International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

# Comprehensive Design, Performance Analysis and Sizing Methodologies for Solar Photovoltaic Systems

Thanakanti Praneeth
Dept. of EEE, MGIT
Hyderabad, India

Dr. P. Ram Kishore Reddy
Dept. of EEE, MGIT
Hyderabad, India

Dr. P. Laxmi Supriya
Dept. of EEE, MGIT
Hyderabad, India

Kondapalli Adarsh Rao
Dept. of EEE, MGIT
Hyderabad, India

***Abstract*—This paper presents an in-depth technical evaluation of solar photovoltaic (PV) systems, detailing the core principles of solar-to-electrical energy conversion, key performance indicators, and structural hardware setups. It systematically analyzes the electrical and environmental variables influencing PV module efficiency, while providing a rigorous breakdown of balance-of-system (BoS) components like charge controllers, inverters, and energy storage units. Additionally, the study outlines precise sizing strategies for both off-grid and grid-tied networks, culminating in a mathematical framework for designing a hybrid wind-solar energy facility. Ultimately, this work offers a structured blueprint for engineering reliable PV infrastructures.**

***Index Terms*—Photovoltaic cells, solar irradiance, maximum power point tracking, grid-connected PV, off-grid systems, inverters, charge controllers, battery storage, hybrid energy systems.**

## I. INTRODUCTION TO PHOTOVOLTAIC TECHNOLOGY

As traditional fossil fuel reserves dwindle and global anxieties over climate change and greenhouse gas emissions intensify, the global energy paradigm is shifting rapidly toward renewable alternatives. Out of all sustainable options available, solar power remains the most plentiful, accessible, and limitless energy source on the planet. Capturing solar irradiance enables decentralized, environmentally friendly, and robust electricity generation. Solar energy reaches the Earth mainly as thermal and luminous energy. Therefore, two primary technologies exist to harvest it: solar thermal systems that capture heat for fluid warming (e.g., domestic or industrial water heating), and photovoltaic (PV) systems designed to transform sunlight directly into electrical power.

The word “photovoltaic” combines the Greek “photo” (light) with “voltaic” (referencing Alessandro Volta and electrical electromotive force), perfectly describing the generation of electricity from illumination. PV systems operate on this exact phenomenon, leveraging both ambient and direct solar radiation to trigger the photovoltaic effect. As solar photons hit a PV cell, they impart energy to the semiconductor’s electrons, detaching them from their atomic structures to produce direct current (DC). This generated power can serve immediate DC electrical loads, be reserved in high-capacity battery arrays, or route through a power conditioning unit (inverter) for conversion into alternating current (AC). After AC conversion, the electricity seamlessly links with standard distribution boards or feeds directly into municipal grids while maintaining electrical stability.

### A. The Photovoltaic Effect and Semiconductor Mechanics

Fundamentally, the operational core of any PV network is the solar cell. The functionality of these units relies heavily on the characteristics of semiconductor substrates, primarily silicon. In its pure state, silicon functions as an electrical insulator; however, its conductive traits are deliberately altered through “doping”—the introduction of specific elemental dopants like phosphorus and boron.

This controlled contamination establishes a structural charge disparity, creating two specialized zones: a p-type layer (positive, doped with boron to yield electron vacancies or “holes”) and an n-type layer (negative, doped with phosphorus to supply surplus electrons). The boundary joining these sections forms the critical p-n junction. When solar energy penetrates this junction, photon energy mobilizes the electrons, and an inherent electric field pushes electrons to the n-side and holes to the p-side. Establishing an external circuit across the top and base of the cell creates a conductive route, yielding an electric current proportional to the available light intensity.

### B. System Scaling: Cells, Modules, Strings, and Arrays

An individual commercial silicon cell generates a minimal open-circuit voltage, typically floating between 0.5V and 0.6V. Since this output is inadequate for standard power applications, numerous cells are linked electrically in series to construct larger, practical devices called PV panels or modules. As an illustration, properly charging a conventional 12V lead-acid battery demands an input near 14V; thus, connecting 36 cells in series became an industry-standard format for simple battery charging operations.

To shield these sensitive electrical pathways from weathering, the cells are heavily encapsulated. Thin layers of Polyvinyl

Butyral (PVB) or Ethyl Vinyl Acetate (EVA) fuse the components, ensuring structural durability and moisture resistance. This internal matrix is conventionally sandwiched between a rugged polymer backsheet and a low-iron, high-transmittance tempered glass face. An anodized aluminum frame surrounds the perimeter to bolster mechanical resistance against heavy snow and wind forces.

