oc} I_{sc})$
Temperature correction	$X_T = X_{STC} [1 + \gamma(T - 25)]$
Array size	$kWp = E_{\text{daily}} \div (PSH \times PR) [\div \eta_{\text{batt}} \text{ for off-grid}]$
DC/AC ratio	$\text{Array kWp} \div \text{inverter kW } (\approx 1.0\text{--}1.25)$

Off-grid inverter	$VA \geq (W_{\text{simultaneous}} \div 0.8) \times 1.25$
Battery energy	$Wh = (E_{\text{daily}} \times \text{days}) \div (\text{DoD} \times \eta_{\text{inv}} \times \eta_{\text{temp}})$
Battery Ah	$Ah = Wh \div V_{\text{system}}$
MPPT controller	$I \geq (P_{\text{array}} \div V_{\text{batt}}) \times 1.25$
Max modules / string	$N_{\text{max}} = \text{floor}(V_{\text{inv,max}} \div V_{\text{oc,cold}})$
Min modules / string	$N_{\text{min}} = \text{ceil}(V_{\text{MPPT,min}} \div V_{\text{mp,hot}})$
DC voltage drop	$V_d = 2 L I \rho \div A$
String fuse	$1.5 I_{\text{sc}} \leq I_{\text{fuse}} \leq 2.4 I_{\text{sc}}$
Specific yield	$Y = kWh \div kWp$
Performance ratio	$PR = E_{\text{AC}} \div (kWp \times H_{\text{POA}})$
Simple payback	$\text{years} = \text{net cost} \div \text{annual savings}$

Module 10 — Summary

- A complete design runs: site → loads → system type → array → layout/shade → inverter/strings → battery → cables/protection → SLD → energy/finance → maintenance.
- Always check string voltages at temperature extremes and every protection rating.
- Document everything — the design report is what makes a system approvable, maintainable and trustworthy.

Practice questions — Module 10

1. Redo the worked project for a home using 3,650 units/year with PSH 5.3 and no backup need. (Ans: $\approx 2.45 \text{ kWp} \rightarrow 5 \times 550 \text{ Wp}$, on-grid 2.5–3 kW)
2. Why were the two rows placed on separate MPPT inputs in the worked project?
3. Recalculate the battery if outages last 5 hours each, twice a night. (Ans: $\approx 1,820 \text{ Wh}$ per outage $\rightarrow 3,640 \text{ Wh} \div 0.837 \approx 4.35 \text{ kWh}$; the 5.1-kWh battery still fits)
4. Estimate CO₂ avoided per year by the worked system at 0.75 kg/kWh. (Ans: ≈ 4.7 tonnes)
5. Draw the SLD for an off-grid 1.65-kWp system with a 24 V battery and MPPT PCU.

BONUS

Customer FAQs, Case Studies and Careers in Solar

The questions customers actually ask, real-world lessons from installations that went right and wrong, and how to build a career in the solar industry.

B.1 Twenty questions customers ask — and good answers

1. Will solar work during the monsoon or on cloudy days?

Yes, but less. On a heavily overcast day a system may produce only 10–30% of a sunny day's energy. Designs use annual averages, so bright months make up for dull ones. Net metering "banks" the extra units from sunny months.

2. Does solar work at night?

No. Panels need light. At night, an on-grid home uses grid power (and the credit from daytime exports); an off-grid or hybrid home uses its batteries.

3. Why did my solar stop during the power cut?

On-grid inverters must shut down when the grid fails (anti-islanding), to protect line workers. For backup you need a hybrid system with a battery.

4. How many units will a 3-kW system give?

In most of India about 3.5–4.5 units per kW per day on average — roughly 11–13 units a day or 4,000–4,500 units a year for 3 kWp, depending on location, tilt, shade and cleaning.

5. How long will the panels last?

Good panels come with 25–30-year performance warranties and often work longer, losing about 0.5% output per year. Inverters usually need replacement once in the system's life (after 10–15 years).

6. Will the panels damage my roof or cause leaks?

Not if installed correctly: proper anchors in sound concrete, sealed penetrations and waterproofing. Elevated structures can even shade and cool the roof. Always ask the installer how anchors will be sealed.

