much more significant downtime. Availability statistics should be requested from the network operator to establish the expected downtime of the network.

- **Capacity:** The capacity of the grid to accept exported power from a solar plant will depend on the existing network infrastructure and current loading of the system. The substation and export line capacity needs to be appropriate for the capacity of the plant being developed. Where the grid network does not have sufficient existing capacity to allow connection, there are a number of solutions available:
    - Curtail the maximum power exported to within allowable limits of the network.
    - Upgrade the network to allow an increased export capacity.
    - Reduce the capacity of the proposed plant.

Initial investigation into the network connection point capacity can often be carried out by reviewing published data. However, discussions with the network operator will be required to fully establish the scope of work associated with any capacity upgrades. The network operator will provide details of the work required, along with cost implications. Certain aspects of a grid network upgrade can be carried out by third party contractors. Others must be conducted by the network operator alone. An early grid feasibility study is the starting point for assessing the suitability of the power evacuation arrangement. Power system studies can also be conducted to model the likely grid capacity.

6.3.10 ACCESS AND RIGHT OF WAY (ROW)

The site should allow access for trucks to deliver plant and construction materials. This may require the upgrading of existing roads or construction of new roads. The closer the site is to a main access road, the lower the cost of adding this infrastructure. At a minimum, access roads should be constructed with a closed-surface gravel chip finish or similar. The site entrance may also need to be constructed, widened or upgraded. Safe packaging of the modules and their susceptibility to damage in transport must also be carefully considered.

ROW is the agreement that allows the project developer's transmission lines to cross property owned by another individual or entity. In order to avoid ROW risks, which may impact on the project schedule, all land permits and agreements need to be planned well in advance (see Box 4 in Chapter 7, "Grid Connection Experience in India").

6.3.11 MODULE SOILING

The efficiency of the solar plant could be significantly reduced if the modules are soiled (covered) by particulates/dust. It is important to take account of local weather, environmental, human and wildlife factors while determining the suitability of a site for a solar PV plant. The criteria should include:

- Dust particles from traffic, building activity, agricultural activity or dust storms.
- Module soiling from bird excreta. Areas close to nature reserves, bird breeding areas and lakes should be particularly carefully assessed.

Soiling of modules will require an appropriate maintenance and cleaning plan and potentially keeping equipment at or close to the site.

6.3.12 WATER AVAILABILITY

Clean, low mineral content water is preferred for cleaning modules. A main water supply, ground water, stored water or access to a mobile water tank may be required; the cost of the various options will have an impact on the project economics. The degree to which water availability is an issue will depend upon the expected level of module soiling, the extent of natural cleaning due to rainfall and the cleaning frequency. The quantity of water required varies according to available cleaning technologies and the local climate, however approximately 1.6 litres per m^2 of PV modules may be required. In arid environments with adjacent communities, attention needs to be paid to existing groundwater reliance by local populations and the impact (if any) of proposed groundwater extraction on local water sources. This is especially important where there are multiple solar developments in close proximity, i.e., where there may be cumulative impacts on water availability that could adversely impact local populations.

6.3.13 FINANCIAL INCENTIVES

Financial incentives such as FiTs or tax breaks, which vary by country and sometime regions within countries, have a strong bearing on the financial viability of a project (see also Section 14 on Financing Solar PV Projects). Such incentives could outweigh the costs associated with one or more of the site selection constraints.

In countries where there are significant incentives (i.e., high FiTs) that override otherwise very unfavourable economic conditions, developers should be cautious and consider the sustainability of those incentives. The potential impacts on the project should be considered should these incentives be withdrawn at any stage. It should be noted that incentives are not site-specific, but are typically dependant on the country or state in which the project is located.

Site Selection Checklist

The checklist below details the basic requirements and procedures to assist developers with the site selection process.

☐ Suitable land area identified for the scale of development proposed.

☐ Ownership of land determined.

☐ Current land use identified (e.g., industrial/agricultural/brownfield).

☐ Advice sought from regulatory authorities on land use restrictions.

☐ Solar resource assessed.

☐ Topographic characteristics obtained.

☐ Proximity to international, national and local environmental designations determined.

☐ Potential access routes to site assessed.

☐ Geotechnical survey completed.

☐ Grid connection assessed (capacity, proximity, right-of-way, stability and availability).

☐ Soiling risks assessed.

☐ Availability of water supply/ground water determined.

☐ GIS assessment of constraints (optional).

☐ Financial incentives identified.

7

Plant Design

7.1 PLANT DESIGN OVERVIEW

Designing a megawatt-scale solar PV power plant is an involved process that requires considerable technical knowledge and experience. There are many compromises that need to be made in order to achieve the optimum balance between performance and cost. This section highlights some of the key issues that need to be considered when designing a solar PV power plant.

For most large solar PV plants, reducing the levelised cost of electricity (LCOE) is the most important design criteria. Every aspect of the electrical system (and of the project as a whole) should be scrutinised and optimised. The potential economic gains from such an analysis are much larger than the cost of carrying it out.

It is important to strike a balance between cost savings and quality. Engineering decisions should be "careful" and "informed" decisions. Otherwise, design made with a view to reduce costs in the present could lead to increased future costs and lost revenue due to high maintenance requirements and low performance.

The performance of a solar PV power plant can be optimised by reducing the system losses. Reducing the total loss increases the annual energy yield and hence the revenue, though in some cases it may increase the cost of the plant. In addition, efforts to reduce one type of loss may conflict with efforts to reduce losses of a different type. It is the skill of the plant designer to make compromises that result in a plant with a high performance at a reasonable cost.

For plant design, there are some general rules of thumb. But specifics of project locations—such as irradiation conditions, temperature, sun angles and shading—should be taken into account in order to achieve the optimum balance between annual energy yield and cost.

Checklists of basic requirements and procedures for plant design considerations to assist solar PV plant developers during

For plant design, there are some general rules of thumb. But specifics of project locations—such as irradiation conditions, temperature, sun angles and shading—should be taken into account in order to achieve the optimum balance between annual energy yield and cost.

the development phase of a PV project are at the end of Chapter 7.

It may be beneficial to use simulation software to compare the impact of different module or inverter technologies and different plant layouts on the predicted energy yield and plant revenue.

The solar PV modules are typically the most valuable and portable components of a PV power plant. Safety precautions may include anti-theft bolts, anti-theft synthetic resins, CCTV cameras with alarms, and security fencing.

The risk of technical performance issues may be mitigated by carrying out a thorough technical due diligence exercise in which the final design documentation from the EPC contractor is scrutinised by an independent technical advisor.

7.2 LAYOUT AND SHADING

The general layout of the plant and the distance chosen between rows of mounting structures will be selected according to the specific site conditions. The area available to develop the plant may be constrained by space and may have unfavourable geological or topographical features. The aim of the layout design is to minimise cost while achieving the maximum possible revenue from the plant. In general this will mean:

- Designing row spacing to reduce inter-row shading and associated shading losses.
- Designing the layout to minimise cable runs and associated electrical losses.
- Creating access routes and sufficient space between rows to allow movement for maintenance purposes.
- Choosing a tilt angle and module configuration that optimises the annual energy yield according to the latitude of the site and the annual distribution of solar resource.
- Orientating the modules to face a direction that yields the maximum annual revenue from power production. In the northern hemisphere, this will be true south.[36] In the southern hemisphere, it is true north.

Computer simulation software may be used to help design the plant layout. Such software includes algorithms which describe the celestial motion of the sun throughout the year for any location on earth, plotting its altitude[37] and azimuth[38] angle on a sun path diagram. This, along with information on the module row spacing, may be used to calculate the degree of shading and simulate the annual energy losses associated with various configurations of tilt angle, orientation, and row spacing.

7.2.1 *GENERAL LAYOUT*

Minimising cable runs and associated electrical losses may suggest positioning a low voltage (LV) or medium voltage (MV) station centrally within the plant. If this option is chosen, then adequate space should be allocated to avoid the risk of the station shading modules behind it.

The layout should allow adequate distance from the perimeter fence to prevent shading. It should also incorporate access routes for maintenance staff and vehicles at appropriate intervals.

7.2.2 *TILT ANGLE*

Every location will have an optimal tilt angle that maximises the total annual irradiation (averaged over the whole year) on the plane of the collector. For fixed tilt grid connected power plants, the theoretical optimum tilt angle may be calculated from the latitude of the site. However, adjustments may need to be made to account for:

- **Soiling:** Higher tilt angles have lower soiling losses. The natural flow of rainwater cleans modules more effectively and snow slides off more easily at higher tilt angles.

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[36] True south differs from magnetic south, and an adjustment should be made from compass readings.

[37] The elevation of the sun above the horizon (the plane tangent to the Earth's surface at the point of measurement) is known as the angle of altitude.

[38] The azimuth is the location of the sun in terms of north, south, east and west. Definitions may vary but 0° represents true south, -90° represents east, 180° represents north, and 90° represents west.

- **Shading:** More highly tilted modules provide more shading on modules behind them. As shading impacts energy yield much more than may be expected simply by calculating the proportion of the module shaded, a good option (other than spacing the rows more widely apart) is to reduce the tilt angle. It is usually better to use a lower tilt angle as a trade-off for loss in energy yield due to inter-row shading.
- **Seasonal irradiation distribution:** If a particular season dominates the annual distribution of solar resource (monsoon rains, for example), it may be beneficial to adjust the tilt angle to compensate for the loss. Simulation software is able to assess the benefit of this option.

7.2.3 PV MODULE CONFIGURATION

The effect of partial shading of the PV modules on electrical production of the PV plant is non-linear due to the way that diodes are interconnected within a PV module and how modules are connected together in a string. Different types of technology will react differently to the electrical shading effect caused by near-shading obstacles and inter-row shading. For example, some thin-film modules are less affected by partial shading than crystalline technologies.

The modules' configuration (i.e., landscape or portrait) and the ways strings are connected together will also impact how the system experiences electrical shading effects. Modules installed in a landscape configuration will typically have smaller electrical shading losses than a system using a portrait configuration, due to the fact that diodes are usually connected along a module's length. However, a portrait configuration may be considered if east and west horizon shading is particularly prevalent.

7.2.4 INTER-ROW SPACING

The choice of row spacing is made by compromising between reducing inter-row shading, keeping the area of the PV plant within reasonable limits, reducing cable runs and keeping ohmic losses within acceptable limits. Inter-row shading can never be reduced to zero: at the beginning and end of the day, the shadow lengths are extremely long. Figure 16 illustrates the angles that must be considered in the design process.

The shading limit angle[39] *a* is the solar elevation angle beyond which there is no inter-row shading on the modules. If the elevation of the sun is lower than *a*, then a

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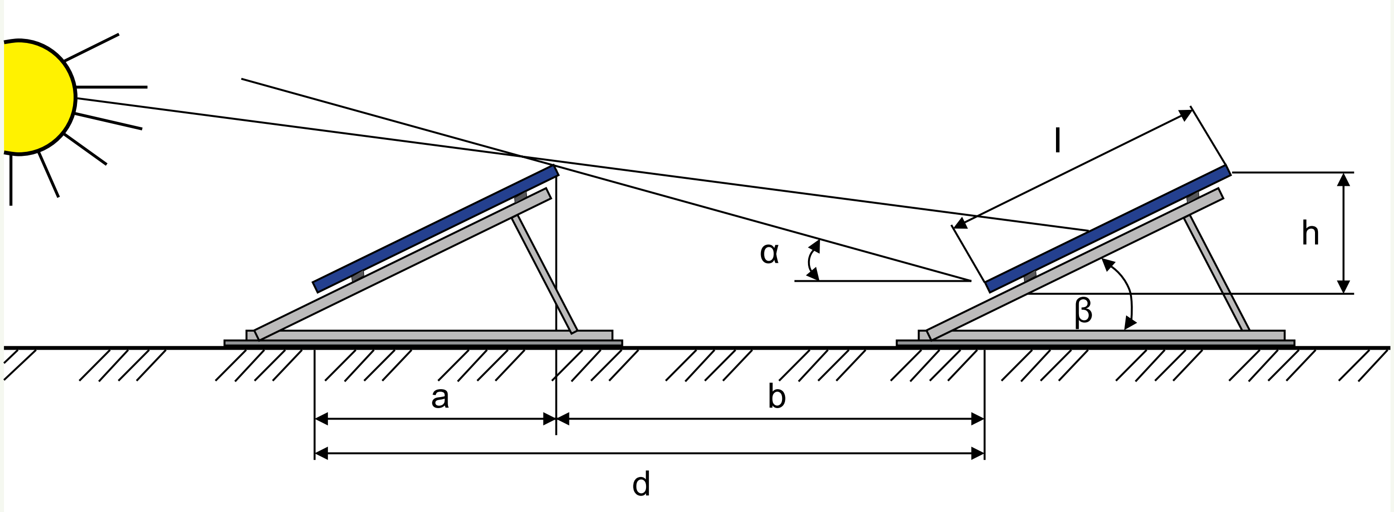
[39] Also known as "critical shading angle."

Figure 16: Shading Angle Diagram



proportion of the module will be shaded, and there will be an associated loss in energy yield.

The shading limit angle may be reduced either by reducing the tilt angle *ß* or increasing the row pitch *d*. Reducing the tilt angle below the optimal is sometimes chosen because this may give only a minimal reduction in annual yield. The ground cover ratio (GCR), given by *l/d* is a measure of the PV module area compared to the area of land required.

For many locations, a design rule of thumb is to space the modules in such a way that there is no shading at solar noon on the winter solstice (December 21st in the northern hemisphere and June 21st in the southern hemisphere). In general, if there is less than a 1 percent annual loss due to shading, then the row spacing may be deemed acceptable.

Detailed energy yield simulations can be carried out to assess losses due to shading, and to obtain an economic optimisation that also takes into account the cost of land, if required.

7.2.5 ORIENTATION

In the northern hemisphere, the orientation that optimises the total annual energy yield is true south. In the tropics, the effect of deviating from true south may not be especially significant.

Some tariff structures encourage the production of energy during hours of peak demand. In such "time of day" rate structures, there may be financial (rather than energy yield) benefits of orientating an array that deviates significantly from true south. For example, an array facing in a westerly direction will be optimised to generate power in the afternoon. The effect of tilt angle and orientation on energy yield production can be effectively modelled using simulation software.

7.3 TECHNOLOGY SELECTION

7.3.1 MODULES

Certification of a module to IEC/CE/UL standards as described in Section 3.3.7 is essential. However, modules may perform differently under the varying conditions of irradiance, temperature, shading and voltage that are actually experienced in the field. This makes selecting modules a more complex process than it may first appear. Many developers employ the services of an independent technical advisor familiar with the bill of materials from which the modules are made, and the specific factory manufacturing conditions. Table 8 gives some of the selection criteria that should be considered.

7.3.1.1 *Quality Benchmarks*

- **Product guarantee:** A material and workmanship product guarantee of ten years has become common. Some manufacturers guarantee up to 12 years.

- **Power guarantee:** In addition to the product guarantee, manufacturers grant nominal power guarantees. These vary between manufacturers. A two-step power warranty (e.g., 90 percent until year 10 and 80 percent until year 25) has been the historical industry standard. However, good module manufacturers are now differentiating themselves by providing a power output warranty that is fixed for the first year and then reduces linearly each year by a proportion of the nominal output power. This linear warranty provides additional protection to the plant owner compared to the two-step warranty which would provide no recourse if, for example, the module degrades to 91 percent of its nominal power in the first year.

  It is rare for module manufacturers to offer a power output guarantee beyond 25 years. The conditions of both the power guarantee and product guarantee vary between manufacturers and should be carefully checked.

- **Lifetime:** Good quality modules with the appropriate IEC certification have a design life in excess of 25 years. Beyond 30 years, increased levels of degradation may be expected. The lifetime of crystalline modules has been proven in the field. Thin-film technology lifetimes are currently unproven and rely on accelerated lifetime laboratory tests, but are expected to be in the order of 25–30 years also.

Table 8: PV Module Selection Criteria

Criterion	Description
Levelised cost of electricity (LCOE)[a]	The aim is to keep the levelised cost of electricity (LCOE) at a minimum. When choosing between high-efficiency/high-cost modules and low-efficiency/low-cost modules, the cost and availability of land and plant components will have an impact. High-efficiency modules require significantly less land, cabling and support structures per MWp installed than low-efficiency modules.
Quality	When choosing between module technologies such as mono-crystalline silicon (mono-c-Si), multi-crystalline silicon (multi-c-Si), and thin-film amorphous silicon (a-Si), it should be realised that each technology has examples of high quality and low quality products from different manufacturers.
PV module performance	Modules tested under a specific set of conditions of irradiance, temperature and voltage, with a specific inverter, may perform very differently under alternative conditions with a different inverter. Independent laboratories such as PV Evolution Labs[b] (PVEL) and TÜV Rheinland[c] can test PV modules according to a matrix of operational conditions under a wide range of environmental conditions in line with IEC 61853-1.
Power tolerance	The nominal power of a module is provided with a tolerance. Most crystalline modules are rated with a positive tolerance (typically 0/+3 percent to 0/±5 percent), while some crystalline, CdTe and CIGS modules may be given with a ±5 percent tolerance. Some manufacturers routinely provide modules at the lower end of the tolerance, while others provide modules that achieve their nominal power or above (positive tolerance). For a large plant, the impact of the module power tolerance on the overall energy yield can have a significant effect.
Flash tests	When ordering a large number of modules, it may be recommended to have a sample of modules independently flash tested from an accredited laboratory (such as Fraunhofer institute[d] or PI Berlin[e]) to confirm the tolerance. Additional acceptance tests such as electroluminescence tests may also be performed.
Temperature coefficient for power	The value of the power change with temperature will be an important consideration for modules installed in hot climates. Cooling by wind can positively affect plant performance in this respect.
Degradation	The degradation properties and long-term stability of modules should be ascertained. PV module manufacturers, independent testing institutes and technical consultants are sources of good information with regards to the potential induced degradation (PID), long-term degradation and, for crystalline modules, light-induced degradation (LID).
Bypass diodes	The position and number of the bypass diodes affect how the module performs under partial shading. The orientation of the PV modules on the support structure (portrait or landscape) can affect the inter-row shading losses (see also Section 5.3).
Warranty terms	The manufacturers' warranty period is useful for distinguishing between modules, but care should be taken with the power warranty. It is recommended that a detailed technical and legal review of warranty terms be conducted.
Suitability for unusual site conditions	Frameless modules may be more suitable for locations that experience snow, as snow tends to slide off these modules more easily. Modules located close to the coast should be certified for salt mist corrosion as described in Section 6.3.3.
Spectral response of the semiconductor	Different technologies have a differing spectral response and so will be better suited for use in certain locations, depending on the local light conditions. Some technologies show an improved response in low light levels compared to other modules.
Maximum system voltage	When sizing strings with modules with a high Open Circuit Voltage (V_{oc}), it should be verified that for extreme ambient temperature conditions (up to 60° and down to -10°), the maximum system voltage (1,000V) will not be exceeded.
Other	Other parameters important for selection of modules include cost ($/Wp) and the expected operational life.

[a] The cost per kWh of electricity generated that takes into account the time value of money.

[b] PV Evolution Labs, http://www.pvel.com

[c] TUV Rheinland, http://www.tuv.com/en/corporate/home.jsp

[d] Fraunhofer Institute, http://www.fraunhofer.de/en.html

[e] PI Berlin, http://www.pi-berlin.com

The module datasheet format and the information that should be included has been standardised and is covered by EN 50380: "Datasheet and nameplate information for photovoltaic modules." An example of the information expected in a datasheet is provided in Table 9.

7.3.2 INVERTERS

No single inverter is best for all situations. In practice, the local conditions and the system components have to be taken into account to tailor the system for the specific application. Different solar PV module technologies and layouts may suit different inverter types. Care needs to be taken in the integration of modules and inverters to ensure optimum performance and lifetime.

The most cost-effective inverter option requires an analysis of both technical and financial factors. Many of the inverter selection criteria listed in Table 10 feed into this analysis. The DC-AC conversion efficiency directly affects the annual revenue of the solar PV plant and varies according to a number of variables, including the DC input voltage and load. Several other factors should inform inverter selection, including site temperature, product reliability, maintainability, serviceability and total cost. Inverters also de-rate with altitude, which may be a consideration in mountainous locations.

Table 9: Comparison of Module Technical Specifications at STC

Manufacturer	Xxxx
Module Model	Xxxx
Type	Multi-crystalline
Nominal power (P_{MPP})	245Wp
Power tolerance	0/+3%
Voltage at P_{MAX} (V_{MPP})	30.2V
Current at P_{MAX} (I_{MPP})	8.13A
Open circuit voltage (V_{OP})	37.5V
Short circuit current (I_{SC})	8.68A
Maximum system voltage	$1000V_{DC}$
Module efficiency	15.00%
Operating temperature	-40°C to +85°C
Temperature coefficient of P_{MPP}	-0.43%/°C
Dimensions	1650×992×40mm
Module area	$1.64m^2$
Weight	19.5kg
Maximum load	5400Pa
Product warranty	10 years
Performance guarantee	92%: after 10 years; 80%: after 25 years

7.3.2.1 *Containerised Inverter Solutions*

Where commercial scale PV systems export power to the grid at medium voltage, it is common that a containerised solution for inverter, transformer and switchgear is provided. This solution enables offsite manufacturing, thus reducing installation time on site.

