Executive Summary

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The World Bank Group (including the International Bank for Reconstruction and Development, the International Development Association, IFC, and the Multilateral Investment Guarantee Agency) helps client countries secure the affordable, reliable, and sustainable energy supply needed to end extreme poverty and promote shared prosperity.

With an installed capacity greater than 137 GWs worldwide and annual additions of about 40 GWs in recent years,[1] solar photovoltaic (PV) technology has become an increasingly important energy supply option. A substantial decline in the cost of solar PV power plants (80% reduction since 2008)[2] has improved solar PV's competitiveness, reducing the needs for subsidies and enabling solar to compete with other power generation options in some markets. While the majority of operating solar projects is in developed economies, the drop in prices coupled with unreliable grid power and the high cost of diesel generators has driven fast-growing interest in solar PV technology in emerging economies as well.

Many emerging economies have an excellent solar resource, and have adopted policies to encourage the development of the solar industry to realize the benefits that expanded use of PV technology can have on their economies and on improving energy security, as well as on the local and global environmental. Also, solar installations can be built relatively quickly, often in 6–12 months, compared to hydro and fossil fuel projects that require more than 4–5 years to complete. This presents a major incentive in rapidly-growing, emerging markets with a high unmet demand and urgent need for power. Assuming that PV technology prices continue to fall relative to competing sources of electricity, the market penetration rate of utility-scale solar power projects can be expected to continue growing rapidly, including in emerging markets.

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1 Source: IEA, "Trends 2014 in Photovoltaic Applications"
2 Source: IRENA, "Rethinking Energy 2014"

of the Sustainable Energy for All Initiative— achieving universal access, accelerating improvements in energy efficiency, and doubling the global share of renewable energy by 2030. The World Bank Group recognizes that each country determines its own path for achieving its energy aspirations, and that each country's transition to a sustainable energy sector involves a unique mix of resource opportunities and challenges, prompting a different emphasis on access, efficiency, and renewable energy.

Enhancing access to power is a key priority for IFC, which supports private sector investment in renewable energy solutions. As of May 2015, IFC has made over 350 investments in power in more than 65 countries. We are often at the forefront of markets opening to private participation. IFC has invested in more than 55 solar projects, representing about 1,400 MW of capacity, with key transactions in Thailand, the Philippines, India, China, Jordan, Mexico, South Africa, Honduras, and Chile.

The objective of this guidebook is to enhance the reader's understanding of how to successfully develop, finance, construct, and operate utility-scale solar PV power plants. It is aimed at project developers entering the market, and meant as a reference source for contractors, investors, government decision makers, and other stakeholders working on PV projects in emerging markets. This report is a substantially expanded version (second edition) of an earlier IFC publication, "*Utility-Scale Solar Power Plants,*" which was released in 2011. Substantial progress in the number of PV projects implemented globally and dramatic reduction in PV technology prices justified the need for an update in this fast moving market.

The guidebook focuses on aspects of project development that are specific to solar. From this perspective it covers all aspects of the overall project development process including site identification, plant design, energy yield, permits/licenses, contractual arrangements, and financing, giving sparser coverage to general project development basics that are not specific to solar.

Project development activities are interrelated and often are carried out in parallel. Technical aspects that determine the plant design and energy yield are accompanied by efforts to secure permits/licenses and financing. Assessments are repeated at increasing levels of detail and certainty as the project moves forward. For example, a preliminary design is initially developed (prefeasibility study) along with a high-level assessment of the regulatory environment and price of power, enabling a "back of the envelope" analysis to be carried out to determine whether the project meets investor requirements. If the project looks promising, the developer decides to proceed further. If the project does not appear to meet hurdle rates, changes to the design or financing adjustments may be considered, or the project development may be terminated. Similar analysis is repeated in the feasibility study at a more granular level of detail, ultimately leading to another "go/no-go" decision. Throughout the project development process, there are several key decision points when modifications are made, and the decision to proceed further is re-assessed. Changes are common until financial closure is achieved. After this, the focus shifts to procuring the equipment, construction, and commissioning the power plant within the projected schedule and budget.

This guide covers the key building blocks to developing a successful utility-scale solar power project (the threshold for "utility-scale" depends on the market, but generally at least 5 MW). Most lessons learned in this segment of the solar industry are drawn from experiences in developed markets. However, this guide makes an effort to anticipate and address the concerns of projects in emerging economies. In doing so, the guidebook covers the key three themes:

1. **Optimum power plant design:** A key project development challenge is to design a PV power plant that is optimally balanced in terms of cost and performance for a specific site.
2. **Project implementation**: Achieving project completion on time and within budget with a power plant that operates efficiently and reliably, and generates the expected energy and revenue, is another key

concern for developers. Key aspects of project implementation include: permits and licensing, selection and contracting of the Engineering, Procurement and Construction (EPC) company, power plant construction, and operations and maintenance (O&M).

3. **Commercial and financing aspects:** PV regulatory frameworks and specific types of incentives/support mechanisms for the development of PV projects, such as preferential tariffs and other direct and indirect financial supports, have an important impact on the financial viability of the project, as they affect the revenue stream. Power Purchase Agreements (PPAs) specify the terms under which the off-taker purchases the power produced by the PV plant; this is the most important document to obtain financing.

The **project development process** starts once interest has been established in a specific power market. Assessment of the market opportunity takes into account broad issues at the national level, such as the regulatory environment, prevailing power prices, structure of the power market, the credit-worthiness of potential off-takers, and any specific financial incentives for developing solar PV power plants. The first tangible steps in the process are development of a concept and identification of a site. The project will then proceed through several development stages, including the prefeasibility study, a more detailed feasibility study, permitting and financing, and finally engineering (detailed design), construction, and commercial operation of the power plant. As the project developer initiates preparatory activities including securing a land lease agreement and permits, preliminary financing schemes are assessed. Energy resource assessment and activities related to project financing run in parallel with the project design (e.g., engineering, construction, etc.). Detailed information on these overlapping work streams and guidance on coordination and successful execution of project activities is provided throughout all fifteen sections of this guidebook, beginning with an overview of the project development process in **Section 2**. A summary of key aspects of project development is provided in this section.

1.1 OPTIMUM POWER PLANT AND PROJECT DESIGN

PV plant design is developed initially as part of a prefeasibility study which is based on preliminary energy resource and yield estimates, as well as other site-specific requirements and constraints. The plant design is further improved during the feasibility study, which considers site measurements, site topography, and environmental and social considerations. Key design features include the type of PV module used, tilting angle, mounting and tracking systems, inverters, and module arrangement. Optimization of plant design involves considerations such as shading, performance degradation, and trade-offs between increased investment (e.g., for tracking) and energy yield. Usually, the feasibility study also develops design specifications on which the equipment to be procured is based. PV technology options are described in **Section 3,** and the PV plant design in **Section 7**.

Solar energy resource depends on solar irradiation of the geographic location as well as local issues like shading. Initially, solar resource assessment can be done based on satellite data or other sources, but as the project development moves forward, ground-based measurements are desirable to provide an increased level of confidence. Solar resource is covered in **Section 4**.

Energy yield is a critical parameter that determines (along with the capital costs and the tariff) the financial viability of the project. Probability-based energy yield (for example P50, P75, P90) are modelled over the operating life of the project. A thorough analysis of the solar resource and projected energy yield are critical inputs for the financial analysis. Details on the methodology, solar data sources and key issues to be considered when estimating the energy resource and project energy yield are provided in **Section 5**.

Site selection is based on many considerations, such as whether the PV plant is close to the grid, and whether the process for obtaining a grid connection agreement is transparent and predictable. Close cooperation with the grid company is essential in obtaining a grid connection agreement. The agreement, as well as applicable regulations should clearly state the conditions of the PV developer's access to the grid, and provide the guidelines for design, ownership, and operation of the grid connection. Access to land is also a basic requirement for project development. Project land must be purchased or leased for longer than the debt coverage period; a minimum of 15–20 years is desirable, although a 40–50 year lease is often signed. In addition to the project site, the developer needs to secure access to the land over which the grid connection will be laid out. Land use issues are reviewed along with the technical aspects of site selection in **Section 6**.

1.2 PROJECT IMPLEMENTATION

The objective of the project implementation process is to complete the project on schedule and within the allocated budget, with a PV power plant that operates efficiently and reliably, and generates the expected volumes of energy and revenue. In order to achieve this objective, a number of key activities need to be completed successfully.

Permits and licensing is often a very bureaucratic process involving multiple agencies in the central and local governments which may not coordinate their procedures and requirements. The list of permits/agreements needed is usually very long and differs from country to country. Typically, at least the following are needed: 1) Land lease agreement; 2) Site access permit; 3) Building permits; 4) Environmental permit; 5) Grid connection agreement; and 6) Operator/generation license. Understanding the requirements and the local context is essential. Consultations with the relevant authorities, the local community, and stakeholders are also important for a smoother approval process.

Environmental and social assessments should be performed early in the project planning process and actions should be taken to mitigate potential adverse impacts.

Grid connection agreement is critical to ensure that the PV plant can evacuate the power generated to the grid. **Section 8** of the report provides more information on permits, licensing and environmental considerations.

Engineering, procurement and construction can be broken into multiple contracts, but care must be taken to spell out responsibilities, so that all parties are clear on who is managing various risks and the overall process. In some cases, overall coordination is performed by the PV plant owner (if it has the in-house engineering expertise and experience in similar projects) or by an engineering company that is hired as a management contractor acting on behalf of the owner. However, the most common approach in building PV plants is turn-key responsibility through an EPC contract. An EPC contract involves one organization (the EPC Contractor) who has full responsibility to complete the project on time, under budget, and within the specified performance. The EPC contactor is paid a higher fee in return for managing and taking responsibility for all the risks of the project. **Section 9** provides more details on the development of a contracting strategy, and **Annex 2** contains Heads of Terms for an EPC contract. **Section 10** reviews the construction process.

Operation and Maintenance (O&M) of PV plants can be performed by the owner or contractors. Regular maintenance (including cleaning of the PV modules) is relatively easy and can be done by local staff trained by the equipment suppliers. Monitoring of plant performance can be achieved remotely by the original equipment manufacturer (OEM) or other asset manager. Spare parts, both for plant inventory and in response to equipment failures, need to be purchased from the OEM or an alternative supplier. **Section 11** provides more information on O&M contracting structures and best practices, while an overview of key terms for an O&M term sheet is found in **Annex 3**.

Annex 4 provides an overview of the rooftop solar market. This is an important development as distributed PV systems have grown and are expected to continue growing substantially. These PV systems are installed on rooftops of residential buildings (typically 10–50 kW) and commercial/industrial buildings (up to 1–2 MWs). From the design and construction point of view, key aspects are: optimal orientation and shading from adjacent (present and future) buildings and plants. Permits are easier to obtain, but they differ from large utility-scale PV plants, as different agencies are involved (mostly local authorities).

Depending on the regulatory framework affecting such installations, net metering or gross metering may be available; this is something that (along with the regulated tariff for electricity sold to the grid) will determine the payback period and overall attractiveness of the project. However, purchasing the PV system is not the only option for the owner of a building. There are companies offering lease agreements including leasing the PV plant or installing the PV plant and paying the owner of the building a rental. Under such agreements, electricity may be sold to the building owner at below-market prices.

1.3 COMMERCIAL AND FINANCING ASPECTS

Activities related to project financing run in parallel with the project design and permitting. As the project developer initiates preparatory activities including securing land lease agreement and permits, preliminary financing schemes are also assessed. Adequate funds should be allocated to complete the initial stages of project development, most importantly for the energy resource assessment, site selection, land lease agreement, and preliminary permits/licenses. Depending on the financing requirements of the project and how much of their own equity the developer can commit to the project, the developer may seek another sponsor. It is not unusual for the initial project developer to sell part or all of the rights to the project to another sponsor who will complete the project, often a sponsor with greater technical expertise and financial resources. As the project progresses, the developer/sponsor will reach out to potential debt financiers to get an idea of current lending rates, requirements and terms, and as the project develops, they will undergo due diligence. The experience and creditworthiness of the sponsor is critical for achieving financial closure and obtaining attractive financing.

Power projects are typically financed on a "back-to-back" basis, meaning that all contracts eventually rely on a bankable PPA. In other words, a PPA with a creditworthy off-taker covering adequately all the key risks of the project provides a sound basis for the project developer to sign EPC and O&M contracts, lease or purchase land, etc., so the project can be implemented.

As the project takes shape, the developer begins negotiations with the off-taker (often but not always a state-owned utility in most emerging economies) on the price, duration, and terms of the PPA. In many markets, PV projects have benefitted from regulatory support providing above-market price for power. For example, under a Feed-in Tariff (FiT) program, the price of electricity from renewable energy is specified for a set period of time, usually 10–25 years. In another example, terms of the PPA may be pre-determined through a tender process in which the developer is submitting a competitive bid (e.g., reverse auction). In a third example, utilities may have an obligation to source a portion of their total energy from renewable sources, and then negotiate with developers according to their own priorities and parameters. In the (relatively rare) instance of a merchant-solar power plant, power will be sold in the open market (i.e., "day-ahead," "hour-ahead" markets) at fluctuating rates rather than at a pre-determined tariff. However, in the future (if PV prices continue to decline) regulatory support may not be needed and merchant PV plants may become more common.

The grid connection and dispatching need to be clarified in the PPA. In most countries, the regulation requires the grid operator to take all the electricity produced by renewable facilities (*"obligation to take"*), but curtailment rules need to be included clearly in the PPA. **Section 12** provides more information on the regulatory support mechanisms used for PV projects. **Section 13** describes key elements of PPAs that are specific to solar, and explains several solar-specific risks that this key legal document is used to mitigate, such as indexing the power-purchase price (tariff) to a foreign currency to avoid devaluation risks.

Key risks associated with PV projects:

- **Completion risks affected by permitting/licensing and construction delays.**
- **Energy yield:** how much energy the facility will be producing depends on the energy resource and the design of the PV plant. An incorrect estimation of the energy resource, an unforeseen change in weather patterns and performance degradation of the PV plant could significantly affect the revenue of the project.
- **Regulatory environment:** Changes impacting the amount of power the off-taker is obligated to purchase and the price they pay can clearly impact the project, especially when applied retroactively. While this is not the norm, several countries (including developed markets generally seen as credible!) have implemented retroactive changes, raising the risk associated regulatory incentives. A comprehensive assessment of the power sector provides useful insight into the sustainability of such regulations. Developers are advised to consider the viability of their projects without subsidies or special treatment, particularly if such consideration makes the effective price of power well above the levelised cost of power in the existing power market.
- **Off-taker creditworthiness:** A thorough due diligence of the off-taker is an essential step before financing is finalized.

The appropriate financing arrangement depends on the specifics of each PV project, including investor risk appetite. The most common arrangement for such projects generally is to use a project finance type arrangement, typically with at least 30 percent equity and the remainder as debt. However, all equity financing may be chosen in certain situations. For example, if local commercial debt is difficult to access or is expensive, or the due diligence process for obtaining debt is expected to slow down a project and tariffs are sufficiently high, equity investors may be incentivized to back the entire project. While debt is cheaper than equity, all equity financing can allow for speedier project development, a priority in markets where a specified amount of construction must be achieved by a certain deadline in order to be eligible for incentives. This dynamic is not unique to solar, but as solar projects have historically been smaller, it has been more feasible for developers to finance them without debt financing, or at least to delay debt financing until the projects were operational, and presented a significantly lower risk profile to lenders. For solar projects that are among the first in their market, local banks may be reluctant to lend until they have evidence of successful projects; in such circumstances, seeking financing from development finance institutions like the IFC, which is willing to be a first-mover in new markets for renewables, may be a solution. **Sections 14 and 15** provide more specifics on financing, due diligence, and the typical financial analysis carried out.

Boxes

Boxes elaborate on a wide variety of topics. They provide case studies and "on the ground lessons learned" from a variety of countries.

Issues and lessons described in these boxes will inform the actions of developers, lenders and contractors thereby promoting good practice in the industry. This will help facilitate financing within the solar sector.

Many of the lessons learned reduce to the same fundamental point: **for a successful project it is essential to have suitable expertise within the project team.** This does not only apply to technical expertise but also to financial, legal and other relevant fields. Suitable expertise can be incorporated in a variety of ways: by hiring staff, using consultants or partnering with other organisations.

Photovoltaic (PV) Project Development 2

Even though each solar PV project may follow a different "road map," the key steps for developing a solar PV project are well established.

2.1 PROJECT DEVELOPMENT OVERVIEW

This section provides an overview of the project development process, from inception of the idea to the start of commercial operation. In broad terms, this process applies to the development of any privately-financed, utility-scale power plant. Aspects of the process that are unique to the use of solar PV technology, such as assessment of solar energy yield, site selection, and technology selection are emphasized more in the subsections below.

Developing a PV project is a process involving many stages and requires a multidisciplinary team of experts. The project developer starts by identifying a power market that offers adequate risk-reward opportunities, then identifies a promising site and secures the land-use rights for this site, carries out two separate rounds of technical-financial assessments (prefeasibility study and feasibility study), obtains all required permits and licenses, secures power purchase and interconnection agreements, arranges financing, and selects a team to design and construct the project (often an EPC contractor), supervises plant construction, and carries out testing and start-up. As the project moves from one stage to the next, the technical-financial assessments become more detailed until a final design is developed and construction starts.