7. Can I run my AC on solar?

Yes. On an on-grid system, any appliance runs normally — solar reduces the net units billed. On an off-grid system, running ACs needs a large inverter, array and battery, which becomes expensive.

8. What happens if I produce more than I use?

Under net metering the surplus is credited and carried forward; at the end of the settlement period any remaining surplus is paid for at a rate set by the state regulator (often lower than the retail tariff). So size to your use, not far beyond it.

9. Is it safe to have solar during lightning and storms?

Yes, with proper earthing, a lightning arrester and surge protection devices, and a structure designed for local wind speeds.

10. How often should I clean the panels?

Every 1–4 weeks depending on dust. Use soft water and a soft brush or cloth, early morning or evening. Never use pressure jets or abrasives.

11. Mono, TOPCon or bifacial — which should I buy?

All are good. TOPCon and other n-type modules offer slightly higher efficiency and better heat performance; bifacial helps on elevated structures over white roofs. Brand quality, warranty and correct installation matter more than the cell type.

12. Can I add more panels later?

Usually yes, if the inverter has spare capacity or a free MPPT input, and the DISCOM approves the higher capacity. Plan for expansion when choosing the inverter.

13. Will my electricity bill become zero?

The energy charges can become close to zero, but fixed/demand charges and taxes on the bill usually remain.

14. Do I need batteries?

Only if you need power during cuts or have no grid. Batteries add significant cost and need replacement; if your grid is reliable, on-grid without batteries gives the best return.

15. Can solar be installed on a rented house or apartment?

It needs the owner's or society's permission and a suitable common roof. Some states allow group or virtual net metering for housing societies.

16. What maintenance does an inverter need?

Keep it in a shaded, ventilated place; keep vents clean; watch the app for alarms. Most have no user-serviceable parts inside.

17. Does heat reduce output?

Yes — about 0.3–0.4% per °C above 25 °C cell temperature. Good airflow under panels reduces this loss.

18. What subsidies are available?

Central and state schemes change over time. For homes, check the national rooftop solar portal and your DISCOM for current subsidy amounts, eligible sizes and empanelled vendors.

19. How do I choose a good installer?

Check experience, references, MNRE/DISCOM empanelment, component brands and datasheets, structure design, warranty terms, after-sales service, and whether they provide a written design and SLD.

20. What happens at the end of the panels' life?

Panels should be given to authorised recyclers who recover glass, aluminium, copper and silicon. Do not dump them with household waste.

B.2 Case studies — lessons from the field

Case 1 — The water tank shadow

A 5-kWp system in Nagpur produced 25% less than expected in winter. A thermal scan showed hot spots on the first row every morning until 10:30. Cause: a 1.8 m water tank south-east of the array; its winter shadow reached 3.5 m, but the array started 1.5 m away. **Fix:** the first row was raised and shifted, and the tank was relocated. **Lesson:** always calculate winter shadows — summer site visits hide them.

Case 2 — The burnt connector

An inverter in Pune kept showing "isolation fault", and one day a burning smell was noticed. A melted MC4 connector was found where two different brands had been mated and the crimp was made with pliers. **Fix:** replaced with matched, genuine connectors crimped with the proper tool. **Lesson:** connectors are small parts with big consequences.

Case 3 — Midday trips

A rural home's on-grid inverter tripped almost every afternoon with "grid over-voltage". Many homes on the same transformer had installed solar, raising the local voltage above 253 V at noon. **Fix:** the AC cable was upsized to reduce the voltage rise, and the DISCOM adjusted the transformer tap. **Lesson:** check grid voltage during the site survey and size AC cables for voltage rise.

Case 4 — The school that went hybrid

A school in Odisha with daily power cuts installed a 10-kWp hybrid system with a 10-kWh LFP battery. The computer lab and fans now run through cuts, and the electricity bill dropped by about 80%. Students monitor generation on a screen in the lobby — turning the system into a teaching tool. **Lesson:** choosing the right system type (Module 5) matters more than the brand of panel.