Containers are generally shipping-type and manufactured from corrugated steel. However they can also be manufactured in glass-reinforced plastic or concrete. The architecture of containers should ensure there is sufficient space for equipment, including access for maintenance. Cabling between equipment should be neatly installed, and often is provided in a compartment below the floor of the container. Having separate compartments for HV/LV equipment and for transformers is good practice. Provision of suitable heating, ventilation or air conditioning is necessary to maintain stable environmental conditions.

7.3.2.2 *Quality Benchmarks*

The warranty offered for inverters varies among manufacturers. A minimum warranty of five years is typical, with optional extensions of up to twenty years or more available from many manufacturers. Some string inverters offer a 7- or 10-year warranty as standard.

Many manufacturers quote inverter lifetimes in excess of 20 years based on replacing and servicing certain components according to specific maintenance regimes. However, real world experience points to an expected lifetime of a central inverter of between 10 and 20 years. This implies that the inverters may need to be replaced or refurbished once or twice during a 25-year plant operational life.

Table 10: Inverter Selection Criteria

Criterion	Description
Project capacity	The plant capacity influences the inverter connection concept. Central inverters are commonly used in megawatt-scale solar PV plants. Inverters are discussed more fully in Section 3.5.
Performance	High efficiency inverters should be sought. The additional yield often more than compensates for the higher initial cost. Consideration must also be given to the fact that efficiency changes according to design parameters, including DC input voltage and load.
Maximum Power Point (MPP) voltage range	A wide inverter MPP range facilitates design flexibility.
3-phase or single phase output	The choice will be subject to project size. Large capacity projects will require 3-phase inverters. National electrical regulations may set limits on the maximum power difference between the phases.
Incentive scheme	Banding of financial incentive mechanisms may have an influence on the choice of inverter. For example, FiT schemes might be tiered for different plant sizes, which may, in turn, influence the optimum inverter capacity.
Module technology	The compatibility of thin-film modules with transformerless inverters should be confirmed with manufacturers.
National and international regulations	A transformer inverter must be used if galvanic isolation is required between the DC and AC sides of the inverter.
Power quality/grid code compliance	Power quality and grid code requirements are country-dependent. It is not possible to provide universally applicable guidelines. The national regulations and standards should be consulted when selecting an inverter and designing a solar PV power plant. National grid codes may specify requirements for: • Frequency limitation. • Voltage limitation. • Reactive power control capability—over-sizing inverters slightly may be required. • Harmonic distortion limitation—to reduce the harmonic content of the inverter's AC power output. • Fault ride through capability.
Product reliability	High inverter reliability ensures low downtime and maintenance and repair costs. If available, inverter mean time between failures, figures and track record should be assessed.
Mismatch	If modules of different specifications or different orientation and tilt angles are to be used, then string or multi-string inverters with multiple MPP trackers may be recommended in order to minimise mismatch losses.[a] This may be especially relevant for rooftop applications where the orientation and tilt angle is often dictated by the properties of the roof space.
Maintainability and serviceability	Access constraints for PV plants in remote locations may influence the choice of inverter manufacturer: a manufacturer with a strong in-country presence may be able to provide better technical support. For PV plants in remote areas, string inverters offer ease of maintenance benefits.
System availability	If a fault arises with a string inverter, only a small proportion of the plant output is lost (i.e., 25kW). Spare inverters can be kept locally and replaced by a suitably-trained electrician. With central inverters, a larger proportion of the plant output will be lost until a replacement is obtained (e.g., 750kW).
Modularity	Ease of expanding the system capacity and flexibility of design should be considered when selecting inverters.
Shading conditions	String or multi-string inverters with multiple MPP trackers may be the preferred choice for sites that suffer from partial shading.
Installation location	Outdoor/indoor placement and site ambient conditions influence the IP rating and cooling requirements. Either forced ventilation or air-conditioning will usually be required for indoor inverters.
Monitoring / recording / telemetry	Plant monitoring, data logging and control requirements define a set of criteria that must be taken into account when choosing an inverter.

[a] Each PV string with a given tilt and orientation will have its own unique output characteristics and therefore needs to be "tracked" separately to maximize yield. An efficient design requires that only identically oriented sub-arrays are allocated to a single maximum power point tracker.

Inverter protection should include:

- Protection against incorrect polarity for the DC cable.
- Over-voltage and overload protection.
- Islanding detection for grid connected systems (depends on grid code requirements).
- Insulation monitoring.

Total harmonic distortion (THD)[40] is a measure of the harmonic content of the inverter output and is limited by most grid codes. For high quality inverters, THD is normally less than 5 percent. Inverters should be accompanied by the appropriate type of test certificates, which are defined by the national and international standards applicable for each project and country.

The inverter datasheet format and the information that should be included is standardised as covered by EN 50524:2009: "Data sheet and name plate for photovoltaic inverters." An example of the information expected in a datasheet is provided in Table 11.

Table 11: Datasheet Information

Inverter Model	xxxxxxxxx
Inputs	
Maximum DC Power	954kW
MPP Voltage Range	681-850V
Maximum Input Voltage	1,000V
Maximum Input Current / MPPT	1,400A
Number of MPP Trackers	1
Outputs	
Rated AC Power at 25°C	935kVA
Maximum AC Output Current	1,411A
Rated AC Voltage	386V
AC Grid Frequency	50Hz
Efficiency	
Maximum Efficiency	98.6%
Euro Efficiency	98.4%
Standby Consumption	< 100W
Operation Consumption	1,900W
General Data	
IP Rating	IP54, IP43
Operating Temperature Range	-25°C to +62°C
Relative Humidity	15-95 %
Dimensions (H x W x D)	2,272 x 2,562 x 956mm
Weight (kg)	1,900kg

7.3.3 TRANSFORMERS

Distribution and grid transformers are the two main types found on solar PV plants. Distribution transformers are used to step up the inverter output voltage for the plant collection system, which is normally at distribution voltage. If the plant is connected to the distribution network, power can then be exported to the grid directly. If the plant is connected to the transmission grid, grid transformers are used to step up the voltage even further. Further description of grid connection considerations is provided in Section 7.4.3.

The total cost of ownership (TCO), and the efficiency (directly related to the load and no-load losses) are major transformer selection criteria, directly affecting the annual revenue of the solar PV plant. As with inverters, several other factors should inform transformer selection, including power rating, construction, site conditions, product reliability, maintainability, serviceability and sound power. A cost-benefit analysis is required to determine the optimal transformer option.

Amorphous core transformers have low losses under no-load conditions and as such can provide cost savings in solar applications where there are significant periods of time when the transformers are not loaded.

Selection criteria (technical and economic factors) include:

- Efficiency, load/no-loadlosses.
- Guarantee.
- Vector group.
- System voltage.
- Power rating.

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[40] Total Harmonic Distortion is a measure of the harmonic content of the inverter output and is limited by most grid codes.

- Site conditions.
- Sound power.
- Voltage control capability.
- Duty cycle.

7.3.3.1 *Quality Benchmarks*

The guarantee offered for transformers varies among manufacturers. A minimum guarantee of 18 months is typical, with optional extensions of up to 10 years or more.

Based on manufacturer data and academic studies looking at large populations of transformers, distribution transformers have mean time to failure (MTTF) of 30 years or more. This is dependent on the transformer load profile and duty cycle.

Protection for typical, oil-immersed transformers used on solar PV plants should include:

- Buchholz relay.
- Pressure relief device.
- Over temperature protection.
- Oil level monitoring.

At a minimum, transformers should be built according to the following standards:

- BS EN 50464-1:2007+A1:2012
- IEC 60076

An example of the information expected in a transformer datasheet is provided in Table 12.

7.3.4 MOUNTING STRUCTURES

The tilt angle and orientation and row spacing are generally optimised for each PV power plant according to location. This helps to maximise the total annual incident irradiation[41] and total annual energy yield. Depending on the latitude, the optimum tilt angle can vary between 10º and 45º. This is covered more fully in Section 7.2. The modules should face due south for the north hemisphere and due north for the south hemisphere. There are several off-the-shelf software packages (such as PVsyst[42] and PV*SOL[43]) that may be used to optimise the tilt angle and orientation according to specifics of the site location (latitude, longitude) and solar resource.

7.3.4.1 *Quality Benchmarks*

The warranty supplied with support structures varies, but may include a limited product warranty of 10-25 years. Warranties could include conditions that all parts are handled, installed, cleaned and maintained in the appropriate way, that the dimensioning is made according to the static loads and that the environmental conditions are not unusual.

The useful life of fixed support structures, though dependent on adequate maintenance and corrosion protection, could be expected to be beyond 25 years.

In marine environments or within 3km of the sea, additional corrosion protection or coatings on the structures may be required.

Tracker warranties vary between technologies and manufacturers, but a 5- to 10-year guarantee on parts and workmanship may be typical.

Tracking system life expectancy depends on appropriate maintenance. Key components of the actuation system such as bearings and motors may need to be serviced or replaced within the planned project life.

Steel driven piles should be hot-dip galvanised to reduce corrosion. In highly corrosive soil, a suitable proposed thickness of coating should be derived by means of calculation. Additional protection such as epoxy coating may sometimes be necessary in order for components to last for the 25- to 35-year system-design life.

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[41] Irradiation is the solar energy received on a unit area of surface. It is defined more fully in section 4.2.

[42] PVsyst, http://www.pvsyst.com

[43] http://www.valentin-software.com/

Table 12: Transformer Specification

Electrical Characteristics					
Rated power	[kVA]	1250	Rated LV insulation level	[kV]	1.1
Insulation liquid		Mineral oil (IEC60296 class IA)	Applied voltage to industrial frequency	[kV]	3
Operation		Reversible	B.I.L. (1.2 / 50 µs)		N/A
Windings HV/LV		Aluminium/Aluminium	Frequency	[Hz]	50
Primary voltage at no load	[V]	33000	Number of phases		3
Primary taps type / tappings		Off load / ±2x2.5%	Vector group		Dyno5yn5
Rated HV insulation level	[kV]	36	No-load losses	[W]	1890
Applied voltage to industrial frequency	[kV]	70	Load losses (ONAN) at 75°C	[W]	14850
B.I.L. (1.2 / 50 µs)	[kV]	170	Impedance voltage (ONAN) at 75°C		6%
Secondary voltage at no load	[V]	380 / 380	Tolerances		IFC 60076-1 Tolerances
Thermal Characteristics					
Thermal insulation class		Class A	Surface treatment		Powder coating
Max. average temperature rise (Oil/Winding)	[K/K]	60/65	Surface colour		RAL7035
Mechanical Characteristics					
Technology		Hermetically sealed	Corrosivity category		C3 (medium corrosivity)
Tank type		With fins or with radiators	Durability (ISO 12944-6)		Medium (5-15 years)
Cover		Bolted	Bolts		Standard
Frame type		Standard	Final colour		RAL 7033 greenish-grey
Accessories/Qty					
Off-load tap changer		1	Pressure release valve		1
Oil filling tube		1	Gas relay		1
Oil drain valve		1	Oil temperature indicator		1
Thermometer pocket		1	Terminal box		1
Outline and Weight					
Overall dimension (L x W x D)	[mm]	2150 x 1350 x 2380	Total weight	[kg]	4900
Site Conditions					
Altitude	[m]	≤ 1000	Minimum standby temperature	[°C]	-25
Maximum ambient temperature	[°C]	40	Electrostatic screen		No
Daily average temperature	[°C]	30	Rectifier supply		No
Yearly average temperature	[°C]	20			

7.4 ELECTRICAL DESIGN

The electrical design of each plant should be considered on a case-by-case basis, as each site poses unique challenges and constraints. While general guidelines and best practices can be formulated, there are no "one-size-fits all" solutions. International standards and country-specific electrical codes should be followed in order to ensure that the installation is safe and compliant.

While the recommendations in the following sections are based on solar PV power plants with centralised inverter architectures, many of the concepts discussed also apply to plants with string inverters.

7.4.1 DC SYSTEM

The DC system comprises the following constituents:

- Arrays of PV modules.
- DC cabling (module, string and main cable).
- DC connectors (plugs and sockets).
- Junction boxes/combiner boxes.
- Disconnects/switches.
- Protection devices.
- Earthing.

When sizing the DC component of the plant, the maximum voltage and current of the individual strings and PV arrays should be calculated using the maximum output of the individual modules. Simulation programs can be used for sizing but their results should be cross checked manually.

DC components should be rated to allow for thermal and voltage limits. As a guide, for mono-crystalline and multi-crystalline silicon (multi-c-Si) modules, the following minimum ratings apply:

- Minimum Voltage Rating: $V_{OC(STC)} \times 1.15$
- Minimum Current Rating: $I_{SC(STC)} \times 1.25$

The multiplication factors used above (1.15 and 1.25) are location-dependent. Different multiplication factors may apply for specific locations. National standards and codes should be consulted.

For non-crystalline silicon modules, DC component ratings should be calculated from manufacturer's data, taking into account the temperature and irradiance coefficients. In addition, certain module technologies have an initial settling-in period during which the V_{OC} and I_{SC} is much higher. This effect should also be taken into consideration. If in doubt, a suitably qualified technical advisor should be consulted.

7.4.1.1 PV Array Design

The design of a PV array will depend on the inverter specifications and the chosen system architecture. Using many modules in series in high voltage (HV) arrays minimises ohmic losses. However, safety requirements, inverter voltage limits and national regulations also need to be considered.

- **Maximum number of modules in a string:** The maximum number of modules in a string is defined by the maximum DC input voltage of the inverter to which the string will be connected ($V_{MAX\ (INV,\ DC)}$). Under no circumstances should this voltage be exceeded. Crossing the limit can decrease the inverter's operational lifetime or render the device inoperable. The highest module voltage that can occur in operation is the open-circuit voltage in the coldest daytime temperatures at the site location. Design rules of thumb for Europe use -10°C as the minimum design temperature, but this will vary according to location. The maximum number of modules in a string (n_{max}) may therefore be calculated using the formula:

  $$V_{OC(MODULE)@\text{coldest module operating temperature}} \times n_{max} < V_{MAX(INV,\ DC)}$$

- **Minimum number of modules in a string:** The minimum number of modules is governed by the requirement to keep the system voltage within the maximum power point (MPP) range of the inverter. If the string voltage drops below the minimum MPP inverter voltage, then the system will underperform.

In the worst case, the inverter may shut down. The lowest expected module voltage occurs during the highest operating module temperature conditions. Design rules of thumb for Europe use 70°C as the design benchmark, but this will vary according to site conditions. The minimum number of modules in a string (n_{min}) may therefore be calculated using the formula:

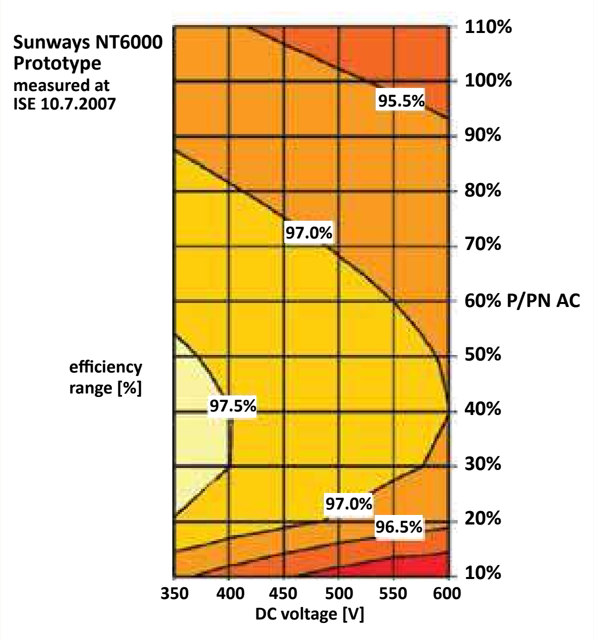
$$V_{MPP(MODULE)@highest\ module\ operating\ temperature} \times n_{min} > V_{MPP(INV\ min)}$$

- **Voltage optimisation:** As the inverter efficiency is dependent on the operating voltage, it is preferable to optimise the design by matching the array operating voltage and inverter optimum voltage as closely as possible. This will require voltage dependency graphs of inverter efficiency (see examples in Figure 17). If such graphs are not provided by inverter manufacturers, they may be obtained from independent sources. Substantial increases in the plant yield can be achieved by successfully matching the operating voltages of the PV array with the inverter.
- **Number of strings:** The maximum number of strings permitted in a PV array is a function of the maximum allowable PV array current and the maximum inverter current. In general, this limit should not be exceeded as it leads to premature inverter ageing and yield loss.

7.4.1.2 *Inverter Sizing*

It is not possible to formulate an optimal inverter sizing strategy that applies in all cases. Project specifics such as the solar resource and module tilt angle play a very important role when choosing a design. While the rule of thumb has been to use an inverter-to-array power ratio less than unity, this is not always the best design approach. For example, this option might lead to a situation where the inverter manages to curtail power spikes not anticipated by irradiance profiles (based on one-hour data). Or, it could fail to achieve grid code compliance in cases where reactive power injection to the grid is required.

Figure 17: Voltage and Power Dependency Graphs of Inverter Efficiency[a]



[a] F.P. Baumgartner, et al., "Status and Relevance of the DC Voltage Dependency of the Inverter Efficiency," 22nd European Photovoltaic Solar Energy Conference and Exhibition, 3-7 September 2007, Fiera Milano, Session 4DO.4.6, https://home.zhaw.ch/~bauf/pv/papers/baumgartner_2007_09_inverter_EUPVSEC_MILANO.pdf (accessed June 2014).

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:

$$0.8 < Power\ Ratio < 1.2$$

Where:

$$Power\ Ratio = \frac{P_{(Inverter\ DC\ rated)}}{P_{(PV\ Peak)}}$$

$$P_{(Inverter\ DC\ rated)} = \frac{P_{(Inverter\ AC\ rated)}}{\eta_{(100\%)}}$$

Guidance on inverter and PV array sizing can be obtained from the inverter manufacturers, who offer system-sizing software. Such tools also provide an indication of the total number of inverters required. If in doubt, a suitably qualified technical advisor should be consulted.

A number of factors and guidelines must be assessed when sizing an inverter:

- The maximum V_{OC} in the coldest daytime temperature must be less than the inverter maximum DC input voltage ($V_{INV, DC MAX}$).
- The inverter must be able to safely withstand the maximum array current.
- The minimum V_{OC} in the hottest daytime temperature must be greater than the inverter DC turn-off voltage ($V_{INV, DC TURN-OFF}$).
- The maximum inverter DC current must be greater than the PV array(s) current.
- The inverter MPP range must include PV array MPP points at different temperatures.
- When first installed, some thin-film modules produce a voltage greater than the nominal voltage. This happens for a period of time until initial degradation has occurred, and must be taken into account.
- Grid code requirements, including reactive power injection specifications.
- The operating voltage should be optimised for maximum inverter efficiency.
- Site conditions of temperature and irradiation profiles.
- Economics and cost-effectiveness.

Inverters with reactive power control are recommended. Inverters can control reactive power by controlling the phase angle of the current injection. Moreover, aspects such as inverter ventilation, air conditioning, lighting and cabinet heating must be considered.

When optimising the voltage, it should be considered that the inverter efficiency is dependent on voltage. Specification sheets and voltage-dependency graphs are required for efficient voltage matching.

7.4.1.3 Cable Selection and Sizing

The selection and sizing of DC cables for solar PV power plants should take into account national codes and regulations applicable to each country. Cables specifically designed for solar PV installations ("solar" cables) are readily available and should be used. In general, three criteria must be observed when sizing cables:

1. **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 V_{OC} voltage of the modules, adjusted for the site minimum design temperature, are used for this calculation.
2. **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 the cable, the method of laying, number of cores and temperature. Care must be taken to size the cable for the worst case of reverse current in an array.
3. **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 percent. Cable losses of less than 1 percent are achievable.

In practice, the minimisation of voltage drop and associated losses will be the limiting factor in most cases.

7.4.1.4 Cable Management

Over-ground cables such as module cables and string cables need to be properly routed and secured to the mounting structure, either using dedicated cable trays or cable ties. Cables should be protected from direct sunshine, standing water and abrasion by the sharp edges of support structures. They should be kept as short as possible.

Plug cable connectors are standard in grid-connected solar PV power plants, due to the benefits they offer in terms of installation ease and speed. These connectors are normally touch-proof, which means they can be touched without risk of shock.

The laying of main DC cables in trenches must follow national codes and take into account specific ground conditions.

7.4.1.5 Module and String Cables

Single-conductor, double-insulation cables are preferable for module connections. Using such cables helps protect against short circuits. When sizing string cables, the number of modules and the number of strings per array need to be considered. The number of modules defines the voltage at which the cable should be rated. The number of strings is used to calculate the maximum reverse current that can flow through a string.

