Solar Power Project Development

One week training course certified by NISE

Solar PV System Description

Organizers
Firstgreen Consulting Pvt Ltd
MNIT Jaipur
Typical Utility-Scale PV Plant

PVCS (Photovoltaic Combining SWGR)

Array 1

Array 2

Array 4

Array 6

Array 8

Array 7

Array 9

Array 10

PCS (Power Conversion Station) c/o Inverters, Fuse Box and Step Up XFMRS
PV Module

Arrays

1000V (DC)

300 to 690V (AC)

34.5kV (AC) typical
4.16 to 27.6kV (AC) alternatives

69 to 745kV (AC)
DC Array

1 Row = \(~50\text{kWdc}\)

\(~1.6\text{ MWac}\)

\(~530\text{ Ft}\)

\(~744\text{ Ft}\)
Combiner Box

- Aggregates DC wiring from multiple strings
- Provides single output to inverter
Inverter

- Converts DC power to AC (low voltage)
Transformer

- Increases low AC voltage to medium AC voltage

300 to 690V (AC)

34.5kV (AC) typical
4.16 to 27.6kV (AC) alternatives
Power Conversion Station

- Houses inverters and other components
Power Conversion Station (PCS) – Inverter & Step-up Transformer
Photovoltaic Combining Switchgear (PVCS)

- Aggregates AC power from multiple transformers

Photovoltaic Combining Switchgear

34.5kV (AC) typical
4.1 to 12.45kV (AC) alternatives

300 to 690V (AC)
Substation and Generator Tie-line

- Provides plant controls, disconnects, and step up transformer
- Delivers electricity to the grid
Meteorological & Other Instrumentation

- Plane of Array & Global Horizontal Solar Irradiance — Accuracy: +/- 2%
- Temperature — Accuracy: +/- .3°C
- Humidity — Accuracy: +/- 2%
- Wind Speed — Accuracy: +/- 2.0%
- Wind Direction — Accuracy: +/- 3.0%
- Barometric Pressure
- Rainfall

- Energy Meter at Various Levels

- Reference Module (~3 per block)
- Module Surface Temperature Sensors
- DC Current Transducer
Plant SCADA System (FSPS)

- Manages real time data of all plant equipment
- Provides user interface for access to:
  - Key operation & performance indicators
  - Status of components
  - Plant operation
  - System/component troubleshooting
- Reporting system for historical data
- Provides remote access

Access to Operational Data

Power Conversion Station (PCS)

Historical Data

SQL Server

Real Time Data Server

Authentication, Authorization and Accounting

Access to Real Time & Historical Data

SCADA HMI

Plant Network

Real Time Data

SCADA Commands

DAS/PLC
Energy yield values represent preliminary estimates based on PVSyst model output for Ahmedabad, India location using standard module manufacturer assumptions and default PVSyst configuration settings; assumes FS-4107-2 module compared to other leading manufacturers modules by technology type.