Case 5 — Cleaning pays

A 50-kWp factory roof near a cement plant showed PR falling from 0.78 to 0.62 within a month of each cleaning. Switching from monthly to twice-weekly cleaning with a water-fed brush raised the average PR to 0.76, adding about 9,000 kWh a year. **Lesson:** monitoring data (Module 9) shows exactly when maintenance pays for itself.

B.3 Careers in solar energy

Solar is one of the fastest-growing employers in India's energy sector. Skills from this course open several paths:

Role	What you do	Skills to build
Solar PV installer / technician	Install structures, modules, wiring; commission and maintain systems	Safety, electrical basics, tools, Module 7–9 skills; Skill India/SCGJ certification
Site surveyor	Assess roofs and shading; collect data for design	Module 2 skills; measurement; photography; customer communication
Design engineer	Size systems, string design, SLDs, layouts, energy simulation	Module 6 and 8; software such as PVsyst, SketchUp/Helioscope-type tools, AutoCAD
O&M engineer	Run and maintain plants; analyse monitoring data	Module 9; data analysis; thermal imaging; I–V tracing
Sales / business development	Explain solar to customers; prepare proposals and financial estimates	Payback and savings calculations; subsidies; communication
Project manager	Plan and supervise installations, teams and budgets	All modules; planning; safety management
Entrepreneur / EPC business	Run your own installation company	Technical + finance + DISCOM process + customer service

Your next steps

1. Complete the course quiz and download your certificate.
2. Do the capstone design (Module 10) for a real building and keep it as a portfolio piece.
3. Visit an installation site or volunteer with a local installer to gain hands-on experience.
4. Learn a design tool (for example PVsyst or an online rooftop design tool) and a drawing tool for SLDs.
5. Keep up with MNRE and your state DISCOM's current rules and schemes.

B.4 Quick revision — one line per module

Module	Remember in one line
1 Renewable energy	Solar is free, clean and modular; power (kW) $\neq$ energy (kWh); 1 kWp $\approx$ 4 units/day in India.
2 Solar radiation	PSH = kWh/m ² /day; face south, tilt $\approx$ latitude; keep clear of winter shadows ($L = h/\tan \alpha$).
3 PV technology	p-n junction; I-V curve with MPP; heat cuts voltage and power; bypass diodes stop hot spots.
4 Components	Inverter (DC→AC, MPPT, anti-islanding), MPPT controller, LFP battery with BMS, proper BOS.
5 System types	On-grid (cheapest, no backup), off-grid (batteries, autonomy), hybrid (both).
6 Sizing	kWp = kWh $\div$ (PSH $\times$ PR); battery Wh = daily $\times$ days $\div$ (DoD $\times$ η); MPPT A = W $\div$ V $\times$ 1.25.
7 Installation & safety	Wind-rated structures, correct clamping, LOTO, "panels are always live in daylight".
8 Wiring & codes	Cold V_{oc} sets max modules; hot V_{mp} sets min; $V_d = 2LIp/A \leq 1.5\text{--}2\%$; earth $\leq 5 \Omega$.
9 O&M	Clean gently and regularly; watch kWh/kWp and PR; troubleshoot systematically.
10 Project	Site $\rightarrow$ loads $\rightarrow$ type $\rightarrow$ size $\rightarrow$ layout $\rightarrow$ strings $\rightarrow$ protection $\rightarrow$ SLD $\rightarrow$ finance $\rightarrow$ maintenance.

REVISION

100 Multiple-Choice Questions

Test yourself on all ten modules. Answers are on the page after the questions.