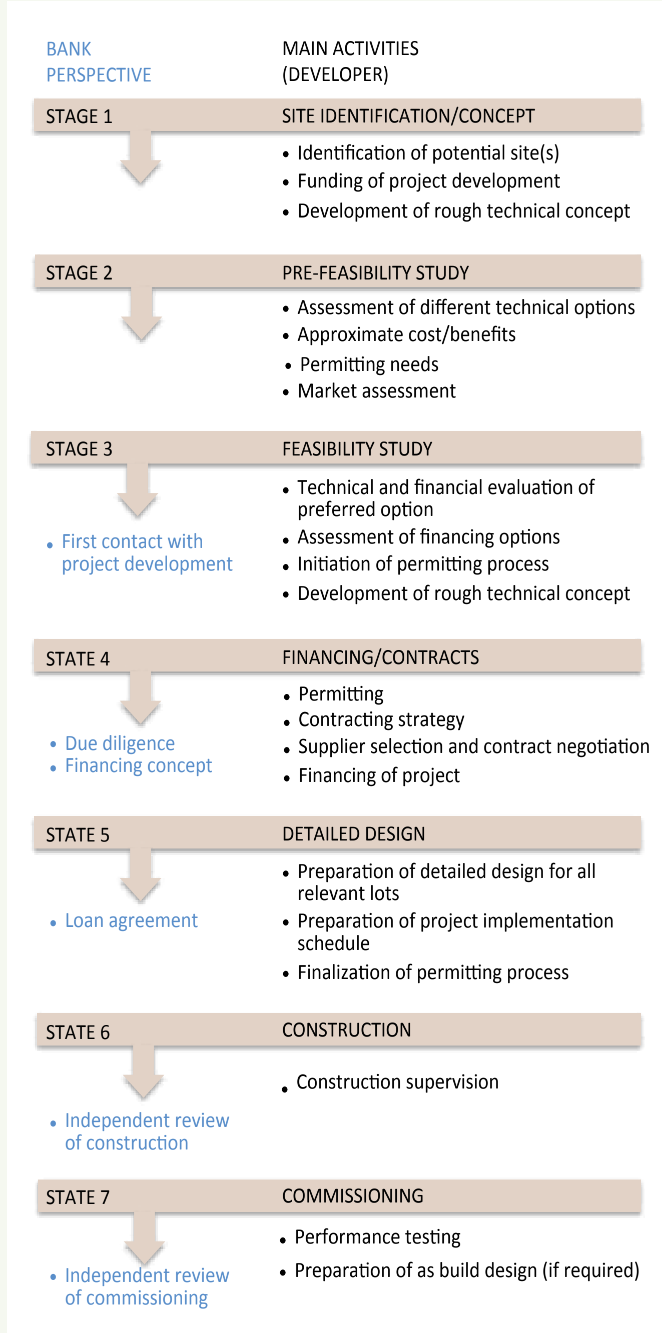
It is important to emphasize the back-to-back nature of many project contracts and documents; a PPA is needed in order for financing to be completed. However, this must be preceded by a grid connection agreement, construction and site access permits, land lease agreement, etc. Throughout this process, technical, commercial, and legal/regulatory experts are involved, working in parallel on distinct yet interdependent activities. While clear responsibilities can be identified for each expert, most project activities are related and the work of one expert influences the work of other experts; hence close coordination is needed. It is crucial to emphasize this latter point. Although this guide lays out the process as a series of steps, some project development activities must happen in parallel. It is up to the individual developer or project manager to oversee the activities and ensure they are coordinated and synchronized appropriately.

The key steps for developing a solar PV project are well established, and yet there is no definitive detailed "road map" a developer can follow. The approach taken in each project depends on site-specific parameters and the developer's priorities, risk appetite, regulatory requirements, and the types of financing support mechanisms (i.e., above market rates/subsidies or tax credits) available in a given market. However, in all cases, certain activities need to be completed that can broadly be organized in the following five stages:

1. Concept development and site identification.
2. Prefeasibility study.
3. Feasibility study.
4. Permitting, financing and contracts.
5. Engineering, construction and commercial operation.

These stages are described in the following subsections and show in Figure 1. A checklist of key tasks corresponding with each stage is provided at the end of the respective sub-section.

Figure 1: Project Development Stages



2.2 STAGE 1 – CONCEPT DEVELOPMENT AND SITE IDENTIFICATION

The concept development stage includes identification of the investment opportunity at a specific site and the formulation of a strategy for project development. It is assumed at this stage that a target market has been identified and the project developer understands any special prerequisites for investing in that specific country and power sector. These market-level decisions require a detailed assessment that carefully considers the risk–reward appetite of the project developer and potential investors.

2.2.1 SITE IDENTIFICATION

A desirable site has favourable local climate, good solar resource (irradiation), land available for purchasing or long-term leasing, an accessible grid connection or a binding regulatory commitment to connect the site to the transmission network, and no serious environmental or social concerns associated with the development of a PV project. Many countries require that the site be part of a list pre-approved by the government; this needs to be confirmed at the outset of the site identification process. Section 6 provides more details on site selection.

2.2.2 THE PV PROJECT

At least a preliminary (conceptual) design should be developed that helps estimate installed capacity or megawatts (MW), expectations, approximate investment requirements, energy yield, expected tariff and associated revenue. This way, a preliminary assessment of costs and benefits can be made, including return on investment (ROI). A preliminary financial model is often developed at this stage.

2.2.3 OUTLINE OF PROJECT STRUCTURE

At the concept stage, a developer may not be ready to invest significant resources, and may leave the project structure undefined. However, it is important to think about structuring issues at an early stage. In emerging markets, the formation of a project company can be challenging, and may involve requirements to appoint country nationals to management positions. International developers/investors will need to carefully consider such requirements, as well as any potential concerns about taxes and repatriation of profits. If a developer is exploring a portfolio of opportunities in a new market, it may be worthwhile to establish or purchase a "placeholder" Special Purpose Vehicle (SPV) that can be utilized when a project moves towards development.

2.2.4 THE REGULATORY FRAMEWORK AND SUPPORT MECHANISMS

Often, support mechanisms (e.g., incentives) play a large role in the economics of PV projects, especially compared to traditional power generating technologies. Support mechanisms for solar and other types of renewables can take many forms, including direct subsidies, tax or investment credits, or favourable FiTs. Many countries set strict criteria for new renewable projects to qualify for financial support. Such criteria for solar PV will vary by country and may also differ based on project size (i.e., commercial rooftop solar versus projects over 1 or 5 MW). Also, actual financial support may vary for peak and off-peak hours. Developers need to understand the regulatory requirements for qualifying for financial support in order to secure the highest available tariff and, critically, must be acutely aware of cut-off dates for particular support mechanisms. Failure to understand support mechanism rules and regulatory dynamics could result in a significant loss of revenue and have a negative impact on project economics. Regulatory frameworks and support mechanisms (e.g., financial incentives) are discussed further in Section 12.

2.2.5 OFF-TAKER DUE DILIGENCE

Credit-worthiness of the off-taker is critical and should be a primary focus of the due diligence to determine the level of risk associated with a PPA. As a legal contract between the solar plant operator and the purchaser of the electricity produced, a PPA defines future project revenues. It is therefore critical to understand at the outset whether there are standardized terms in a given market for developing a PPA, or whether the agreement will be negotiated ad-hoc. If the agreement is not part of a structured program, such as a government tender, there may be other standardized terms required by the off-taker or broader regulatory framework. In many developing countries, there is only one company responsible for purchasing and distributing power. Even in countries that have begun privatization of power generation, this company is often partially or fully state owned. Understanding the off-taker's role compared to other regulatory authorities, as well as the off-taker's creditworthiness and the expected tenor and terms of the PPA, is paramount, as these will impact the terms of the debt financing and, therefore, the viability of the project.

2.2.6 FINANCING STRATEGY

At the concept stage, available funds are usually minimal, but the developer should still begin to sketch out an internal budget that will meet requirements as the project moves ahead. At this time, the developer should also consider whether a secondary equity investor will be needed. As the project progresses through the concept phase, the developer will begin to explore debt financing options; availability and terms vary widely across markets. It is important for developers to begin conversations with local financiers early, particularly in markets where there is less familiarity with solar technologies, as negotiations can take substantially longer in this context. This assumes use of a project finance structure, which for solar power projects is commonly a mixture of non-recourse debt and equity. Financing is discussed in greater detail in Section 14.

The concept stage is an iterative process that aims to develop an understanding of the risk, project-specific costs and revenues that enable an assessment of project economics. The developer's objective is to obtain sufficient information to make an informed decision about the probability that the project can be taken forward. If the project looks promising, the developer is likely to decide to proceed to the next stage.

Concept Stage Checklist

The checklist below covers key questions and factors the developer should consider when deciding whether to proceed to the next stage, which is to conduct a prefeasibility study.

- ☐ Project structure outlined.
- ☐ Does the country and power sector provide adequate risk-reward benefits to private investors?
- ☐ Regulatory support and tariffs, especially the duration and timeline for any incentives for solar power.
- ☐ Suitable site identified taking account of site constraints.
- ☐ Grid access (proximity, capacity, and policy provisions for access).
- ☐ Appropriate funds available to carry out the feasibility assessments.
- ☐ Identification of off-taker and available infrastructure to take the power generated.

2.3 STAGE 2 – PREFEASIBILITY STUDY

The aim of a prefeasibility study is to develop a preliminary plant design and investment requirements, which allow further assessment of the financial viability of a project. This assessment involves more detail than the previous stage and determines whether to proceed further with the project and commit additional financial resources. The prefeasibility study can be carried out as a desktop study even though a site visit is desirable. Given the uncertainty of data available at this stage, viability will be determined in reference to a minimum financial hurdle rate, and will take into account a wide margin of error (e.g., +/-30%) to compensate for the lack of site-specific assessment data.

A prefeasibility study should, at a minimum, include an assessment of:

- The project site and boundary area, ensuring access to the site is possible, both legally and technically.
- A conceptual design of the project giving different options of technology (if applicable) and the financial impacts, including estimation of installed capacity.
- The approximate costs for land, equipment, development, construction and operation of the project, as well as predicted revenue.
- Estimated energy yield of the project. While site-specific analysis should be performed at a later stage, for prefeasibility purposes, published, high-level solar resource data and estimates of plant losses, or an assumed performance ratio (based on nominal values seen in existing projects) can be used. Seasonal production estimates should be taken into account.
- The anticipated electricity tariff to be received based on market analysis in a deregulated market, a published FiT in a market with specific incentives for renewables, or the relevant components of the tariff in a market under consideration.
- A financial model to determine the commercial viability of the project for further investment purposes.
- Grid connection cost and likelihood of achieving a connection within the required timeline.
- Identification of key environmental and social considerations and other potential "deal-breakers."
- Permitting requirements, costs, and likelihood of achieving consent.

- Assessment of the current regulatory environment, stability assessment and possible risk of future changes (for example, likelihood of changes during upcoming regional/national elections).
- An initial concept of the project's legal/corporate structure; this should be formulated to take advantage of existing/future incentives. At the prefeasibility stage, the developer may begin making assumptions about the project company which, if the project moves ahead, would be set up to develop and own the specific project or portfolio.
- Solutions to specific challenges; as challenges to the project arise, possible solutions will begin to be identified. For example, if the power off-taker does not have a strong credit rating, the developer may want to explore the possibility of a sovereign guarantee, and/or support from an export credit agency or a multilateral institution – for example, a partial risk guarantee from the World Bank.
- Preliminary timeline for project activities; while the scheduled workflow will inevitably change significantly, it is important to begin to understand the spacing and timing of key required activities at an early stage.

2.4 STAGE 3 – FEASIBILITY STUDY

The feasibility phase will build on the work undertaken at the prefeasibility stage by repeating the assessment in more detail using site-specific data, such as solar resource measurements, and should consider any previously identified constraints in more detail. If multiple sites are being assessed, then the preferred site needs to be selected. The objective of the feasibility study is to provide more detailed information on the potential project design, the investment requirements, and to plan for financing and implementation. If the results of the study are favourable, the developer should be prepared to invest more to advance the project to the financing stage.

A typical scope for a feasibility study is outlined below in terms of key technical, regulatory, financial, and commercial aspects.

Prefeasibility Checklist

Below is a checklist of key considerations for the developer during the prefeasibility stage:

- ☐ Assessment of the site and boundary areas including access permissions and restrictions.
- ☐ Conceptual design completed including consideration of technology options and their financial impacts.
- ☐ Approximate costs for land, equipment, delivery, construction, and operation identified along with predicted revenue.
- ☐ Indicative energy yield completed.
- ☐ Identification of anticipated electricity tariff to be received, and review of expected terms/conditions of PPAs in the relevant market.
- ☐ High-level financial analysis completed.
- ☐ Cost and likelihood of achieving grid connection in the required timescales identified.
- ☐ Main environmental constraints identified along with other potential "deal breakers."
- ☐ Assessment of current and potential future regulatory environment completed.
- ☐ An initial concept of the project's legal/corporate structure.
- ☐ Solutions to project challenges.
- ☐ Permitting requirements/costs identified.
- ☐ Preliminary project timeline/workflow showing spacing of key activities drafted.

2.4.1 *TECHNICAL DESIGN OF SYSTEM*

- Outline system design. Essentially, this is a plan for the project's physical development, including the lay-out, identification of equipment, and costs, etc. The system design is often required to obtain permits/consents. To select an initial conceptual design, it is worthwhile to evaluate various design configurations and module sizes, so that a design can be selected that is optimised for the site.
- Assessment of shading and initial solar PV plant layout. This is discussed in Section 7. The process enables optimisation and typically takes into account:
  - Shading angles.
  - Operations and maintenance (O&M) requirements.

- Module cleaning strategy.
- Tilt angle, orientation, and tracking.
- Temperature and wind profiles of the site.
- Cable runs and electrical loss minimisation.

- Production of a detailed site plan, including site surveys, topographic contours, depiction of access routes, and other civil works requirements.
- Calculation of solar resource and environmental characteristics, especially those that will impact performance of technical requirements (temperature, wind speed, and geological hazards). These are discussed in Section 4. While the accuracy of satellite data is increasing and is acceptable in many cases, it is often desirable to implement site-specific measurements of irradiation[3] as early in the project planning process as possible; the feasibility study stage is a good time to bring such data into the planning process. Note that irradiation levels often vary across seasons, and this needs to be accounted for in the financing model.
- Electrical cabling design and single line diagrams (see Section 7.4).
- Electrical connections and monitoring equipment.
- Grid connection design, including transformers and metering, etc.
- Full energy yield analysis using screened solar data and the optimised layout (discussed in Section 5).
- Assessment of all technology options and cost/benefit analysis of potential suppliers given the project location, including:
  - Module selection. This is an optimized selection based on the feasibility phase output, current availability, and pricing in the market place. Note that in countries where the solar industry is still in its infancy, there may be challenges when importing solar modules and other critical components of plant infrastructure. Examples include delays at customs and difficult negotiations on the terms of sale with manufacturers lacking a local sales representative or distributor.
  - Inverter selection. Manufacturers are predominately based in Europe and North America, though others are emerging in China and Japan. As above, importation can result in delays to project schedules. See Section 3.5 for further information.
  - Mounting frame or tracking system selection, including consideration of site specific conditions.

2.4.2 PERMITTING AND ENVIRONMENTAL, HEALTH AND SAFETY (EHS) REQUIREMENTS

- Detailed review and inventory of all necessary permits and licences needed for constructing and operating the power plant. Examples are environmental permits, land use permits, and generator licences. For more information, see Section 8.
- Pre-application discussions with the relevant consenting authority about the schedule for permitting, to understand the financial implications.
- Detailed review of environmental and social considerations, such as wildlife conservation or other designations that may affect permissible activities at the project sites; this is usually performed with a desk-based assessment and if possible supplemented by an initial site survey.
- Initial consultation with key stakeholders, including local community stakeholders, as relevant.
- Grid connection issues. This should be a more detailed assessment of likelihood, cost, and timing of grid connection, as well as transmission line capacities and constraints. This may also include submission of an initial application into the grid interconnection queue or achieving a "feasibility stage tariff" approval from the regulator.

3 Irradiation is a measure of the energy incident on a unit area of a surface in a given time period. This is obtained by integrating the irradiance over defined time limits and is measured in energy per square meter (often kWh/m^2).

2.4.3 FINANCIAL FEASIBILITY OF PROJECT

- Financial modelling to determine commercial viability and attractiveness of the project is discussed further in Section 14. Such modelling includes all costs and revenues. It should also involve a sensitivity analysis to start assessing the project risks.
- Further assessment of the anticipated electricity tariff. This is especially pertinent in markets where the tariff is expected to fluctuate, either by:
    - Deliberate design, such as in a power market where the developer is an Independent Power Producer (IPP) selling power in a wholesale or spot exchange;
    - Market forces, such as use of Renewable Energy Credits (RECs) or another market-based instrument, which could contribute to the developer's revenue; or
    - Potential for revision of negotiated tariffs, such as if the government decides to revise the tariffs retroactively (uncommon but has occurred) or the off-taker asks for re-negotiation.

2.4.4 PROJECT DEVELOPMENT/COMMERCIAL ASPECTS

- Project implementation plan – Level 1 (minimum) including a Gantt chart laying out the project timeline, resource requirements, project development budget, procurement concept (e.g., full turnkey or multi-contracting approach), and O&M concept.
- Option agreements for land access for all privately held land or access roads, or a concession agreement with the relevant authority.
- Evaluation of the commercial structure of the project. This includes evaluating the project company or companies, which may involve a Special Purpose Vehicle (SPV), depending on company structures allowed under local law. This also includes evaluating any off-shore parent-company structures and incorporation location based on legal, financial and tax criteria corresponding to the project.
- Investment and funding requirements and the investment concept. This should include equity contribution amounts and sources, equity partner requirements and financing assumptions to be included in the financial model.
- A project structure and risk-mitigation strategy. In many emerging markets, to make a project "bankable" (i.e., able to attract reasonably-priced debt financing) it is typically necessary to secure credit enhancements, which can be either private (letters of credit, escrow accounts) or governmental (sovereign guarantees).
- Procurement of Owner's Engineer. As the intention to proceed with the project grows, so too the technical scope for the EPC or other technical tendering procurement contracts needs to be drafted and reviewed by the Owner's Engineer. The EPC's Owner's Engineer scope of work may also include support for the technical procurement (e.g., PV plant components) and technical design review. The same firm usually follows through as the Owner's Engineer during the construction phase.
- Tender and award of Owner's Counsel to support contracts development and negotiation as well as any relevant legal-structuring needs and company set-up during the development phase.