For larger power demands, modules are aggregated into expansive arrays. Wiring multiple modules in series (linking negative to positive terminals sequentially) creates a “PV string,” which scales up the total system voltage while keeping the current stable. Alternatively, grouping strings in parallel (positive to positive, negative to negative) forms a broader “Solar Array.” This parallel wiring boosts total current capacity without altering the string voltage, allowing engineers to precisely match the array’s output to an inverter’s input thresholds.

### *C. PV Materials and Market Dominance*

Presently, silicon is the leading material in the commercial solar sector, representing roughly 85% of global solar cell fabrication. Silicon-based setups are praised for their robust longevity, regularly achieving lifespans beyond 30 years. They also demonstrate an excellent energy payback window of roughly 2 to 8 years, indicating that the modules generate more power early in their life cycle than the total energy expended to manufacture them.

Commercial silicon cells generally fall into two categories: Poly-crystalline (multi-crystal) and Mono-crystalline (single-crystal). Mono-crystalline variations are sliced from a unified crystal ingot, yielding superior conversion efficiencies and smaller spatial footprints, though they incur higher manufacturing expenses. Poly-crystalline alternatives are cast by fusing various silicon shards; this method slightly reduces overall efficiency but significantly lowers production costs.

## II. PHOTOVOLTAIC PERFORMANCE AND ENVIRONMENTAL FACTORS

The energy yield of a PV module is intrinsically tied to the solar resources it intercepts.

### *A. Environmental Factors*

- **Solar Irradiance:** This metric defines the intensity of solar power striking a planar surface, quantified in Watts per square meter.
- **Solar Insolation:** Insolation quantifies the cumulative solar irradiance collected by a PV surface over a specific timeframe, typically denoted as kWh/m$^2$/day, widely known as Peak Sun Hours (PSH). For instance, an ideal 1kW array situated in a region experiencing 5 PSH will yield roughly $1\text{kW} \times 5\text{h} = 5\text{kWh}$ of raw daily energy, excluding systemic losses.
- **Orientation and Tilt:** Orientation dictates the compass heading the panels face (e.g., true south in the Northern Hemisphere), whereas tilt refers to the angular elevation of the modules relative to a flat horizon.
- **Shading:** Obstruction of sunlight is a dominant factor in array efficiency degradation. Even the minor partial shading of a single cell within a 36-cell module can trigger disproportionately massive power drops.

### *B. Electrical Characteristics, P-V and I-V Curves*

Standard solar cells yield a resting open-circuit voltage near 0.5 to 0.6 volts when isolated from a load. Manufacturers provide distinct current-voltage (I-V) diagrams illustrating the specific current and voltage coordinates where optimal power is realized.

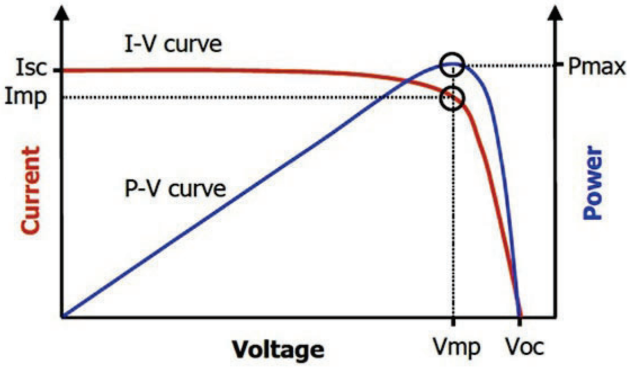

Fig. 1. Representative Current-Voltage (I-V) and Power-Voltage (P-V) Profiles for a PV Module.

- **Short Circuit Current** ($I_{sc}$)**:** The absolute maximum current a PV module can emit, occurring when external circuit resistance drops to zero.
- **Open Circuit Voltage** ($V_{oc}$)**:** The maximum voltage recorded when the module operates with an infinite resistance (no connected load), resulting in zero current flow.
- **Maximum Power Point** ($P_{max}$)**:** The precise operational coordinate where the module yields its highest possible power output, calculated as $P_{max} = I_{max} \times V_{max}$.

### *C. Temperature, Intensity and Efficiency Constraints*

Increased photon density elevates the cell’s current output while voltage remains largely static. Conversely, high operational temperatures drastically impair performance. Under peak solar exposure, the array’s voltage drops by approximately 5% for every 25°C surge above baseline cell temperature.

Real-world output is further diminished by numerous operational losses, as summarized in Table I.