The cables should be rated to the highest temperature they may experience (for instance, 80°C). Appropriate de-rating factors for temperature, installation method and cable configuration should also be applied.

7.4.1.6 Main DC Cable

In order to reduce losses, the overall voltage drop between the PV array and the inverter should be minimised. A benchmark voltage drop of less than 3 percent (at STC) is suitable, and cables should be sized using this benchmark as a guide. In most cases, over-sizing cables to achieve lower losses is a worthwhile investment.

7.4.1.7 Combiner Boxes

Combiner boxes are needed at the point where the individual strings forming an array are marshalled and connected together in parallel before leaving for the inverter through the main DC cable. Junctions are usually made with screw terminals and must be of high quality to ensure lower losses and prevent overheating.

Combiner boxes have protective and isolation equipment, such as string fuses and disconnects[44] (also known as load break switches), and must be rated for outdoor placement using, for example, ingress protection (IP). An explanation of the IP bands is provided in Table 13. Depending on the solar PV plant architecture and size, multiple levels of junction boxes can be used.

It is important to remember that the module side of the terminals of a DC PV system remain live during the day. Therefore, clear and visible warning signs should be provided to inform anyone working on the junction box. For safety reasons all junction boxes should be correctly labelled.

Disconnects and string fuses should be provided. Disconnects permit the isolation of individual strings, while string fuses protect against faults, as discussed in Section 7.4.1.9. Disconnects should be capable of breaking normal load and should be segregated on both the positive and negative string cables.

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[44] Disconnects should be not confused with disconnectors/isolators that are dead circuit devices (or devices that operate when there is no current flowing through the circuit).

Table 13: Definition of Ingress Protection (IP) Ratings

Example: IP65 1st digit 6 (Dust tight) 2nd digit 5 (Protected against water jets)

1st digit	Protection from solid objects	2nd digit	Protection from moisture
0	Non-protected	0	Non-protected
1	Protection against solid objects greater than 50mm	1	Protected against dripping water
2	Protection against solid objects greater than 12mm	2	Protected against dripping water when tilted
3	Protection against solid objects greater than 2.5mm	3	Protected against spraying water
4	Protection against solid objects greater than 1.0mm	4	Protected against splashing water
5	Dust protected	5	Protected against water jets
6	Dust tight	6	Protected against heavy seas
		7	Protected against immersion
		8	Protected against submersion

7.4.1.8 Connectors

Specialised plug and socket connections are normally pre-installed on module cables to facilitate assembly. These plug connectors provide secure and touch-proof connections.

Connectors should be correctly rated and used for DC applications. As a rule, the connector current and voltage ratings should be at least equal to those of the circuit they are installed on.

Connectors should carry appropriate safety signs that warn against disconnection under load. Such an event can lead to arcing (producing a luminous discharge across a gap in an electrical circuit), and put personnel and equipment in danger. Any disconnection should take place only after the circuit has been properly isolated.

7.4.1.9 String Fuses/Miniature Circuit Breakers (MCBs)

String fuses or miniature circuit breakers (MCBs) are required for over-current protection. They must be rated for DC operation. National codes and regulations may need to be consulted when selecting and sizing fuses and MCBs.

The following guidelines apply to string fuses/MCBs:

- All arrays formed of four or more strings should be equipped with breakers. Alternatively, breakers should be used where fault conditions could lead to significant reverse currents.
- Since faults can occur on both the positive and negative sides, breakers must be installed on all unearthed cables.
- To avoid nuisance tripping, the nominal current of the breaker should be at least 1.25 times greater than the nominal string current. National electrical codes should be consulted for recommendations. Overheating of breakers can cause nuisance tripping. For this reason, junction boxes should be kept in the shade.
- The string fuse/MCB must trip at less than twice the string short-circuit current (I_{SC}) at STC or at less than the string cable current carrying capability, whichever is the lower value.
- The trigger current of fuse/MCB should be taken into account when sizing string cables. It should not be larger than the current at which the string cable is rated.
- The string fuse/MCB should be rated for operation at the string voltage. The following formula is typically used to guide string fuse rating, although national codes of practice should be consulted:

$$\text{String Fuse Voltage Rating} = V_{OC(STC)} \times M \times 1.15$$

where M is the number of modules in each string.

7.4.1.10 DC Switching

Switches are installed in the DC section of a solar PV plant to provide protection and isolation capabilities. DC switches/disconnects and DC circuit breakers (CBs) are discussed below.

- **DC Switches/Disconnects:** Judicious design practice calls for the installation of switching devices in PV array junction boxes. DC switches provide a manual means of electrically isolating entire PV arrays, which is required during installation and maintenance. DC switches must be:
  - Double-pole to isolate both the positive and negative PV array cables.
  - Rated for DC operation.
  - Capable of breaking under full load.
  - Rated for the system voltage and maximum current expected.
  - Equipped with safety signs.
- **DC Circuit Breaker (CB):** String fuses/MCBs cannot be relied upon for disconnection of supply in case of fault conditions. This is due to the fact that PV modules are current-limiting devices, with an I_{SC} only a little higher than the nominal current. In other words, the fuse would not blow, or the MCB would not trip since the fault current would be less than the trigger current. For this reason, most PV codes and regulations recommend

that main DC CBs should be installed between the PV array fields and the grid-connected inverters.

Certain inverter models are equipped with DC CBs. As such, installation of additional CBs may become redundant. However, national regulations must be consulted to confirm the standards.

7.4.1.11 Quality Benchmarks

Module cables must:

- Adhere to local and international standards including IEC 60502, IEC 60228, 60364-1, 60332-1-2, 60754-1 and -2, 61034.
- Be specified for a wide temperature range (e.g., -55 to 125°C).
- Be resistant to ultraviolet (UV) radiation and weather if laid outdoors without protection.
- Be single core and double insulated.
- Have mechanical resistance to animals, compression, tension and bending.
- Be attached to cable trays with cable ties to support their weight and prevent them from moving in the wind.
- Be protected from sharp support stricture edges with anti-abrasion pads.
- Use cable connectors that adhere to international protection rating IP67.

Sometimes specific cable options are preferable because they offer increased protection:

- Single conductor cable-insulated and sheathed. For example, properly rated HO7RNF cables.
- Single conductor cable in suitable conduit/trunking.
- Multi-core, steel wire armoured—only suitable for main DC cables and normally used where an underground or exposed run is required.

7.4.2 AC SYSTEM

7.4.2.1 AC Cabling

Cabling for AC systems should be designed to provide a safe and cost effective means of transmitting power from the inverters to the transformers and beyond. Cables should be rated for the correct voltage and have conductors sized, taking into account the operating currents and short-circuit currents (I_{SC}).

When specifying cabling the following design considerations should be taken into account:

- Cable must be rated for the maximum expected voltage.
- Conductor should be able to pass the operating and I_{SC} safely.
- Conductor should be sized appropriately to ensure that losses produced by the cable are within acceptable limits, and that the most economic balance is maintained between capital cost and operational cost (losses).
- Conductors should be sized to avoid voltage drop outside statutory limits and equipment performance.
- Insulation should be adequate for the environment of installation.
- A suitable number of cores should be chosen (either single or multi-core).
- Earthing and bonding should be suitably designed for the project application.
- Installation methods and mechanical protection of the cable should be suitably designed for the project.

Cables should comply with relevant IEC standards and appropriate national standards. Examples of these include:

- IEC 60502 for cables between 1kV and 36kV.
- IEC 60364 for LV cabling.
- IEC 60840 for cables rated for voltages above 30kV and up to 150kV.

7.4.2.2 *AC Switchgear*

Appropriately rated switchgear and protection systems should be included to provide disconnection, isolation, earthing and protection. On the output side of the inverters, provision of a switch disconnector is recommended as a means to isolate the PV array.

The appropriate type of switchgear will be dependent on the voltage of operation. Switchgear up to 33kV is likely to be an internal metal-clad, cubicle-type with gas- or air-insulated busbars and vacuum or SF6 breakers. For higher voltages, the preferred choice may be air-insulated outdoor switchgear or, if space is constrained, gas-insulated indoor switchgear.

All switchgear should:

- Be compliant with relevant IEC standards and national codes.
- Clearly show the ON and OFF positions with appropriate labels.
- Have the option to be secured by locks in off/earth positions.
- Be rated for operational and short-circuit currents.
- Be rated for the correct operational voltage.
- Be provided with suitable earthing.

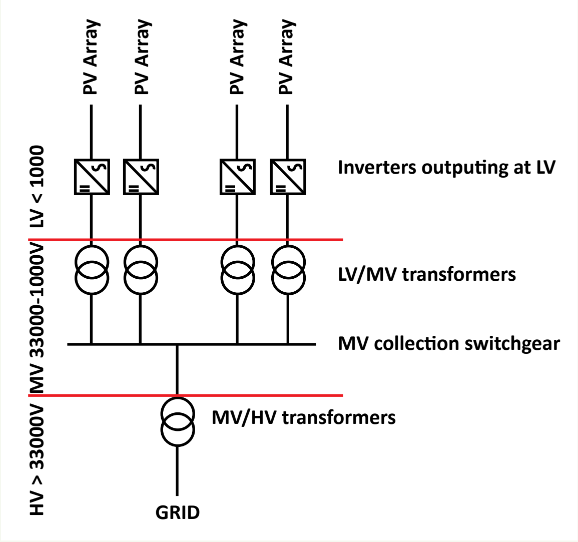
7.4.2.3 *Sizing and Selecting Transformers*

In general, the inverters supply power at low voltage (typically 300-450V). But for a commercial solar power plant, grid connection is typically made at 11kV and above (HV levels). It is therefore necessary to step up the voltage using one or more transformers between the inverter and the grid connection point.

The position of the transformer in the electrical system will define the required voltage on the primary and secondary sides of the transformer.

Figure 18 shows a high-level, single line diagram showing typical voltages of operation for the AC system of a solar power plant. Where there is a need to supply power from the grid back to the plant, an auxiliary transformer is required.

Figure 18: Typical Transformer Locations and Voltage Levels in a Solar Plant where Export to Grid is at HV



The selection of an appropriate transformer should consider several basic issues. These include the required capacity, position within the electrical system, physical location and environmental conditions under which the transformer will operate. The capacity of the transformer (specified in MVA) will depend on the projected maximum power exported from the solar array.

The main export transformers will form a major element of the main substation design and, as such, their selection should also consider the technical requirements of the grid company. Such transformers should conform to local and/or international specifications, as required.

Output power from PV arrays follows a well-understood cyclic duty corresponding to the path of the sun through the day. This allows consideration of a dynamic rating to be applied to the transformer selection.

The transformer solution should comply with national and international standards including IEC 60076. The design should consider the following points:

- **Losses:** Transformers can lose energy through magnetising current in the core, a phenomenon known as iron losses, and also copper losses in the windings. Minimising the losses in a transformer is a key requirement, as this will increase the energy supplied to the grid and thereby enhance the revenue of a solar PV power plant.
- **Test Requirements:** Transformers should be subjected to a number of routine and type tests performed on each model manufactured; these tests are set out in IEC 60076. The manufacturer also can be requested to undertake special tests mentioned in IEC 60076.
- **Delivery and Commission:** Consideration should be given to the period of time required for manufacture and delivery of transformers. Most large transformers (above 5MVA) will be designed and built on order, and will therefore have a lengthy lead-time, which can be in the order of years.

The delivery of large transformers (above 30MVA) to the site also needs to be planned. Large transformers can be dis-assembled to some extent, but the tank containing the core and winding will always need to be moved in one piece. In the case of transformers of 100MVA capacity, the burden of transportation will still be significant and road delivery may require special measures, such as police escort.

The positioning of the transformer in the power plant should also be decided at the planning stage. By doing this, a transformer can be easily and safely installed, maintained, and in the event of a failure, replaced. Liquid-filled transformers should be provided with a bund to catch any leakage. Oil-filled transformers, if sited indoors, are generally considered a special fire risk. As such, measures to reduce the risk to property and life should be considered.

7.4.2.4 Plant Substation

Equipment such as LV/MV transformers, MV switchgear, Supervisory Control and Data Acquisition (SCADA) systems, protection and metering systems can be placed within the plant substation.

The layout of the substation should optimise the use of space while still complying with all relevant building codes and standards. A safe working space should be provided around the plant for the operation and maintenance staff. Air conditioning should be considered due to the heat generated by the electronic equipment. In some cases, large substation facilities need to be designed and constructed according to the grid company's requirements and interconnect agreement specifications.

Separation between MV switch rooms, converter rooms, control rooms, storerooms and offices is a key requirement, in addition to providing safe access, lighting and welfare facilities.

Lightning protection should be considered to alleviate the effect of lightning strikes on equipment and buildings.

Metering: Tariff metering will be required to measure the export of power. This may be provided at the plant substation in addition to the point of connection to the grid.

Data monitoring/SCADA: SCADA systems provide control and status indication for the items included in the substation and across the solar PV power plant. The key equipment may be situated in the substation or in a dedicated control and protection room.

7.4.2.5 Earthing and Surge Protection

Earthing should be provided as a means to protect against electric shock, fire hazard and lightning. By connecting to the earth, charge accumulation in the system during an electrical storm is prevented. The earthing of a solar PV power plant encompasses the following:

- Array frame earthing.
- System earthing (DC conductor earthing).
- Inverter earthing.
- Lightning and surge protection.

National codes and regulations and the specific characteristics of each site location should be taken into account when designing the earthing solution. The solution should be designed to reduce the electric shock risk to people on site and the risk of damage and fire during a fault or lightning strike.

The entire solar PV power plant and the electrical room should be protected from lightning. Protection systems are usually based on early streamer emission and lightning conductor air terminals. The air terminal will be capable of handling multiple strikes of lightning current and should be maintenance-free after installation.

These air terminals will be connected to respective earthing stations. Subsequently, an earthing grid will be formed, connecting all the earthing stations through the required galvanised iron tapes.

The earthing arrangements on each site will vary, depending on a number of factors:

- National electricity requirements.
- Installation guidelines for module manufacturers.
- Mounting system requirements.
- Inverter requirements.
- Lightning risk.

While the system designer must decide the most appropriate earthing arrangement for the solar PV plant according to location specific requirements, one can follow the general guidelines given below:

- Ground rods should be placed close to junction boxes. Ground electrodes should be connected between the ground rod and the ground lug in the junction box.
- A continuous earth path is to be maintained throughout the PV array.
- Cable runs should be kept as short as possible.
- Surge suppression devices can be installed at the inverter end of the DC cable and at the array junction boxes.
- Many inverter models include internal surge arrestors. Separate additional surge protection devices may also be required.

7.4.3 GRID CONNECTION

Solar plants need to meet the requirements of the grid company of the network onto which they will export power. Technical requirements for connection are typically set out in grid codes, which are published by the grid company and cover topics including planning, connection and operation of the plant. Grid codes will vary by country and may include:

- Limits on harmonic emission.
- Limits on voltage flicker.
- Limits on frequency variation.
- Reactive power export requirements.
- Voltage regulation.
- Fault level requirements.
- System protection.

In addition to meeting the country grid code requirements, site-specific requirements may be requested by the grid company should there be any unusual network conditions at the precise site location.

When designing the grid connection solution, careful consideration should be given to the following constraints:

- **Scheduling:** The grid connection schedule will impact the planned energisation date and generation targets. Key electrical components such as transformers can have long lead and delivery times. Supplier locations and likely lead times should be investigated at the planning stage and carefully considered in the project plan (see Box 4 “Grid Connection - Experience in India”).

  In addition to local connection works, wider network upgrades and modifications beyond the point of connection can have significant influence on the date of energisation and commercial operation. Connection issues are case-dependent and usually outside the developer’s sphere of influence. It is therefore important that communication is established with the relevant grid companies and that discussions are undertaken to fully understand the implications and

Box 4: Grid Connection – Experience in India

Export Cable

In India, projects are typically required to be commissioned within 12 months from the date of execution of the PPA. This is intended to allow ample time for planning and executing the export cable works. However, there have been a number of projects in India where commissioning has been delayed because power evacuation could not commence due to unavailability of the export line. This can be avoided by planning the export line routes and signing right-of-way agreements with the property owners at an early stage of project development.

Grid Stability

The smooth operation of a grid-connected solar PV power plant is dependent on the voltage and frequency of the grid staying within certain limits that are acceptable for the inverter. Grid instability may result from varying loads applied on the utility substation. With no historical load data available at the local substation level for the majority of Indian utilities, grid availability can become a significant risk to project development. In order to understand the risk, it is recommended that the developer conduct a thorough grid quality evaluation by physically verifying the voltage and frequency variations for a minimum period of two weeks during the project planning phase.

In addition to monitoring, measures during the component selection phase can also mitigate the risk of grid instability causing downtime. These measures include:

1) Selecting inverters that have a dynamic grid support function with low voltage, high voltage and frequency ride-through features.

2) Using plant transformers equipped with on-load tap changers.

Reactive Power Compensation

While few of the Indian states force project developers to maintain a power factor close to unity, there are other states that charge for the reactive power consumed by the PV plant. Although most modern central inverters can be made to operate at leading power factor, supplying the reactive power during hours of high irradiance, there may be a need to include a capacitor bank to compensate reactive power during periods of low irradiance. It is advisable to select inverters that can compensate the reactive power.

the timescales involved in both local and regional connection timescales.

- **Connection Voltage:** The connection voltage must be suitable for the plant capacity. Different connection voltages will entail differing costs of electrical equipment, such as switchgear and transformers, as well as conductor specifications. Differing connection voltages may also impact on the time required to provide the connection.

  Excessive loading of local transmission or distribution network equipment, such as overhead lines or power transformers, may lead to grid instability. In this case, the voltage and frequency of the grid may fall outside the operational limits of the inverters and plant downtime may result. In less developed regional networks, the risk of downtime caused by grid instability should be assessed by developers with a grid quality evaluation. Lack of such an evaluation can have serious impacts on project economics and result in downtime exceeding the assumptions that were used in the project's financial model.

7.4.4 QUALITY BENCHMARKS

The AC cable should be supplied by a reputable manufacturer accredited to ISO 9001. The cable should have:

- Certification to current IEC and national standards such as IEC 60502 for cables between 1kV and 36kV, IEC 60364 for LV cabling and IEC 60840 for cables rated for voltages above 30kV and up to 150kV.
- Type testing completed to appropriate standards.
- A minimum warranty period of two years.
- A design life equivalent to the design life of the project.
- Ultraviolet (UV) radiation and weather resistance (if laid outdoors without protection).

- Mechanical resistance (for example, compression, tension, bending and resistance to animals).

AC switchgear should be supplied by a reputable manufacturer accredited to ISO 9001 and should have:

- Certification to current IEC and appropriate national standards such as IEC 62271 for HV switchgear and IEC 61439 for LV switchgear.
- Type testing to appropriate standards.
- A minimum warranty period of two years.
- An expected lifetime at least equivalent to the design life of the project.

Transformers should be supplied by reputable manufacturers accredited to ISO 9001 and should have:

- Certification to IEC and appropriate national standards such as IEC 60076 for the power transformer, IEC 60085 for electrical insulation and IEC 60214 for tap changers.
- Type testing to appropriate standards.
- A minimum warranty period of two years.
- An expected lifetime at least equivalent to the design life of the project.
- Efficiency of at least 96 percent.

7.5 SITE BUILDINGS

A utility-scale solar PV power plant requires infrastructure appropriate to the specifics of the design chosen. Locations should be selected in places where buildings will not cast shading on the PV modules. It may be possible to locate buildings on the perimeter of the plant. If they are located centrally, appropriate buffer zones should be allowed for. Depending on the size of the plant, infrastructure requirements may include:

- **Office:** A portable office and sanitary room with communication devices. This must be watertight and prevent entry of insects. It should be located near the site entrance so that vehicular traffic does not increase the risk of dust settling on the modules.
- **LV/MV station:** Inverters may either be placed among the module support structures (if string inverters are chosen) in specially designed cabinets or in an inverter house along with the medium voltage transformers, switchgear and metering system.[45] This LV/MV station may be equipped with an air conditioning system if it is required to keep the electrical devices within their design temperature envelopes.
- **MV/HV station:** An MV/HV station may be used to collect the AC power from the medium voltage transformers and interface to the high voltage power grid.
- **Communications:** The plant monitoring system and the security system will require a communications medium with remote access. There can also be a requirement from the grid network operator for specific telephone landlines for the grid connection. Often, an internet broadband (DSL) or satellite communications system is used for remote access. A GSM (Global System for Mobile Communications) connection or standard telephone line with modems are alternatives, although they have lower data transfer rates.

7.5.1 QUALITY BENCHMARKS

Some benchmark features of PV plant infrastructure include:

- Watertight, reinforced concrete stations or pre-fabricated steel containers. All buildings and foundations should be designed and constructed in accordance with the Structural Eurocodes (in Europe) or the appropriate country building codes, standards and local authority regulations.
- Sufficient space to house the equipment and facilitate its operation and maintenance.
- Inclusion of:
  - Ventilation grilles, secure doors and concrete foundations that allow cable access.

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[45] For string inverters, the "LV/MV station" may be used to collect the AC power.