- Which is a renewable energy source?
(a) Coal (b) Natural gas (c) Solar (d) Diesel
- The photovoltaic effect was first observed by:
(a) Einstein (b) Becquerel (c) Edison (d) Volta
- The first practical silicon solar cell was made in:
(a) 1839 (b) 1905 (c) 1954 (d) 1990
- 1 kWh equals:
(a) 100 Wh (b) 1,000 Wh (c) 10,000 Wh (d) 1,000 W
- Power is measured in:
(a) kWh (b) Ah (c) W (d) Wh/day
- A 100 W bulb used for 5 hours consumes:
(a) 20 Wh (b) 500 Wh (c) 5 kWh (d) 105 Wh
- Panel ratings in Wp are measured at:
(a) 500 W/m² (b) 800 W/m² (c) 1,000 W/m² (d) 1,361 W/m²
- The solar constant is about:
(a) 1,000 W/m² (b) 1,361 W/m² (c) 500 W/m² (d) 2,000 W/m²
- Irradiance is measured in:
(a) kWh/m²/day (b) W/m² (c) W (d) Ah
- A site with 5.4 kWh/m²/day has PSH of:
(a) 4.5 (b) 5.4 (c) 54 (d) 1.0
- STC cell temperature is:
(a) 0 °C (b) 20 °C (c) 25 °C (d) 45 °C
- Radiation scattered by the sky is called:
(a) Direct (b) Diffuse (c) Reflected (d) Beam
- Albedo radiation is:
(a) From clouds (b) Reflected from the ground (c) Direct beam (d) Infrared only
- In India, fixed panels should face:
(a) North (b) East (c) South (d) West
- Optimum fixed tilt is roughly equal to:
(a) 0° (b) 45° always (c) Site latitude (d) 90°
- Earth's axial tilt is:
(a) 15° (b) 23.45° (c) 30° (d) 45°
- Noon sun altitude = $90^\circ - \phi + \delta$. At $\phi = 20^\circ$, $\delta = -23.45^\circ$, it is:
(a) 46.55° (b) 86.55° (c) 66.55° (d) 23.45°
- A 2 m high obstacle with $\alpha = 30^\circ$ casts a shadow of about:
(a) 1.15 m (b) 2 m (c) 3.46 m (d) 4 m
- Typical performance ratio of a rooftop system:
(a) 0.30 (b) 0.50 (c) 0.77 (d) 0.99
- Approximate roof area per kWp:
(a) 1–2 m² (b) 6–8 m² (c) 20 m² (d) 50 m²
- Silicon's band gap is about:
(a) 0.1 eV (b) 1.1 eV (c) 3.4 eV (d) 11 eV

22. n-type silicon is doped with:
(a) Boron (b) Phosphorus (c) Aluminium (d) Gallium
23. p-type silicon is doped with:
(a) Boron (b) Phosphorus (c) Arsenic (d) Antimony
24. The built-in electric field of a cell is in the:
(a) Glass (b) Frame (c) Depletion region (d) Junction box
25. Voltage of one silicon cell is about:
(a) 0.05 V (b) 0.5–0.6 V (c) 5 V (d) 12 V
26. A solar cell produces:
(a) AC (b) DC (c) Pulsating AC (d) Three-phase AC
27. Modern mono module efficiency is about:
(a) 6% (b) 12% (c) 21% (d) 45%
28. V_{oc} is measured when:
(a) Terminals shorted (b) No load connected (c) At MPP (d) At night
29. Maximum power point is where:
(a) V is max (b) I is max (c) $V \times I$ is max (d) $V = I$
30. Rising temperature mainly reduces a panel's:
(a) Current (b) Voltage (c) Weight (d) Area
31. Rising irradiance mainly increases a panel's:
(a) Current (b) Temperature coefficient (c) Resistance (d) Frame size
32. Typical P_{max} temperature coefficient:
(a) $+0.35\%/^{\circ}\text{C}$ (b) $-0.35\%/^{\circ}\text{C}$ (c) $-3.5\%/^{\circ}\text{C}$ (d) 0
33. Bypass diodes protect against:
(a) Lightning (b) Hot spots from shading (c) Theft (d) Grid failure
34. Typical fill factor of a good module:
(a) 0.3 (b) 0.5 (c) 0.8 (d) 1.2
35. Bifacial modules gain energy from:
(a) Moonlight (b) Reflected light on the back (c) Wind (d) Heat
36. Annual degradation of modern panels is about:
(a) 0.5% (b) 5% (c) 10% (d) 20%
37. A 550 W panel of area 2.58 m^2 has efficiency of about:
(a) 11% (b) 21% (c) 31% (d) 55%
38. The inverter's main job is to:
(a) Store energy (b) Convert DC to AC (c) Clean panels (d) Measure sunlight
39. Indian grid frequency is:
(a) 50 Hz (b) 60 Hz (c) 100 Hz (d) 230 Hz
40. Anti-islanding means the inverter:
(a) Works on islands (b) Shuts down when the grid fails (c) Charges batteries (d) Tracks the sun
41. For motors and electronics, use an inverter with:
(a) Square wave (b) Modified sine (c) Pure sine wave (d) Triangle wave
42. A microinverter is installed:
(a) At the meter (b) Behind each panel (c) In the battery (d) At the substation
43. MPPT controllers compared with PWM:
(a) Harvest less (b) Harvest 15–30% more (c) Are identical (d) Need 12 V panels