It should be noted that the feasibility study may overlap with activities related to permitting, financing, and contracts (see next phase) that are being carried out in parallel. Coordination of all technical, commercial, and regulatory activities is essential for the success of the project.

Feasibility Checklist

Below is a checklist for developers with the key considerations that must be addressed during the feasibility stage.

- [ ] Detailed site plan produced.
- [ ] Solar resource assessed including assessment of shading.
- [ ] Environmental characteristics that may affect performance identified.
- [ ] Detailed review of environmental and social considerations conducted.
- [ ] Detailed review of required permits and licences undertaken.
- [ ] Assessment of Capex for technology and supplier options; cost/benefit for options and project location completed.
- [ ] Pre-application discussions with relevant consenting authority undertaken.
- [ ] Initial consultations with key stakeholders including from the community completed.
- [ ] Grid connection assessment completed.
- [ ] Predicted energy yields established.
- [ ] Further assessment of anticipated electricity tariff undertaken.
- [ ] Financial analysis carried out. Preliminary financing planned.
- [ ] Project implementation plan developed.
- [ ] Options agreements for land access (where required) secured.
- [ ] Evaluation and concept of the commercial structure of the project and project company(s) carried out.

2.5 STAGE 4 – PERMITTING, CONTRACTS AND FINANCING

After the feasibility stage and assuming that the project still seems to be financially viable, the project moves to the next stage. This includes obtaining final permits, securing project finance and pre-implementation activities (commercial contracts). The timing and sequencing of this stage will vary significantly by project, but this phase usually includes the following activities:

- Engagement of relevant community or stakeholders.
- Preparation and submission of relevant permit and licence applications and associated documents for the proposed project.
- Environmental and social assessments (agreed in consultation with permitting authority and other statutory bodies), which may include a full Environmental and Social Impact Assessment (ESIA).
- Preparation and submission of a grid connection application.
- Review of the design and any permit/consent conditions; revision of design or consents as needed.
- Contractor prequalification, ranking, and short list selection.
- Decision on the financing approach (e.g., sources and proportions of equity and debt, including construction financing).
- Securing financing for the project as described in Section 14.
- Decision on contracting strategy (i.e., EPC contract or multi-contract).
- Preparation of solar PV module tender documentation. Supplier/contractor selection and contract negotiations.
- Preparation of construction or balance of plant tender documentation.
- Preparation of PPA documentation and final negotiations.
- Preparation of O&M concept and contracts, as relevant.
- Preparation of Owner's Engineer tender (if technical advisor is not continued into construction).
- Contracting and procurement of relevant insurances (i.e., construction, operation, etc.).
- Preparation of Lender's Engineers and Lender's Council tenders.
- Finalisation of grid interconnection agreement with grid operator or relevant authority.
- Preparation of detailed, bankable financial model covering the full lifecycle of the plant. Typically this will only be completed after negotiating the EPC or equipment and Balance of Plant (BoP) contracts, as

well as O&M contracts, so that the financial model can incorporate final costs of capital and O&M.

- Completion of a project risk analysis.
- Transportation analysis as necessary for difficult-to-reach project locations.
- Finalisation of all land, surface area, and access agreements—and trigger land agreement options to convert to long-term leases or easements, as necessary.
- Finalisation of the detailed project implementation plan.

The remainder of this section provides more information on the three key activities of this phase: permitting, financing, and contracts.

2.5.1 PERMITTING

An approved permit must be obtained before construction of a project commences. Permit requirements vary widely between different countries and regions and are discussed in detail in Section 8. In general, the type of permits may include, but are not limited to:

- Land lease agreement(s).
- Access agreements.
- Planning/land use consents.
- Building/construction permits.
- Environmental permits (forestry, endangered species, EIA, etc.).
- Social impacts (i.e., cultural heritage/archaeological sites, stakeholder consultations).
- Energy permit.
- Grid connection application.
- Operator/generation licences.

It is important to consider the permitting requirements at an early stage, as the application timeline for different permits will vary. The best approach is usually through early discussions with the relevant consenting authority. Such discussions should establish what supporting documents will be required when submitting permitting applications (i.e., environmental assessment, transport studies, etc.) as well as timescales for consent to be granted following submission. Supporting documentation requirements and response time will usually vary with the size of the PV plant, its location, and contextual sensitivities.

Obtaining permits sometimes requires amending the design of the PV plant, so that it conforms to the requirements of the local authority and addresses the concerns of other key agencies during the permitting process. Hence, it is difficult to overemphasize the importance of early discussions with relevant parties, so that their feedback can be incorporated into the design process at an early stage.

Once consents are obtained, it is important to consider any attached conditions that must be addressed prior to and/or during construction. Consent conditions will depend on site-specific characteristics and may present constraints to the development timeline. For example, a condition of consent may be that construction is not permitted during certain times of the year to avoid disturbing a particular species' breeding season. A review of all conditions should be carried out after consent is obtained to establish requirements and to open a dialogue to clarify any uncertainties with the relevant authority. It is likely that meeting certain conditions will require preparing additional documents for the consenting authority, whose written approval may be required before the development can proceed.

2.5.1.1 Environmental and social considerations

The likely environmental and social effects of a solar project should be considered and the impact of the project assessed. Part of this assessment could be done as a desk-top study, but a site visit is essential in order to assess the current situation of the site and surrounding environment. National legislation should be reviewed to determine any country-specific requirements related to developing solar projects. Similarly, referring to international best practices will ensure adverse project impacts are minimized and positive relationships developed with stakeholders.

Environmental and social considerations are covered in detail in Section 8.

Outcomes of environmental and social assessments, as well as stakeholder consultation, often provide feedback into the design process. Sometimes this includes design changes, or developing measures to mitigate any significant impacts. It is therefore important that these assessments are carried out in a timely manner that allows for any potentially necessary design amendments. Furthermore, leading lending institutions will require that the project adhere to rigorous environmental standards and principles, such as the Equator Principles (EPs)[4] and/or IFC Performance Standards (IFC PSs). Further details on environmental and social considerations and lending requirements are provided in Section 8.

2.5.2 FINANCING

Financing a solar PV project is similar in principle to financing other types of power projects, however, certain risks that are unique to solar PV must be accounted for in the financing plan. Risks associated specifically with solar PV projects are related to the energy resource (irradiation), project siting and permitting, solar technology (relatively new), potential degradation of PV modules, and reliability of long-term plant performance, as well as potential uncertainty of the tariff and revenue collection.

- PV project financing generally involves two key components:
    - Equity, from one or more investors, injected directly or via a special purpose vehicle (SPV or "project company").
    - Non- or limited-recourse debt from one or more lenders, secured against the assets owned by the SPV.

In order to obtain financing, the developer must prepare comprehensive documentation of the project, so that financiers may carry out their due diligence to assess the risks of the prospective investment. Detailed design and comprehensive documentation that enable reliable revenue projections are particularly critical, because the lender depends entirely on the cash flow of the project for repayment, as opposed to the balance sheet of the sponsor. Commercial banks in new markets may not be familiar with solar projects, so developers should be prepared for a rigorous due diligence process, and incorporate sufficient time in the project schedule to identify and address lender requirements.

Throughout the planning process, the developer constantly assesses and tries to manage risks, so there is favourable risk-reward balance. More information on some of the typical risks specific to solar PV projects is found in Section 10.

More details on PV project financing are provided in Section 13.

2.5.3 CONTRACTS

2.5.3.1 Contract Strategy

Contracts present developers with several important considerations. Perhaps foremost is establishing a project company or SPV (special purpose vehicle); if not already initiated, an SPV should be formally established. The developer typically creates and owns the project company, potentially with equity co-investment from another financial backer (sponsor), such as an infrastructure fund. All contracts, land agreements, financing and secured project permits and licenses need to be issued in the name of the SPV; transferring these later to the SPV can be very difficult and time consuming. Also, lenders often insist upon the rights of assignability (e.g., the right for project assets and liabilities to be assigned to them in the event of default). Considering assignability at early stages of incorporation can save significant time later in the development process.

With regard to procurement and construction of the PV plant, a strategy needs to be developed to address technology, construction, and performance risks, while still meeting investment requirements. There are two main contracting methods that a developer may consider:

4 A list of all EP financial institutions can be found at http://www.equator-principles.com/index.php/members-reporting

multiple contracts or a single EPC contract. In the former case, multiple contractors are engaged to deliver/construct different parts of the PV plant, but one company (typically the owner/developer or the Owner's Engineer or a third party) retains the responsibility of integrating all components and services provided under the various contracts. In the case of an EPC contract, one company is assigned full responsibility for completing the entire project. The next sub-section discusses key contract-related activities. In addition, contractual aspects are covered in more detail in Section 9, and a template EPC Contract Heads of Terms is provided in Annex 2.

A multi-contract approach requires significantly more management effort on the part of the developer, and also exposes the developer to significantly more risk. However, a multi-contract approach is generally cheaper than an EPC. While the EPC option is higher cost, it transfers a substantial amount of risk from the developer to the EPC contractor.

If an EPC is chosen, it is critical that the developer ensures that the EPC contract clearly defines expectations, requirements, and responsibilities. The developer should be certain that the contract is satisfactory in this regard before signing, as it will be much easier and more economical to make changes to the contract before it is signed. If the developer has little or no experience, or is unsure of any aspect of the project, he should seek advice from a consultant experienced in the respective topic. It is highly recommended that an Owner's Engineer is engaged during the development and construction phase, in order to ensure the quality of all contractor work, as well as the meeting of timelines and maintenance of budgets. The Owner's Engineer can also ensure consistency between the OEM (Original Equipment Manufacturer) of the solar modules and warranty requirements across other contracts and their respective works.

There is no single preferred contracting approach. The approach taken will depend on the experience, capabilities and cost-sensitivity of the developer. However, turnkey EPC contracts are most commonly used in the solar industry.

Checklist for Permitting, Financing, and Contracts

Below is a checklist of critical issues that a developer needs to consider during the stage of project development that involves securing permitting, contracts, and financing.

- [ ] Preparation and submission of relevant permit and license applications.
- [ ] Environmental and social assessments (as required) completed.
- [ ] Grid connection application prepared and submitted. Grid connection agreement signed.
- [ ] Review of design and permit/consent conditions completed.
- [ ] Contracting strategy approach determined.
- [ ] Financing structure decided. Financing secured for the project.
- [ ] Community or stakeholder engagement completed.
- [ ] Solar PV tender documentation prepared.
- [ ] Supplier selection and ranking undertaken.
- [ ] PPA documentation prepared.
- [ ] O&M concept and contracts prepared.
- [ ] Owner's Engineer tender prepared.
- [ ] Relevant insurance procured and contracted.
- [ ] Lender's Engineer and Lender's Council tenders prepared.
- [ ] Tendering and evaluation of bidders for all contracts carried out.
- [ ] Contract negotiations completed.
- [ ] Bank-grade energy yield completed.
- [ ] Detailed bankable financial model completed.
- [ ] Transportation analysis (if required) carried out.
- [ ] All land and access agreements finalised.
- [ ] Project risk analysis completed.
- [ ] PPA finalised with off-taker.
- [ ] Detailed project implementation plan finalised.
- [ ] Technical and legal due diligence completed (if required).

2.5.3.2 *Coordination of Contract Signing*

It is critical that the developer or project sponsor closely coordinates the structure, terms and timelines for execution of key strategic documents. Without close coordination, there are likely to be conflicts or contradictions between documents, or worse, the developer can create financial obligations that cannot be met. Critical path analysis is essential to identify interdependencies and key activities that require close monitoring to avoid project delays.

Project timelines and corresponding contractual signing should be coordinated to avoid sub-optimal bargaining positions in reaching financial close. Examples of poor coordination include:

- The signing of a PPA without knowing the requirements of the grid interconnection agency and/or without having a grid connection agreement.
- Signing of an EPC contract without the necessary financial commitment from investors. If the financing is not yet in place, a developer should commit only to an EPC agreement that is not binding until financial close is reached.
- Signing of an EPC contract before all permits and licenses are obtained.

The EPC contract and PPA should be negotiated in parallel to the financing, as some financial institutions may need to request changes to the contract terms.

2.6 STAGE 5 – ENGINEERING, PROCUREMENT, CONSTRUCTION AND COMMERCIAL OPERATION

A single EPC contract is most commonly used for developing PV plants. In this case, one contractor is responsible for the complete project. The EPC contractor is required to confirm the solar energy resource, develop the detailed design of the PV plant, estimate its energy yield, procure the equipment according to specifications agreed upon with the developer, construct the PV plant, carry out the acceptance tests, and transfer the plant for commercial operation to its owner/operator.

2.6.1 ENGINEERING AND PROCUREMENT

The key aspects of EPC activities are discussed below. Section 9 provides more information on EPC contracts, as well as the alternative approach that involves the developer managing multiple contracts.

2.6.1.1 *Development of Detailed PV Design*

The EPC contractor will prepare the necessary detail documentation for the solar PV plant to be tendered and constructed. The following documentation will be prepared:

- Detailed layout design.
- Detailed civil design (buildings, foundations, drainage, access roads).
- Detailed electrical design.
- Revised energy yield.
- Construction plans.
- Project schedule.
- Interface matrix.
- Commissioning plans.

Key electrical systems must be designed in rigorous detail. This will include equipment required for protection, earthing and interconnection to the grid. The following designs and specifications should be prepared:

- Overall single line diagrams.
- Medium voltage (MV) and low voltage (LV) switch gear line diagrams.
- Protection systems.
- Interconnection systems and design.
- Auxiliary power requirements.
- Control systems.

Civil engineering items should be developed to a level suitable for construction. These will include designs of array foundations and buildings, as well as roads and infrastructure required for implementation and operation. The design basis criteria should be determined in accordance with national standards and site specific constraints such as geotechnical conditions. For example, wind loadings should be calculated to ensure that the design will be suitable for the project location.

2.6.1.2 Energy Yield

A bank-grade energy yield will be required to secure financing. Most often investors will require a P90 energy yield, or an estimate of the annual energy production which is reached with a probability of 90 percent. It is advised that this energy yield is either carried out or reviewed by an independent specialist. This will ensure that confidence can be placed in the results and will help attract investment.

The energy yield should include:

- An assessment of the inter-annual variation and yield confidence levels.
- Consideration of site-specific factors, including soiling or snow, and the cleaning regime specified in the O&M contract.
- Full shading review of the PV generator including near and far shading.
- Detailed losses and performance degradation over time.
- A review of the proposed design to ensure that parameters are within design tolerances.

2.6.1.3 Detailed Project Documentation

The EPC contractor will develop a detailed project report, which along with all project documentation (drawings, etc.) is housed in a "data room" that provides easy access to all parties involved in the project. This information will be used to secure financing from banks or investors. Documentation should be presented in a clearly organized way. Examples of the information that should be included are detailed below:

- Site layout showing the location of modules, inverters, and buildings.
- Indicative plans showing:
    - Mounting frame and module layout.
    - Inverter locations and foundations/housings.
    - Security measures.
- Initial electrical layouts:
    - Schematics of module connections through to the inverter.
    - Single line diagrams showing anticipated cable routes.
    - Grid connection and potential substation requirements.
- Bill of materials for major equipment.
- Energy yield analysis.
    - Losses assumed with regard to the energy yield forecast.
- Financial model inputs including:
    - Long term O&M costs and contingencies (up to the end of the design life and/or debt term).
    - Availability assumptions.
    - Degradation of module performance assumptions.
    - Spare parts inventory cost.
    - Connection cost for electricity and services.
    - Cash flow model including maintenance of a specified debt service coverage ratio (DSCR)[5] if applicable, and contingency reserve to be used for inverter replacement, weather damage, and other unexpected costs associated with plant operation.
- Copies of all contracts negotiated:
    - PPA.
    - EPC Contract.
    - Equity subscription agreement and incorporation documents for project SPV.

5 DSCR is the ratio of cash available for debt servicing to interest, principal and lease payments.

- Copies of applicable insurance and other risk-mitigation.
- Other documents, such as currency hedging agreements, etc., as applicable.

- Details of the permitting and planning status.
- Environmental impact, restrictions, and mitigation plans.

2.6.2 CONSTRUCTION AND COMMERCIAL OPERATION

After the contract(s) have been awarded (whether multiple or a single EPC), the role of the developer is to oversee the implementation of the project. This can be done using the developer's own staff, if they have the expertise and experience, or by hiring an Owner's Engineer. Each contractor designs, procures, and installs the components of the PV plant under the terms of its contract. If multiple contracts are awarded, coordination of schedule and interfaces is critical.

Critical tasks that need to be carried out independently for each type of contract include:

- Planning and sequencing of tasks.
- Cost management.
- Risk management.
- Coordination among all organizations involved in the project.

More information on construction is provided in Section 10.

Commercial operation commences after commissioning, which includes performance and reliability tests specified in the contract. Such tests may be conducted for individual components and then for the overall system. Component-by-component testing is always needed, but especially so in the case of multiple contracts in order to assess whether each contractor has fulfilled its obligations. Successful tests are usually a trigger to release payments to the contractor(s). Unsuccessful tests may result in design modifications, and even legal action if the PV plant cannot meet performance and reliability guarantees.