<table>
<thead>
<tr>
<th>Category</th>
<th>CdTe Thin-Film</th>
<th>Multi C-Si</th>
<th>Mono C-Si</th>
<th>Thin –Film a-Si</th>
<th>CIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module Efficiency (@ STC)</td>
<td>15%</td>
<td>14-16%</td>
<td>15-18%</td>
<td>6-8%</td>
<td>7-14%</td>
</tr>
<tr>
<td>Temp. Coefficient</td>
<td>-0.34%/°C</td>
<td>-0.4% to -0.5%/°C</td>
<td>-0.4% to -0.5%/°C</td>
<td>-0.2% to -0.3%/°C</td>
<td>-0.3% to -0.4%/°C</td>
</tr>
<tr>
<td>Annual Degradation</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.8-1.5%</td>
<td>1%</td>
</tr>
<tr>
<td>Initial Field Power</td>
<td>~3% or less drop in power output in initial months – already compensated in nameplate ratings</td>
<td>~4% or less drop in power output (Light Induced Degradation) – not always compensated in ratings</td>
<td>~4% or less drop in power output (Light Induced Degradation) – not always compensated in ratings</td>
<td>~10% to 25% drop in power output (Light Induced Degradation) – typically compensated in nameplate ratings</td>
<td>Varies significantly based on process and manufacturer.</td>
</tr>
<tr>
<td>Shading</td>
<td>FS module power loss is proportional to shading: 10% shading equals 10% output loss</td>
<td>Typical C-Si Power Loss: 10% shading equals 30% energy output loss</td>
<td>Typical C-Si Power Loss: 10% shading equals 30% energy output loss</td>
<td>Comparable to CdTe</td>
<td>Comparable to CdTe</td>
</tr>
<tr>
<td>Energy Yield¹</td>
<td>1799 kWh/kWpDC/yr</td>
<td>1662 kWh/kWpDC/yr</td>
<td>1666 kWh/kWpDC/yr</td>
<td>1715 kWh/kWpDC/yr</td>
<td>1781 kWh/kWpDC/yr</td>
</tr>
<tr>
<td>Energy Density</td>
<td>120.4 GWh/km²</td>
<td>110.7 GWh/km²</td>
<td>125.9 GWh/km²</td>
<td>53.7 GWh/km²</td>
<td>110.5 GWh/km²</td>
</tr>
</tbody>
</table>
Basic Characteristics of System Sizing
Solar Insolation

Irradiance: Intensity of Solar energy \( \text{kW/m}^2 \)

Insolation: Quantity of Solar energy \( \text{kWh/m}^2 \)

Max. Irradiance per day
(1.09 kW/m\(^2\))

Irradiance at 9:30 am
(0.8 kW/m\(^2\))

Insolation per day
(7.7 kWh/m\(^2\))
Daily insolation

Solar Energy changes daily

<table>
<thead>
<tr>
<th>Condition</th>
<th>Insolation</th>
<th>Peak sun hours</th>
<th>Available power (@100Wp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunny</td>
<td>7.7 kWh/m²</td>
<td>7.7 h</td>
<td>492 Wh</td>
</tr>
<tr>
<td>Sunny</td>
<td>5.4 kWh/m²</td>
<td>5.4 h</td>
<td>345 Wh</td>
</tr>
<tr>
<td>Cloudy</td>
<td>5.7 kWh/m²</td>
<td>5.7 h</td>
<td>364 Wh</td>
</tr>
<tr>
<td>Cloudy</td>
<td>3.3 kWh/m²</td>
<td>3.3 h</td>
<td>211 Wh</td>
</tr>
<tr>
<td>Rain</td>
<td>0.6 kWh/m²</td>
<td>0.6 h</td>
<td>38 Wh</td>
</tr>
</tbody>
</table>

Power Generation changes daily
IV Curve

**I-V Curve**
- $I_{sc}$ (Short circuit current)

**Power Curve**
- $I_{mp}$ (Max. power current)
- $V_{mp}$ (Max. power voltage)
- $P_m$ (Max. Power Point)
- $V_{oc}$ (Open circuit voltage)

Voltage (V) vs. Current (A)
Characteristics of an IV Curve

- I-V curve changes depending on temperature

Voc(t) = Voc + α (t – 25)
α = -2.2 [mV/°C] x Number of cells

Voc(t) = ?
t = 75 °C, 36 cells, Voc = 21.7 [V]

Voc(75) = Voc + α (75 – 25)
= 21.7 - 0.0022 * 36 * 50
= 17.74 [V]
Characteristics of an IV Curve

- I-V curve changes depending on irradiance

\[ \text{Isc(IRR)} = \frac{\text{Isc} \times \text{irr}}{1.0} \] (irr: irradiance [kW/m²])

Isc: Short circuit current at STC

\[ \text{Isc}(0.8) = \text{Isc} \times 0.8 / 1.0 \]
\[ = 7.5 \times 0.8 \]
\[ = 6.0 \text{ [A]} \]
Series connection of PV cells

PV module

36 cells in series
Parallel Connection of a PV cell
Series and Parallel Connections

PV module

Diagram of series and parallel connections with current (A) and voltage (V) values and power (W) shown.