- Interior lighting and electrical sockets that follow country-specific regulations.
- Either adequate forced ventilation or air conditioning with control thermostats, depending on environmental conditions.
- Weather bars or upstands to prevent flooding of electrical equipment buildings.

7.6 SITE SECURITY

Solar PV power plants represent a large financial investment. The PV modules are not only valuable, but also portable. There have been many instances of module theft and also theft of copper cabling. Security solutions are required to reduce the risk of theft and tampering. These security systems will need to satisfy the insurance provider requirements and would typically include several of the following:

- **Security fence:** A galvanised steel wire mesh fence with anti-climb protection is typically recommended. A fence may also be part of the grid code requirements for public safety. Measures should be taken to allow small animals to pass underneath the fence at regular intervals.
- **CCTV cameras:** Security cameras are increasingly becoming a minimum requirement for any PV plant's security system. Several types of cameras are available, the most common being thermal and day/night cameras. Cameras should ideally have strong zooming capabilities and should be easy to manipulate remotely (e.g., with the help of pan-tilt-zoom support) for external users to be able to identify sources of intrusion with more ease. Day/night cameras typically have ranges of 50m to 100m and are coupled with infrared illuminators. Thermal cameras are more expensive, however, they have lower internal power consumption and a longer range (typically above 150m), which means that fewer cameras are needed to cover the entire perimeter fence.
- **Video analytics software:** Some security systems use video analytics software in conjunction with the CCTV cameras. This software can enable the user to define security areas and distinguish potential intruders from other alerts caused by weather, lighting conditions or motion associated with vegetation, traffic or animals. This system allows grazing livestock to remain within the plant boundary without alarms being raised. Video analytics software can considerably reduce the rate of security system false alarms.
- **Sensors:** There are a variety of detectors available on the market. These include photoelectric beams, trip wires, passive infrared (PIR), microwave, magnetic and motion sensors, among others. Although having many sensors independently controlled can be the cause of a higher false alarm rate, interlinking them and using digital signal processing (DSP) techniques can reduce this risk and provide a more robust security system. Care should be taken that the chosen system is not triggered by grazing animals.
- **Warning devices:** Simple devices warning of the use of CCTV cameras or monitoring of the site will dissuade most intruders. These can include warning signs, horns installed around the site and pre-recorded warning messages.
- **Security staff:** A permanent guarding station with a security guard often provides the level of security required in an insurance policy. This option is mostly used in particularly remote locations or areas of high crime or vandalism rates. Where armed guards are present and/or where public security forces are assigned to provide asset protection (typically in post-conflict contexts), screening and training of security staff members backed up by operational policies is recommended regarding the appropriate use of force/firearms and appropriate conduct towards workers and community members.
- **Remote alarm centre:** PV plants will transmit data via communication means such as satellite or landline to an alarm centre, usually located in a large town or city and potentially far away from the site. The security system should be monitored 24 hours a day. Any detection that is verified as an intrusion should raise alerts at the local police or security company for further action.

- **Other security measures:** Additional security measures may include:
    - Reducing the visibility of the power plant by planting shrubs or trees at appropriate locations. Care should be taken that these do not shade the PV modules.
    - Anti-theft module mounting bolts may be used and synthetic resin can be applied once tightened. The bolts can then only be released after heating the resin up to 300°C.
    - Anti-theft module fibre systems may be used. These systems work by looping a plastic fibre through all the modules in a string. If a module is removed, the fibre is broken, which triggers an alarm.

7.6.1 QUALITY BENCHMARKS

Some benchmark security features include:

- Metallic fence at least 2m high.
- Video surveillance system, which includes cameras with zooming and remote manipulating capabilities.
- Sensors and/or video analytics software.
- Warning signs.
- Digital video recorder, which records data for a minimum of 12 months.
- Alarm system fitted to the power plant gate, the medium voltage station, metering station and any portable cabins.

7.7 PLANT MONITORING

7.7.1 MONITORING TECHNOLOGY

A monitoring system is an essential part of a PV plant. Monitoring devices are crucial for the calculation of liquidated damages (LDs) and confirmation that the EPC contractor has fulfilled its obligations. Automatic data acquisition and monitoring technology is also essential during the operational phase in order to maintain a high level of performance, reduce downtime and ensure rapid fault detection.

A monitoring system allows the yield of the plant to be monitored and compared with theoretical calculations and raise warnings on a daily basis if there is a performance shortfall. Faults can therefore be detected and rectified before they have an appreciable effect on production. Without a reliable monitoring system it can take many months for a poorly performing plant to be identified. This can lead to unnecessary revenue loss.

The key to a reliable monitoring and fault detection methodology is to have good simultaneous measurements of the solar irradiance, environmental conditions and plant power output. This is achieved by incorporating a weather station on site to measure the plane of array irradiance, module and ambient temperature, and preferably global horizontal irradiance, humidity and wind speed.

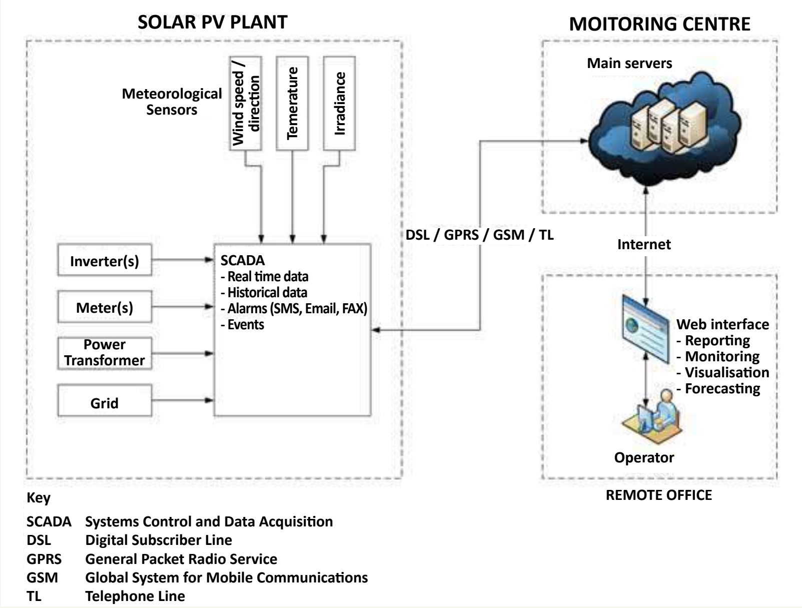
In large-scale solar PV power plants, voltage and current will typically be monitored at the inverter, combiner box or string level, each offering more granularity than the previous. Monitoring at the inverter level is the least complex system to install. However it only offers an overview of the plant's performance, while the other two options, although more expensive, provide more detailed information on the system components' performance and improved fault detection and identification.

Data from the weather station, inverters, combiner boxes, meters and transformers will be collected in data loggers and passed to a monitoring station, typically via Ethernet, CAT5/6, RS485 or RS232 cables. Communication protocols are varied, although the most commonly used worldwide are Modbus, TCP/IP and DNP3. If more than one communications protocol is considered for a monitoring system, protocol converters can be used.

Figure 19 illustrates the architecture of an internet portal-based monitoring system, which may include functionality for:

- **Operations management:** The performance management (either onsite or remote) of the solar PV power plant to enable the monitoring of inverters or strings at the combiner box level.

Figure 19: PV System Monitoring Schematic



- **Alarm management:** Flagging any element of the power plant that falls outside pre-determined performance bands. Failure or error messages can be automatically generated and sent to the power plant service team via fax, email or text message.
- **Reporting:** The generation of yield reports detailing individual component performance, and benchmarking the reports against those of other components or locations.

7.7.2 QUALITY BENCHMARKS

Monitoring systems should be based on commercially available software/hardware that is supplied with user manuals and appropriate technical support.

Depending on the size and type of the plant, minimum parameters to be measured include:

- **Plane of array irradiance and horizontal plane irradiance:** Measured using secondary standard pyranometers with a measurement tolerance within ±2 percent.[46] Plane of array pyranometers are essential for contractually-binding performance ratio (PR) calculations, while horizontal plane pyranometers are useful in order to compare measured irradiation with global horizontal irradiation resource predictions. It is considered best practice to install irradiation sensors at a variety of locations within multi-megawatt plants, while avoiding locations that are susceptible to shading. Table 14 gives a rule of thumb for the number of pyranometers recommended according to the plant capacity.
- **Ambient temperature:** Measured in a location representative of site conditions with accuracy better than ±1°C. Ideally, temperature sensors should be placed next to the irradiation sensors, particularly if the PR at provisional acceptance is calculated using a temperature compensation factor (see Section 9: EPC Contracts).
- **Module temperature:** Measured with accuracy better than ±1°C, PT1000 sensors should be thermally

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[46] For example, Kipp & Zonen CMP 11, http://www.kippzonen.com/Product/13/CMP-11-Pyranometer#.VBmlTGMgsuc

Table 14: Recommended Number of Pyranometers Depending on Plant Capacity

Plant DC Capacity (MWp)	< 1	1–5	5–10	10–20	> 20
Number of Plane of Array Pyranometers	0	2	2	3	4
Number of Horizontal Pyranometers	0	0	1	1	1

bonded to the back of the module in a location positioned at the centre of a cell.

- **Array DC voltage:** Measured to an accuracy of within 1 percent.
- **Array DC current:** Measured to an accuracy of within 1 percent.
- **Inverter AC power:** Measured as close as possible to the inverter output terminals with an accuracy of within 1 percent.
- **Power to the utility grid.**
- **Power from the utility grid.**

Measurement of key parameters should be done at one-minute intervals.

7.8 OPTIMISING SYSTEM DESIGN

The performance of a PV power plant may be optimised by a combination of several enabling factors: premium modules and inverters, a good system design with high-quality and correctly-installed components and a good preventative maintenance and monitoring regime leading to low operational faults.

The aim is to minimise losses. Measures to achieve this are described in Table 15. Reducing the total loss increases the annual energy yield and hence the revenue, though in some cases it may increase the cost of the plant. Interestingly, efforts to reduce one type of loss may be antagonistic to efforts to reduce losses of a different type. It is the skill of the plant designer to make suitable compromises that result in a plant with a high performance at a reasonable cost according to the local conditions. The ultimate aim of the designer is to create a plant that maximises financial

Table 15: Performance Optimisation Strategies

Loss	Mitigating Measure to Optimise Performance
Shading	• Choose a location without shading obstacles. • Ensure that the plant has sufficient space to reduce shading between modules. • Have a robust O&M strategy that removes the risk of shading due to vegetation growth.
Incident angle	• Use anti-reflection coatings, textured glass, or tracking.
Low irradiance	• Use modules with good performance at low light levels.
Module temperature	• Choose modules with an improved temperature coefficient for power at high ambient temperature locations.
Soiling	• Choose modules less sensitive to shading. • Ensure a suitable O&M contract that includes an appropriate cleaning regiment for the site conditions.
Module quality	• Choose modules with a low tolerance or positive tolerance.
Module mismatch	• Sort modules with similar characteristics into series strings where possible. • Avoid partial shading of a string. • Avoid variations in module tilt angle and orientation within the same string.
DC wiring resistance	• Use appropriately dimensioned cable. • Reduce the length of DC cabling.
Inverter performance	• Choose correctly sized, highly efficient inverters.
AC losses	• Use correctly dimensioned cable. • Reduce the length of AC cabling. • Use high-efficiency transformers.
Plant downtime	• Use a robust monitoring system that can identify faults quickly. • Choose an O&M contractor with good repair response time. • Keep spares holdings.
Grid availability	• Install PV plant capacity in areas where the grid is strong and has the potential to absorb PV power.
Degradation	• Choose modules with a low degradation rate and a linear power guarantee.
MPP tracking	• Choose high-efficiency inverters with maximum power point tracking technology on multiple inputs. • Avoid module mismatch.
Curtailment of tracking	• Ensure that tracking systems are suitable for the wind loads to which they will be subjected.

returns by minimising the levelised cost of electricity (LCOE).

7.9 DESIGN DOCUMENTATION REQUIREMENTS

There are a number of minimum requirements that should be included as part of design documentation. These include:

- Datasheets of modules, inverters, array mounting system and other system components.
- Wiring diagrams including, as a minimum, the information laid out in Table 16.
- Layout drawings showing the row spacing and location of site infrastructure.
- Mounting structure drawings with structural calculations reviewed and certified by a licensed engineer.
- A detailed resource assessment and energy yield prediction.
- A design report that will include information on the site location, site characteristics, solar resource, design work, energy yield prediction, and a summary of the results of the geotechnical survey.

Table 16: Annotated Wiring Diagram Requirements

Section	Required Details
Array	• Module type(s). • Total number of modules. • Number of strings. • Modules per string.
PV String Information	• String cable specifications—size and type. • String over-current protective device specifications (where fitted)—type and voltage/current ratings. • Blocking diode type (if relevant).
Array electrical details	• Array main cable specifications—size and type. • Array junction box locations (where applicable). • DC isolator type, location and rating (voltage/current). • Array over-current protective devices (where applicable)—type, location and rating (voltage/current).
Earthing and protection devices	• Details of all earth/bonding conductors—size and connection points. This includes details of array frame equipotential bonding cable (where fitted). • Details of any connections to an existing Lightning Protection System (LPS). • Details of any surge protection device installed (both on AC and DC lines), to include location, type and rating.
AC system	• AC isolator location, type and rating. • AC overcurrent protective device location, type and rating. • Residual current device location, type and rating (where fitted). • Grid connection details and grid code requirements.
Data acquisition and communication system	• Details of the communication protocol. • Wiring requirements. • Sensors and data logging.

Box 5: Example of Poor Design

It is far cheaper and quicker to rectify design faults prior to construction than during or after construction. Therefore, it is vital to apply suitable technical expertise to every aspect of plant design. Should the developer not have all the required expertise in-house, then a suitably experienced technical advisor should be engaged. Regardless of the level of expertise in-house, it is good practice to carry out a full, independent technical due diligence of the design before construction commences. This will be an essential requirement if financing is being sought.

As an example, consider the faults that independent technical consultants identified with a 5MWp project that had been constructed in India in 2010:

- **Foundations:**
  - The foundations for the supporting structures consisted of concrete pillars, cast in situ, with steel reinforcing bars and threaded steel rods for fixing the support structure base plates. This type of foundation is not recommended due to the inherent difficulty in accurately aligning numerous small foundations.
  - Mild steel was specified for the fixing rods. As mild steel is prone to corrosion, stainless steel rods would have been preferable.
- **Support structures:**
  - The support structures were under-engineered for the loads they were intended to carry. In particular, the purlins sagged significantly under the load of the modules. Support structures should be designed to withstand wind loading and other dynamic loads over the life of the project. Extensive remedial work was required to retrofit additional supporting struts.
  - The supporting structure was not adjustable because no mechanism was included to allow adjustment in the positioning of modules. The combination of the choice of foundation type and choice of support structure led to extensive problems when it came to aligning the solar modules to the required tilt angle.
- **Electrical:**
  - String diodes were used for circuit protection instead of string fuses/MCBs. Current best practice is to use string fuses/MCBs, as diodes cause a voltage drop and power loss, as well as a higher failure rate.
  - No protection was provided at the combiner boxes. This meant that for any fault occurring between the array and the DC distribution boards (DBs), the DBs would trip, taking far more of the plant offline than necessary.
  - No-load break switches were included on the combiner boxes before the DBs. This meant it was not possible to isolate individual strings for installation or maintenance.

The design faults listed above cover a wide range of issues. However, the underlying lesson is that it is vital to apply suitable technical expertise on every aspect of the plant design through in-house or acquired technical expertise. Independent technical due diligence should be carried out on the design prior to construction.

Detailed below are checklists of basic requirements and procedures for plant design considerations. They are intended to assist solar PV plant developers during the development phase of a PV project.

PV Module Selection Checklist

- ☐ Supplier identification and track record checked.
- ☐ Minimum certification obtained.
- ☐ Product and power warranty terms and conditions in line with the market standards.
- ☐ Third-party warranty insurance provided (if available).
- ☐ Technology suitable for the environmental conditions (e.g., high temperatures, diffuse irradiation, humidity).
- ☐ Technology suitable for shading conditions (number of bypass diodes).
- ☐ Power tolerance in line with the market standards.

Transformer Selection Checklist

- ☐ Suitable capacity for project size.
- ☐ Compatibility with the national grid regulations.
- ☐ Supplier identification and track record checked.
- ☐ Minimum certification obtained.
- ☐ Product warranty terms and conditions in line with the market standards.
- ☐ Suitable for the environmental conditions (e.g., outdoor/indoor, ambient temperature and altitude).
- ☐ Efficiency in line with the market standards.
- ☐ Load/no-load losses in line with market standards.

Mounting Structure Selection Checklist

- ☐ Supplier identification and track record checked.
- ☐ Minimum certification obtained.
- ☐ Product warranty terms and conditions in line with market standards.
- ☐ Suitable for the environmental and ground conditions (thermal expansion, marine atmosphere, soil acidity).

Inverter Selection Checklist

- ☐ Suitable capacity for project size.
- ☐ Compatible with national grid code.
- ☐ Supplier identification and track record checked.
- ☐ Minimum certification obtained.
- ☐ Product supply terms and conditions in line with the market standards.
- ☐ Technology and model suitable for the environmental conditions (e.g., outdoor/indoor, derate at high temperatures, MPP range).
- ☐ Compatible with thin-film modules (transformer or transformerless inverter).
- ☐ Efficiency in line with the market standards.

General Design Checklist

- ☐ Tilt angle and orientation of the PV array suitable for the geographical location.
- ☐ Inter-row distance suitable for the site.
- ☐ Shading from nearby objects considered and suitable buffer zone included.
- ☐ PV string size suitable for the inverter under the site environmental conditions.
- ☐ Inverter size suitable for the PV array size (power ratio and inverter MPP range).
- ☐ Transformer correctly sized.
- ☐ Combiner boxes (IP rating) suitable for the environmental conditions.
- ☐ DC and AC cables sized correctly.
- ☐ LV and HV protection equipment (fuses, switchgears, and circuit breakers) correctly sized.
- ☐ Suitable earthing and lightening protection designed for site specific conditions.
- ☐ Civil works (foundations, drainage) suitable for environmental risks.
- ☐ Monitoring system in line with market standards.
- ☐ Security system in line with market standards and accepted by insurance provider.

8 Permits, Licensing and Environmental Considerations

8.1 PERMITS, LICENSING AND ENVIRONMENT OVERVIEW

Permitting and licensing requirements for solar PV power plants vary greatly from country to country and within different country regions. It is important therefore to establish with the appropriate planning/government authority the relevant laws/regulations and associated permits that will be required for the project.

In order to deliver a project which will be acceptable to international lending institutions (e.g., to enable finance to be provided), environmental and social assessments should be carried out in accordance with the requirements of the key international standards and principles, namely the Equator Principles and IFC's Performance Standards (IFC PS). National standards should also be observed which may be more stringent than lender requirements.

A checklist of the basic requirements and procedures for permitting and licensing is at the end of Chapter 8.

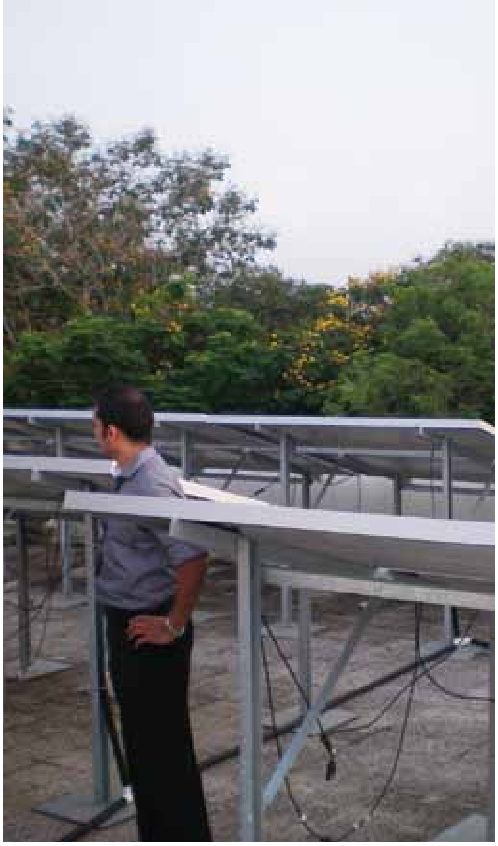
The following sections describe permitting and licensing requirements.

8.2 PERMITTING AND LICENSING REQUIREMENTS

Permitting and licensing procedures vary depending on plant location and size. For small PV installations, permitting regimes are often simplified and obtained at a local authority level. However large-scale plants can have more extensive requirements that are determined at a national or regional level. The key permits, licences and agreements typically required for renewable energy projects include:

- Land lease agreement.
- Planning/land use consents.
- Building permits.

Permitting and licensing procedures vary depending on plant location and size. For small PV installations, permitting regimes are often simplified and obtained at a local authority level. However large-scale plants can have more extensive requirements that are determined at a national or regional level.



- Environmental permits.
- Grid connection application.
- Operator/generation licences.