## III. PV SYSTEM CONFIGURATIONS

### *A. Grid-Connected Systems*

In grid-tied PV architectures, the solar arrays interface directly with a synchronized inverter feeding into the municipal power grid, avoiding the need for localized battery storage. When localized generation exceeds immediate consumption, the surplus energy flows back into the broader utility grid, a transaction often credited to the user via “Net Metering.”

TABLE I
PRIMARY CAUSES OF ARRAY OUTPUT REDUCTIONS

| Loss Factor | Estimated Loss (%) | De-rating Factor |
|---|---|---|
| Thermal/Temperature | 10% | 0.90 |
| Soiling/Dirt | 3% | 0.97 |
| Manufacturer's Tolerance | 3% | 0.97 |
| Shading | 2% | 0.95 |
| Orientation/Tilt Angle | 1% | 0.99 |
| Wiring Voltage Drop | 2% | 0.98 |

- **Benefits:** Lowers reliance on grid energy, demands less physical space (no batteries), and lowers upfront capital costs.
- **Drawbacks:** Fails to provide electricity during active municipal grid outages.

### *B. Off-Grid (Stand-Alone) Systems*

Stand-alone configurations operate independently from centralized utility networks. They rely on deep-cycle battery banks—usually lead-acid—to stockpile harvested solar energy. These systems utilize automated charge controllers to regulate array outputs, ensuring optimal battery charging profiles without pushing the cells into dangerous overcharge states.

- **Benefits:** Grants total energy autonomy and is highly effective for isolated geographical zones.
- **Drawbacks:** Necessitates oversized system capacities to guarantee availability, incurs much higher hardware expenses, and poses the risk of total power depletion during prolonged cloudy periods.

## IV. INVERTERS AND CHARGE CONTROLLERS

### *A. Inverters (Power Conditioning Units)*

The primary role of an inverter is the seamless transformation of direct current (DC) into usable alternating current (AC).

- **Power Conversion Efficiency:** State-of-the-art units boast laboratory efficiencies up to 94%, though practical environmental conditions typically yield an operational efficiency range of 88% to 92%.
- **Surge Capacity:** Robust inverters are engineered to handle brief overloads beyond their continuous rating, safely accommodating the inrush currents generated by inductive AC loads like electric motors.
- **Maximum Power Point Tracking (MPPT):** Integrated MPPT algorithms dynamically fine-tune the electrical operating point of the array, ensuring it runs at maximum thermodynamic efficiency regardless of shifting sun angles.
- **Installation Constraints:** Inverters should never share enclosed compartments with battery banks. The corrosive hydrogen gas released by charging lead-acid batteries can degrade internal circuitry, and the active switching components within the inverter create a profound ignition hazard.

### *B. Charge Controllers*

For off-grid environments utilizing storage, a solar charge regulator (charge controller) is mandatory. It acts as a gatekeeper, preventing severe overcharging—which violently boils battery electrolytes and ruins cells—while also halting extreme depletion cycles that permanently degrade the battery's chemical lifespan.

*1) Operational Mechanics:* Controllers dictate current flow based on the real-time "State-of-Charge" (SOC) of the battery bank. Once optimal charge levels are reached, the device throttles or fully disconnects the incoming array power. If battery reserves plummet below a defined safety threshold, a Low Voltage Disconnect (LVD) relay triggers, shedding electrical loads to prevent damage. Advanced models leverage MPPT technology to bridge the voltage gap between the PV array and the battery bus, ensuring the highest possible amperage delivery.

*2) Types of Charge Controllers:*

- **Shunt Controllers:** Employ a parallel regulating switch to short the array when the batteries hit maximum charge. They require robust heat sinks to safely shed excess current as thermal energy.
- **Series Controllers:** Interrupt the physical circuit path when high-voltage limits are triggered. They are typically compact, budget-friendly, and capable of managing heavy electrical loads.
- **Pulse Width Modulation (PWM):** Instead of binary on/off switching, PWM technology rapidly tapers the input current. This holds the battery voltage steady during the final absorption stages, minimizing electrolyte loss.
- **Multistage Controllers:** Employ variable current and voltage phases based on the battery's changing SOC, maximizing both charging speed and battery lifespan.

*3) Selection Criteria:* Correctly sizing a controller demands careful review of system specs:

- **Voltage and Current Handling:** The device's input tolerances must safely exceed the maximum short-circuit current and open-circuit voltage generated by the interconnected arrays.
- **Battery Interaction:** Charge parameters must be precisely matched to the battery chemistry. For example, a 12V flooded lead-acid bank may demand a bulk charge of 15.0V, while a sealed AGM battery must be strictly capped at 14.1V to stop it from drying out.
- **Temperature Compensation:** Optimal charging voltages shift inversely with ambient temperatures. In regions facing thermal fluctuations beyond 17°C, active temperature monitoring is critical to prevent aggressive overcharging in the heat or sluggish charging in the cold.
- **Preventing Undercharge:** Lacking thermal sensors, a controller in a freezing environment will prematurely throttle the charging current. This results in chronic undercharging, which rapidly leads to terminal plate sulfation.