Series connection: 15A, 720W
Parallel connection: 10A, 640W

80W at 21V
5A at 63V

Estimating the output power

\[
\text{Output from PV module (DC Electricity)} = 7.7 \text{ kW/m}^2/\text{day} \times 7.7 \text{ h/day} \times 150 \text{ W} \times 0.8 = 924 \text{ Wh/day}
\]
Effect of Shadow

PV cell

I-V Curve
0.6V

PV cell

I-V Curve
0.6V

PV module

I-V Curve
21.6V

PV module

I-V Curve
21.6V

?
By Pass Diode

2 diodes are factory built-in each PV module

Bypass diode

- Bypass diodes have no role at normal operation (under clean surface, no shading)
- In case cell(s) have less output current such as shading, bird droppings, it will bypass the current.
• Mono-crystalline wafers are sliced from a large single crystal ingot in a relatively expensive process.
• Cheaper, multi-crystalline wafers may be made by a variety of techniques.
• One of the technologies involves the carefully controlled casting of molten poly-silicon, which is then sliced into wafers.
Crystalline wafers provide high efficiency solar cells but are relatively costly to manufacture. In comparison, thin film cells are typically cheaper due to both the materials used and the simpler manufacturing process.

The most well-developed thin film technology uses silicon in its less ordered, non-crystalline (amorphous) form.

Other technologies use cadmium telluride and copper indium (gallium) di-selenide with active layers less than a few microns thick. In general, thin film technologies have a less established track record than many crystalline technologies.
CdTe has superior temperature coefficient. CdTe responds to sunlight differently than typical crystalline silicon technologies and has less temperature-related losses. As a result, CdTe modules produce more energy than competing solar systems with the same power rating.
Silicon Hetero Junction (SHJ)

- The silicon heterojunction (SHJ) are silicon solar cells with high efficiency at low temperatures (<250°C) with simple processing.
- Well-designed a-Si:H emitters superior to conventional emitters
- A back collector with very effective back-surface field that reduces the recombination velocity
- No localized current conduction windows are needed, in contrast to dielectric back-surface passivation layers.
• Amorphous silicon cells degrade through a process called the Staebler – Wronski Effect.
• This degradation can cause reductions of 10-30% in the power output of the module in the first six months of exposure to light. Thereafter, the degradation stabilises and continues at a much slower rate.
• The performance of the modules may tend to recover during the summer months, and drop again in the colder winter months.
• Additional degradation for both amorphous and crystalline technologies occurs at the module level and may be caused by:
  – Effect of the environment on the surface of the module (for example pollution).
  – Discolouration or haze of the encapsulates or glass.
  – Lamination defects.
  – Mechanical stress and humidity on the contacts.
  – Cell contact breakdown.
  – Wiring degradation.
• Depending on the site and precise characteristics of the solar irradiation, trackers may increase the annual energy yield by up to 27% for single-axis and 37% for dual-axis trackers.
• Almost all tracking system plants use crystalline silicon modules. This is because their higher efficiency reduces additional capital and operating costs required for the tracking system (per kWp installed).
• High wind capability and storm mode: dual-axis tracking systems especially need to go into a storm mode when the wind speed is over 16-20 m/s. This could reduce the energy yield and revenues at high wind speed sites.

• Direct/diffuse irradiation ratio: tracking systems will give greater benefits in locations that have a higher direct irradiation component.
Radiation Gain record of a typical tracker system

Normalized productions (per installed kWp): Nominal power 1000 kWp

Monthly Radiation Gain

Accumulated annual gain is 43.6%
Central inverters

- Central inverters offer high reliability and simplicity of installation. However, they have disadvantages: increased mismatch losses and absence of maximum power point tracking (MPPT) for each string.
- This may cause problems for arrays that have multiple tilt and orientation angles, suffer from shading, or use different module types.
- Central inverters are usually three-phase and can include grid frequency transformers.
- Central inverters are sometimes used in a “master slave” configuration.