Upon completion of acceptance tests, the contractor(s) should provide the plant owner with "hand-over documentation," which should include design data, drawings, O&M procedures, information about spare parts, and any other information pertinent to complete handover of the plant and its successful future operation and maintenance.

Solar PV Technology

3

Modules are either mounted on fixed angle frames or on sun-tracking frames. Fixed frames are simpler to install, cheaper, and require less maintenance. However, tracking systems can increase yield by up to 45 percent. Tracking, particularly for areas with a high direct/diffuse irradiation ratio, also enables a smoother power output.

3.1 SOLAR PV TECHNOLOGY OVERVIEW

This section discusses module technologies, mounting systems, inverters and methods of quantifying plant performance. It provides an overview of current commercially available technologies used in utility-scale solar PV projects. The purpose is to provide a framework of understanding for developers and investors before they commit to a specific technology.

PV cell technologies are broadly categorised as either crystalline or thin-film. Crystalline silicon (c-Si) cells provide high efficiency modules. They are sub-divided into mono-crystalline silicon (mono-c-Si) or multi-crystalline silicon (multi-c-Si). Mono-c-Si cells are generally the most efficient, but are also more costly than multi-c-Si. Thin-film cells provide a cheaper alternative, but are less efficient.[6] There are three main types of thin-film cells: Cadmium Telluride (CdTe), Copper Indium (Gallium) Di-Selenide (CIGS/CIS), and Amorphous Silicon (a-Si).

The performance of a PV module will decrease over time due to a process known as degradation. The degradation rate depends on the environmental conditions and the technology of the module.

Modules are either mounted on fixed-angle frames or on sun-tracking frames. Fixed frames are simpler to install, cheaper and require less maintenance. However, tracking systems can increase yield by up to 45 percent. Tracking, particularly for areas with a high direct/diffuse irradiation ratio also enables a smoother power output.

Inverters convert direct current (DC) electricity generated by the PV modules into AC electricity, ideally conforming to the local grid requirements. They are arranged either in string or central configurations. Central configuration inverters are considered to be more suitable for multi-MW plants. String inverters enable

6 Less efficient modules mean that more area is required to produce the same power.

individual string Maximum Power Point Tracking (MPPT)[7] and require less specialised maintenance skills. String configurations offer more design flexibility.

PV modules and inverters are all subject to certification, predominantly by the International Electrotechnical Commission (IEC). New standards are currently under development for evaluating PV module components and materials.

The performance ratio (PR) of a well-designed PV power plant will typically be in the region of 77 percent to 86 percent (with an annual average PR of 82 percent), degrading over the lifetime of the plant. In general, good quality PV modules may be expected to have a useful life of 25 to 30 years.

3.2 OVERVIEW OF GROUND MOUNTED PV POWER PLANT

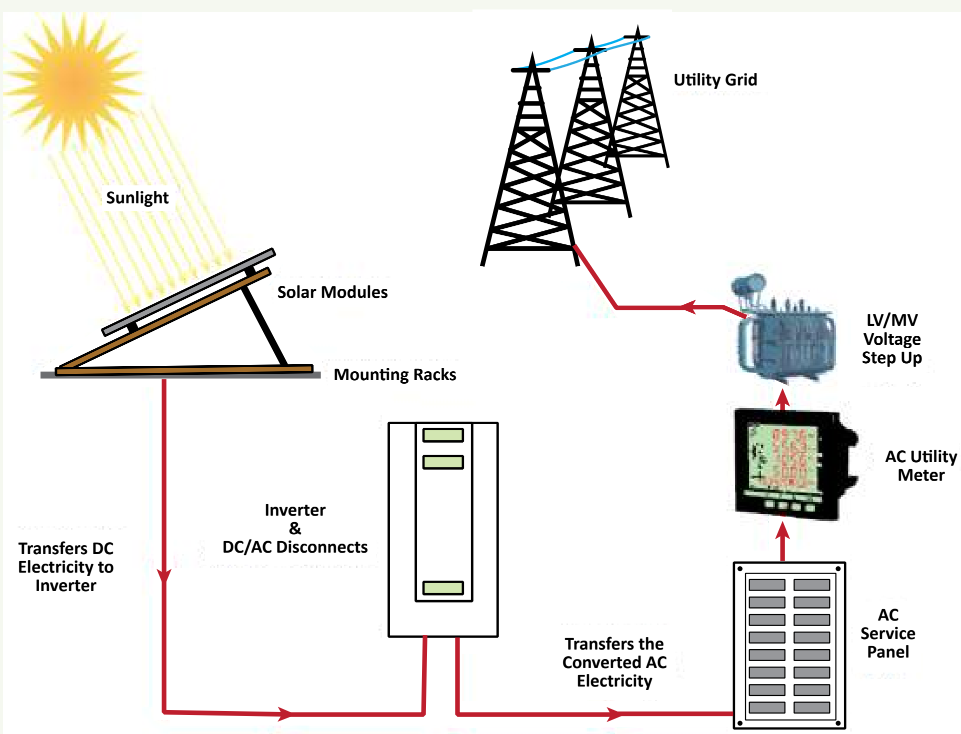
Figure 2 gives an overview of a megawatt-scale grid-connected solar PV power plant. The main components include:

- **Solar PV modules:** These convert solar radiation directly into electricity through the photovoltaic effect in a silent and clean process that requires no moving parts. The PV effect is a semiconductor effect whereby solar radiation falling onto the semiconductor PV cells generates electron movement. The output from a solar PV cell is DC electricity. A PV power plant contains many cells connected together in modules and many modules connected together in strings[8] to produce the required DC power output.

7 The purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions.

8 Modules may be connected together in a series to produce a string of modules. When connected in a series the voltage increases. Strings of modules connected in parallel increase the current output.

Figure 2: Overview of Solar PV Power Plant



- **Inverters:** These are required to convert the DC electricity to alternating current (AC) for connection to the utility grid. Many modules in series strings and parallel strings are connected to the inverters.
- **Module mounting (or tracking) systems:** These allow PV modules to be securely attached to the ground at a fixed tilt angle, or on sun-tracking frames.
- **Step-up transformers:** The output from the inverters generally requires a further step-up in voltage to reach the AC grid voltage level. The step-up transformer takes the output from the inverters to the required grid voltage (for example 25kV, 33kV, 38kV, or 110kV, depending on the grid connection point and country standards).
- **The grid connection interface:** This is where the electricity is exported into the grid network. The substation will also have the required grid interface switchgear such as circuit breakers (CBs) and disconnects for protection and isolation of the PV power plant, as well as metering equipment. The substation and metering point are often external to the PV power plant boundary and are typically located on the network operator's property.[9]

3.3 SOLAR PV MODULES

This section describes commercially available technology options for solar PV modules, discusses module certification and describes how solar PV module performance can degrade over time.

3.3.1 BACKGROUND ON PV MATERIALS

Unusual semiconducting properties required for PV cells limit the raw materials from which they may be manufactured. Silicon is the most common material, but cells using CdTe and CIGS/CIS are also viable. Emerging PV technologies such as organic cells are made from polymers. However, they are not commercially available yet.

Each material has unique characteristics that impact the cell performance, manufacturing method and cost.

PV cells may be based on either silicon wafers (manufactured by cutting wafers from a solid ingot block of silicon) or "thin-film" technologies for which a thin layer of a semiconductor material is deposited on low-cost substrates.

PV cells can further be characterised according to the long-range structure of the semiconductor material, "mono-crystalline," "multi-crystalline" (also known as "poly-crystalline") or less-ordered "amorphous" material.

Figure 3 shows the most commonly used PV technologies:

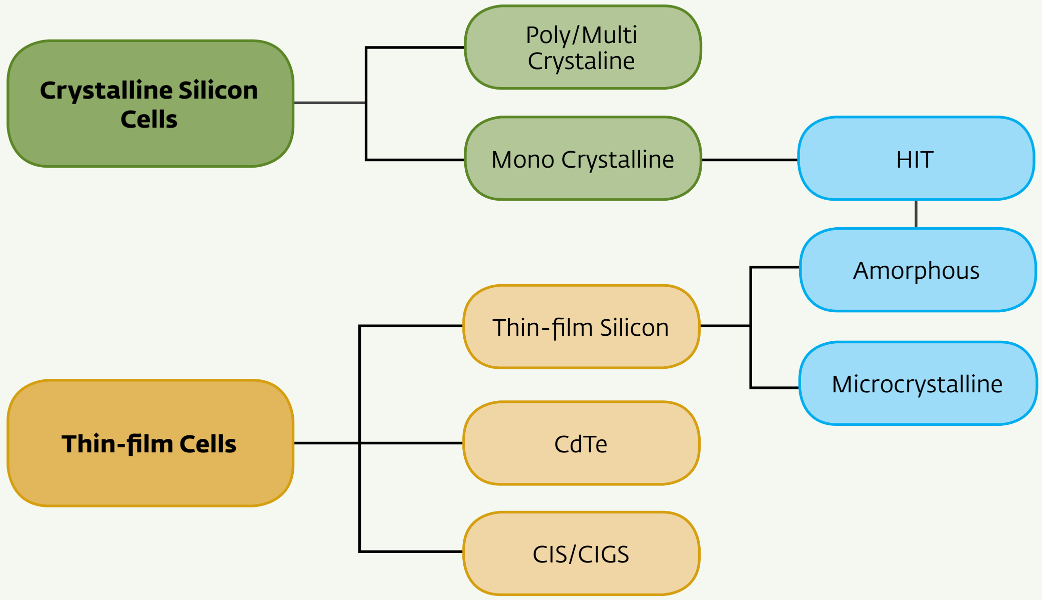
- **Crystalline Silicon (c-Si):** Modules are made from cells of either mono-crystalline or multi-crystalline silicon. Mono-c-Si cells are generally the most efficient, but are also more costly than multi-c-Si.
- **Thin-film:** Modules are made with a thin-film deposition of a semiconductor onto a substrate. This class includes semiconductors made from:
  - Amorphous Silicon (a-Si).
  - Cadmium Telluride (CdTe).
  - Copper Indium Selenide (CIS).
  - Copper Indium (Gallium) Di-Selenide (CIGS/CIS).
- **Heterojunction with intrinsic thin-film layer (HIT):** Modules are composed of a mono-thin c-Si wafer surrounded by ultra-thin a-Si layers.

Due to reduced manufacturing costs and maturity of the technology, wafer-based crystalline modules are expected to maintain a market share of up to 80 percent until at least 2017.[10] Thin-film (17 percent) and high efficiency (3 percent) modules are expected to make up the remaining 20 percent.

9 Responsibility for this is defined in the grid connection contract. Normally, the onus is on the grid operator to maintain the equipment in the grid operator's boundary—and there will be a cost to be paid by the PV plant owner.

10 European Photovoltaic Industry Association, 'Global Market Outlook for Photovoltaics 2013-2017', http://www.epia.org/fileadmin/user_upload/Publications/GMO_2013_-_Final_PDF.pdf, 2013 (accessed July 2014).

Figure 3: PV Technology Classes



3.3.2 CRYSTALLINE SILICON (c-Si) PV MODULES

C-Si modules consist of PV cells connected together and encapsulated between a transparent front (usually glass) and a backing material (usually plastic or glass).

Mono-c-Si wafers are sliced from a large single crystal ingot in a relatively expensive process.

Cheaper, multi-c-Si wafers may be made by a variety of techniques. One of the technologies involves the carefully controlled casting of molten multi-silicon, which is then sliced into wafers. These can be much larger than mono-crystalline wafers. Multi-crystalline cells produced in this way are currently cheaper, but the end product is generally not as efficient as mono-crystalline technology.

Both mono-crystalline and multi-crystalline module prices have decreased considerably in the last two years.

3.3.3 THIN-FILM PV MODULES

Crystalline wafers provide high-efficiency solar cells, but are relatively costly to manufacture. In comparison, thin-film cells are typically cheaper due to both the materials used and the simpler manufacturing process. However, thin-film cells are less efficient.

A well-developed thin-film technology uses silicon in its less-ordered, non-crystalline (amorphous) form. Other technologies use CdTe and CIGS/CIS with active layers less than a few microns thick. Some thin-film technologies have a less established track record than many crystalline technologies. The main characteristics of thin-film technologies are described in the following sections.

3.3.3.1 Amorphous Silicon (a-Si)

In a-Si technologies, the long-range order of c-Si is not present and the atoms form a continuous random network. Since a-Si absorbs light more effectively than c-Si, the cells can be much thinner.

A-Si can be deposited on a wide range of both rigid and flexible low-cost substrates. The low cost of a-Si makes it suitable for many applications where low cost is more important than high efficiency.

3.3.3.2 *Cadmium Telluride (CdTe)*

CdTe is a compound of cadmium and tellurium. The cell consists of a semiconductor film stack deposited on transparent conducting oxide-coated glass. A continuous manufacturing process using large area substrates can be used. Modules based on CdTe produce a high energy output across a wide range of climatic conditions with good low light response and temperature response coefficients. CdTe modules are well established in the industry and have a good track record.

3.3.3.3 *Copper Indium (Gallium) Di-Selenide (CIGS/CIS)*

CIGS/CIS is a semiconductor consisting of a compound of copper, indium, gallium and selenium.

CIGS absorbs light more efficiently than c-Si, but modules based on this semiconductor require somewhat thicker films than a-Si PV modules. Indium is a relatively expensive semiconductor material, but the quantities required are extremely small compared to wafer-based technologies.

Commercial production of CIGS/CIS modules is in the early stages of development. However, it has the potential to offer the highest conversion efficiency of all the thin-film PV module technologies.

3.3.4 HETEROJUNCTION WITH INTRINSIC THIN-FILM LAYER (HIT)

The HIT solar cell is composed of a mono-thin-crystalline silicon wafer surrounded by ultra-thin amorphous silicon layers. HIT modules are more efficient than typical crystalline modules, but they are more expensive.

3.3.5 MODULE DEGRADATION

The performance of a PV module decreases over time. Degradation has different causes, which may include effects of humidity, temperature, solar irradiation and voltage bias effects; this is referred to as potential induced degradation (PID).[11] Other factors affecting the degree of degradation include the quality of materials used in manufacture, the manufacturing process, and the quality of assembly and packaging of the cells into the module. Maintenance has little effect on the degradation rate of modules, which is predominantly dependent on the specific characteristics of the module being used and the local climatic conditions. It is, therefore, important that reputable module manufacturers are chosen and power warranties and degradation rates are carefully reviewed by an independent technical advisor.

The extent and nature of degradation varies among module technologies. For crystalline modules, the degradation rate is typically higher in the first year upon initial exposure to light and then stabilises. The initial irreversible light-induced degradation (LID) occurs due to defects that are activated on initial exposure to light. It can be caused by the presence of boron, oxygen or other chemicals left behind by the screen printing or etching process of cell production. Depending on the wafer and cell quality, the LID can vary from 0.5 percent-2.0 percent.[12]

Amorphous silicon (a-Si) cells degrade through a process called the Staebler-Wronski Effect.[13] This degradation can cause reductions of 10–30 percent in the power output of the module in the first six months of exposure to light. Thereafter, the degradation stabilises and continues at a much slower rate.

A-Si modules are generally marketed at their stabilised performance levels. Interestingly, degradation in a-Si modules is partially reversible with temperature. In other words, the performance of the modules may tend to recover during the summer months, and drop again in the colder winter months.

11 PID is dependent on temperature, humidity, and system voltage and ground polarity. It can be detected with a relatively short test. The degradation is reversible by applying a suitable external voltage.

12 Pingel et al., *Initial degradation of industrial silicon solar cells in solar panels*, Solon SE, 2011. B.Sopori et al., "Understanding Light-induced degradation of c-Si solar cells," 2012 IEEE Photovoltaic Specialists Conference, Austin, Texas, June 3-8 2012, Conference Paper NREL/CP-5200-54200, June 2012. Accessed from http://www.nrel.gov/docs/fy12osti/54200.pdf (accessed July 2014).

13 An effect in which the electronic properties of the semiconductor material degrade with light exposure.

Additional degradation for both amorphous and crystalline technologies occurs at the module level and may be caused by:

- Effect of the environment on the surface of the module (for example, pollution).
- Discolouration or haze of the encapsulant or glass.
- Lamination defects.
- Mechanical stress and humidity on the contacts.
- Cell contact breakdown.
- Wiring degradation.

PV modules may have a long-term power output degradation rate of between 0.3 percent and 1.0 percent per annum. For crystalline modules, a generic degradation rate of 0.4 percent per annum is often considered applicable. Some module manufacturers have carried out specific independent tests showing that lower degradation rates can be safely assumed. For a-Si and CIGS modules, a generic degradation rate of 0.7–1.0 percent is often considered reasonable, however a degradation rate of more than 1.5 percent has sometimes been observed. For CdTe a value of 0.4–0.6 percent is often applicable.

In general, good quality PV modules can be expected to have a useful life of 25 to 30 years. The risk of increased rates of degradation becomes higher thereafter.

3.3.6 MODULE EFFICIENCY

Table 1 shows the commercial efficiency of some PV technology categories. As may be expected, while higher efficiency technologies are more costly to manufacture, less efficient modules require a larger area to produce the same nominal power. As a result, the cost advantages gained at the module level may be offset by the cost incurred in providing additional power system infrastructure (cables and mounting frames) and the cost of land for a larger module area. Therefore, using the lowest cost module does not necessarily lead to the lowest cost per watt peak (Wp)[14] for the complete plant. The relationship between the plant layout and module efficiency is discussed in Section 7.2.

At the time of writing, c-Si technology comprises almost 80 percent of globally installed solar capacity and is likely to remain dominant until at least 2017. As of 2014, CdTe accounted for the large majority of installed thin-film capacity. CIGS is thought to have promising cost reduction potential, however the market share is still low. A-Si seems to have poor prospects for penetrating the utility-scale ground-mount market, mainly due to the reduced cost of the more efficient crystalline technologies.