In addition to the key permits, licences and agreements listed above, under the FiT requirements or other support, it may be necessary for a developer to register as a "qualified/privileged/special renewable energy generator" to obtain support. Depending on the country in question, there may also be a requirement for the developer to demonstrate compliance with these requirements.

The sequence of requirements can vary from country to country and it is recommended that an early meeting is held with the relevant planning/government authority to establish and confirm relevant laws and associated permits that will be necessary for the project. The timescales for obtaining relevant permissions should also be ascertained at an early date, as many permissions will be required to be in place prior to construction of the plant.

8.2.1 LAND LEASE AGREEMENT

If the land is not privately owned, an agreement to procure or lease the necessary land from the land owner is a key requirement. The land lease agreement must be secured as a first step to enable the project to be developed on the required land. This does not apply to rooftop locations. A lease agreement typically lasts for 25 years, often with a further extension clause.

The leases and option agreements should include restrictions on developments to be installed on land adjacent to the site that could have an effect on the performance of the solar PV arrays. Furthermore, the areas of land required for new access roads also need to be taken into consideration.

8.2.2 PLANNING AND LAND USE CONSENTS

All relevant planning consents/land-use authorisations must be in place prior to the construction of a project. Consenting requirements vary widely in different countries and regions and also depend on the size of the plant. Advice on planning-consent requirements in the project area can be obtained from the local planning department, relevant government department or from an experienced consultant. The type of information that needs to be considered includes:

- Planning consents/permits and land-use authorisations required to construct and operate a solar renewable energy development.
- Any standard planning restrictions for the area of the development (for example, land-use zoning regulations).
- Supporting information required to be submitted with planning application (location/layout/elevation plans, description of project, access details, environmental assessments, etc.—as required by the relevant authority).
- Method of submission (online or via the planning department office).
- Timescales for submission and determination.
- Process for making amendments to consent at a later date.

A permit from the roads authority may also be necessary, depending on the works required.

8.2.3 BUILDING PERMITS

Some countries may require a separate building permit to be obtained, depending on the nature of the project. Where this is required, it should be noted that the consenting authority may differ from the authority issuing the planning/land-use permits.

Before a building permit is obtained, it may be necessary to have other required permits in place or to complete a change in land-use categorisation. As above, consultation at an early stage with the relevant authority is recommended to establish country- and locally-specific requirements.

8.2.4 ENVIRONMENTAL PERMITS

All necessary environmental permits, licences and requirements must be obtained prior to commencing construction. Environmental permits are country- and project-specific. Consultation with the relevant environmental agencies and departments should be undertaken to determine the requirement for any environmental permits relevant to the project. A specialist environmental consultant can also provide advice on the specific requirements.

Environmental permits and licences that may be required include:

- Environmental impact assessment (EIA) permit.
- Endangered/protected species licence.
- Agricultural protection permits.
- Historic preservation permits.
- Forestry permits.

Further detail on environmental considerations is detailed in Section 8.3 below.

8.2.5 *GRID CONNECTION APPLICATION*

A grid connection permit is required for exporting power to the network, which normally specifies the point of connection and confirms the voltage-level that will be applied to that connection. The grid connection application should be submitted to the relevant transmission or distribution utility company for the project.

The permit must be in place well in advance of the date that first export to the grid is required in order to allow sufficient timescales for associated works to be completed. Solar PV power plants will need to meet the requirements of the grid company that operates the network onto which they will export power. This is discussed further in Section 10.4.

8.2.6 *ELECTRICITY GENERATION LICENCE*

The operator of an electricity generating facility is required to hold a generating licence, which permits an operator to generate, distribute and supply electricity. Developers should be aware of the country-specific requirements and timeframes required for obtaining a generating licence. For example, in many European and Asian countries, an electricity generation licence is obtained after construction of the plant, while in some African countries the licence is required early in the project development process.

8.3 ENVIRONMENTAL AND SOCIAL REQUIREMENTS

Development of any solar project will have both environmental and social implications. The scale and nature of these impacts depends on a number of factors including plant size, location, proximity to settlements and applicable environmental designations. These issues are discussed further in the following sections.

8.3.1 *APPLICABLE STANDARDS*

In order to deliver a project that will be acceptable to international lending institutions (e.g., to enable finance to be provided), work should be carried out in accordance with the requirements of the key standards and principles set out in the following sections.

8.3.1.1 Equator Principles

The Equator Principles[47] (EP) consists of ten principles relating to environmental and social assessment and management. In addition, they include reporting and monitoring requirements for Equator Principles Financial Institutions (EPFIs). The EP set a financial industry benchmark that have been adopted by financial institutions for determining, assessing and managing environmental and social risk in projects.

There are currently 78 EPFIs in 34 different countries that have officially adopted the EP standards.[48] These institutions will not provide financing to clients that are unwilling or unable to comply with the EPs. Some of these

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[47] World Bank Group, "The Equator Principles: A financial industry benchmark for determining, assessing and managing environmental and social risk in projects," 2013. http://www.equator-principles.com/resources/equator_principles?III.pdf (accessed June 2014).

[48] World Bank Group, "The Equator Principles: Members & Reporting," http://www.equator-principles.com/index.php/members-reporting

lenders, such as the European Bank for Reconstruction and Development (EBRD), may have additional standards to which borrowers must adhere. Further information on financing requirements can be found in Section 14 (Financing Solar PV Projects).

The EPs apply globally and to all industry sectors, hence their relevance to the solar industry. The ten EPs address the following topics:

- EP1 - Review and Categorisation
- EP2 - Environment and Social Assessment
- EP3 - Applicable Environmental and Social Standards
- EP4 - Environmental and Social Management System and Equator Principles Action Plan
- EP5 - Stakeholder Engagement
- EP6 - Grievance Mechanism
- EP7 - Independent Review
- EP8 - Covenants
- EP9 - Independent Monitoring and Reporting
- EP10 - Reporting and Transparency

8.3.1.2 IFC Performance Standards on Social and Environmental Sustainability

As set out in EP3, countries not designated as High Income Organization of Economic Cooperation and Development (OECD) countries should apply the social and environmental sustainability standards laid down by the IFC.[49] These standards have been developed for the IFC's own investment projects but have set an example for private companies and financial institutions worldwide.

The IFC PS relate to the following key topics:

- Performance Standard 1: Assessment and Management of Environmental and Social Risks and Impacts
- Performance Standard 2: Labour and Working Conditions
- Performance Standard 3: Resource Efficiency and Pollution Prevention
- Performance Standard 4: Community Health, Safety and Security
- Performance Standard 5: Land Acquisition and Involuntary Resettlement
- Performance Standard 6: Biodiversity Conservation and Sustainable Management of Living Natural Resources
- Performance Standard 7: Indigenous Peoples
- Performance Standard 8: Cultural Heritage

Compliance with the IFC performance standards will not only ensure a socially and environmentally sustainable project but will also facilitate the sourcing of finance for a project.

8.3.1.3 World Bank Group General Environmental Health and Safety (EHS) Guidelines

The General EHS Guidelines is a technical reference document containing general and industry-specific examples of good international industry practice. The General EHS Guidelines contain guidance on environmental, health, and safety issues that are applicable across all industry sectors.

8.3.1.4 Local, National and International Environmental and Social Legislation and Regulations

Environmental and social legislation and regulations vary between countries and specific regions; however the EP and IFC PS set the minimum acceptable standard for project developments worldwide.

A large number of countries have national legislative requirements that are on par with or higher than the EP/IFC standards. If national requirements are more onerous, project developers should review and adhere to these standards.

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[49] IFC, "Performance Standards on Environmental and Social Sustainability," 2012, http://www.ifc.org/wps/wcm/connect/c8f524004a73daeca09afdf998895a12/IFC_Performance_Standards.pdf?MOD=AJPERES (accessed June 2014).

In countries where environmental and social legislation requirements are less demanding, a project must be developed in accordance with these requirements in addition to the lender's standards, which must as a minimum meet the EP/IFC standards.

8.3.2 ENVIRONMENTAL AND SOCIAL IMPACT ASSESSMENT

Projects may be required to carry out an initial scoping or a full Environmental (and Social) Impact Assessment (EIA or ESIA), depending on national regulatory requirements.

Relevant in-country environmental and social impact assessment regulations and legislation should be reviewed in the first instance to determine country-specific requirements, alongside the requirements of the EPs and IFC PS. In general, in order to attract financing and meet regulatory requirements, a screening study variously referred to as an Initial Environmental Examination (IEE) or Environmental Scoping Study needs to be commissioned involving an independent environmental consultancy to establish the nature and scale of environmental impacts and extent of assessment required. Once the level of potential impacts and site sensitivity has been determined, it can then be confirmed if a full environmental and social assessment is required.

If deemed necessary, the likely environmental effects of the proposed development should be considered as part of a full ESIA and based upon current knowledge of the site and the surrounding environment. This information will determine what specific studies are required. The developer should then assess ways of avoiding, reducing or offsetting any potentially significant adverse effects as described in IFC PS 1. The studies will also provide a baseline that can be used in the future to monitor the impact of the project. Note that only impacts deemed to be "significant" need to be considered as part of an ESIA.

Key environmental considerations for solar PV power plants are detailed below. Note that the list of considerations is not exhaustive. Environmental and social topics for assessment should be determined on a project by project basis. It is recommended that the environmental assessment should be carried out by an experienced independent consultant familiar with conducting Environmental & Social Impact Assessment (ESIA) studies.

8.3.2.1 Construction Phase Impacts

Construction activities lead to temporary air emissions (dust and vehicle emissions), noise related to excavation, construction and vehicle transit, solid waste generation and wastewater generation from temporary building sites and worker accommodation. In addition, occupational health and safety (OHS) is an issue that needs to be properly managed during construction in order to minimize the risk of preventable accidents leading to injuries and/or fatalities—there have been a number of fatal incidents in recent history at solar power plant construction sites around the world. Proper OHS risk identification and management measures should be incorporated in every project's management plan and standard EPC contractual clauses. Where projects have construction worker-accommodation camps, accommodation should meet basic requirements in relation to space, water supply, adequate sewage and garbage disposal, protection against heat, cold, damp, noise, fire and disease-carrying animals, storage facilities, lighting and (as appropriate to size and location) access to basic medical facilities or personnel.

8.3.2.2 Water Usage

Although water use requirements are typically low for solar PV plants, Concentrated Solar Power (CSP) plants may have higher requirements and clusters of PV plants may have a high cumulative water use requirement in an arid area where local communities rely upon scarce groundwater resources. In such scenarios, water consumption should be estimated and compared to local water abstraction by communities (if any), to ensure no adverse impacts on local people. O&M methods in relation to water availability and use should be carefully reviewed where risks of adverse impacts to community usage are identified.

8.3.2.3 Land Matters

As solar power is one of the most land-intensive power generation technologies, land acquisition procedures and in particular the avoidance or proper mitigation of involuntary land acquisition/resettlement are critical to the success of the project(s). This includes land acquired either temporarily or permanently for the project site itself and any associated infrastructure—i.e., access roads, transmission lines, construction camps (if any) and switchyards. If involuntary land acquisition is unavoidable, a Resettlement Action Plan (dealing with physical displacement and any associated economic displacement) or Livelihood Restoration Plan (dealing with economic displacement only) is typically required by financiers to make the project bankable. This is often a crucial issue with respect to local social license to operate, and needs to be handled with due care and attention by suitably qualified persons.

8.3.2.4 Landscape and Visual Impacts

Key impacts can include the visibility of the solar panels within the wider landscape and associated impacts on landscape designations, character types and surrounding communities. Common mitigation measures to reduce impacts can include consideration of layout, size and scale during the design process and landscaping/planting in order to screen the modules from surrounding receptors. Note that it is important that the impact of shading on energy yield is considered for any new planting requirements.

Solar panels are designed to absorb, not reflect, irradiation. However, glint and glare should be a consideration in the environmental assessment process to account for potential impacts on landscape/visual and aviation aspects.

8.3.2.5 Ecology and Natural Resources

Potential impacts on ecology can include habitat loss/fragmentation, impacts on designated areas and disturbance or displacement of protected or vulnerable species. Receptors of key consideration are likely to include nationally and internationally important sites for wildlife and protected species such as bats, breeding birds and reptiles. Ecological baseline surveys should be carried out where potentially sensitive habitat, including undisturbed natural habitat, is to be impacted, to determine key receptors of relevance to each site. Mitigation measures can include careful site layout and design to avoid areas of high ecological value or translocation of valued ecological receptors. Habitat enhancement measures could be considered where appropriate to offset adverse impacts on sensitive habitat at a site, though avoidance of such habitats is a far more preferable option (as per the site selection discussion in Section 6.3).

8.3.2.6 Cultural Heritage

Potential impacts on cultural heritage can include impacts on the setting of designated sites or direct impacts on below-ground archaeological deposits as a result of ground disturbance during construction. Where indicated as a potential issue by the initial environmental review/scoping study, field surveys should be carried out prior to construction to determine key heritage and archaeological features at, or in proximity to, the site. Mitigation measures can include careful site layout and design to avoid areas of cultural heritage or archaeological value and implementation of a 'chance find' procedure that addresses and protects cultural heritage finds made during a project's construction and/or operation phases.

8.3.2.7 Transport and Access

The impacts of transportation of materials and personnel should be assessed in order to identify the most appropriate transport route to the site while minimizing the impacts on project-affected communities. The requirement for any oversized vehicles/abnormal loads should be considered to ensure access is appropriate. On-site access tracks should be permeable and developed to minimise disturbance to agricultural land. Where project construction traffic has to traverse local communities, traffic management plans should be incorporated into the environmental and social management plan and EPC requirements for the project.

8.3.2.8 *Drainage/Flooding*

A review of flood risk should be undertaken to determine if there are any areas of high flood risk associated with the site. Existing and new drainage should also be considered to ensure run-off is controlled to minimise erosion.

8.3.3 CONSULTATION AND DISCLOSURE

It is recommended that early stage consultation is sought with key authorities, statutory bodies, affected communities and other relevant stakeholders.[50] This is valuable in the assessment of project viability, and may guide and increase the efficiency of the development process. Early consultation can also inform the design process to minimise potential environmental impacts and maintain overall sustainability of the project.

The authorities, statutory bodies and stakeholders that should be consulted vary from country to country but usually include the following organisation types:

- Local and/or regional consenting authority.
- Government energy department/ministry.
- Environmental agencies/departments.
- Archaeological agencies/departments.
- Civil aviation authorities/Ministry of Defence (if located near an airport).
- Roads authority.
- Health and safety agencies/departments.
- Electricity utilities.
- Military authorities.

Community engagement is an important part of project development and should be an on-going process involving the disclosure of information to project-affected communities.[51] The purpose of community engagement is to build and maintain over time a constructive relationship with communities located in close proximity to the project and to identify and mitigate the key impacts on project-affected communities. The nature and frequency of community engagement should reflect the project's risks to, and adverse impacts on, the affected communities.

8.3.4 ENVIRONMENTAL AND SOCIAL MANAGEMENT PLAN (ESMP)

Whether or not an ESIA or equivalent has been completed for the site, an ESMP should be compiled to ensure that mitigation measures for relevant impacts of the type identified above (and any others) are identified and incorporated into project construction procedures and contracts. Mitigation measures may include, for example, dust suppression during construction, safety induction, training and monitoring programs for workers, traffic management measures where routes traverse local communities, implementation of proper waste management procedures, introduction of periodic community engagement activities, implementation of chance find procedures for cultural heritage, erosion control measures, fencing off of any vulnerable or threatened flora species, and so forth. The ESMP should indicate which party will be responsible for (a) funding, and (b) implementing each action, and how this will be monitored and reported on at the project level. The plan should be commensurate to the nature and type of impacts identified.

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[50] IFC, "Performance Standards on Environmental and Social Sustainability," 2012, Performance Standard 1, paragraphs 25-31, http://www.ifc.org/wps/wcm/connect/115482804a0255db96fbffd1a5d13d27/PS_English_2012_Full-Document.pdf?MOD=AJPERES (accessed June 2014).

[51] IFC, "Stakeholder Engagement: A Good Practice Handbook for Companies Doing Business in Emerging Markets," 2007, http://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/ifc+sustainability/publications/publications_handbook_stakeholderengagement__wci__1319577185063 (accessed June 2014).

Box 6: Permits, Licensing and Environmental Considerations

There are many types of permits required for a multi-megawatt solar PV power plant, which in accordance with country requirements will vary in terms of purpose of requirements. Shown below is an indicative, non-exhaustive list of the key permits that were required to be obtained in South Africa for a ground-mounted fixed-tilt PV plant. These permits apply specifically to the case study; permitting requirements differ across other regions of South Africa and especially in different countries. Some of the case study's permits were issued with condition-requirements including time limits for commencing and rules for the processes of construction, operation and decommissioning. The majority of these permits were applied for and in place prior to the start of construction, as is deemed best practice.

An Environmental Impact Report was compiled for the project under the required Environmental Impact Assessment (EIA) Regulations and Natural Environmental Management Act. The EIA process was used to inform the preferred layout for the project in order to reduce the potential for significant environmental impacts. Elements of the project design thus reduced the potential for impact on water resources and included a visual buffer zone from nearby roads, railway lines and farms, in addition to avoiding sensitive areas/heritage resources. Mitigation measures proposed to further reduce impacts during construction included:

- Pre-construction ecological checks.
- Rehabilitation/re-vegetation of areas damaged by construction activities.
- Implementation of soil conservation measures, such as stockpiling topsoil or gravel for remediation of disturbed areas.
- Bunding of fuel, oil and used storage areas.

Implementing these mitigation measures ensured that the only significant impacts likely to arise from the project would be those associated with visual impacts.

International lending standards (Equator Principles and IFC Performance Standards) were also applicable, such that this project required an appropriate degree of environmental and social assessment to meet these standards. A principle finding of the environmental assessment work carried out to meet these international criteria was a recommendation for a bird breeding survey in order to assess fully the project impacts upon the population of a species of conservation concern. This recommendation was identified following the completion of the EIA, highlighting the importance of the consideration of Equator Principles and IFC Performance Standards alongside EIA preparation from the very outset of the project. This will help ensure reaching a standard that is acceptable to lenders.

The following table provides the key permits that were required in order to develop the project.

Permit	Authority	Requirements
Land-use Re-zoning	Relevant Municipality	• Standard condition requirements
Environmental Authorisation	Department of Environmental Affairs	30 condition requirements that included: • Work must commence within a period of five years from issue. • Requirement to appoint an independent Environmental Control Officer (ECO) for the construction phase of development to ensure all mitigation/rehabilitation measures are implemented.
Heritage Resources	South Africa Heritage Resources Agency (SAHRA)	SAHRA recommendations were incorporated into the condition requirements of the Environmental Authorisation to include avoidance of areas with important heritage resources.
Mineral Resources	Department of Mineral Resources	No condition requirements.
Aviation Consent	Civil Aviation Authority	No condition requirements.
Water Use Licence	Department of Water Affairs	No condition requirements.
Building Permit	Relevant Municipality	No condition requirements.

Permitting, Licensing and Environmental and Social Considerations Checklist

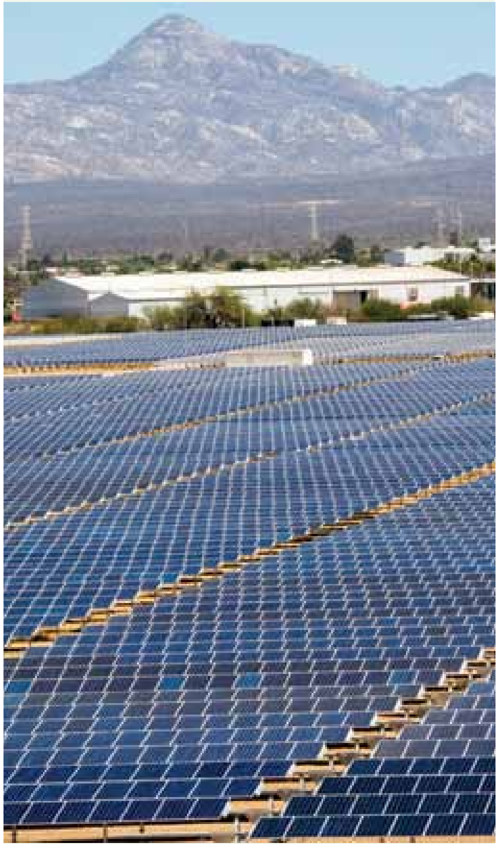
The checklist below details the basic requirements and procedures to assist developers with the permitting and licensing aspects of a project.

- ☐ Land lease agreement obtained.
- ☐ Advice sought on planning/consenting/permitting from local regulatory authorities and any environmental assessments required.
- ☐ Initial Environmental Examination (IEE) completed.
- ☐ Environmental and social assessments carried out (as required).
- ☐ Relevant supporting documents for consent/licensing applications completed (including environmental assessment reports, access details, drawings and plans).
- ☐ Community consultation undertaken.
- ☐ Consents, licences and permit applications completed.
- ☐ Grid connection application completed.
- ☐ Electricity generation licence obtained.