44. Energy in a 12 V 150 Ah battery:
(a) 162 Wh (b) 1.8 kWh (c) 18 kWh (d) 12.5 Wh
45. Two 12 V 100 Ah batteries in series give:
(a) 12 V 200 Ah (b) 24 V 100 Ah (c) 24 V 200 Ah (d) 12 V 100 Ah
46. Two 12 V 100 Ah batteries in parallel give:
(a) 12 V 200 Ah (b) 24 V 100 Ah (c) 24 V 200 Ah (d) 6 V 200 Ah
47. LFP batteries typically allow a DoD of:
(a) 20% (b) 50% (c) 80–95% (d) 120%
48. Lead-acid batteries release which gas when charging?
(a) Oxygen only (b) Hydrogen (c) Chlorine (d) CO₂
49. A BMS is essential for:
(a) Lead-acid (b) Lithium batteries (c) Panels (d) Cables
50. An SPD protects against:
(a) Dust (b) Voltage surges (c) Theft (d) Low irradiance
51. An on-grid system during a power cut:
(a) Keeps working (b) Shuts down (c) Charges batteries (d) Doubles output
52. Net metering bills the consumer for:
(a) Import only (b) Export only (c) Import – export (d) Import + export
53. Days of autonomy relate to:
(a) Panel warranty (b) Battery supply without sun (c) Inverter life (d) Installation time
54. A hybrid system uses:
(a) Grid only (b) Battery only (c) Grid and battery (d) Neither
55. Best choice for a remote village with no grid:
(a) On-grid (b) Off-grid or mini-grid (c) Gross metering (d) Net metering
56. Solar pumps usually avoid batteries because:
(a) Pumps can't use DC (b) Water is stored instead (c) Batteries are illegal (d) Pumps run at night
57. A home uses 300 units/month. Daily energy is:
(a) 3 kWh (b) 10 kWh (c) 30 kWh (d) 100 kWh
58. Array kWp = $12 \div (5 \times 0.8) =$
(a) 2 (b) 3 (c) 4 (d) 48
59. A 6.6 kWp array on a 6 kW inverter has DC/AC ratio:
(a) 0.9 (b) 1.0 (c) 1.1 (d) 1.6
60. Motor starting current is typically:
(a) Less than running (b) Equal (c) 3–7 × running (d) Zero
61. $2,000 \text{ Wh} \div 24 \text{ V} \approx$
(a) 48 Ah (b) 83 Ah (c) 120 Ah (d) 240 Ah
62. MPPT current for 1,200 W at 24 V with 1.25 factor:
(a) 50 A (b) 62.5 A (c) 25 A (d) 125 A
63. Simple payback = net cost ÷ :
(a) Array size (b) Annual savings (c) Tariff (d) Subsidy