String Inverters

- String inverters, which are usually in single phase
- In comparison, the failure of a large central inverter—with a long lead time for repair—can lead to significant yield loss before it can be replaced.
• In the case of transformer – less string inverters, the PV generator voltage must either be significantly higher than the voltage on the AC side, or DC-DC step-up converters must be used.

• The absence of a transformer leads to higher efficiency, reduced weight, reduced size (50-75% lighter than transformer-based models and lower cost due to the smaller number of components.

• On the downside, additional protective equipment must be used, such as DC sensitive earth-leakage circuit breakers (CB)

• Inverters with transformers provide galvanic isolation. Central inverters are generally equipped with transformers.

• In general, one of the quantities used to describe the quality of a grid-connected inverter is total harmonic distortion (THD).

• It is a measure of the harmonic content of the inverter output and must be limited in most grid codes.
Inverters can have a typical European Efficiency of 95% and peak efficiencies of up to 98%. Most inverters employ MPPT algorithms to adjust the load impedance and maximise the power from the PV array. The highest efficiencies are reached by transformer–less inverters.

\[ n_{Con} = \frac{P_{AC}}{P_{DC}} = \frac{\text{(Fundamental component of AC power output)}}{\text{(DC power input)}} \]
Sizing of the PV plant

- Layout in the land area available
- Appropriate buffer zone around the plant to account for shading / other activities
- Overall size appropriate for the grid connection as per the policy
The performance ratio of a photovoltaic system is the quotient of alternating current (AC) yield and the nominal yield of the generator’s direct current (DC).

It indicates which portion of the generated current can actually be used. A photovoltaic system with a high Efficiency can achieve a performance ratio over 70%.

The performance ratio is also often called the Quality Factor (Q). A Solar Module based on crystalline cells can even reach a quality factor of 0.85 to 0.95 (performance ratio = 85 - 95%).

\[
PR = \frac{(AC \text{ Yield (kWh)})}{(Installed \text{ Capacity (kWp)} \times \text{Plane of Array Irradiation(kWh/m}^2)) \times 100\%}
\]
Capacity Factor

• The capacity factor of a PV power plant (usually expressed as a percentage) is the ratio of the actual output over a period of one year and its output if it had operated at nominal power the entire year.

• \[ \text{CF} = \frac{\text{Energy generated per annum (kWh)}}{8760 \times \text{Installed Capacity (kWp)}} \]
The “specific yield” (kWh/kWp) is the total annual energy generated per kWp installed. It is often used to help determine the financial value of an array and compare operating results from different technologies and systems.

The specific yield of a plant depends on:
• The total annual irradiation falling on the collector plane.
• The performance of the module, including sensitivity to high temperatures and low light levels.
• System losses including inverter downtime.
### Module Technical Specifications

<table>
<thead>
<tr>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
</tr>
<tr>
<td>Module Model</td>
</tr>
<tr>
<td>Nominal Power ($P_{MPP}$)</td>
</tr>
<tr>
<td>Power Tolerance</td>
</tr>
<tr>
<td>Voltage at $P_{MAX}$ ($V_{MPP}$)</td>
</tr>
<tr>
<td>Current at $P_{MAX}$ ($I_{MPP}$)</td>
</tr>
<tr>
<td>Open Circuit Voltage ($V_{OP}$)</td>
</tr>
<tr>
<td>Short Circuit Current ($I_{SC}$)</td>
</tr>
<tr>
<td>Maximum System Voltage</td>
</tr>
<tr>
<td>Module Efficiency</td>
</tr>
<tr>
<td>Operating Temperature</td>
</tr>
<tr>
<td>Temperature Coefficient of $P_{MPP}$</td>
</tr>
<tr>
<td>Dimensions</td>
</tr>
<tr>
<td>Module Area</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Maximum Load</td>
</tr>
<tr>
<td>Product Warranty</td>
</tr>
<tr>
<td>Performance Guarantee</td>
</tr>
</tbody>
</table>