EPC Contracts

9

While multiple contracts could be signed to build a PV plant, the most common approach is a single EPC contract. Often, a standard form ("boilerplate contract") is used.



9.1 EPC CONTRACTS OVERVIEW

Engineering, procurement and construction (EPC) contracts are the most common form of contract for the construction of solar PV power plants. Under an EPC contract, a principal contractor is engaged to carry out the detailed engineering design of the project, procure all the equipment and materials necessary, and then construct and commission the plant for the client. In addition, the contractor commits to delivering the completed plant for a guaranteed price and by a guaranteed date and furthermore that the completed plant must perform to a guaranteed level. Failure to comply with any of these requirements will usually result in the contractor having to pay financial compensation to the owner in the form of liquidated damages (LDs). See the checklist at the end of the chapter highlighting the basic requirements that a developer may wish to consider during the EPC contracting process.

The following sections describe the most important features of an EPC contract. A full EPC contract term sheet detailing key contractual terms specific to solar PV power plant construction is presented in Annex 1.

9.2 BASIC FEATURES OF AN EPC CONTRACT

The EPC contract for any project-financed solar PV power plant will typically be held between a project company (the owner) and the EPC contractor (the contractor).

It is common practice to use a standard form of contract (sometimes referred to as a "boilerplate contract") as a template and basis for the EPC contract. The following standard form of contracts are considered good options for delivery of solar PV power plants on a turnkey basis:

- The Conditions of Contract for EPC/Turnkey Project First Edition, 1999, published by the Federation Internationale des Ingenieurs-Conseils (FIDIC).

- The Institution of Engineering and Technology's Model Form of General Conditions of Contract (MF/1 Rev. 4)

The key clauses for a project owner in any construction contract are those that relate to time, cost and quality. In the case of solar PV power plant construction, a strong EPC contract will address the following areas:

- A "turnkey" scope of work.
- A fixed completion price.
- A fixed completion date.
- Restrictions on the ability of the contractor to claim extensions of time and additional costs.
- A milestone payment profile that is suitably protective to the owner and based upon the completion of pre-defined sub-tasks.
- Plant PR guarantees.
- LDs for both delay and performance.
- Financial security from the contractor and/or its parent organisation.
- A defects warranty.

Each of these areas is discussed further below with specific reference to solar PV power plants.

9.3 SCOPE OF WORK

The benefit of an EPC contract to a plant owner is that the contractor assumes full responsibility for all design, engineering, procurement, construction, commissioning and testing activities. Given this transfer of risk, the scope of work detailed within the EPC contract should be sufficiently prescriptive to ensure that all key supply and engineering tasks relating to the construction of a solar PV power plant have been adequately considered and specified.

The contractor's scope of work should include all supervision, management, labour, plant equipment, temporary works and materials required to complete the works, including:

- Plant design.
- PV modules.
- Inverters.
- Mounting structures, including piled or ballasted foundations.
- DC cabling.
- AC cabling.
- Switchgear.
- Transformers.
- Grid connection interface.
- Substation building.
- Earthing and lightning protection.
- Metering equipment.
- Monitoring equipment.
- Permanent security fencing.
- Permanent security system.
- Temporary onsite security during construction.
- Temporary and permanent site works, including provision of water and power.
- Permanent access tracks (both internal and external).
- Site drainage.
- Plant commissioning.
- Handover documentation (including as-built drawings, O&M manual and commissioning certificates).
- Spare parts package.

All technical requirements should be fully specified within a schedule to the contract. These should be suitably prescriptive and unambiguous. The more detailed and accurate the scope of work, the lower the risk that requests for variation will be made by the contractor during the construction phase. The contract should also clearly define terminal points, or points that designate where the contractor's scope of work ends.

9.4 PRICE AND PAYMENT STRUCTURE

On signing of the contract, the contractor commits to delivering the works for a fixed price. The contract should make it explicitly clear that at the time of signing, the contractor is satisfied as to the correctness and sufficiency of the contract price to deliver the works in line with the contractually agreed specifications.

The contract price should cover all of the contractor's obligations under the contract and all items necessary for the proper design, execution and completion of the works. The owner should not be required to increase the contract price, other than in accordance with the express provisions of the contract.

During the construction phase, payment will typically be made to the contractor by way of milestones relating to the completion of individual work items. The payment schedule should be fair and reasonable for both parties and should allow the contractor to remain "cash neutral" throughout the build process, as the contractor will be paying the sub-contractors and equipment providers on a regular basis. Payment milestones should be drafted to be clear, measureable, and made on completion (rather than commencement) of the individual scope items.

Any advance payment made to the contractor on signing of the contract should be accompanied by an advance payment guarantee, usually in the form of a bond held within a bank that can be drawn upon in the event of contractor default or insolvency. The value of each milestone should roughly reflect the value of the completed works. It is normal that approximately 5-10 percent of the contract value should be held back until handover of the works (Provisional Acceptance) has been achieved.

An example payment schedule is shown in Table 17.

Table 17: Typical EPC Payment Schedule

Payment	Payment Due Upon	Percent of Contract Price
1	Advance payment (commencement date)	10-20
2	Civil works completed	10-20
3	Delivery of components to site (usually on a pro-rata basis)	40-60
4	Modules installed	5-15
5	Grid connection achieved (energisation)	5-15
6	Mechanical completion	5-10
7	Provisional acceptance—plant taken over	5-10

9.5 COMPLETION AND HANDOVER OF THE PLANT

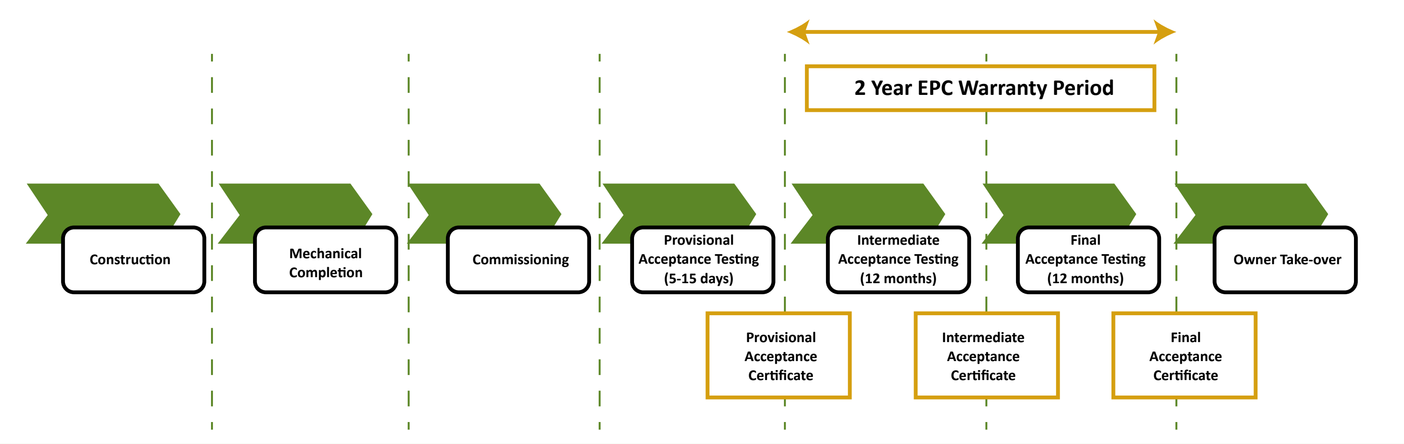
The contract should clearly outline the criteria for completing the contractor's scope of work and therefore when handover of the completed plant from contractor to owner can occur. Until this time, the contractor remains fully responsible for the site and construction activities. Completion typically takes the form of a number of acceptance tests and inspections to be conducted by the owner or an independent third party that demonstrates that the plant has been installed and is performing as per the contractually agreed specifications. The requirements in these areas are generally detailed in a dedicated testing and commissioning schedule.

A diagram outlining key completion events occurring during a solar PV plant construction project (in chronological order from left to right) is shown in Figure 20. These are described further below.

9.5.1 *GUARANTEED COMPLETION DATE*

The contract should include a guaranteed completion date, which is typically either specified as a fixed date or as a fixed period after commencement of the contract. The actual works stage to which the guaranteed completion date relates will be project-specific, and this may be driven by a country's regulatory regime as well as the date that projects become eligible for receiving tariff support. For example, the guaranteed completion date could coincide with the date the plant is scheduled to be connected to the local electricity grid, commissioned or is ready to be handed over to the owner. The key point is that the owner needs to be certain as to what date the plant

Figure 20: Typical EPC Construction Phase and Handover Protocol



will be exporting to the grid and therefore generating a return on the investment. Inability to meet the expected completion date for beginning to export power to the grid has important implications from a regulatory or financial perspective.

To mitigate the risk of the owner suffering financial loss resulting from the contractor failing to deliver a completed plant to the agreed timetable, the contract should include a provision for claiming financial compensation ("liquidated damages" or LDs) from the contractor. LDs should be sized to be a genuine pre-estimate of the loss or damage that the owner will suffer if the plant is not completed by the target completion date. Delay LDs are usually expressed as a rate per day that represents the estimated lost revenue for each day of delay. For a solar PV project, this is a relatively straightforward calculation and can be based upon an energy yield estimate for the completed plant utilising a long-term solar irradiation dataset for the project location.

If there is potential for the owner to suffer additional financial losses beyond lost revenue resulting from delay (perhaps due to the presence of a tariff reduction date) then provisions addressing the owner's right to collect LDs for any such losses should also be included in the contract.

9.5.2 *MECHANICAL COMPLETION*

Mechanical completion of a project refers to the stage whereby all principal sub-components forming the final power plant have been installed and are mechanically and structurally complete. At such a time, it would be advisable for the owner or a third party independent of the contractor to inspect the works in order to compile an initial list of construction defects (commonly referred to as a "punch list" or "snagging list").

Mechanical completion allows for commissioning activities to commence.

9.5.3 *COMMISSIONING*

Commissioning should be considered throughout the course of the construction phase, however, most of the commissioning activities will occur following mechanical completion when the system is ready to be energised.

The commissioning process certifies that the owner's requirements have been met, the power plant installation is complete and the power plant complies with grid and safety requirements. Successful completion of the commissioning process is crucial to achieving provisional acceptance, the process of handover of the plant from contractor to owner.

Commissioning should prove three main criteria:

1. The power plant is structurally and electrically safe.
2. The power plant is sufficiently robust (structurally and electrically) to operate for the specified lifetime.
3. The power plant operates as designed and its performance falls in line with pre-determined parameters.

Critical elements of a PV power plant that require commissioning include:

1. PV module strings.
2. Inverters.
3. Transformers.
4. Switchgear.
5. Lightning protection systems.
6. Earthing protection systems.
7. Electrical protection systems.
8. Grid connection compliance protection and disconnection systems.
9. Monitoring systems (including meteorological sensors).
10. Support structure and tracking systems (where employed).
11. Security systems.

9.5.3.1 Typical Commissioning Tests

Prior to connecting the power plant to the grid, electrical continuity and conductivity of the plant's various sub-components should be thoroughly checked by the contractor (or specialist electrical subcontractor). Once mechanically and electrically complete, the following tests should be conducted on all module strings and on the DC side of the inverters:

- **Polarity Check:** The polarity of all DC cables should be checked. This is one of the simplest and most important safety commissioning tests. Several rooftop fires involving PV systems have been traced back to reverse polarity.
- **Open Circuit Voltage (V_{oc}) Test:** This test checks whether all strings are properly connected and whether all modules are producing the voltage level as per the module data sheet. The V_{oc} of each string should be recorded and compared with temperature-adjusted theoretical values. For plants with multiple identical strings, voltages between strings should be compared to detect anomalies during stable irradiance conditions. Values from individual strings should fall within 5 percent of each other.
- **Short Circuit Current Test (I_{sc}):** This test verifies whether all strings are properly connected and the modules are producing the expected current. The I_{sc} of each string should be recorded and compared with temperature-adjusted theoretical values. For plants with multiple identical strings, voltages between strings should be compared to detect anomalies during stable irradiance conditions. Values from individual strings should fall within 5 percent of each other.
- **Insulation Resistance Test:** The insulation resistance of all DC and AC cabling installed should be tested with a megohmmeter. The purpose of the test is to verify the electrical continuity of the conductor and verify the integrity of its insulation.
- **Earth Continuity Check:** Where protective or bonding conductors are fitted on the DC side, such as bonding of the array frame, an electrical continuity test should be carried out on all such conductors. The connection to the main earthing terminal should also be verified.

After the above commissioning tests have been successfully completed and the correct functioning and safe operation of subsystems have been demonstrated, commissioning of the inverters may commence. The inverter manufacturer's directions for initial start-up should always be adhered to.

9.5.3.2 Grid Connection Interface

Grid connection should only be performed once all DC string testing has been completed. It is likely that the distribution or transmission system operator will wish to witness the connection of the grid and/or the protection relay. Such a preference should be agreed in advance as part of the connection agreement.

The grid connection agreement often stipulates certain requirements, such as electrical protection, disconnection and fault, to which the solar PV power plant is required to adhere. Usually, these conditions need to be met and demonstrated before commissioning the grid connection interface and energisation of the plant.

9.5.3.3 General Commissioning Recommendations

Commissioning activities should commence following mechanical completion of the plant's various sub-components or, where appropriate, sequentially as module strings are connected. One exception to this rule is for power plants employing modules that require a settling-in period, such as thin-film amorphous silicon (a-Si) modules. In this case, performance testing should begin once the settling-in period has been completed and the modules have undergone initial degradation.

Since irradiance has an impact on performance, commissioning should be carried out under stable sky conditions and ideally at irradiance levels above 500W/m^2. The temperature of the cells within the modules should be recorded in addition to the irradiance and time during all testing.

Commissioning activities should incorporate both visual inspection and functional testing. Such testing should be conducted by experienced and specialist organisations, typically sub-contractors to the EPC contractor.

The testing outlined in this section does not preclude local norms, which will vary from country to country.

Test results should be recorded as part of a signed-off commissioning record. While the contractor would be expected to carry out these tests, it is important that the owner is aware of them and makes sure that the required documentation is completed, submitted and recorded.

A useful reference for commissioning of PV systems can be found in IEC standard 62446:2009 *Grid connected photovoltaic systems—Minimum requirements for system documentation, commissioning tests and inspection*.

9.6 PROVISIONAL ACCEPTANCE

Provisional acceptance is a common term used to refer to the stage at which the contractor has complied with all of its construction-related obligations and the plant is ready to be handed over to the owner. The criteria for achieving provisional acceptance should be clearly outlined in the contract and may include:

- Mechanical completion having taken place in accordance with the agreed technical specification and the plant being free from defects (other than non-critical punch list items).
- The aggregate value of the punch list items does not exceed a pre-determined value (typically 1–2 percent of the contract price).
- Grid connection and energisation of the plant have been achieved.
- All commissioning tests have been successfully completed.
- The provisional acceptance performance ratio (PR) test has been passed.
- All equipment and sub-contractor warranties have been assigned to the project company.
- All handover documentation is in place and hard and soft copies provided to the owner.
- Operation and maintenance training of the owner's personnel has taken place.
- Any delay or performance-related liquidated damages (LDs) incurred by the contractor during the construction phase have been paid to the owner.
- Any performance security or bond required during the EPC warranty period has been delivered to the owner.

Once provisional acceptance has been achieved, the owner would typically be obliged to make the final milestone payment to the contractor, at which point 100 percent of the contract value would have been paid.

The provisional acceptance date would also mark the commencement of the contractor's EPC warranty period, which commonly lasts for 24 months.

9.6.1 PERFORMANCE RATIO TESTING

Prior to granting provisional acceptance, the owner needs confirmation that the completed plant will perform in line with the contractually agreed criteria (in terms of output, efficiency and reliability). The industry standard for achieving this within solar EPC contracts is through testing of the plant's PR.

A standard PR test period at the stage of provisional acceptance would be for a minimum of five consecutive days (commonly up to 15 days) of continuous testing. It is desirable to test plant efficiency and reliability over a range of meteorological conditions.

Calculation of the plant PR is determined using the contractually agreed formulae. Attempting to predict the plant performance during varying environmental conditions experienced over the years with just several days of testing is a complex task and different methodologies are used (e.g., temperature compensation or seasonal adjustment). For this reason, an independent technical advisor is often employed to draft the formulae defining the provisional acceptance performance tests.

The PR measured over the test period should be compared against the guaranteed value stated in the contract. If the measured PR exceeds the guaranteed value then the test is passed. If the measured PR is below the guaranteed value, the contractor should perform investigations into the reasons for plant under-performance and rectify these prior to repeating the test.

Given the short duration of the test, it would be unusual that performance LDs would be attached to the result. It is normal that LDs are instead linked to the results of the annual PR tests measured at the end of one or two years of plant operation. It is unusual for PR guarantees to extend beyond two years within an EPC contract, although they sometimes may be part of a long-term O&M contract.

9.6.2 INTERMEDIATE AND FINAL ACCEPTANCE

The contractor will typically be required to deliver a number of guarantees in relation to their works. These are described below.

- **Defects Warranty:** It would be normal for the contractor to provide a fully-wrapped plant defects warranty for a period of at least two years following the date of provisional acceptance. This makes the contractor responsible for the rectification of any defects that may be identified during this period.
- **Performance Warranty:** In addition to the short-term PR test at provisional acceptance, it is industry standard for the contractor to provide a PR guarantee to be measured at one or two separate occasions within the defects warranty period. Industry best practice is for the PR to be tested annually over the first year and then over the second year of plant operation. Testing plant PR annually removes the risk of seasonable bias affecting the PR calculation and allows for a true appraisal of plant performance.

Given that an EPC warranty period typically lasts two years from the date the plant is accepted by the owner, PR testing over the first year of operation is commonly referred to as the intermediate acceptance test. PR testing during the second year of plant operation is commonly referred to as final acceptance testing. If these performance tests are passed (along with other contractual conditions) then an Intermediate Acceptance Certificate (IAC) and Final Acceptance Certificate (FAC) may be signed.

If the PR measured during the IAC or FAC tests were less than the guaranteed levels, then the contractor would be required to pay LDs to the owner to compensate for anticipated revenue losses over the project lifetime. To be enforceable in common law jurisdictions, LDs must be a genuine pre-estimate of the loss that the owner would suffer over the life of the project as a result of the plant not achieving the specified performance guarantees. LDs are usually a net present value (NPV) calculation based on the revenue forgone over the life of the project as a result of the shortfall in performance.

At the end of typically two years of plant operation (following the provisional acceptance date) and assuming successful IAC and FAC PR tests, rectification of any observed defects and payment of any incurred delay or performance-related LDs, the owner is obliged to sign the FAC. This has the effect of discharging the contractor's construction-related obligations and handing the plant over to the owner. At such a time, any performance bond that may have been in place to secure the contractor's obligations during the EPC warranty period would be returned to the contractor.

EPC Contracting Checklist

Below is a checklist of basic requirements that a developer may wish to consider during the EPC contracting process.

- ☐ Legal and Technical Advisors engaged to advise on form of contract.
- ☐ Scope of work drafted to include all engineering, procurement, construction, commissioning and testing tasks.
- ☐ Proposed contractor able to provide security by way of performance bond or parent company guarantee. Security to remain in place until Final Acceptance (FA) is achieved.
- ☐ Payment milestone profile drafted to be suitably protective; milestone amounts sized to accurately reflect works completed with sufficient funds held back until plant is taken over.
- ☐ Contractor provides a defects warranty period of at least two years commencing on the date of provisional acceptance.
- ☐ Defined terms, such as 'commissioning,' 'work completion,' 'provisional acceptance' and 'final acceptance' are clear and measureable.
- ☐ Contract contains provision for PR testing at two to three stages during the contractor's warranty period. Performance ratio (PR) test prior to provisional acceptance should be conducted over a period of at least five days. Repeat PR tests at IAC and FAC to be over full 12-month periods.
- ☐ Contract contains provision for obtaining LDs in event of delay or plant underperformance.
- ☐ LDs sized to be a genuine pre-estimate of losses likely to be incurred.

10 Construction

10.1 CONSTRUCTION OVERVIEW

The construction phase of a solar PV power plant should be managed so that the project attains the required standards of quality within the time and cost constraints. During construction, issues such as environmental impact, and health and safety of the workforce (and other affected people) should be carefully managed.

Key project management activities that will need to be carried out, either by the developer or a contractor, include interface management, project planning and task sequencing, management of quality, management of environmental aspects, and health and safety.

There are a number of common issues that may arise during the construction phase. Most of these can be avoided through appropriate design, monitoring, quality control and testing onsite.

Provided at the end of the chapter is a checklist of both basic required procedures and recommended actions, which should assist developers during the construction phase of a solar PV project.

The following sections summarise critical considerations for the construction of a megawatt-scale solar PV power plant.

10.2 CONSTRUCTION MANAGEMENT

The management of the construction phase of a solar PV project should be in accordance with general construction-project management best practices.

The approach to construction project management for a solar PV power plant will depend on many factors. Of these, one of the most important is the project contract strategy, whether multi-contract or full turnkey EPC. The vast majority of megawatt-scale solar PV power plants are built using a fully-wrapped EPC approach.