3.3.7 CERTIFICATION

The International Electrotechnical Commission (IEC) issues internationally accepted standards for PV modules. Technical Committee 82, "*Solar photovoltaic energy systems,*" is responsible for writing all IEC standards pertaining to photovoltaics. PV modules will typically

14 Watt Peak value specifies the output power achieved by a solar module under full solar radiation (under set Standard Test Conditions

Table 1: Characteristics of some PV Technology Classes

Technology	Crystalline Silicon	Heterojunction with intrinsic Thin-film Layer	Amorphous Silicon	Cadmium Telluride	Copper Indium Gallium Di-Selenide
Category	c-Si	HIT	a-Si	CdTe	CIGS or CIS
Current commercial efficiency (Approx.)	13%-21%	18%-20%	6%-9%	8%-16%	8%-14%
Temperature co-efficient for power[a] (Typical)	-0.45%/°C	0.29%/°C	-0.21%/°C	-0.25%/°C	-0.35%/°C

a The temperature co-efficient for power describes the dependence on power output with increasing temperature. Module power generally decreases as the module temperature increases..

be tested for durability and reliability according to these standards. Standards IEC 61215 (for c-Si modules) and IEC 61646 (for thin-film modules) include tests for thermal cycling, humidity and freezing, mechanical stress and twist, hail resistance and performance under standard test conditions (STC).[15] These are an accepted minimum quality mark and indicate that the modules can withstand extended use. However, they say very little about the performance of the module under field conditions.

An IEC standard for power and energy rating of PV modules at different irradiance[16] and temperature conditions became available in 2011. IEC 61853-1 "Photovoltaic Module Performance Testing and Energy Rating" provides the methodology for ascertaining detailed module performance. An accurate protocol for comparing the performance of different module models is thus now available.

IEC standards 61853-2-3-4 are currently under development. IEC 61853-2 will describe procedures for measuring the effect of angle of incidence on module performance. IEC 61853-3 will describe the methodology for calculating module energy ratings (watt-hours). IEC 61853-4 will define the standard time periods and weather conditions that can be used for calculating energy ratings.

An IEC standard relating to potential induced degradation (PID) is expected to be issued at the end of 2014.

Table 2 summarises major PV quality standards. Standards in development for evaluating PV module components (e.g., junction boxes) and materials (e.g., encapsulants and edge seals) will give further direction to the industry.

3.3.8 MODULE MANUFACTURERS

Manufacturers of PV modules are based predominantly in Asia (China, Japan, Taiwan, India and Korea). European and North American manufacturers have lost a significant portion of their market share in recent years. A 2014 survey by *Photon International* (Feb. 2014) indicated that there are 89 suppliers of PV modules and over 3,250 products currently available. The same survey indicated 129 suppliers in 2013. This is illustrative of the consolidation that has been occurring in the module manufacturing industry.

Financial institutions often keep lists of module manufacturers they consider bankable. However, these lists can quickly become dated as manufacturers introduce new products and quality procedures.

While there is no definitive and accepted list of modules that are considered "bankable," Bloomberg New Energy Finance[17] runs an annual survey of EPC contractors, debt lenders and independent technical consultants, and summarises which manufacturers are considered "bankable" by the respondents. Market research organisation NPD Solarbuzz[18] also issues annual updates of the top ten module manufacturers.

When assessing the quality of a module for any specific project, it is recommended that an independent technical advisor is approached to review the PV module technical specifications, quality assurance standards, track record and experience, as well as compliance with relevant international and national technical and safety standards. The expected degradation of the modules should be ascertained and the module warranties should be reviewed and compared to industry norms.

3.3.9 MODULE TECHNOLOGY DEVELOPMENTS

Solar PV module technology is developing rapidly. While a wide variety of different technical approaches are being explored, the effects of these approaches are focused on either improving module efficiency or reducing manufacturing costs.

15 Standard Test Conditions are defined as follows—irradiation: 1000 W/m², temperature: 25°C, AM: 1,5 (AM stands for Air Mass, the thickness of the atmosphere; at the equator, air mass = 1, in Europe approx. 1,5).

16 Irradiance is the power of the sunlight incident on a surface per unit area and is measured in power per square meter (W/m2).

17 Bloomberg New Energy Finance, "Sustainable Energy in America 2015," http://about.bnef.com

18 Solar Buzz, "Top Ten PV Module Suppliers in 2013," http://www.solarbuzz.com

Table 2: PV Module Standards

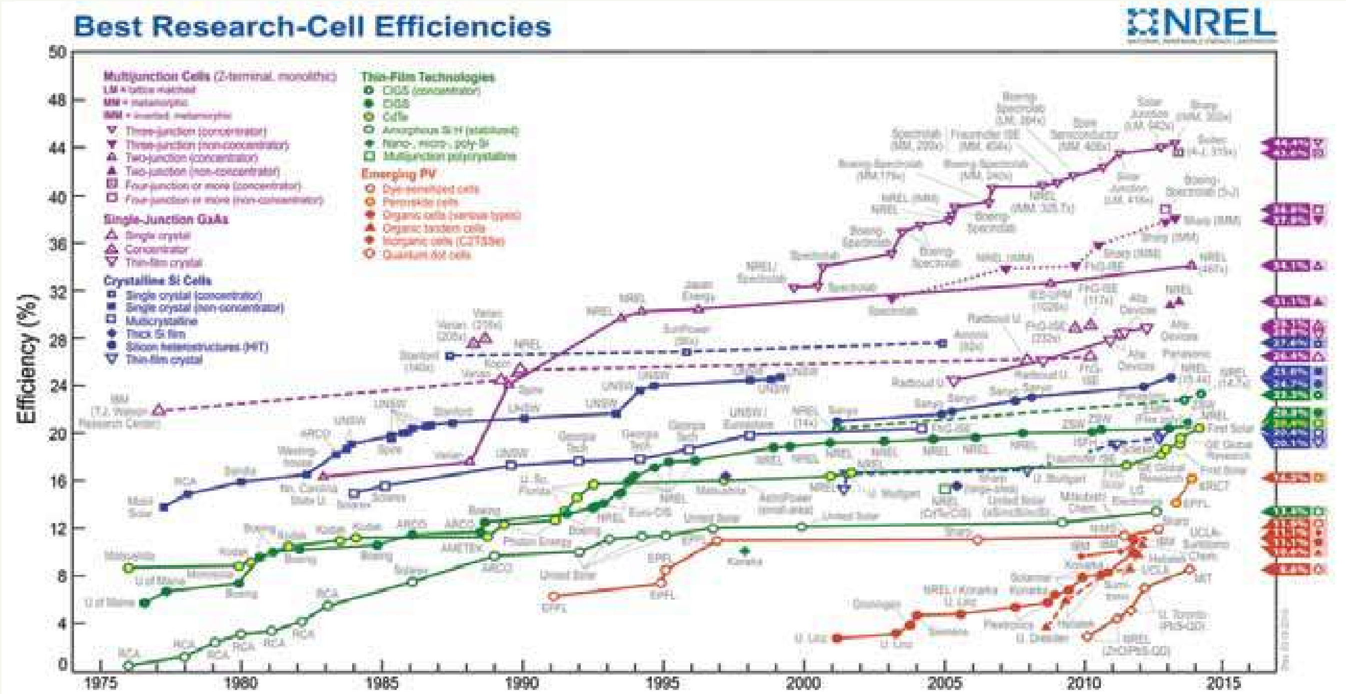
Test	Description	Comment
IEC 61215	Crystalline silicon (c-Si) terrestrial PV modules - Design qualification and type approval	Includes tests for thermal cycling, humidity and freezing, mechanical stress and twist and hail resistance. The standard certification uses a 2,400Pa pressure. Modules in heavy snow locations may be tested under more stringent 5,400Pa conditions.
IEC 61646	Thin-film terrestrial PV modules - Design qualification and type approval	Very similar to the IEC 61215 certification, but an additional test specifically considers the additional degradation of thin-film modules.
EN/IEC 61730	PV module safety qualification	Part 2 of the certification defines three different Application Classes: 1) Safety Class O - Restricted access applications. 2) Safety Class II - General applications. 3) Safety Class III - Low voltage (LV) applications.
IEC 60364-4-41	Protection against electric shock	Module safety assessed based on: 1) Durability. 2) High dielectric strength. 3) Mechanical stability. 4) Insulation thickness and distances.
IEC 61701	Resistance to salt mist and corrosion	Required for modules being installed near the coast or for maritime applications.
IEC 61853-1	Photovoltaic Module Performance Testing and Energy Rating	Describes the requirements for evaluating PV module performance in terms of power rating over a range of irradiances and temperatures.
IEC 62804 (pending issue)	System voltage durability test for c-Si modules	Describes the test procedure and conditions for conducting a PID test. The PV module will be deemed to be PID resistant if power loss is less than 5% following testing.
Conformité Européenne (EC)	The certified product conforms to the European Union (EU) health, safety and environmental requirements.	Mandatory in the European Economic Area.
UL 1703	Comply with the National Electric Code, Occupational Safety and Health Administration and the National Fire Prevention Association. The modules perform to at least 90% of the manufacturer's nominal power.	Underwriters Laboratories Inc. (UL) is an independent U.S. based product safety testing certification company which is a Nationally Recognised Testing Laboratory (NRTL). Certification by an NRTL is mandatory in the U.S.

Incremental improvements are being made to conventional c-Si cells. One of these improvements is the embedding of the front contacts in laser-cut microscopic grooves in order to reduce the surface area of the contacts and so increase the area of the cell that is exposed to solar radiation. Similarly, another approach involves running the front contacts along the back of the cell and then directly through the cell to the front surface at certain points.

Different types of solar cells inherently perform better at different parts of the solar spectrum. As such, one area of interest is the stacking of cells of different types. If the right combination of solar cells is stacked (and the modules are sufficiently transparent) then a stacked or "multi-junction" cell can be produced that performs better across a wider range of the solar spectrum. This approach is taken to the extreme in III-V cells (named after the respective groups of elements in the Periodic Table) in which the optimum materials are used for each part of the solar spectrum. III-V cells are very expensive, but have achieved efficiencies in excess of 40 percent. Less expensive approaches based on the same basic concept include hybrid cells (consisting of stacked c-Si and thin-film cells) and multi-junction a-Si cells.

Other emerging technologies, which are not yet market-ready, but could be of commercial interest in the future,

Figure 4: Development of Research Cell Efficiencies



Source: Data from United States National Renewable Energy Laboratory http://www.nrel.gov/ncpvl, accessed April 2014.

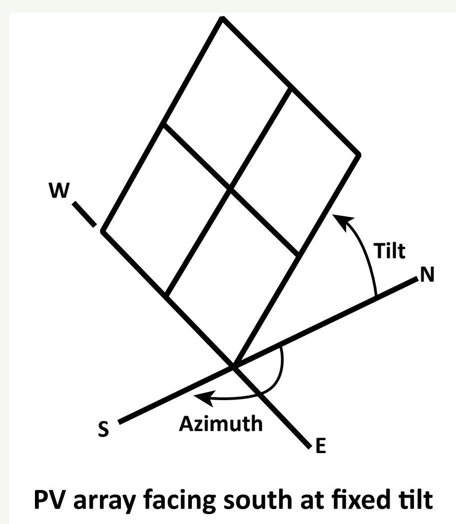
include spherical cells, sliver cells and dye-sensitized or organic cells. Dye-sensitized solar cells have gained attention recently because of their low production costs and ease of fabrication. However, their low efficiency and their instability over time is still a significant disadvantage.

Figure 4 illustrates the development of the efficiencies of research cells from 1975 to the present day. It should be noted that commercially available cells lag signifcantly behind research cells in terms of efficiency. See Box 1 for a discussion of module risk on project economics.

3.4 MOUNTING AND TRACKING SYSTEMS

PV modules must be mounted on a structure to keep them oriented in the correct direction and to provide them with structural support and protection. Mounting structures may be fixed or tracking. Fixed tilt arrays are typically tilted away from the horizontal plane in order to maximise the annual irradiation they receive. The optimum tilt angle is dependent on the latitude of the site location. The direction the system is facing is referred to as its orientation or azimuth, as shown in Figure 5. The ideal azimuth for a system in the northern hemisphere is

Figure 5: PV Array Tilt and Azimuth



Box 1: Module Risk

PV modules typically comprise approximately 50% of the system cost of a solar PV power plant. They are expected to have a functional life for the duration of the project, typically in excess of 25 years. Module failure or abnormal degradation can therefore significantly impact project economics. Careful selection of the PV modules is required. Although modules are an up-front capital cost, developers should think of long-term revenues.

The "bankability" of a module may be understood in different ways by developers, financiers and module manufacturers. The "bankability" usually includes an overall assessment of:

- Module technical characteristics.
- Quality of the manufacturing facility.
- Certification and testing procedures.
- Track record of the company and module.
- Warranty conditions.
- Company financial position.

To fully understand module risk, a full assessment of these criteria should be undertaken.

Current certification standards do not fully assess the technical adequacy of PV modules over the project life. A bath-tub failure curve is typical for PV modules, with increased risk of failure during the early years (infant-failures), low risk for the mid-term of the project (midlife-failures) and increased risk at the end of the project lifetime as modules deteriorate (wear-out-failures). From the lenders perspective, revenues from projects are most important during the first 15 years to coincide with typical debt terms. A lender is therefore well protected if the risk of infant-failure can be passed on to the EPC contractor or module manufacturer.

Most EPC contractors are willing to provide plant (PR) guarantees during the EPC warranty period (typically two years). Accompanied by a linear power warranty provided by the module manufacturer, a degree of infant failure module risk is covered.

The interests of the owner can be protected still further with additional testing of the modules during the EPC warranty period accompanied by appropriate termination scenarios whereby the owner has the right to reject the plant if it fails performance tests. Examples of module testing include external or on-site flash testing of a sample of modules upon delivery and prior to the end of the EPC warranty period, electro-luminescence testing and thermographic testing. These tests help to identify defects that may not affect the plant power within the EPC warranty period, but may do so in the future.

Many module manufacturers now typically offer a 25-year linear power output warranty. However, during historical periods of PV module over-supply, a large number of module manufacturers have entered insolvency, and many more have had poor financial positions. This means that not all module manufacturers can be assumed to be in a position to honour long-term warranty claims. Some module manufacturers, therefore, provide additional risk protection by offering third-party warranty insurance so that power output warranties can still be honoured in the case of manufacturer bankruptcy.

Developers, owners and financiers are advised to consider incorporating such additional risk reduction strategies into project contracts in order to match the project risk with their own risk profile requirements.

geographic south, and in the southern hemisphere it is geographic north.

3.4.1 FIXED MOUNTING SYSTEMS

Fixed mounting systems keep the rows of modules at a fixed tilt angle[19] while facing a fixed angle of orientation.[20]

Mounting structures will typically be fabricated from steel or aluminium, although there are also examples of systems based on wooden beams. A good quality mounting structure may be expected to:

- Have undergone extensive testing to ensure the designs meet or exceed the load conditions experienced at the site. This would include the design of the corrosion protection system to resist below-ground and atmospheric corrosion.
- Have been designed specifically for the site location with structural design calculations provided for

19 The tilt angle or "inclination angle" is the angle of the PV modules from the horizontal plane.

20 The orientation angle or "azimuth" is the angle of the PV modules relative to south. Definitions may vary but 0° represents true south, -90° represents east, 180° represents north, and 90° represents west.

verification of the site-specific design, and a structural warranty document provided.

- Allow the desired tilt angle to be achieved within a few degrees.
- Allow field adjustments that may reduce installation time and compensate for inaccuracies in placement of foundations.
- Minimise tools and expertise required for installation.
- Adhere to the conditions described in the module manufacturer's installation manual.
- Allow for thermal expansion, using expansion joints where necessary in long sections, so that modules do not become unduly stressed.

Purchasing quality structures from reputable manufacturers is generally a low-cost, low-risk option. Some manufacturers provide soil testing and qualification in order to certify designs for a specific project location.

Alternatively, custom-designed structures may be used to solve specific engineering challenges or to reduce costs. If this route is chosen, it is important to consider the additional liabilities and cost for validating structural integrity. This apart, systems should be designed to ease installation. In general, installation efficiencies can be achieved by using commercially available products.

The topographic conditions of the site and information gathered during the geotechnical survey will influence the choice of foundation type. This, in turn, will affect the choice of support system design as some designs are more suited to a particular foundation type.

Foundation options for ground-mounted PV systems include:

- **Concrete piers cast in-situ:** These are most suited to small systems and have high tolerance to uneven and sloping terrain. They do not have large economies of scale.
- **Pre-cast concrete ballasts:** This is a common choice for manufacturers with large economies of scale. It is suitable even at places where the ground is difficult to penetrate due to rocky outcrops or subsurface obstacles. This option has low tolerance to uneven or sloping terrain, but requires no specialist skills for installation. Consideration must be given to the risk of soil movement or erosion.
- **Driven piles:** If a geotechnical survey proves suitable, a structural steel profile driven into the ground can result in low-cost, large-scale installations that can be quickly implemented. Specialist skills and pile driving machinery are required, but may not always be available.
- **Earth screws:** Helical earth screws typically made of steel have good economics for large-scale installations and are tolerant to uneven or sloping terrain. These require specialist skills and machinery to install.
- **Bolted steel baseplates:** In situations where the solar plant is located over suitable existing concrete ground slabs, such as disused airfield runway strips, a steel baseplate solution bolted directly to the existing ground slabs may be appropriate.