54. Why avoid 12 V for kW-scale systems?
 (a) Too little voltage drop (b) Very high currents and thick cables (c) No batteries available (d) Illegal
55. For an off-grid design, PSH is often taken for the:
 (a) Best month (b) Worst month (c) Night (d) Equinox only
56. Structures in cyclone areas are designed using:
 (a) IS 875 Part 3 (b) IS 456 only (c) IEC 61215 (d) IS 3043
57. Best mounting material against rust:
 (a) Painted mild steel (b) Hot-dip galvanised steel / aluminium (c) Wood (d) PVC
58. Module clamps should be placed:
 (a) Anywhere (b) In the manufacturer's clamping zones (c) On the glass (d) On the junction box
59. Micro-cracks are commonly caused by:
 (a) Rain (b) Standing on panels (c) Moonlight (d) Low tilt
70. PV panels are live:
 (a) Only at noon (b) Whenever light falls on them (c) Only when connected to grid (d) Never
71. LOTO stands for:
 (a) Load-Out Test-On (b) Lock-Out Tag-Out (c) Line-Open Turn-Off (d) Low-Output Test
72. Correct ladder angle ratio is about:
 (a) 1:1 (b) 1:4 (c) 1:10 (d) 4:1
73. Most PV fires begin at:
 (a) Glass (b) Poor DC connections (c) Frames (d) Mounting feet
74. Typical earth-pit resistance target:
 (a) $\leq 5 \Omega$ (b) 50Ω (c) 500Ω (d) $5 \text{ k}\Omega$
75. Series connection of modules adds:
 (a) Current (b) Voltage (c) Resistance only (d) Nothing
76. Parallel connection of strings adds:
 (a) Voltage (b) Current (c) Tilt (d) Temperature
77. Max modules per string is limited by:
 (a) Hot V_{mp} (b) Cold V_{oc} vs inverter max voltage (c) I_{mp} (d) Panel weight
78. Min modules per string is limited by:
 (a) Cold V_{oc} (b) Hot V_{mp} vs MPPT minimum (c) Fuse rating (d) Tilt
79. In $V_d = 2LI\rho/A$, the factor 2 accounts for:
 (a) Two panels (b) Go and return conductors (c) Safety (d) AC
80. Recommended DC voltage drop limit:
 (a) $\leq 1.5\text{--}2\%$ (b) 10% (c) 20% (d) Any
81. String fuses are generally needed when:
 (a) 1 string (b) 2 strings (c) 3 or more strings in parallel (d) Never
82. Correct fuse type for PV strings:
 (a) Glass AC fuse (b) gPV DC-rated fuse (c) Kit-kat fuse (d) None
83. Mixing MC4 connector brands can cause:
 (a) Higher output (b) Overheating and burns (c) Better sealing (d) Nothing

34. A lightning arrester needs:
(a) No earthing (b) Its own earth pit and down conductor (c) Only a fuse (d) Battery
35. The drawing showing all components and protection is the:
(a) Floor plan (b) SLD (c) Sun path (d) Datasheet
36. Commissioning test standard:
(a) IEC 62446-1 (b) IS 875 (c) IEC 61215 (d) IS 456
37. Best time to clean panels:
(a) Noon (b) Early morning or evening (c) During rain (d) Any time with hot water
38. Never clean panels with:
(a) Soft water (b) Microfibre (c) Pressure jet or abrasives (d) Soft brush
39. Specific yield is:
(a) $\text{kWh} \div \text{kWp}$ (b) $\text{kWp} \div \text{kWh}$ (c) $W \times h$ (d) $V \times A$
39. 600 kWh from 4 kWp with 180 kWh/m^2 gives PR of:
(a) 0.60 (b) 0.75 (c) 0.83 (d) 0.95
31. A flat-topped daily power curve suggests:
(a) Shading (b) Inverter clipping (c) Night (d) Earth fault
32. "Isolation fault" alarms point to:
(a) High irradiance (b) Insulation damage / moisture (c) Low tariff (d) Good earthing
93. One string about one module's voltage low suggests:
(a) Normal (b) Failed module or shorted bypass diodes (c) Clouds (d) Grid failure
94. A tool to find hot spots:
(a) Hammer (b) Thermal camera (c) Compass (d) Ladder
95. Grid over-voltage trips are often fixed by:
(a) More panels (b) Bigger AC cable / DISCOM tap change (c) Cleaning (d) Removing earthing
96. Lead-acid electrolyte should be topped up with:
(a) Tap water (b) Acid (c) Distilled water (d) Oil
97. Good annual specific yield in India:
(a) 300 kWh/kWp (b) 1,300–1,600 kWh/kWp (c) 5,000 kWh/kWp (d) 10 kWh/kWp
98. CO_2 avoided by 4,000 kWh at 0.75 kg/kWh :
(a) 300 kg (b) 3 tonnes (c) 30 tonnes (d) 0.3 kg
99. Which comes first in a design?
(a) Inverter choice (b) Load assessment (c) Cable size (d) Fuse size
100. Panel performance warranty is typically:
(a) 1 year (b) 5 years (c) 25–30 years (d) 100 years