> There are a number of common issues that may arise during the construction phase. Most of these can be avoided through appropriate design, monitoring, quality control and testing onsite.

- From a developer's perspective, construction project management for a full turnkey EPC contract will be significantly less onerous than that required for a multi-contract approach.
- An EPC contract is nearly always more expensive than an equivalent, well-managed multi-contract approach.
- A multi-contract approach gives the developer greater control over the final plant configuration.
- EPC avoids interface issues between contractors and shifts risks to the EPC contractor instead of the project developer.

Regardless of the contract strategy selected, there are a number of key activities that will need to be carried out, either by the developer or a contractor. These activities are described in the following sections.

Typical EPC contract terms may be found in Annex 2: Contract Heads of Terms.

10.3 INTERFACE MANAGEMENT

Interface management is of central importance to the delivery of any complex engineering project, and solar PV projects are no exception. The main interfaces to be considered in a solar PV project are listed in Table 18. It should be noted that the interfaces may differ, depending on the contracting structure and specific requirements of particular projects.

For a multi-contract strategy, the developer should develop a robust plan for interface management. This plan should list all project interfaces, describe which organisations are involved, allocate responsibility for each interface to a particular individual, and explicitly state when the interface will be reviewed. In general, design and construction programmes should be developed to minimise interfaces wherever possible.

Opting for a turnkey EPC contract strategy will, in effect, pass the onus for interface management from the developer to the EPC contractor. But interface management will remain an important issue and one that requires on-going supervision. To some extent interfaces between the project and its surroundings (for example, grid connection) will remain the responsibility of the developer. Furthermore, in many countries legal responsibility will remain with the developer regardless of the form of contract that is put in place with the contractor.

Figure 21: O&M Workers at a Large-scale Solar PV Power Plant

Image courtesy of First Solar

If a turnkey EPC strategy is chosen, then a contractor with a suitable track record in the delivery of complex projects should be selected to minimise this type of legal risk. Information should also be sought from potential contractors on their understanding of the project interfaces and their proposed approach to managing them.

10.4 PROGRAMME AND SCHEDULING

A realistic and comprehensive construction programme is a vital tool for the construction planning and management of a solar PV project. The programme should be sufficiently detailed to show:

- Tasks and durations.
- Restrictions placed on any task.

Table 18: Solar PV Project Interfaces

Item	Element	Organisations	Interface / Comments
1	Consents/Permits	• All contractors • Landowner • Planning authority	Monitoring of compliance with all consent conditions and permits.
2	Civil Works	• Civil contractor • Mounting or tracking system supplier • Central inverter supplier • Electrical contractor • Grid connection contractor • Security contractor • Installation/crane contractor	Site clearance. Layout and requirements for foundations, plinths, hardstandings, cable trenches, earthing, ducts, roads and access tracks.
3	Security	• Civil contractor • Electrical contractor • Security contractor • Communications contractor	Layout of the security system, including power cabling and communications to the central monitoring system.
4	Module Mounting or Tracking System	• Mounting or Tracking system supplier • Civil contractor • Module supplier • Electrical contractor	Foundations for the mounting or tracking system, suitability for the module type and electrical connections, and security of the modules. Earthing and protection of the mounting or tracking system.
5	Inverter	• Civil contractor (for central inverters) • Mounting system supplier (for string inverters) • Module supplier • Inverter supplier • Electrical contractor • Grid network operator • Communications contractor	Foundations for larger central inverters, or suitability for the mounting system. Suitability of the module string design for the inverter. Interface with the communications for remote monitoring and input into the SCADA system. Many grid requirements or constraints can be managed within the design.
6	AC/DC and Communications Cabling	• Electrical contractor • Civil contractor • Communications contractor • Security contractor • Power purchase (off-taker) company • Grid network operator	Liaison with regard to cable redundancy, routes, sizes, weights, attachments and strain relief requirements. Liaison with regards to the signalling requirements within the site and to be provided to external parties throughout operation.
7	Grid Interface	• Civil contractor • Electrical contractor • Inverter supplier • Network operator	Liaison with regard to required layout of building equipment and interface with site cabling installed by the site contractor. More interface outside the site boundary for the grid connection cable/line to the network operator's facilities.
8	Communications	• Electrical contractor • Security contractor • Communications Contractor • Owner and commercial operator	Interface between the security system, inverter system, central monitoring (SCADA), the monitoring company, and the owner or commercial operator of the PV plant.
9	Commissioning	• All contractors	Commissioning of all systems will have several interface issues particularly if problems are encountered.

- Contingency of each task.
- Milestones and key dates.
- Interdependencies between tasks.
- Parties responsible for tasks.
- Project critical path.
- Actual progress against plan.

All tasks and the expected timescales for completion should be detailed along with any restrictions on a particular task. For example, if permits or weather constraints are predicted to potentially stop construction during particular months, this should be noted.

For a solar PV project, it is likely that the programme will incorporate different levels of detail around each of the following main work areas:

- Final design works.
- Procurement and manufacture of equipment.
- Site access.
- Security.
- Foundation construction.
- Mounting frame construction.
- Module installation.
- Substation construction.
- Electrical site works.
- Grid interconnection works.
- Commissioning and testing.

A high-level programme should be produced to outline the timescales of each task, the ordering of the tasks and any key deadlines. This should be completed as part of the detailed design.

The programme will then be built up to detail all the associated tasks and sub-tasks, ensuring that they will be completed within the critical timescale. A thorough programme will keep aside time and resources for any contingency. It will also allocate allowance for weather risk or permit restrictions for each task.

Interdependencies between tasks will allow the programme to clearly define the ordering of tasks. A project-scheduling package will then indicate the start date of dependent tasks and highlight the critical path.

Critical path analysis is important to ensure that tasks that can affect the overall delivery date of the project are highlighted and prioritised. A comprehensive programme should also take into account resource availability. This will ensure that tasks are scheduled when required staff or plant components are available. For example, when exporting to a high voltage transmission line, a large substation facility may need to be designed and built according to the grid company requirements and interconnect agreement specifications. The outage date for connecting to the transmission line will be planned well in advance. If the developer misses the outage date, significant delays can be incurred, which can have a major impact on the development. The outage date is thus a critical path item around which the project development and construction timeline may need to be planned.

Incorporating a procurement schedule that focuses on items with a long manufacturing lead-time (such as transformers, central inverters and modules) will ensure that they are ordered and delivered to schedule. It will also highlight any issues with the timing between delivery and construction, and the need for storage onsite.

To share this information and to save time and effort, it is strongly recommended that an “off-the-shelf” project-scheduling package is used and that the programme is monitored against site progress regularly.

To obtain visibility of the works on a day-to-day basis, and receive early notice of any slippage in programme, a good management and tracking tool to use is a weekly look-ahead programme. This can be drawn up either by the EPC contractor or the project management team onsite.

10.4.1 MILESTONES

Milestones are goals that are tied in with contractual obligations, incentives or penalties. Incorporating milestones in the programme helps the project team to focus on achieving these goals. In effect, construction must be planned around certain milestones or fixed dates (for example, the grid connection date).

If the contracted milestones are included in the programme, the impact of slippage on these dates will be apparent. Appropriate budgetary and resourcing decisions can then be made to address those delays. The milestones can also indicate when payments are due to a contractor. Payment of contracted milestones should be associated with the delivery of all relevant documentation to ensure the work has been built to specification and quality standards. This will ensure that the contractors are focused on delivering the paperwork as well as the physical works. It will also help to minimise the potential for programme slippage later in the works due to awaiting documentation.

10.4.2 PLANNING AND TASK SEQUENCING

Appropriate sequencing of tasks is a vital part of the planning process. The tasks must be sequenced logically and efficiently. The overall sequence of works is generally site access, site clearance, security, foundation construction, cable trenches and ducts, substation construction, mounting frame construction, module installation, electrical site works, communications, site grid works and finally, testing and commissioning. Each of these work areas should be broken down into a series of sub-tasks. Alongside these, an assessment of the inputs required for each task (especially when interfaces are involved) will help develop a logical and efficient sequence.

Consideration should also be given to any factors that could prevent or limit possible overlap of tasks. These factors could include:

- Access requirements.
- Resource availability (plant, equipment and manpower).
- Training and learning curve of manpower, especially if in a new market or if local resources are being utilised.
- Consenting (or other regulatory) restrictions.
- Safety considerations.
- Grid availability.

10.4.3 RISK MANAGEMENT

The risks associated with the project should be identified, assessed and managed throughout the construction process. The hazards need to be incorporated in the planning and scheduling of the project. Each aspect of the project should be assessed for likelihood and impact of potential risks. The next step would be to develop a suitable action plan to mitigate identified risks. If a particular risk could affect the delivery of the whole project, alternatives for contingency (in terms of time and budget) should be included.

Risk items may include timing delays, weather risk, grid connection delays, staff and equipment availability, transportation, ground conditions and environmental or health and safety incidents. Many of these risks will have been mitigated during the planning and design stage, for example, by completing studies and plant design.

Some risks will remain until the equipment is on site: lost equipment or equipment damaged in transport, for example. This risk is reduced by selecting an experienced supplier with suitable transport equipment. Insurance will cover the cost associated with sourcing replacement equipment, however if a key component such as the grid transformer is lost, then insurance will not compensate for the time delays and loss of generation associated with the component not being available. Such risks should be considered when drafting the EPC contract terms.

10.5 QUALITY MANAGEMENT

Controlling construction quality is essential for the success of the project. The required level of quality should be defined clearly and in detail in the contract specifications.

A quality plan is an overview document (generally in a tabular form), that details all works, deliveries and tests to be completed within the project. This allows work to be signed off by the contractor and enables the developer to confirm if the required quality procedures are being met. A quality plan will generally include the following information:

- Tasks (broken into sections, if required).
- Contractor completing each task or accepting equipment.
- Acceptance criteria.
- Completion date.
- Details of any records to be kept (for example, photographs or test results).
- Signature or confirmation of contractor completing tasks or accepting delivery.
- Signature of person who is confirming tasks or tests on behalf of the developer.

Quality audits should be completed regularly. These will help developers verify if contractors are completing their works in line with their quality plans. Audits also highlight quality issues that need to be addressed at an early stage. Suitably experienced personnel should undertake these audits.

10.6 ENVIRONMENTAL AND SOCIAL MANAGEMENT

As noted in Section 8.3.4, the environmental and social impact assessment (ESIA) or equivalent undertaken for each project should result in an associated Environmental and Social Management Plan (ESMP), which sets out key environmental, health, safety and social impacts identified for the project and addresses how these will be mitigated. It is important that this document is referenced or incorporated into the EPC contract so that the construction contractor(s) can take appropriate steps that adhere to the mitigation strategy. Implementation of the ESMP is necessary to ensure that all national and lender-specific conditions related to environmental, health, safety and social impacts of the project are met. Contractor performance should be monitored and corrected as necessary. Further details on health and safety aspects of the ESMP are provided below in Section 10.7.

10.7 HEALTH AND SAFETY MANAGEMENT

The health and safety (H&S) of the project work force should be carefully overseen by the project developer. Apart from ethical considerations, the costs of not complying with H&S legislation can represent a major risk to the project. Furthermore, a project with a sensitive approach to H&S issues is more likely to obtain international financing.

The World Bank Group General EHS Guidelines cover H&S during construction, including:

- General facility design and operation.
- Communication and training.
- Physical hazards.
- Chemical hazards.
- Biological hazards.
- Personal protective equipment (PPE).
- Special hazard environments.
- Monitoring.

Solar-specific construction experience indicates that falls from height, electrocution, incidents involving heavy lifting machinery (i.e., cranes) and traffic accidents are the most common causes of serious worker injuries or fatalities in solar projects.

The EHS guidelines give guidance on how each of these aspects of H&S should be approached, outlining minimum requirements for each aspect and listing appropriate control measures that can be put in place to reduce risks.

Furthermore, IFC PS2 sets out requirements in relation to occupational H&S.

As a minimum standard, compliance with local H&S legislation should be documented and rigorously enforced. Where local legal requirements are not as demanding as the EHS guidelines, it is recommended that the EHS guidelines and requirements within IFC PS2 are followed.

10.8 SPECIFIC SOLAR PV CONSTRUCTION ISSUES

The following sections describe common pitfalls or mistakes that can occur during the construction phase of a solar PV project. Most of these pitfalls can be avoided by appropriate design, monitoring, quality control and onsite testing.

10.8.1 CIVIL WORKS

The civil works relating to the construction of a solar PV plant are relatively straightforward. However, there can be serious and expensive consequences if the foundations and road networks are not adequately designed for the site. The main risks lie with the ground conditions. Importantly, inadequate ground investigation reports that do not provide sufficient detailed ground information may result in misinterpretation of ground conditions leading to inappropriate foundation design. Importantly, ground surveys lacking meticulous detailing or proper data interpretation could lead to risks such as installing unsuitable foundations.

Brownfield sites pose a risk during the civil engineering works. Due to the nature of the excavation works digging or pile driving for foundations, it is important to be aware of hazardous obstacles or substances below ground level. This is especially important when considering former industrial sites or military bases. Typical hazards may include ground gases and leachate from former landfill operations, contaminated land due to historical industrial works or processes and unexploded ordnance from previous wartime activities, such as on or near active/retired military bases or other sites that may have been mined or bombed.

10.8.2 MECHANICAL

The mechanical construction phase usually involves the installation and assembly of mounting structures on the site. Some simple mistakes can turn out to be costly, especially if these include:

- Incorrect use of torque wrenches.
- Cross bracing not applied.
- Incorrect orientation.
- Misalignment of structures.
- Lack of anti-corrosion paint applied to structures.

If a tracking system is being used for the mounting structure, other risks include:

- Lack of clearance for rotation of modules.
- Actuator being incorrectly installed (or specified), resulting in the modules moving or vibrating instead of locking effectively in the desired position.

These mistakes are likely to result in remedial work being required before hand-over and involve extra cost.

10.8.3 ELECTRICAL

Cables should be installed in line with the manufacturer's recommendations. Installation should be done with care as damage can occur when pulling the cable into position. The correct pulling tensions and bending radii should be adhered to by the installation contractor to prevent damage to the cable. Similarly, cables attached to the mounting structure require the correct protection, attachment and strain relief to make sure that they are not damaged.

Underground cables should be buried at a suitable depth (generally between 500mm and 1,000mm) with warning tape or tiles placed above and marking posts at suitable intervals on the surface. Cables may either be buried directly or in ducts. If cables are buried directly, they should be enveloped in a layer of sand or sifted soil in order to avoid damage by backfill material.

Comprehensive tests should be undertaken prior to energisation to verify that there has been no damage to the cables.

In markets where electrical standards are being updated or have been recently updated the developer should consider obtaining expert advice from an electrical engineer or consultant to confirm prior to order that any electrical equipment imported into the country, including cables, will meet the local requirements.

10.8.4 GRID CONNECTION

The grid connection will generally be carried out by a third party over whom the project developer may have limited control. Close communication with the grid connection contractor is essential to ensure that the grid requirements are met. Delay in the completion of the grid connection will affect the energisation date, which will delay the start of commercial operation.

Where the grid network contains only traditional generation sources there is an additional risk that the grid code requirements for renewable generation will not have been fully established at the time of contract signature. In these cases, certain provisions may need to be included in the PPA; also, it is especially important to maintain regular communication with the grid operator and if possible engage the support of local consultants. Communicating with other solar plant developers in the area, if there are any, is strongly recommended and may enable the developer to benefit from the lessons learned during the implementation of these other projects that have already been constructed.

10.8.5 LOGISTICAL

Logistical issues can arise if designs or schedules have not been well thought through. Issues that may arise include:

- Lack of adequate clearance between rows of modules for access (*see* Figure 22).
- Constrained access due to inclement weather conditions.

For larger tracking systems, central inverters, or pre-manufactured inverter stations, cranes may be required. Therefore, suitable access and space for manoeuvrability, including room for the crane to extend its legs for stability within the site, is essential (*see* Figure 23). This issue should also be assessed from an operational perspective to ensure any equipment can be replaced upon failure or end of life.

10.8.6 SECURITY

A robust security plan needs to be put in place, especially in areas where there may have been objections to the works or where unemployment or crime is an issue. The project is likely to have a substantial quantity of metal including copper with significant scrap value. The modules themselves can be the targets of theft and may also be damaged by malicious acts.

The security arrangements for the site need planning and adequate budgeting. Security arrangements can provide a sustained benefit to the region by creating jobs for local personnel.

Figure 22: Spacing between Module Rows

Image courtesy of First Solar

Figure 23: Module Installation on a Large Tracking System

Image courtesy of a+f GmbH

10.8.7 *EMERGING MARKET ISSUES*

In new markets, there may be limited options for obtaining/importing the equipment required, starting up new manufacturing plants, or modifying construction facilities to satisfy local demand. Any supply solution that is adopted has associated risks.

Imported equipment can be subject to long transport times and customs delays, especially if this is the first import for a company or project.

New manufacturing suppliers in emerging markets can have quality issues associated with the work; additional time and monitoring is generally required to ensure that the products being delivered by such suppliers meet quality requirements. The packaging and transportation of these products to the construction site also requires careful consideration of how to prevent damage during transportation.

Employees for project installation companies in emerging markets are often inexperienced. This can lead to incorrect installation methods or procedures, and may include a lack of knowledge of the possible impact of completing works in the wrong order, which can have a costly impact on the project. However, with appropriate training, the use of inexperienced local staff can present a low-cost and locally-beneficial method of developing a solar PV power plant.

Strict quality management is required. A rigorous plan should be developed to ensure that risks and problems are identified early and quickly so that they can be resolved in a timely way.

10.9 CONSTRUCTION SUPERVISION

It is recommended that the owner of and lenders to the project are kept informed of developments during construction. Construction supervision may be carried out by in-house resources. Alternatively, a “technical advisor” or “Owner’s Engineer” may be commissioned to carry out the work on their behalf.

The role of the technical advisor during the construction phase involves ensuring contractor compliance with the relevant contracts, as well as reporting on progress and budget. The construction supervision team generally comprises a site engineer supported by technical experts based in an office. The main parts of the technical advisor’s role are: review of proposed designs, construction monitoring and witnessing of key tests.

Design reviews will generally be carried out on:

- Design basis statements.
- Studies/investigations.
- Design specifications.
- Design of structures.
- Drawings (all revisions).
- Calculations.
- Execution plans.
- Risk assessments and method statements.
- Quality plans.

- Safety plans/reports.
- Material and equipment selection.
- O&M manuals.
- Test reports.

The objective of the design review is to ensure that the contractor has designed the works in accordance with the contract agreements and relevant industry standards. The review also aims to ascertain that the works will be suitably resourced and sequenced to deliver the project as specified. The design review can also cover specific areas such as grid compliance or geotechnical issues, depending upon the specific project requirements and experience of the developers.

Key stages and tests for witnessing include:

- Inspection of road construction.
- Inspection of foundations.
- Verification of cable routes.
- Inspection of cable tracks.
- Witnessing of delivery/off-load of solar modules, transformers, inverters and switchgear.
- Inspection of module, switchgear and inverter installation.
- Witnessing of site acceptance tests.
- Witnessing of completion tests.
- Monitoring and expediting defects.

Besides the Owner's Engineer, the lender's engineer has the additional role of signing off and issuing certificates that state the percentage of the project completed. The lenders will require these certificates prior to releasing funds in accordance with the project payment milestones. In some cases there is a requirement for an independent or consulting engineer to verify that the works meet all standards and codes on behalf of the grid company or power purchaser.

Box 7: Construction Lessons Learned

The construction of a solar PV power plant is a relatively straightforward process. However, there are common mistakes that EPC contractors can easily avoid with correct planning and training procedures. Examples of such mistakes are itemised below.

PV Module Installation

Common issues during installation of modules include:

- Inadequate number of clamps used, or incorrect positioning resulting in reduced module load-bearing capacity.
- Modified or wrong type of clamp used as a result of inadequate spacing between modules, compromising integrity of the fixing and leading to invalidation of warranty.
- Module clamp bolts initially hand tightened and then tightened to the correct torque after a period of delay. There is a risk that strong winds can blow the modules off the structure if the time lag between assembly and tightening is too long. Tightening of bolts should occur shortly after assembly.
- Over-tightening of clamp bolts with power tools leading to deformation of clamp and damage to corrosion-resistant coatings.
- Damaged or scratched modules due to poor installation technique. The front and rear surface of modules should not come into contact with support structures.

Mounting Structure

Common issues in relation to the construction of the mounting structures include:

- Dissimilar metals not isolated from one another leading to material incompatibility issues in the form of galvanic corrosion. Isolation solutions such as neoprene pads can be used.
- Deformation of mounting structure during piling process, compromising galvanisation or structure.
- Piles installed out of position, leading to piles and steel sections being forced or bent out of alignment in order to line up with framing sections.