Fixed tilt mounting systems are simpler, cheaper and have lower maintenance requirements than tracking systems. They are the preferred option for countries with a nascent solar market and limited indigenous manufacturing of tracking technology.

3.4.2 TRACKING SYSTEMS

In locations with a high proportion of direct irradiation, single- or dual-axis tracking systems can be used to increase the average total annual irradiation. Tracking systems follow the sun as it moves across the sky. These are generally the only moving parts employed in a solar PV power plant.

Single-axis trackers alter either the orientation or tilt-angle only, while dual-axis tracking systems alter both orientation and tilt angle. Dual-axis tracking systems are able to face the sun more precisely than single-axis systems.

Depending on the site and precise characteristics of the solar irradiation, trackers may increase the annual energy yield by up to 27 percent for single-axis and 45 percent for dual-axis trackers. Tracking also produces a smoother power output plateau, as shown in Figure 6. This helps meet peak demand in afternoons, which is common in hot climates due to the use of air conditioning units.

Almost all tracking system plants use crystalline silicon (c-Si) modules. This is because their higher efficiency reduces additional capital and operating costs required for the tracking system (per kWp installed). However, relatively inexpensive single-axis tracking systems are used with some thin-film modules.

There are many manufacturers and products of solar PV tracking systems. Most fall into one of six basic design classes (classic dual-axis, dual-axis mounted on a frame, dual-axis on a rotating assembly, single-axis tracking on a tilted axis, tracking on a horizontal axis and single-axis tracking on a vertical axis). In general, the simpler the construction, the lower the extra yield compared to a fixed system, and the lower the maintenance requirement.

Figure 6: Benefit of Dual Axis Tracking System

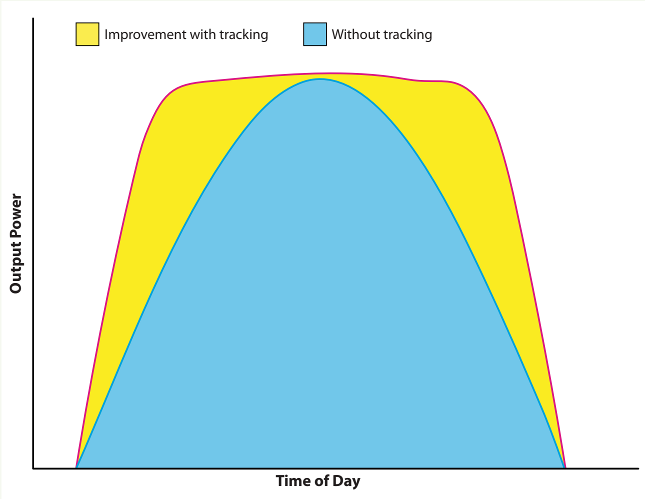


Image courtesy of Future Mechatronic Systems

Aspects to take into account when considering the use of tracking systems include:

- **Financial:**
  - Additional capital costs for the procurement and installation of the tracking systems.
  - Additional land area required to avoid shading compared to a free field fixed tilt system of the same nominal capacity.
  - Increased installation costs due to the need for large tracking systems that may require cranes to install. Higher maintenance cost for tracking systems due to the moving parts and actuation systems.
- **Operational:**
  - Tracking angles: all trackers have angular limits, which vary among different product types. Depending on the angular limits, performance may be reduced.
  - High wind capability and storm mode: dual-axis tracking systems in particular need to go into a storm mode when the wind speed is over 16-20m/s. This may reduce the energy yield and hence revenues at high wind speed sites.
  - Direct/diffuse irradiation ratio: tracking systems will give greater benefits in locations that have a higher direct irradiation component.

The higher financial and operational costs of tracker installations, combined with the reduced costs of the silicon-based modules has reduced the interest being shown in tracking projects in recent years.

3.4.3 CERTIFICATION

Support structures should adhere to country-specific standards and regulations, and manufacturers should conform to ISO 9001:2000. This specifies requirements for a quality management system where an organisation needs to:

- Demonstrate its ability to consistently provide products that meet customer and applicable regulatory requirements.
- Aim to enhance customer satisfaction through the effective application of the system. These include processes for continual improvement, as well as the assurance of conformity to customer and applicable regulatory requirements.

3.5 INVERTERS

Inverters are solid state electronic devices. They convert DC electricity generated by the PV modules into AC electricity, ideally conforming to the local grid requirements. Inverters can also perform a variety of functions to maximise the output of the plant. These range from optimising the voltage across the strings and monitoring string performance to logging data and providing protection and isolation in case of irregularities in the grid or with the PV modules.

3.5.1 INVERTER CONNECTION CONCEPTS

There are two broad classes of inverters: central inverters and string inverters. The central inverter configuration shown in Figure 7 remains the first choice for many medium- and large-scale solar PV plants. A large number of modules are connected in a series to form a high voltage (HV) string. Strings are then connected in parallel to the inverter.

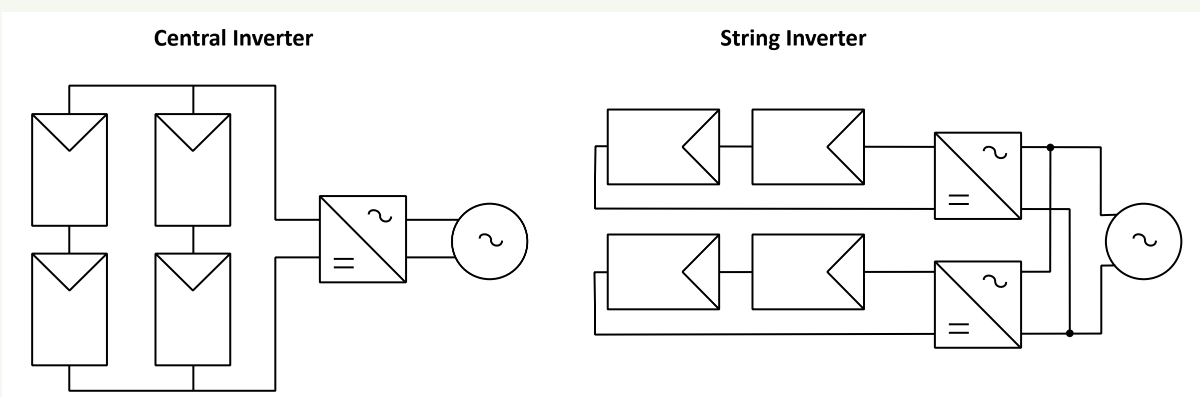
Central inverters offer high reliability and simplicity of installation. However, they have disadvantages: increased mismatch losses[21] and absence of maximum power point tracking (MPPT)[22] for each string. This may cause problems for arrays that have multiple tilt and orientation angles, or suffer from shading, or use different module types.

Central inverters are usually three-phase and can include grid frequency transformers. These transformers increase the weight and volume of the inverters, although they provide galvanic isolation from the grid. In other words, there is no electrical connection between the input and output voltages—a condition that is sometimes required by national electrical safety regulations.

21 Mismatch refers to losses due to PV modules with varying current/voltage profiles being used in the same array.

22 Maximum Power Point Tracking is the capability of the inverter to adjust its impedance so that the string is at an operating voltage that maximises the power output.

Figure 7: PV System Configurations



Central inverters are sometimes used in a "master-slave" configuration. This means that some inverters shut down when the irradiance is low, allowing the other inverters to run more closely to optimal loading. When the irradiance is high, the load is shared by all inverters. In effect, only the required number of inverters is in operation at any one time. As the operating time is distributed uniformly among the inverters, design life can be extended.

In contrast, the string inverter concept uses multiple inverters for multiple strings of modules. String inverters provide MPPT on a string level with all strings being independent of each other. This is useful in cases where modules cannot be installed with the same orientation or where modules of different specifications are being used or when there are shading issues.

String inverters, which are usually in single phase, also have other advantages. First of all, they can be serviced and replaced by non-specialist personnel. Secondly, it is practical to keep spare string inverters on site. This makes it easy to handle unforeseen circumstances, as in the case of an inverter failure. In comparison, the failure of a large central inverter, with a long lead time for repair, can lead to significant yield loss before it can be replaced.

Inverters may be transformerless or include a transformer to step up the voltage. Transformerless inverters generally have a higher efficiency, as they do not have transformer losses.

In the case of transformerless string inverters (see Figure 8), the PV generator voltage must either be significantly higher than the voltage on the AC side, or DC-DC step-up converters must be used. The absence of a transformer leads to higher efficiency, reduced weight, reduced size (50-75 percent lighter than transformer-based models[23]) and lower cost due to the smaller number of components. On the downside, additional protective equipment must be used, such as DC sensitive earth-leakage circuit breakers (CB), and live parts must be protected. IEC Protection Class II[24] must be implemented across the installation. Transformerless inverters also cause increased electromagnetic interference (EMI).[25]

Inverters with transformers provide galvanic isolation. Central inverters are generally equipped with transformers. Safe voltages (<120V) on the DC side are possible with this design. The presence of a transformer also leads to a reduction of leakage currents, which in turn reduces EMI. But this design has its disadvantages in the form of losses (load and no-load[26]) and increased weight and size of the inverter.

3.5.2 INVERTER ELECTRICAL ARRANGEMENT

Inverters operate by use of power switching devices such as thyristor or Insulated Gate Bipolar Transistor (IGBT)[27] to chop the DC current into a form of pulses that provide a reproduction of an AC sinusoidal waveform. The nature of the generated AC wave means that it may spread interference across the network. Therefore, filters must be applied to limit Electromagnetic Compatibility (EMC) interference emitted into the grid. Circuit protection functions should be included within a good inverter design.

Inverters should be provided with controllers to measure the grid output and control the switching process. In addition, the controller can provide the MPPT functionality.

23 Navigant Consulting Inc., "A Review of PV Inverter Technology Cost and Performance Projections," National Renewable Energy Laboratory, U.S. Department of Energy, Jan 2006, http://www.nrel.gov/docs/fy06osti/38771.pdf (accessed July 2014).

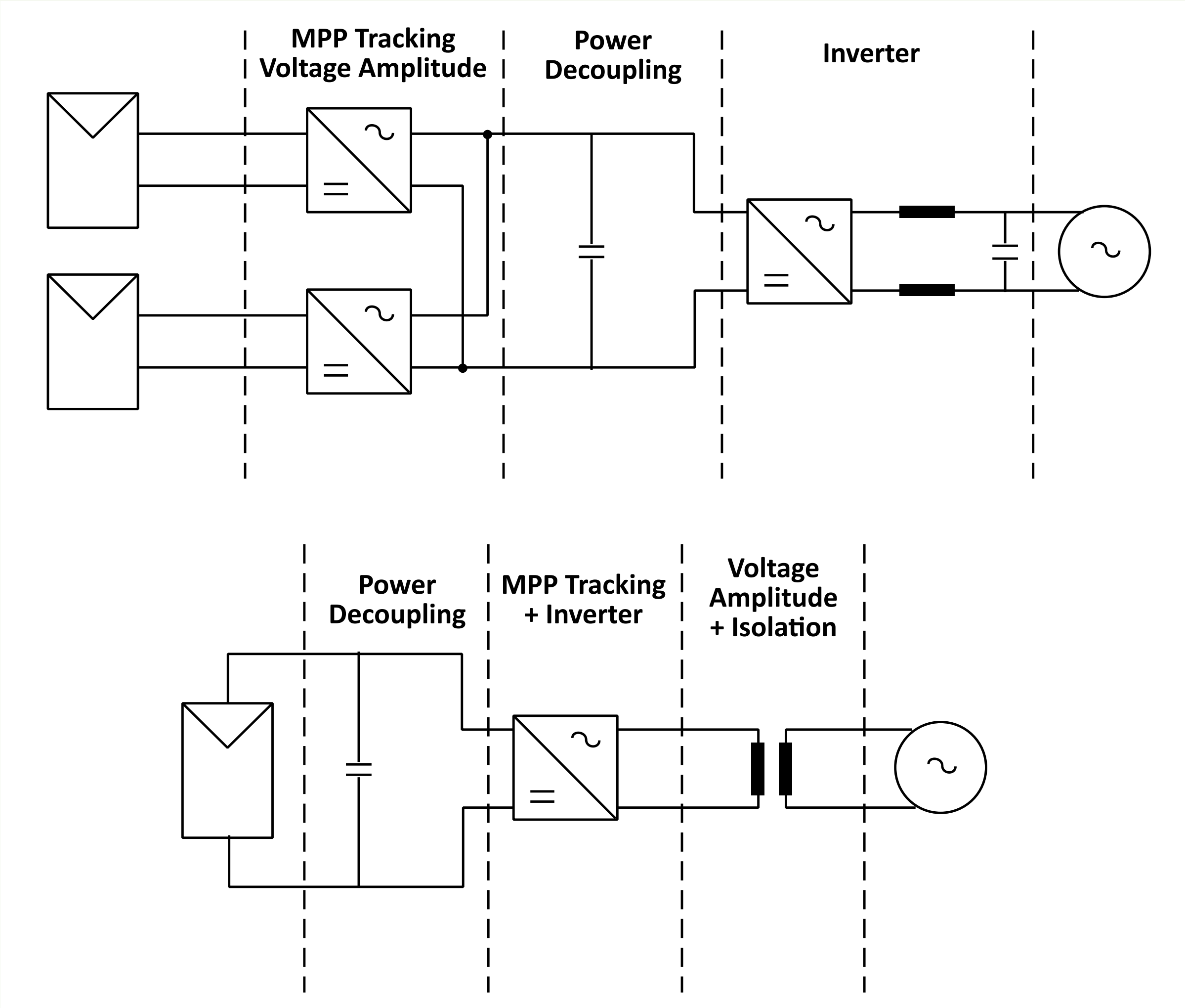
24 IEC Protection Class II refers to a device that is double insulated and therefore does not require earthing.

25 Electromagnetic disturbance affects an electrical circuit due to either electromagnetic induction or electromagnetic radiation emitted from an external source. The disturbance may interrupt, obstruct, or otherwise degrade or limit the effective performance of the circuit.

26 The load-dependent copper losses associated with the transformer coils are called load losses. The load-independent iron losses produced by the transformer core magnetising current are called no-load losses.

27 Insulated Gate Bipolar Transistor is a three-terminal power semiconductor device primarily used as an electronic switch and in newer devices is noted for combining high efficiency and fast switching.

Figure 8: Transformer and Transformerless Inverter Schematic



3.5.3 EFFICIENCY

A number of different types of efficiencies have been defined for inverters. These describe and quantify the efficiency of different aspects of an inverter's operation. The search for an objective way of quantifying inverter performance is still ongoing. New ways of measuring efficiency are frequently suggested in the literature. The most commonly used methods are discussed below.

The conversion efficiency is a measure of the losses experienced during the conversion from DC to AC. These losses are due to multiple factors: the presence of a transformer and the associated magnetic and copper losses, inverter self-consumption, and losses in the power electronics. Conversion efficiency is defined as the ratio of the fundamental component of the AC power output from the inverter, divided by the DC power input:

$$n_{Con} = \frac{P_{AC}}{P_{DC}} = \frac{\textit{Fundamental component of AC power output}}{\textit{DC power input}}$$

The conversion efficiency is not constant, but depends on the DC power input, the operating voltage, and the weather conditions, including ambient temperature and irradiance. The variance in irradiance during a day causes fluctuations in the power output and maximum power point (MPP) of a PV array. As a result, the inverter is continuously subjected to different loads, leading to varying efficiency. The voltage at which inverters reach their maximum efficiency is an important design variable, as it allows system planners to optimise system wiring.

Due to the dynamic nature of inverter efficiency, diagrams are also more suited to depiction than uniform numeric values. An example depicting the dependency of the inverter efficiency on the inverter load is given in Figure 9.

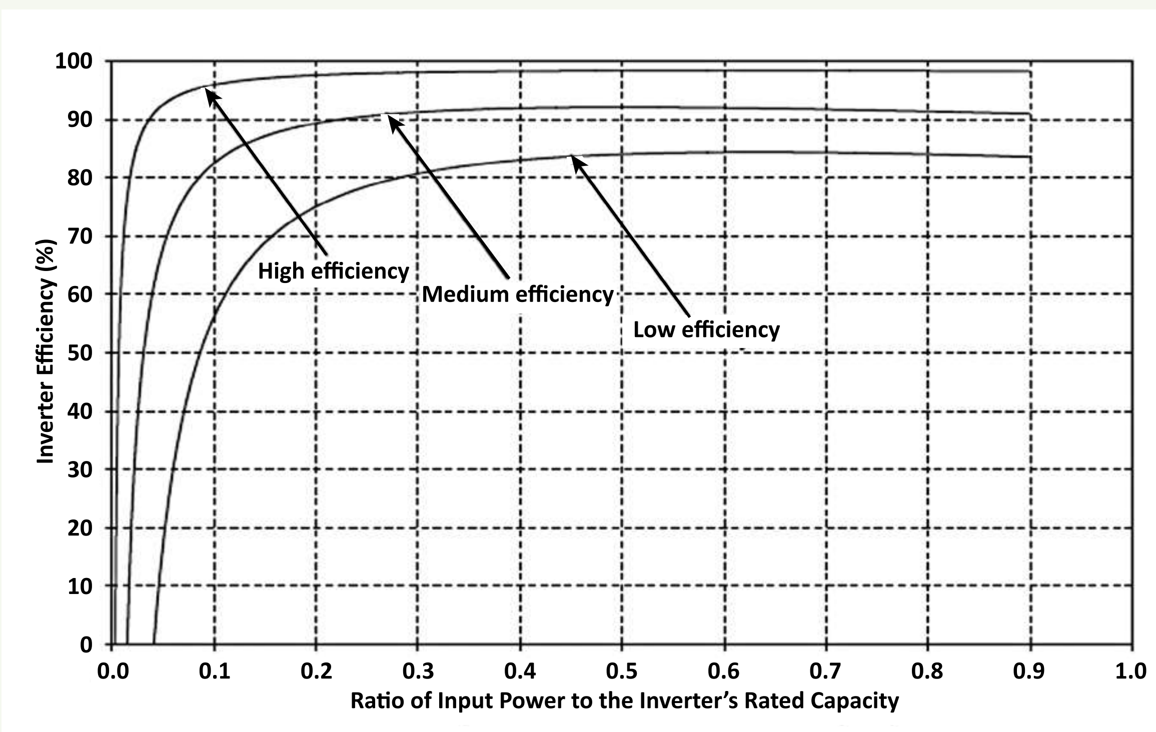
The European Efficiency is an accepted method of measuring inverter efficiency. It is a calculated efficiency averaged over a power distribution corresponding to the operating climatic conditions of a central European location. As a useful means of comparing inverter efficiencies,[28] the efficiency standard also attempts to capture the fact that in central Europe, most energy is generated near the middle of a PV module's power range.