ANSWERS

MCQ Answer Key

Check your answers. If you got a question wrong, return to the module shown in brackets.

Q	Ans	Q	Ans	Q	Ans	Q	Ans	Q	Ans
1	c	21	b	41	c	61	b	81	c
2	b	22	b	42	b	62	b	82	b
3	c	23	a	43	b	63	b	83	b
4	b	24	c	44	b	64	b	84	b
5	c	25	b	45	b	65	b	85	b
6	b	26	b	46	a	66	a	86	a
7	c	27	c	47	c	67	b	87	b
8	b	28	b	48	b	68	b	88	c
9	b	29	c	49	b	69	b	89	a
10	b	30	b	50	b	70	b	90	c
11	c	31	a	51	b	71	b	91	b
12	b	32	b	52	c	72	b	92	b
13	b	33	b	53	b	73	b	93	b
14	c	34	c	54	c	74	a	94	b
15	c	35	b	55	b	75	b	95	b
16	b	36	a	56	b	76	b	96	c
17	a	37	b	57	b	77	b	97	b
18	c	38	b	58	b	78	b	98	b
19	c	39	a	59	c	79	b	99	b
20	b	40	b	60	c	80	a	100	c

Short-answer exam questions (2–3 marks)

1. Define peak sun hours.
2. State the Standard Test Conditions.
3. What is the difference between irradiance and irradiation?
4. Why should the tilt angle not be less than about 10° ?
5. Define fill factor.
6. What is a hot spot?
7. State two functions of a charge controller.
8. What is depth of discharge?
9. What is anti-islanding?
10. Distinguish net metering and gross metering.
11. Define DC/AC ratio.
12. Why must string V_{oc} be checked at the lowest temperature?
13. Give two reasons for using separate earth pits.
14. What is specific yield?
15. List four items of PPE for rooftop solar work.

Long-answer exam questions (5–10 marks)

1. Explain the working of a crystalline silicon solar cell with a neat labelled diagram.
2. Draw and explain the I–V and P–V characteristics of a PV module. Show the effect of temperature and irradiance.
3. Compare on-grid, off-grid and hybrid systems with block diagrams, and state where each is suitable.
4. A household uses 4,200 kWh/year. PSH = 5.0, PR = 0.78. Size the array, choose the number of 540-Wp modules, and select an inverter.
5. Design an off-grid system for loads of 2.5 kWh/day with 2 days' autonomy using (a) lead-acid and (b) LFP batteries. Compare the results.
6. Explain the method of string sizing with a numerical example, checking cold V_{oc} , hot V_{mp} and current.
7. Describe the steps in installing a rooftop solar system and the safety precautions at each step.

8. Explain the earthing and lightning protection of a rooftop PV system with a diagram.
9. Describe a preventive maintenance schedule for a 10-kWp rooftop plant.
10. Explain how monitoring data (daily curve, specific yield, PR) helps in troubleshooting, with examples of faults.

REFERENCE

Glossary of Solar Terms

Key words used throughout these notes, in alphabetical order.

AC (alternating current)

Current that reverses direction periodically — 50 times a second in India.

Air mass (AM)

Relative path length of sunlight through the atmosphere; STC uses AM1.5.

Albedo

Fraction of light reflected by a surface such as the ground or roof.

ALMM

MNRE's Approved List of Models and Manufacturers for solar modules.

Ampere-hour (Ah)

Battery capacity unit: current $\times$ hours.

Anti-islanding

Inverter protection that stops export when the grid fails.

Array

All the PV modules of a system connected together.