Civil Works

Common issues in relation to the construction of the mounting structures include:

- Poor dust suppression leading to excessive accumulation of dirt on modules.
- Missing or delayed perimeter fencing leading to animal or human intrusion. A fence should be installed prior to construction commencing.
- Drains becoming blocked with silt during earth works.
- Inadequate surface water run-off management during construction, leading to delays caused by flooded and waterlogged sites.
- Exceeding load-bearing capacity of exiting public tracks, causing damage.
- Lack of levelling works after installation.

Equipment Enclosures / Housings

The integrity of the controlled environment within equipment enclosures/housings can be compromised if not installed correctly. Examples of common issues include:

- Unused glands not sealed or replaced with dummies.
- Unsealed cable conduits.
- Damaged or missing gaskets on entrance doors.
- Unsealed cable trenches leading into inverter housings.
- Water ingress due to any/all of the above, leading to a humid atmosphere causing corrosion damage to electrical components.

Environmental Monitoring

Incorrect positioning of the environmental monitoring equipment can lead to inaccuracies during performance assessment. The most common reasons for these inaccuracies include:

- Pyranometers not positioned at the same tilt angle as the modules.
- Pyranometers subject to shading, causing reporting of elevated performance ratio (PR) calculations.

(continued)

Box 7: Construction Lessons Learned (continued)

Cable Management

The most common issues in relation to cable management include:

- Cables crossing over sharp edges of mounting structures without suitable padding.
- Insufficient labelling of cable ends.
- Long unsupported spans due to an insufficient number of cable ties.
- Cable bending radius too tight.
- Inadequate cable burial depths.
- Inadequate conduit cable protection.

Signage

Basic information requirements which are often omitted include:

- General health and safety information including emergency contact numbers.
- Lack of warning labels on electrical components.
- Lack of warning labels on perimeter fence.
- Support structure identification labelling.

Spare Parts

- The permanent storage area for spare components is often not available when such components are delivered to the site, leading to damage from poor temporary storage conditions.

Construction Phase Checklist

Provided below is a checklist of basic required procedures in addition to a list of recommended actions. It is intended to assist solar PV power plant developers during the construction phase of a PV project.

Required

- ☐ Contract, fully signed and reviewed by technical advisor covering all interfaces.
- ☐ Design documentation completed.
- ☐ Detailed programme of works completed.
- ☐ Quality plan completed.
- ☐ Health and safety plan completed.
- ☐ Monthly reporting in place.
- ☐ All consenting, permitting and financing requirements in place.
- ☐ Commissioning and testing plan agreed to by all parties, detailing requirements and any tests needing witnesses or sign-off.

Recommended

- ☐ Interface matrix drawn up.
- ☐ Deliverables schedule prepared for all documentation.
- ☐ Weekly look-ahead programme in place.
- ☐ Risk register detailing all potential risks and any mitigation measures in place.
- ☐ Environmental plan completed.
- ☐ Monthly report structure completed.
- ☐ Matrix detailing the requirements and due dates prepared.

Operation and Maintenance

11

An operation and maintenance (O&M) contract is crucial for the successful performance of the PV plant during its operating life.

11.1 OPERATION AND MAINTENANCE (O&M) OVERVIEW

Compared to other power generating technologies, solar PV power plants have low maintenance and servicing requirements. However, proper maintenance of a PV plant is essential to maximise both energy yield and the plant's useful life. Optimal operations must strike a balance between maximising production and minimising cost.

The presence of an operation and maintenance (O&M) contract is crucial to define the parameters for the operation and maintenance of a project during its life. If an O&M contractor is being employed to undertake these tasks, it is important that all requirements relating to preventative and corrective maintenance, performance monitoring and reporting are clearly stated in the contract along with the frequency with which these activities need to be conducted. This allows contractor performance to be measured and if necessary challenged.

It is normal for an O&M contractor to guarantee plant performance during the contract term. Typically this is achieved through the presence of an availability- or performance-ratio warranty covering the entire plant. In the event of the contractor not honouring its obligations, resulting in the plant performing below the guaranteed value, the owner would be eligible to claim for compensation to cover lost revenues.

The basic requirements for drafting an O&M contract for a Solar PV power plant are set out in a checklist at the end of the chapter.

11.2 O&M CONTRACTS

It is common practice on solar PV projects that O&M is carried out by a principal contractor, who is responsible for all aspects of O&M, including any of the works performed by subcontractors that may be engaged to deliver specialist services, such as inverter servicing, ground-keeping, security or module cleaning.

An O&M contract is required between the project company and the O&M provider that details the legal and technical aspects of the O&M provision. More information on O&M contracts is provided in Section 11.7, with typical O&M terms outlined in Annex 2.

Maintenance can be broken down as follows:

- **Scheduled maintenance:** Planned in advance and aimed at fault prevention, as well as ensuring that the plant is operated at its optimum level.
- **Unscheduled maintenance:** Carried out in response to failures.

Suitably thorough and regularly scheduled maintenance should minimise the requirement for unscheduled maintenance although, inevitably, some unforeseen failures will still occur. A robust and well-planned approach to both scheduled and unscheduled maintenance is therefore important.

11.3 SCHEDULED/PREVENTATIVE MAINTENANCE

Appropriate scheduling and frequency of preventative maintenance is dictated by a number of factors. These include the technology selected, environmental conditions of the site, warranty terms and seasonal variances. Scheduled maintenance is generally carried out at intervals planned in accordance with the manufacturer's recommendations, and as required by equipment warranties. Scheduled maintenance that requires plant shutdown should be conducted where possible during non-peak production periods, such as early morning or evening.

Although scheduled maintenance will both maximise production and prolong the life of the plant, it does represent a cost to the project both in terms of expenses incurred and lost revenue due to reduced power generation. Therefore, the aim should be to seek the optimum balance between the cost of scheduled maintenance and increased yield over the life of the system.

Specific scheduled maintenance tasks are covered in the following sections.

11.3.1 *MODULE CLEANING*

Module cleaning is a simple but important task. It can produce significant and immediate benefits in terms of energy yield.

The frequency of module cleaning will depend on local site conditions and the time of year. As the level of module soiling is site-specific, the duration between cleans will vary significantly between sites. The frequency to clean modules will be dictated by factors such as site and surrounding area ground covering (dusty and arid sites will result in more soiling) and local rainfall patterns (drier areas will result in more soiling).

Figure 24 illustrates the cleaning of modules in a large tracking installation (water is seen being sprayed on the module surface).

Other, lower-tech methods of cleaning include the use of a brush trolley, shown in Figure 25, and use of a dust broom, shown in Figure 26.

Figure 24: Module Cleaning Using Crane

Image courtesy of a+f GmbH

When scheduling module cleaning, consideration should be given to the following:

- Environmental and human factors (for instance, autumn fall debris and soiling from local agricultural and industrial activities).
- Weather patterns: cleaning during rainy periods is less likely to be required.

Figure 25: Module Cleaning Using Brush Trolley

Image courtesy of First Solar

Figure 26 : Module Cleaning Using Dust Broom

Image courtesy of First Solar

- Dust carried from deserts by wind that may also appear following rain.
- Dust caused by vehicular traffic.
- Site accessibility based upon weather predictions.
- Availability of water and cleaning materials.[52]

If the system efficiency is found to be below the expected level, then the cleanliness of the modules should be checked and cleaning conducted as necessary.

The optimum frequency of module cleaning can be determined by assessing the costs and benefits of conducting the procedure. The benefit of cleaning should be seen in an improved system performance ratio (PR) due to the lower soiling loss and resultant increase in revenue. A cost estimate to clean the PV modules should be obtained from the O&M contractor and compared with the potential increase in revenue. The agreed O&M contract should detail an agreed number of cleans per annum and their frequency. It should also outline the labour rate or unit price at which the owner may request an additional plant-wide clean of modules to allow this cost-benefit analysis to be conducted.

11.3.2 *MODULE CONNECTION INTEGRITY*

Checking module connection integrity is important for systems that do not incorporate monitoring at the module string level. This is more likely for plants utilising central inverter technology. In such cases, faults within each string of modules may be difficult to detect given that the current within each string is not being monitored and continuously compared to other strings.

If string level monitoring is not used, then the O&M contractor should check the connections between modules within each string periodically, at least on an annual basis.

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[52] Water in the amount of about 1.6 l/m2 of module surface may be required for each module clean, dependent on the method adopted.

11.3.3 JUNCTION OR STRING COMBINER BOX

All junction boxes or string combiner boxes should be checked periodically for water ingress, dirt or dust accumulation and integrity of the connections within the boxes. Loose connections could affect the overall performance of the PV plant. Any accumulation of water, dirt or dust could cause corrosion or short circuit within the junction box.

Where string level monitoring is not used, the O&M contractor should conduct periodic checks, at least on an annual basis, of the integrity of the fuses in the junction boxes, combiner boxes and, in some cases, the module connection box.

11.3.4 HOT SPOTS

Potential faults across the PV plant can often be detected through thermography. This technique helps identify weak and loose connections in junction boxes and inverter connections, which is a common problem in hot climates where large variations between day and night temperatures can cause contacts to loosen. Thermography may also detect hot spots within inverter components and on modules that are not performing as expected.

A trained specialist should conduct thermography using a thermographic camera at least on an annual basis.

11.3.5 INVERTER SERVICING

Generally, inverter faults are the most common cause of system downtime in PV power plants. Therefore, the scheduled maintenance of inverters should be treated as a centrally important part of the O&M strategy.

The maintenance requirements of inverters vary with size, type and manufacturer. The specific requirements of any particular inverter should be confirmed by the manufacturer and used as the basis for planning the maintenance schedule.

Regular preventative maintenance for an inverter should, as a minimum, include:

- Visual inspections.
- Cleaning/replacing cooling fan filters.
- Removal of dust from electronic components.
- Tightening of any loose connections.
- Any additional analysis and diagnostics recommended by the manufacturer.

11.3.6 STRUCTURAL INTEGRITY

The module mounting assembly, cable conduits and any other structures built for the solar PV power plant should be checked periodically for mechanical integrity and signs of corrosion. This will include an inspection of support structure foundations for evidence of erosion from water run-off.

11.3.7 TRACKER SERVICING

Similarly, tracking systems also require maintenance checks. These checks will be outlined in the manufacturer's documentation and defined within the warranty conditions. In general, the checks will include inspection for wear and tear on the moving parts, servicing of the motors or actuators, checks on the integrity of the control and power cables, servicing of the gearboxes and ensuring that the levels of lubricating fluids are appropriate.

The alignment and positioning of the tracking system should also be checked to ensure that it is functioning optimally. Sensors and controllers should be checked periodically for calibration and alignment.

11.3.8 BALANCE OF PLANT

The remaining systems within a solar PV power plant, including the monitoring and security systems, auxiliary power supplies, and communication systems, should be checked and serviced regularly. Communications systems within and externally connected to the PV plant should be checked for signal strength and connection.

11.3.9 VEGETATION CONTROL

Vegetation control and grounds keeping are important scheduled tasks for solar PV power plants. Vegetation (for example, long grass, trees or shrubs) has the potential to shade the modules and reduce performance. Prudent grounds keeping can also reduce the risk of soiling on the modules from leaves, pollen or dust.

11.4 UNSCHEDULED MAINTENANCE

Unscheduled maintenance is carried out in response to failures. As such, the key parameters when considering unscheduled maintenance are diagnosis, speed of response and repair time. Although the shortest possible response is preferable for increasing energy yield, this should be balanced against the likelihood of increased contractual costs of achieving shorter response times.

The agreed response times should be clearly stated within the O&M contract and will depend on the site location—and whether it is manned. Depending on the type of fault, an indicative response time may be within 48 hours, with liquidated damages payable by the contractor if this limit is exceeded. The presence of an availability guarantee within the O&M contract will also provide motivation for the contractor to provide an efficient and speedy repair in the event of equipment failure and resulting plant downtime.

For a well-designed and well-constructed plant, a large proportion of unscheduled maintenance issues may be related to inverter faults. Depending on the nature of the fault, it may be possible to rectify the failure remotely. This option is clearly preferable, if possible.

Other common unscheduled maintenance requirements include:

- Tightening cable connections that have loosened.
- Replacing blown fuses.
- Repairing lightning damage.
- Repairing equipment damaged by intruders or during module cleaning.
- Rectifying SCADA faults.
- Repairing mounting structure faults.
- Rectifying tracking system faults.

The contractual aspects of unscheduled O&M are described in more detail below.

11.5 SPARE PARTS

In order to facilitate a rapid response in the event of equipment failure, a suitably stocked spare parts inventory is essential. Because spare parts cost money, their purchase should be justified by the benefit they bring in reducing plant downtime and avoiding revenue loss. The optimum spare parts strategy will depend on the size of the plant, local availability of replacement parts and the potential for sharing critical equipment across a number of plants under common ownership. In general, adequate supplies of the following essential components should be held:

- Mounting structure pieces.
- Junction/combiner boxes.
- Fuses.
- DC and AC cabling components.
- Communications equipment.
- Modules (in case of module damage).
- Spare inverters (if string inverters are being used) or components according to manufacturer's recommendations in the case of central inverters.
- Spare motors, actuators and sensors where tracking systems are used.

It is important that spares stock levels are maintained. Therefore, when the O&M contractor uses components from the spares inventory, the contractor should be responsible for replenishing the stocks as soon as is feasible. This arrangement will reduce the time gap between the identification of the fault and replacement of the non-operational component. This can be of particular importance for remote locations where poor accessibility or adverse weather conditions can delay the delivery of components to the site. Consultation with manufacturers to detail the spare parts inventory, based upon estimated component lifetimes and failure rates, is recommended.

11.6 PERFORMANCE MONITORING, EVALUATION AND OPTIMISATION

To optimise system performance, there is a need to ensure that the plant components function efficiently throughout the lifetime of the plant. Continuous monitoring of PV systems is essential to maximise the availability and yield of the system.

Section 7.7 describes monitoring systems for PV plants. A SCADA system is able to monitor the real-time efficiency of the PV system and continuously compare it with the theoretical efficiency to assess if the system is operating optimally. This information can be used by the O&M contractor to establish the general condition of the system and schedule urgent repair or maintenance activities such as cleaning.

11.7 O&M CONTRACTS FOR SOLAR PV PLANTS

This section describes the key issues with O&M contracts for solar PV power plants. For reference, the typical terms commonly seen in O&M contracts are included in Annex 3: O&M Term Sheet.

It is common for the PV plant O&M to be carried out by specialist contractors. The contractor will be responsible for the O&M of the whole plant, its subcomponents and also the work of any subcontractors. In addition to operating the plant and maintaining all equipment, the O&M contractor may also be responsible for the provision of plant security and grounds keeping.

The duration of O&M contracts will vary on a project-by-project basis. Some plant owners (typically investment funds) like the cost surety and predictability that a lengthy contract term can bring. As such, contract durations in excess of 20 years, covering the anticipated project lifetime are often seen. For other owners, a shorter duration, such as one to five years, may be more desirable because it allows owners to take advantage of falling market costs and negotiate more favourable terms when their current contract expires. In all cases, termination events should be clearly defined to allow the owner to terminate the contract, irrespective of its duration, in the event of contractor default, underperformance or insolvency.

11.7.1 PURPOSE OF AN O&M CONTRACT

The purpose of an O&M contract is to optimise the performance of the plant within established cost parameters. To do this effectively, the contract must be suitably detailed and comprehensive. In particular, the O&M contract should clearly set out:

- Services to be carried out by, and obligations of, the contractor.
- Frequency of the services.
- Obligations of the owner.
- Standards, legislation and guidelines with which the contractor must comply.
- Payment structure.
- Performance guarantees and operational targets.
- Methodologies for calculating plant availability and/or performance ratio.
- Methodologies for calculating liquidated damages/bonus payments in the event of plant under- or over-performance.
- Terms and conditions.
- Legal aspects.
- Insurance requirements and responsibilities.

These issues are discussed in the following sections.

11.7.2 CONTRACTOR SERVICES AND OBLIGATIONS

The O&M contract should list the services to be performed by the contractor. This list should be site- and equipment-specific, and include the following:

- Plant monitoring requirements.
- Scheduled maintenance requirements.
- Unscheduled maintenance requirements.
- Agreed targets and/or guarantees (for example, response time or system availability figure)

- Reporting requirements (including performance, environmental, health and safety, and labour relations reporting).

While the O&M contractor's primary role is to maintain the plant, ensuring that it and all subcomponents are functioning and able to export electrical energy to the grid, the contractor should also be contractually obliged to optimise plant performance. Additionally, it should be stipulated that all maintenance tasks should be performed in such a way that their impact on the productivity of the system is minimised. In particular, the contract should state that preventative maintenance tasks that require the removal of equipment from service should be kept to a minimum and performed during low irradiation hours.

The O&M contract will typically define the terms by which the contractor is to:

- Provide, at intervals, a visual check of the system components for visible damage and defects.
- Provide, at intervals, a functional test of the system components.
- Ensure that the required maintenance will be conducted on all components of the system. As a minimum, these activities should be in line with manufacturer recommendations and the conditions of the equipment warranties.
- Provide appropriate cleaning of the modules and the removal of snow (site-specific).
- Make sure that the natural environment of the system is maintained to avoid shading and aid maintenance activities.
- Replace defective system components and system components whose failure is deemed imminent.
- Provide daily (typically during business hours) remote monitoring of the performance of the PV plant to identify when performance drops below set trigger levels.

A schedule of preventative maintenance activities should be prepared and appended to the O&M contract to easily track whether the agreed timetable is being met. As well as ensuring that all equipment is being serviced in line with manufacturer's guidelines, this also allows for contractor performance to be measured.

11.7.3 OBLIGATIONS ON THE OWNER

In an O&M contract, the obligations of the owner/developer are generally limited to:

- Granting the O&M contractor access to the system and all the associated land and access points.
- Obtaining all approvals, licences and permits necessary for the legal operation of the plant.
- Providing the O&M contractor with all relevant documents and information, such as those detailed above, that are necessary for the operational management of the plant.

11.7.4 STANDARDS, LEGISLATION AND GUIDELINES

This section of the contract outlines the various conditions with which the O&M contractor must comply while carrying out the O&M of the plant. These conditions should be drawn from the following documentation:

- Building or construction permits.
- Planning consents and licences.
- Grid connection statement, the grid connection agreement and power purchase agreement.
- Operating manuals for system components.
- Applicable legislation.
- Local engineering practices (unless the documents and conditions listed above require a higher standard).

11.7.5 PAYMENT

The cost and remuneration of the O&M contract are generally broken down into:

- Fixed remuneration and payment dates.
- Other services remuneration and expenditure reimbursement.

Fixed remuneration outlines the payment for the basic services that are to be provided by the contractor under the O&M contract. This section should include the following:

- Cost—usually a fixed price per kWp installed.
- Payment structure (monthly or quarterly, generally in arrears).
- Payment indexation over the duration of the contract.

Remuneration for other services includes payment for any services beyond the scope of the contract. This should include:

- Method for determining level of other services carried out.
- Agreed rates for conducting these services.
- Agreed method for approving additional expenses or services with the owner.
- Any required spare parts and other components not covered by individual warranties or held in the owner's inventory.

11.7.6 WARRANTIES/PERFORMANCE GUARANTEES

The contract should include a plant-wide performance guarantee to be calculated on a regular basis. On large-scale solar PV power plants this typically takes the form of an availability or performance ratio (PR) warranty. An availability warranty provides a measure of plant 'uptime' and how successful the contractor is in keeping the plant functional and capable of exporting electrical energy to the grid. A PR warranty provides a measure of plant efficiency at converting solar irradiation into electrical energy. While a PR warranty may be preferable because it incentivizes the contractor to optimise plant performance rather than just ensure its operational readiness, some third-party O&M providers are reluctant to provide such a warranty on systems they did not design or construct.

A PR guarantee is an industry standard and is considered a pre-requisite to a suitable long-term O&M strategy. The guarantee makes it the responsibility of the O&M contractor to ensure that the plant achieves a PR level greater than the guaranteed value. If the plant operates below this value, the contractor will be liable to pay compensation in the form of liquidated damages to the owner. Damages should be set at a level that is a genuine estimate of the loss or damage that the owner will suffer in the event of plant under-performance.

11.7.7 LEGAL

The contract will have a section outlining the governing law and jurisdiction of the O&M contract. The governing law is normally the law of the country in which the project is located. A legal succession or a transfer of rights condition is required for the developer to reserve the right to assign the O&M contract to a third party.

It is also recommended that every contract have a non-disclosure agreement. This agreement between the O&M contractor and the developer will outline the information that is to be treated as confidential, as well as that information which can be disclosed to third parties.

11.7.8 INSURANCE

The contract should have a section outlining the insurance responsibilities of the contractor for the O&M activities. This insurance should cover damage to the plant, as well as provide cover for employees conducting maintenance.

It is normal for the O&M contractor to arrange and pay for the full site insurance.

11.7.9 TERM OF AGREEMENT

Every O&M contract needs to have a section that outlines when the contract shall become effective and the duration of the contract from the effective date. This section should also include provisions to renew or extend the contract upon conclusion of the originally agreed term.

It is also recommended that this section include the circumstances in which either the maintenance contractor or the developer would be entitled to terminate the contract.