Another method of comparing efficiencies is using the Californian Efficiency. While the standard is based on the same reasoning as the European Efficiency, it is calibrated for locations with higher average irradiance.

Inverters can have a typical European Efficiency of 95 percent and peak efficiencies of up to 98 percent. Most inverters employ MPPT algorithms to adjust the load

28 If $h_{50\%}$ denotes the efficiency at a load equal to 50% of the nominal power, the European Efficiency is defined as:
$n_{Euro} = 0.03 \times n_{5\%} + 0.06 \times n_{10\%} + 0.13 \times n_{20\%} + 0.1 \times n_{30\%} + 0.48 \times n_{50\%} + 0.2 n_{100\%}$

Figure 9: Efficiency Curves of Low, Medium and High Efficiency Inverters as Functions of the Input Power to Inverter Rated Capacity Ratios



Source: J.D. Mondol, Y. G. Yohanis, B. Norton, "Optimal sizing of array and inverter for grid-connected photovoltaic systems," *Solar Energy*, Vol.80, Issue 12, 2006, p.1517-1539, (accessed July 2014).

impedance and maximise the power from the PV array. The highest efficiencies are reached by transformerless inverters.

3.5.4 CERTIFICATION

In order to ensure a high level of quality and performance, and to minimise risk, inverters must be compliant with a number of standards. The requirements, in terms of compliance with standards, depend on the location of the project and the type of inverter.

Important standards bodies for inverters are Deutsches Institut für Normung (DIN), Verband der Elektrotechnik, Elektronik und Informationstechnik (VDE), IEC, and European Norm (EN). Inverters must be Conformance European (CE)-compliant in order to be installed in Europe. Table 3 is a non-exhaustive list of standards to which inverters should conform according to European practice.

3.5.5 INVERTER MANUFACTURERS

Manufacturers of solar inverters are predominantly based in Europe and North America, however big players from China and Japan have entered the inverter market. Some of the leading suppliers, such as SMA, ABB (which acquired Power One) and Kaco, have lost portions of their market share mainly due to reduced sales volumes in the Asia market.

A 2014 survey by *Photon International* (Apr. 2014) indicated that there were over 60 inverter suppliers and over 1,757 products, 1,445 of which are in the 10kW to 500kW category.

Market research organisations such as IHS, Solarbuzz and Bloomberg New Energy Finance[29] give annual lists of the top ten inverter suppliers.

It is recommended that an independent technical advisor should review the technology and type of inverter with regards to technical specification, quality recognition, track record, and experience of the supplier, as well as compliance with relevant international and national technical and safety standards. Warranties should also be reviewed and assessed for compliance with industry norms.

3.6 QUANTIFYING PLANT PERFORMANCE

The performance of a PV power plant is expected to fall during its lifetime, especially in the second and third decade of its life as modules continue to degrade and plant components age. In addition to the quality of the

29 IHS Technology, https://technology.ihs.com; Solar Buzz, http://www.solarbuzz.com; Bloomberg New Energy Finance, http://www.nef.com.

Table 3: Indicative List of Inverter-related Standards

EN 61000-6-1: 2007	Electromagnetic compatibility (EMC). Generic standards. Immunity for residential, commercial and light-industrial environments.
EN 61000-6-2: 2005	EMC. Generic standards. Immunity for industrial environments.
EN 61000-6-3: 2007	EMC. Generic standards. Emission standard for residential, commercial and light-industrial environments.
EN 61000-6-4: 2007	EMC. Generic standards. Emission standard for industrial environments.
EN 55022: 2006	Information technology equipment. Radio disturbance characteristics. Limits and methods of measurement.
EN 50178: 1997	Electronic equipment for use in power installations.
IEC 61683: 1999	Photovoltaic systems—Power conditioners—Procedure for measuring efficiency.
IEC 61721: 2004	Characteristics of the utility interface.
IEC 62109-1&2: 2011-2012	Safety of power converters for use in photovoltaic power systems.
IEC 62116 : 2008	Islanding prevention measures for utility-interconnected photovoltaic inverters.

initial installation, a high degree of responsibility for the performance of a PV plant lies with the O&M contractor. This section discusses how the operational performance of a PV plant may be quantified.

3.6.1 PERFORMANCE RATIO

The Performance Ratio (PR) is a parameter commonly used to quantify PV plant performance. Usually expressed as a percentage, the PR provides a benchmark to compare plants over a given time independent of plant capacity or solar resource. A plant with a high PR is more efficient at converting solar irradiation into useful energy.

The PR is defined as the ratio between the exported AC yield and the theoretical yield that would be generated by the plant if the modules converted the irradiation received into useful energy according to their rated capacity. The full definition of PR is given in IEC 61724 "Photovoltaic system performance monitoring—Guidelines for measurement data exchange and analysis." It may be expressed as:

$$PR = \frac{\text{AC Yield (kWh)} \times 1\left(\text{kW}/\text{m}^2\right)}{\text{DC Installed Capacity (kWp)} \times \text{Plane of Array Irradiation(kWh/m}^2\text{)}} \times 100\%$$

The PR quantifies the overall effect of system losses on the rated capacity, including losses caused by modules, temperature, low light efficiency reduction, inverters, cabling, shading and soiling.

The PR of a plant may be predicted using simulations, or alternatively may be calculated for an operational plant by measuring irradiation and the AC yield.

As PV plant losses vary according to environmental conditions through the year, the plant PR also varies. For example, the more significant negative temperature coefficient of power for crystalline modules may lead to increased losses at high ambient temperatures. A PR varying from approximately 77 percent in summer up to 86 percent in winter (with an annual average PR of 82 percent) would not be unusual for a well-designed solar PV power plant that is not operating in high ambient temperature conditions.

Some plants using a-Si modules show the opposite effect: in summer months, the PR increases, dropping again in the colder winter months. This is due to the fact that Staebler-Wronski degradation is partially reversible at high temperatures. It is common to observe seasonal oscillations in the PR of a-Si plants due to this thermal annealing process.

Averaged across the year, a PR in the upper seventies or lower eighties is typical for a well-designed plant. This may be expected to reduce as the plant ages, depending on the module degradation rates.

3.6.2 SPECIFIC YIELD

The "specific yield" (kWh/kWp) is the total annual energy generated per kWp installed. It is often used to help determine the financial value of a plant and compare operating results from different technologies and systems. The specific yield of a plant depends on:

- The total annual irradiation falling on the collector plane. This can be increased by optimally tilting the modules or employing tracking technology.
- The performance of the module, including sensitivity to high temperatures and low light levels.
- System losses including inverter downtime.

Some module manufacturers claim much higher kWh/kWp energy yields for their products than those of their competitors. However the divergence between actual peak power and nominal power and correction for other technical distortions should also be taken into account.

3.6.3 CAPACITY FACTOR

The capacity factor of a PV power plant (usually expressed as a percentage) is the ratio of the actual output over a period of a year and its output if it had operated at nominal power the entire year, as described by the formula:

$$CF = \frac{\text{Energy generated per annum (kWh)}}{\text{8760 (hours/annum)} \times \text{Installed Capacity (kWp)}}$$

The use of the term “capacity factor” is less common in the solar industry than “specific yield.” Capacity factor and specific yield are simply related by the factor 8760. The capacity factor of a fixed tilt PV plant can vary from 12 percent to 24 percent depending on the solar resource and the performance ratio of the plant. In Germany, a capacity factor of 12 percent may be typical. Higher capacity factors in the region of 16 percent may be experienced in southern Spain, which has a higher solar resource. For Thailand and Chile, capacity factors may be in the region of 18 percent and 22 percent, respectively. A 5MWp plant in Chile will generate the equivalent energy of a continuously operating 1.1MW plant.

4 The Solar Resource

4.1 SOLAR RESOURCE OVERVIEW

The solar resource expected over the lifetime of a solar PV plant is most accurately estimated by analysing historical solar resource data for the site. Obtaining a first approximation of the power output of a PV plant depends on the plane of array irradiance. The accuracy of any solar energy yield prediction is therefore heavily dependent on the accuracy of the historical solar resource dataset. Obtaining reliable historical resource data is a crucial step in the development process and essential for project financing.

There are two main sources of solar resource data: satellite-derived data and land-based measurement. Since both sources have particular merits, the choice will depend on the specific site. Land-based site measurement can be used to calibrate resource data from satellites in order to improve accuracy and certainty.

As solar resource is inherently intermittent, an understanding of inter-annual variability is important. Often ten years or more of data are desirable to calculate the variation with a reasonable degree of confidence, although many projects have been completed with less detailed levels of historical data (see the checklist at the end of Chapter 4).

The following sections describe how the solar resource may be quantified and summarises the steps in the solar resource assessment process.

4.2 QUANTIFYING SOLAR RESOURCE

The solar resource of a location is usually defined by the direct normal irradiation,[30] the diffuse horizontal irradiation and the

30 DNI is the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line from the direction of the sun at its current position in the sky.

As solar resource is inherently intermittent, an understanding of inter-annual variability is important. At least ten years of data are usually required to calculate the variation with a reasonable degree of confidence.

global horizontal irradiation.[31] These parameters are described below:

- **Direct Normal Irradiation (DNI):** The beam energy component received on a unit area of surface *directly facing the sun at all times*. The DNI is of particular interest for solar installations that track the sun and for concentrating solar technologies (concentrating technologies can only make use of the direct beam component of irradiation).
- **Diffuse Horizontal Irradiation (DHI):** The energy received on a unit area of horizontal surface from radiation that is scattered off the atmosphere or surrounding area is known as DHI.
- **Global Horizontal Irradiation (GHI):** The total solar energy received on a unit area of a horizontal surface is the GHI. It includes energy from the sun that is received in a direct beam (the horizontal component of the DNI) and the DHI. The yearly sum of the GHI is of particular relevance for PV power plants, which are able to make use of both the diffuse and beam components of solar irradiation.

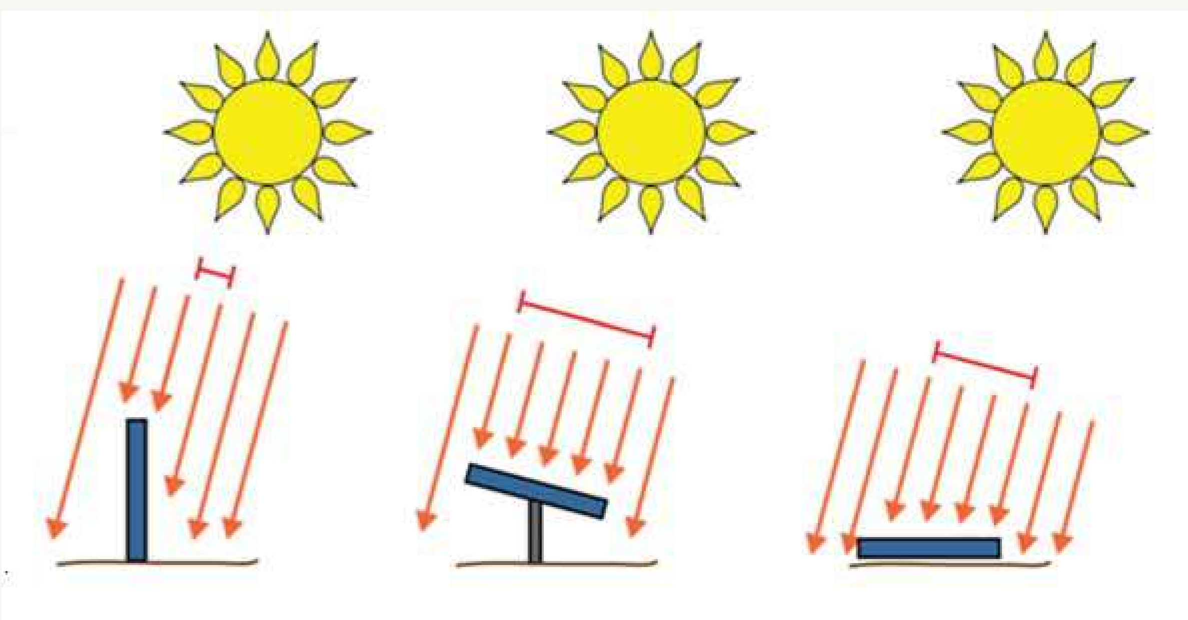
In the northern hemisphere, a surface tilted at an angle towards the south receives a higher total annual global irradiation compared to a horizontal surface. This is because a surface tilted towards the south more directly faces the sun for a longer period of time. In the southern hemisphere a surface tilted towards the north receives a higher total annual global irradiation. Figure 10 illustrates why the tilt angle is important for maximising the energy incident on the collector plane.

The amount of irradiation received can be quantified for any tilt angle by the global tilted irradiation (GTI).[32] The optimal tilt angle varies primarily with latitude and may also depend on local weather patterns and plant layout configurations. Simulation software may be used to calculate the irradiation on a tilted plane. Part of this calculation will take into account the irradiance reflected from the ground towards the modules. This is dependent

31 GHI is the total amount of shortwave radiation received from above by a surface horizontal to the ground.

32 GTI is the total irradiation that falls on a tilted surface.

Figure 10: Effect of Tilt on Solar Energy Capture



on the ground reflectance, or albedo. These terms are defined below:

- **Global Tilted Irradiation (GTI):** The total solar energy received on a unit area of a tilted surface. It includes direct beam and diffuse components. A high value of long-term annual GTI average is the most important resource parameter for project developers.
- **Albedo:** The ground reflectance or albedo is highly site-dependent. A higher albedo translates into greater reflection. Fresh grass has an albedo factor of 0.26, reducing down to a minimum of approximately 0.15 when dry. Asphalt has a value between 0.09 and 0.15, or 0.18 if wet. Fresh snow has an albedo of approximately 0.8, meaning that 80 percent of the irradiation is reflected.

4.3 SOLAR RESOURCE ASSESSMENT

Long-term annual average values of GHI and DNI can be obtained for a site by interpolating measurements taken from nearby ground-based measurement stations or by solar models that utilise satellite, atmospheric and meteorological data. Ideally, historical time series of hourly GHI and DHI values are used for PV project development. Data representing a period of at least ten continuous years are desirable to account for climate variability. However, such extensive historical data is not always available, particularly from ground-based measurement stations. Satellite data sources are therefore often acceptable.

Data in hourly or sub-hourly time steps are preferred. Statistical techniques can be used to convert average monthly values into simulated hourly values if these are not immediately available.

Ground-based solar resource measurement stations are very unevenly distributed throughout the world. Countries have different standards of calibration, maintenance procedures and historical measurement periods. In addition, as the distance from a solar measuring station increases, the uncertainty of interpolated irradiation values increases. On the other hand, the development of solar models using satellite data has advanced as the accuracy of such data increases. The precise distance at which satellite data become preferable over data interpolated from ground sensors depends on the individual case. The relative merits of ground-based measurements and satellite-derived data are discussed below.

4.3.1 GROUND BASED MEASUREMENTS

The traditional approach to solar resource measurement is to use ground-based solar sensors. A variety of sensors for measurements of global and diffuse radiation is available from a number of manufacturers with different accuracy and cost implications. The two main technology classes are:

- **Thermal Pyranometers:** These typically consist of a black metal plate absorber surface below two hemispherical glass domes in a white metal housing. Solar irradiance warms up the black metal plate in proportion to its intensity. The degree of warming, compared to the metal housing, can be measured with a thermocouple. High precision measurements of global irradiance ion can be achieved with regular cleaning and recalibration. Also, diffuse irradiance can be measured if a sun-tracking shading disc is used to block out beam irradiance travelling directly from the sun. An example of a pyranometer is shown in Figure 11. The theoretical uncertainty of daily aggregated values measured by pyranometers (depending on the

Figure 11: Pyranometer Measuring GHI Image

Image courtesy of NREL

accuracy class) is in the range of ± 2 percent to ± 8 percent. Thermal pyranometers have a relatively slow response time and may not be able to capture rapidly varying irradiance levels due to clouds.

- **Silicon Sensors:** Typically, these are cheaper than pyranometers and consist of a PV cell, often using crystalline silicon (c-Si). The current delivered is proportional to the irradiance. Temperature compensation can be used to increase accuracy, but its scope is limited by the spectral sensitivity of the cell. Some wavelengths (i.e., long wavelength infrared) may not be accurately measured, resulting in a higher measurement uncertainty of daily aggregated values of approximately ± 5 percent compared to thermal pyranometers.

Each sensor type is subject to ageing, and accuracy reduces with time. Therefore, it is important to re-calibrate at least every two years. It can be expected that annual GHI solar irradiation from well-maintained ground-based sensors can be measured with a relative accuracy of ± 3 percent to ± 5 percent, depending on the category of the sensor, position of the site, calibration and maintenance. Maintenance is very important since soiled or ill-calibrated sensors can easily yield unreliable data.