**Electrical Characteristics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power at STC ($P_{MAX}$)</td>
<td>36.8 W</td>
</tr>
<tr>
<td>Optimum Operating Voltage ($V_{OPT}$)</td>
<td>45.2 V</td>
</tr>
<tr>
<td>Optimum Operating Current ($I_{OPT}$)</td>
<td>5.20 A</td>
</tr>
<tr>
<td>Short-Circuit Voltage ($I_{SC}$)</td>
<td>41.3 V</td>
</tr>
<tr>
<td>Short-Circuit Current ($I_{SC}$)</td>
<td>4.30 A</td>
</tr>
</tbody>
</table>

**Mechanical Characteristics**

- **Solar Cell**: Monocrystalline silicon (200 Wp)
- **No. of Cells**: 36 (6 x 6)
- **Dimensions**: 1560 x 660 x 30 mm (61.4 x 25.9 x 1.2 in)
- **Weight**: 13.2 kg (29.1 lbs)
- **Front Glass**: 3.2 mm (0.13 inch) tempered glass
- **Frame**: Anodized aluminum alloy
- **Junction Box**: IP67 sealed
- **Output Cables**: 4.0 mm² (0.06 inch²), symmetrical lengths (1000 mm (39.4 inches) and 1000 mm (39.4 inches)
- **Connectors**: MC4 connectors

**Temperature Characteristics**

- **Nominal Operating Curve Temperature (NOCT)**: 45°C ± 2°C
- **Temperature Coefficient of $P_{MPP}$**: -0.43% /°C
- **Temperature Coefficient of $I_{MPP}$**: -0.24% /°C
- **Temperature Coefficient of $V_{MPP}$**: 0.004% /°C

**Packing Configuration**

<table>
<thead>
<tr>
<th>Container</th>
<th>36 GP</th>
<th>40 GP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pieces per pallet</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Pallets per container</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Pieces per container</td>
<td>312</td>
<td>312</td>
</tr>
</tbody>
</table>
Cable Sizing

The cable voltage rating
- The voltage limits of the cable—to which the PV string or array cable will be connected—must be taken into account.
- Calculations of the maximum VOC voltage of the modules, adjusted for the site minimum design temperature, are used for this calculation.

The current carrying capacity of the cable
- The cable must be sized in accordance with the maximum current. It is important to remember to de-rate appropriately, taking into account the location of cable, the method of laying, number of cores and temperature. Care must be taken to size the cable for the worse case of reverse current in an array.

The minimisation of cable losses
The cable voltage drop and the associated power losses must be as low possible. Normally, the voltage drop must be less than 3%, but national regulations must be consulted for guidance. Cable losses of less than 1% are achievable.

\[ \text{Minimum Voltage Rating} = V_{oc(STC)} \times M \times 1.15 \]
\[ \text{Minimum Current Rating} = I_{sc(STC)} \times N \times 1.25 \]
Cable Sizing

- Voltage Drop = Current x Cable Resistant
- Voltage Drop is a power loss in cable
  - Current=10A, Vdrop=1V — 10W loss
  - Current=20A, Vdrop=2V — 40W loss
  \[ P(W) = I(A) \times E(V) = I^2(A) \times R(\Omega) \]
- Cable Resistance is determined by Size and Length
- Current is determined by
  \[ \frac{[PV \text{ capacity or Load}]}{[System Voltage]} \]
  - 1kW / 12V = 83.3A
  - 1kW / 120V = 8.3A

- To reduce voltage drop
  - Use of thicker cable
  - Minimize the cable length
  - Use of higher system voltage to reduce current

- Voltage Drop is critical in low voltage system, especially 12V system
Inverter Sizing

Inverter

• Project specifics such as the solar resource and module tilt angle play a very important role when choosing a design.