## V. BATTERIES AND STORAGE

Storage systems buffer the disparity between solar generation hours and actual consumption times.

- **Lead-Antimony Batteries:** Highly resilient to mechanical shock and capable of deep cycling, though they exhibit rapid self-discharge and mandate strict, routine water maintenance.
- **Lead-Calcium Batteries:** Deliver reliable deep-cycle capabilities with the added benefits of prolonged lifespans and drastically reduced watering requirements.
- **Nickel-Cadmium Batteries:** Boast exceptional longevity, high tolerance to full depletion, and superior performance in freezing conditions; however, they require a substantially higher capital investment.

## VI. DESIGN, SIZING, AND MODEL CALCULATIONS

Engineering an off-grid setup requires sequential planning: assessing daily load, sizing the inversion equipment, specifying the battery bank, calculating the total array wattage, and selecting an appropriate regulator.

The following mathematical sizing represents a hybrid wind-solar facility engineered to satisfy a 936Wh daily load profile (comprising two 18W CFL bulbs and two 60W fans operating 6 hours daily). The energy generation relies equally on solar PV (468Wh) and wind generation (468Wh).

### A. Array and Turbine Capacity Estimation

**Solar PV Component**:

$$P_{\text{actual}} = 40\text{W} \times 0.75 = 30\text{W} \tag{1}$$

$$P_{\text{end\_use}} = 30\text{W} \times 0.81 = 24.3\text{W} \tag{2}$$

$$E_{\text{per\_panel}} = 24.3\text{W} \times 8\text{h} = 194.4\text{Wh} \tag{3}$$

$$\text{Panels needed} = \frac{468\text{Wh}}{194.4\text{Wh}} \approx 2.41 \implies 3 \text{ panels} \tag{4}$$

$$\text{Total PV Cap.} = 3 \times 40\text{W} = 120\text{W} \tag{5}$$

**Wind Turbine Component**:

$$P_{\text{actual}} = 100\text{W} \times 0.70 = 70\text{W} \tag{6}$$

$$P_{\text{end\_use}} = 70\text{W} \times 0.81 = 56.7\text{W} \tag{7}$$

$$E_{\text{per\_turbine}} = 56.7\text{W} \times 10\text{h} = 567\text{Wh} \tag{8}$$

$$\text{Total Wind Cap.} = 100\text{W (1 turbine needed)} \tag{9}$$

### B. Inverter and Battery Bank Sizing

$$\text{Inverter Input} = \frac{156\text{W}}{0.9} \approx 173.3\text{W} \implies \text{Select 200VA} \tag{10}$$

$$E_{\text{battery\_req}} = \frac{936\text{Wh}}{0.81} \approx 1155.6\text{Wh} \tag{11}$$

$$\text{Battery Capacity} = \frac{1155.6\text{Wh}}{12\text{V} \times 0.5 \times 0.9} \approx 213.9\text{Ah} \tag{12}$$

Selected storage baseline: A single 220Ah, 12V battery array to provide 1 day of system autonomy.

Financial estimations for this hybrid design equal approximately Rs. 77,700. This includes PV modules (Rs. 24,000), wind generation (Rs. 30,000), chemical storage (Rs. 15,000), AC inversion (Rs. 5,000), alongside a 5% auxiliary buffer for electrical routing and hardware (Rs. 3,700).

## REFERENCES

[1] H. Yang, L. Lu, and W. Zhou, "A novel optimization sizing model for hybrid solar-wind power generation system," *Solar Energy*, vol. 81, no. 1, pp. 76–84, 2007.

[2] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Transactions on Industry Applications*, vol. 41, no. 5, pp. 1292–1306, 2005.

[3] International Electrotechnical Commission, *IEC 62109-1: Safety of power converters for use in photovoltaic power systems*, Geneva, Switzerland, 2010.

[4] C. S. Solanki, *Solar Photovoltaics: Fundamentals, Technologies and Applications*, 3rd ed., PHI Learning Pvt. Ltd., New Delhi, 2015.

[5] B. S. Borowy and Z. M. Salameh, "Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system," *IEEE Transactions on Energy Conversion*, vol. 11, no. 2, pp. 367–375, 1996.