Azimuth

Compass direction of the sun or of a panel's facing.

Balance of system (BOS)

All system components other than the PV modules.

Band gap

Minimum energy needed to free an electron in a semiconductor (~ 1.1 eV for silicon).

Bifacial module

Module that collects light on both front and back.

BMS

Battery management system that protects and balances lithium cells.

Bypass diode

Diode that lets current flow around shaded cells, preventing hot spots.

Charge controller

Device regulating battery charging from PV (PWM or MPPT).

Clipping

Inverter limiting output at its maximum rating when DC power is higher.

C-rate

Charge/discharge current relative to capacity.

DC (direct current)

Current flowing in one direction — produced by PV cells and batteries.

Days of autonomy

Days a battery can run loads with no solar input.

Declination

Angle between sun's rays and the equatorial plane ($\pm 23.45^\circ$).

Degradation

Gradual loss of module output over the years ($\sim 0.5\%$ /year).

Depletion region

Zone at a p-n junction with a built-in electric field.

Depth of discharge (DoD)

Percentage of battery capacity used.

Diffuse radiation

Sunlight scattered by the atmosphere, arriving from the whole sky.

DISCOM

Electricity distribution company.

Doping

Adding impurities to silicon to make n-type or p-type material.

Earthing

Connecting metal parts to earth for safety.

Efficiency (η)

Output power $\div$ input power.

Fill factor (FF)

$(V_{mp} \times I_{mp}) \div (V_{oc} \times I_{sc})$.

GHI / GTI

Global horizontal / global tilted irradiance.

gPV fuse

DC fuse designed for photovoltaic strings.

Hot spot

Overheated cell caused by shading or defects.

Hybrid inverter

Inverter managing PV, battery and grid together.

 I_{sc}

Short-circuit current — maximum module current.

Insolation / irradiation

Solar energy received per area over time
(kWh/m²/day).

Irradiance

Solar power per area (W/m²).

I–V curve

Graph of module current versus voltage.

Junction box

Box on the module back containing bypass diodes and output cables.

kWh

Kilowatt-hour — one unit of electrical energy.

kWp

Kilowatt-peak — array power at STC.

LFP

Lithium iron phosphate battery chemistry.

LOTO

Lock-out/tag-out safety procedure.

MC4

Standard weatherproof DC connector for PV cables.

Micro-crack

Invisible crack in a cell that can grow and cause losses.

Microinverter

Small inverter mounted at each panel.

MNRE

Ministry of New and Renewable Energy, Government of India.

MPP / MPPT

Maximum power point / the tracker that keeps a PV array at it.

Net metering

Billing only the difference between imported and exported energy.

NOCT / NMOT

Typical real-world operating cell temperature.

Off-grid

System with batteries and no grid connection.

On-grid

Grid-tied system without batteries.

p-n junction

Boundary between p-type and n-type semiconductors.

Peak sun hours (PSH)

Hours of equivalent 1,000 W/m² sunlight per day.

Performance ratio (PR)

Actual $\div$ ideal energy output, after losses.

Photon

A packet of light energy.

Photovoltaic effect

Generation of voltage and current in a material exposed to light.

PWM

Pulse-width modulation — switching technique used in controllers and inverters.

RCCB / RCD

Device that trips on earth-leakage current.

SLD

Single-line diagram of the electrical system.

Soiling

Dust and dirt on modules that reduces output.

Specific yield

Energy per kWp installed (kWh/kWp).

SPD

Surge protection device.

State of charge (SoC)

How full a battery is, in percent.

STC

Standard Test Conditions: 1,000 W/m², AM1.5, 25 °C.

String

Modules connected in series.

Temperature coefficient

Change in a parameter per °C of cell temperature.

Tilt angle

Angle of the panel from horizontal.

V_{mp} / I_{mp}

Voltage and current at the maximum power point.

V_{oc}

Open-circuit voltage — maximum module voltage.

Watt-peak (Wp)

Module power rating at STC.

Keep learning

Use the AI tutor on www.aitutorspark.co.in to ask any question from these notes — it will explain step by step. Complete the course quiz to earn your certificate. All the best!