• Voltage, Capacity, ambient conditions and grid code should be considered while deciding specs of Inverter.

**Rule of thumb has been to use an inverter-to-array power ratio less than unity**

• The optimal sizing is, therefore, dependent on the specifics of the plant design. Most plants will have an inverter sizing range within the limits defined by:

\[
\text{Power Ratio} = \frac{P_{\text{Inverter DC rated}}}{P_{\text{PV Peak}}} = \frac{P_{\text{Inverter AC rated}}}{n_{100\%}}
\]
## Inverter Sizing Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid code</td>
</tr>
<tr>
<td>Product reliability</td>
</tr>
<tr>
<td>Module supply</td>
</tr>
<tr>
<td>Maintainability and serviceability</td>
</tr>
<tr>
<td>System availability</td>
</tr>
<tr>
<td>Modularity</td>
</tr>
<tr>
<td>Shading conditions</td>
</tr>
</tbody>
</table>
# Inverter Specifications

<table>
<thead>
<tr>
<th>Model</th>
<th>XXX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>XXX</td>
</tr>
<tr>
<td>Type (e.g. string, central, etc)</td>
<td>String</td>
</tr>
</tbody>
</table>

## DC
- **Maximum power**: 21.2 kW
- **MPPT range**: 480…800 V
- **Maximum voltage**: 1000 V
- **Maximum current**: 41 A

## AC
- **Rated power**: 19.2 kW
- **Maximum power**: 19.2 kW
- **Grid connection**: 3 AC 400 V + N, 50 – 60 Hz
- **Maximum current**: 29 A
- **Corr (DPF)**: 1 (+0.9 on demand)
- **THD**: <2.5%
- **Maximum efficiency**: 98.2%
- **European efficiency**: 97.8%
- **Internal consumption during night-time**: <0.5 W

<table>
<thead>
<tr>
<th>Transformer present</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling</td>
<td>Natural convection</td>
</tr>
<tr>
<td>Dimensions (W x H x D)</td>
<td>530 x 601 x 277 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>41 kg</td>
</tr>
<tr>
<td>Working environment</td>
<td>-25…+55°C, up to 2000 m above sea level (ASL)</td>
</tr>
<tr>
<td>IP rating</td>
<td>IP 65 as per EN 60259</td>
</tr>
<tr>
<td>Warranty</td>
<td>3 years (basic); can be extended to 20 years</td>
</tr>
<tr>
<td>Standards compliance</td>
<td>EN 61000-6-4:2007, EN 61000-6-2:2005, DIN IEC 721-3-3, VDE 0126-1-1</td>
</tr>
<tr>
<td>Certificates</td>
<td>CE, UL, CSA</td>
</tr>
</tbody>
</table>

**Efficiency**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power factor at nominal power</td>
<td>1</td>
</tr>
<tr>
<td>Inverter peak efficiency</td>
<td>96.8%</td>
</tr>
<tr>
<td>CEC efficiency at 208 V nominal value</td>
<td>95.0%</td>
</tr>
<tr>
<td>CEC efficiency at 240 V nominal value</td>
<td>95.5%</td>
</tr>
</tbody>
</table>

**SB 3000US**

![Efficiency curve SB 3000US/3000US-12](image)
Transformer Sizing

• The required size of the transformer, its position within the electrical system, and the physical location of installations should be considered.
• The size of the transformer, which will depend on the projected maximum power exported from the solar array, should be specified in MVA.
• Power would generally be expected to flow from the solar arrays to the grid. To prepare for the reverse case (a need to supply power back to the plant), this should be specified or an auxiliary transformer used.
• The position of the transformer in the electrical system will define the required voltage levels on the primary and secondary sides of the transformer.
• Tertiary supplies for substation auxiliary services and/or harmonic mitigation should also be considered.
Thank You

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