Section 7.7.2 gives quality benchmarks for the irradiation monitoring of mega-watt scale PV power plants to enable developers to use equipment that will be acceptable for investors and financial institutions.

4.3.2 SATELLITE-DERIVED DATA

Satellite-derived data offer a wide geographical coverage and can be obtained retrospectively for historical periods during which no ground-based measurements were taken. This is especially useful for assessing hourly or sub-hourly time series or aggregated long-term averages. A combination of analytical, numerical and empirical methods can offer 15-minute or 30-minute data with a nominal spatial resolution down to 90m x 90m, depending on the region and satellite.

One advantage of a satellite resource assessment is that data are not susceptible to maintenance and calibration discontinuities. Radiometric and geometric variations in the satellite sensors can be controlled and corrected. The same sensor is used to assess locations over a wide area for many years. This can be particularly useful in comparing and ranking sites because bias errors are consistent. Monthly GHI, DHI (or DNI) solar radiation maps at a spatial resolution of approximately 4km are today a standard for the generation of long-term historical time series and spatially continuous solar atlases, such as those shown in Figure 12 and Figure 13.

Efforts are underway to improve the accuracy of satellite-derived data. One way is to use more advanced techniques for better mapping clouds, especially in high mountains, coastal zones, and high reflectivity surfaces, such as salt plains and snow-covered regions. Substantial improvements can also be seen in improved atmospheric models and input data, such as aerosols and water vapour. Higher spatial and temporal resolution of the input atmospheric databases helps to improve mapping of locally generated dust, smoke from biomass burning and anthropogenic pollution. Effects of terrain features (elevation and shading effects) are also better considered by new approaches.

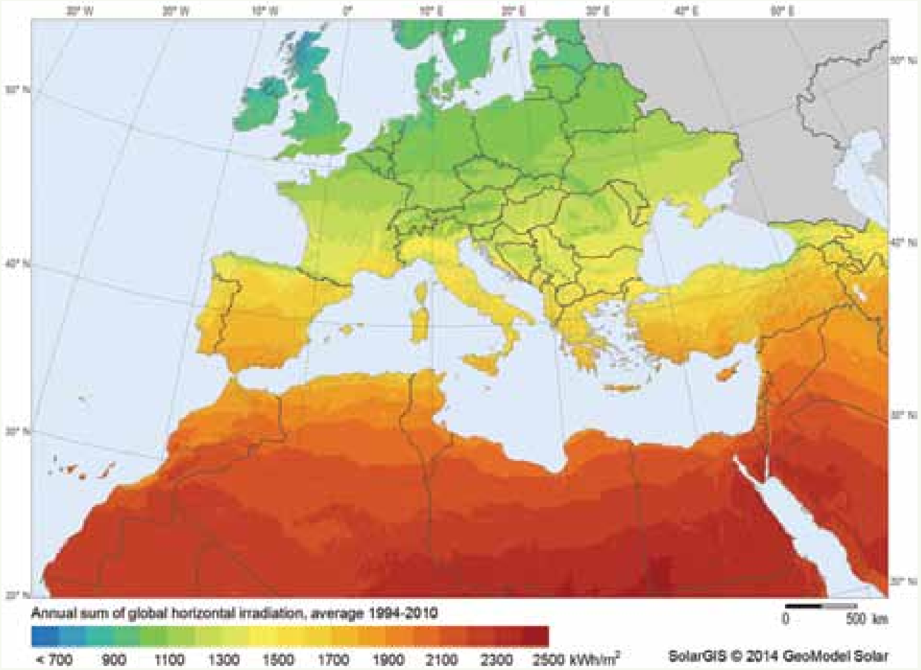
4.3.3 SITE ADAPTION OF SATELLITE DERIVED RESOURCE DATA

For locations that have a low density of meteorological stations, and rely on satellite data, site-solar resource monitoring may be considered during the feasibility stage of the project. Short-term site resource measurements may be used to adapt (calibrate) long-term satellite-derived time series. This site adaption of the satellite data reduces bias (systematic deviation) and random deviation of hourly or sub-hourly values. In general, measurement data for a minimum of nine months can be used to reduce existing bias, and improve the estimation of the long-term mean. The best results however are obtained by monitoring for a minimum of 12 months to better capture seasonal variations.

4.3.4 VARIABILITY IN SOLAR IRRADIATION

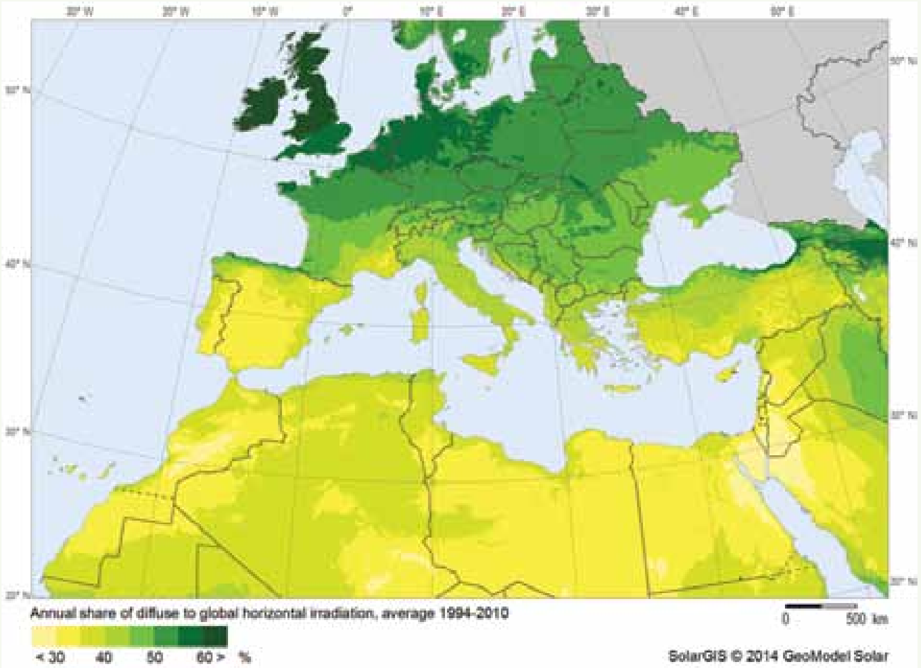
Solar resource is inherently intermittent: in any given year, the total annual global irradiation on a horizontal plane varies from the long-term average due to weather

Figure 12: Annual Sum of GHI, average 1994-2010



Source: Image courtesy of Geomodel Solar http://geomodelsolar.eu/

Figure 13: Annual Share of DHI to GHI, average 1994-2010



Source: Image courtesy of Geomodel Solar http://geomodelsolar.eu/

fluctuations. Even though the owner of a PV power plant may not know what energy yield to expect in any given year, one can have a good idea of the expected yield averaged over the long term.

To help lenders understand the risks and perform a sensitivity analysis, it is important to quantify the limits of such year-by-year variability, or "inter-annual variation." Usually, 10 years of ground measurements or satellite data are desirable, although an assessment of the inter-annual variation can sometimes be obtained with reasonable confidence using a data set covering a shorter historical period. Research papers[33] show that for southern Europe (including Spain), the coefficient of variation (standard deviation divided by the mean[34]) is below 4 percent. In Central Europe it can be above 12 percent.

Table 4: Inter-annual Variation in Global Horizontal Irradiation as Calculated from SolarGIS Database

Location	Number of Years of Data	Coefficient of Variation
New Delhi	15	3.4%
Mumbai	15	2.5%
Chennai	15	2.2%

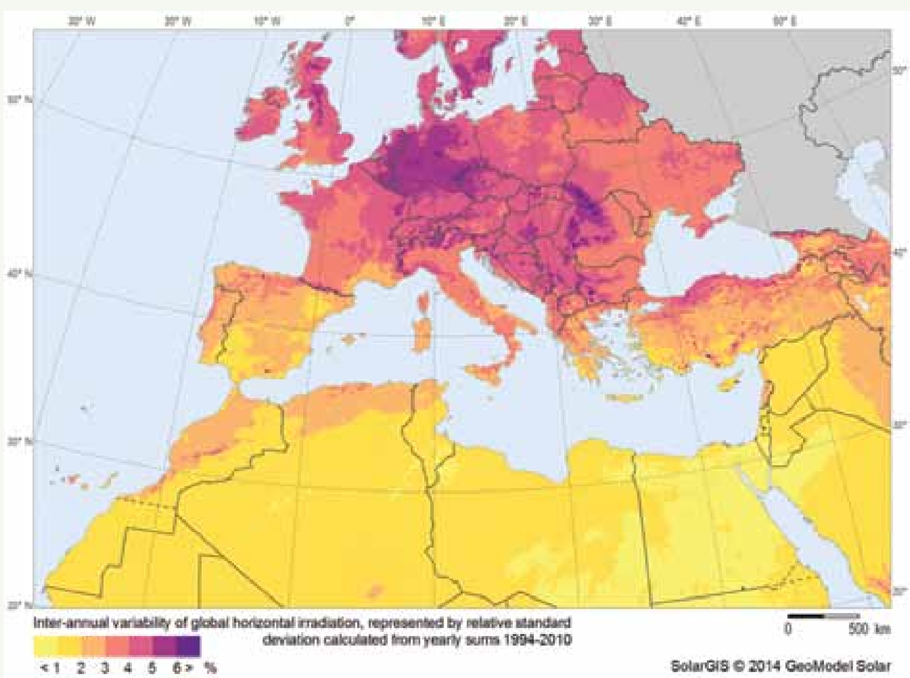
Table 4 shows the coefficient of variation for three locations in India as derived from data provided by SolarGIS.

Figure 14 shows how the inter-annual variability varies depending on the site location for Europe, North Africa and the Middle East.

33 M. Suri, T. Huld, E.D. Dunlop, M. Albuisson, M. Lefevre & L. Wald, "Uncertainties in photovoltaic electricity yield prediction from fluctuation of solar radiation," Proceedings of the 22nd European Photovoltaic Solar Energy Conference, Milan, Italy, 3-7 September 2007 (accessed July 2014).

34 The coefficient of variation is a dimensionless, normalised measure of the dispersion of a probability distribution. It enables the comparison of different data streams with varying mean values.

Figure 14: Inter-annual Variability in GHI (relative standard deviation) 1994-2010



Source: Image courtesy of Geomodel Solar http://geomodelsolar.eu/

4.3.5 SOURCES OF SOLAR RESOURCE DATA

There are a variety of different solar resource datasets that are available with varying accuracy, resolution, historical time period and geographical coverage. The datasets either make use of ground-based measurements at well-controlled meteorological stations or use processed satellite data. Table 5 summarizes some of the more globally applicable datasets. Further information on which dataset is available for a specific country or region may be obtained online.[35]

35 United Nations Environment Programme, "Solar Dataset," http://www.unep.org/climatechange/mitigation/RenewableEnergy/SolarDataset/tabid/52005/Default.aspx (accessed July 2014).

In financing solar power projects, financial institutions are becoming more sophisticated in their analysis of the solar resource. Their requirements are moving towards the analysis of multiple datasets, cross referencing with values obtained from high resolution satellite data and a robust uncertainty analysis.

In a competitive market, financial institutions will tend to give better terms of financing to those projects that have the lowest risk to the financial return. An important component of the risk assessment is the confidence that can be placed in the solar resource at the site location. Developers can reduce the perceived long-term solar resource risk by:

Table 5: Solar Resource Datasets

Data Source	Type	Description
SolarGIS [1]	Commercial satellite derived	Solar resource data are available for latitudes between 60° North and 50° South at a spatial resolution of 250m. The solar resource parameters are calculated from satellite data, atmospheric data and digital terrain models. Solar resource data are available from years 1994, 1999, or 2006 (depending on the region) up to the present time and have time resolution of up to 15 minutes. The database has been extensively validated at more than 180 locations globally.
3Tier [2]	Commercial satellite derived	The dataset has global coverage between 48° S to 60° N with spatial maps and hourly time series of irradiance at a spatial resolution of approximately 3km (2 arc minutes). Depending on the location, data is available beginning in 1997, 1998, or 1999 up to the present day. The satellite algorithm error is based on validation against 120 reference stations across the globe with a standard error for global horizontal irradiance of 5 percent.
HelioClim v4.0 [3]	Commercial satellite derived	Has a spatial resolution of approximately 4km. The region covered extends from -66° to 66° both in latitude and longitude (mainly Europe, Africa and the Middle East). The data are available from February 2004 and are updated daily.
Meteonorm v7.0 [4]	Commercial	Interpolated global solar resource database. It enables the production of typical meteorological years for any place on earth. It includes a database for radiation for the period 1991-2010. Where a site is over 10km from the nearest measurement station, a combination of ground and satellite measurements are used. Additionally, uncertainty and P10/90 estimates are given.
NASA Surface Meteorology and Solar Energy data set [5]	Free	Satellite-derived monthly data for a grid of 1°x1° (equal to 100km x 100km at the equator) covering the globe for a 22 year period (1983-2005). The data may be considered reasonable for preliminary feasibility studies of solar energy projects in some regions however these data have a low spatial resolution.
PVGIS – Classic [6]	Free	The original PVGIS database for Europe is based on an interpolation of ground station measurements for the period 1981-1990 (10 years).
PVGIS – ClimSAF [7]	Free	Data for a total of 14 years that is satellite-derived. From the first generation of Meteosat satellites, there are data from 1998 to 2005, and from the second generation, there are data from June 2006 to December 2011. The spatial resolution is 1.5 arc-minutes or approximately 2.5km directly below the satellite at 0° N.
PVGIS – HelioClim [8]	Free	Data are monthly values for any location in Africa and parts of the Middle East. Data are derived from satellite-based calculations. The spatial resolution of the original calculation is 15 arc-minutes, or about 28km directly below the satellite (at the equator, 0° W). The data cover the period 1985-2004.

- Comparing different data sources, assessing their uncertainty and judiciously selecting the most appropriate data for the site location.
- Assessing the inter-annual variation in the solar resource in order to quantify the uncertainty in the revenue in any given year.

This analysis requires a considerable degree of experience and technical understanding of the statistical properties of each dataset. Technical advisors are available to perform this task.

Box 2: Case Study of Solar Resource for a Location in India

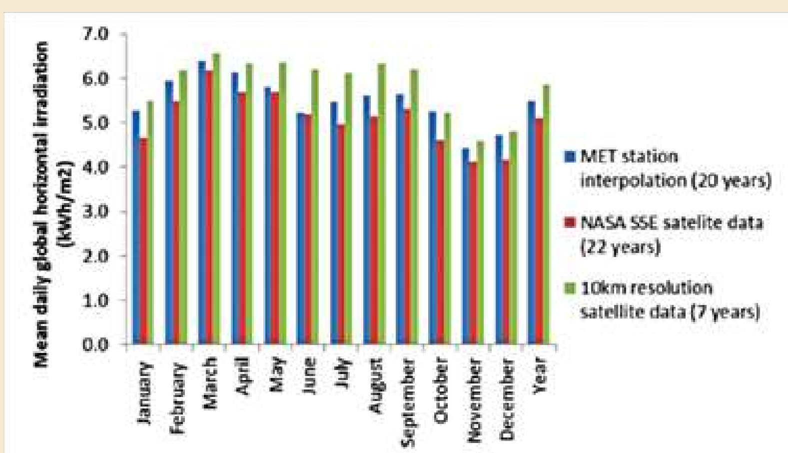
There are a variety of possible solar irradiation data sources that may be accessed for the purpose of estimating the irradiation at potential solar PV sites in India. The data sources for solar radiation in India are of varying quality. Comparison and judicious selection of data sources by specialists in solar resource assessment is recommended when developing a project. Some of the more accessible data sources include:

- India Meteorological Department data from 23 field stations of the radiation network, measured from 1986 to 2000.
- SolMap project, data measured at approximately 115 Solar Measuring Stations over India.[a]
- NASA's Surface Meteorology and Solar Energy data set. Due to large deviation from other databases, and course spatial resolution, it is not advised to apply this database for solar energy projects in India. The data can provide some indication about the inter-annual variability.
- The METEONORM global climatological database and synthetic weather generator. This database has limitations in regions with sparse availability of historical ground Solar Measuring Stations, such as India.
- Satellite-derived geospatial solar data products from the United States-based National Renewable Energy Laboratory (NREL). Annual average DNI and GHI, latitude tilt, and diffuse data are available at 40km resolution for South and East Asia and at 10km resolution for India.
- Commercial databases. SolarGIS has historical coverage of 15+ years at 3km spatial resolution and 30 minute time resolution. The database is updated daily and has been validated over India.[b]

In order to support financing, the developer of the 5 MW plant in Tamil Nadu had a basic solar resource assessment carried out. However, only one data source was used and there was no assessment made of the inter-annual variability of the resource. Nor was any analysis provided of the historical period on which the data were based. The location of the 5 MW plant in Tamil Nadu was more than 200km from the nearest meteorological station. Data interpolated from these distant meteorological stations had a high degree of uncertainty.

The image below compares the data obtained for the site location from three data sources. There is a significant discrepancy between them. A robust solar resource assessment would compare the data sources, discuss their uncertainty and select the data most likely to represent the long-term resource at the site location. An improved resource assessment could be carried out by purchasing commercially available satellite-derived data for the site location.

Where there is significant uncertainty in the data sources (or in the case of large-capacity plants), a short-term data monitoring campaign may be considered. Short-term monitoring (ideally up to one year in duration) may be used to calibrate long-term satellite-derived data and increase the confidence in the long-term energy yield prediction.



a Responsible organisation being the Centre for Wind Energy Technology (CWET), Chennai, Tamil Nadu, India.

b SolarGIS is available for many countries globally and in some independent studies has been ranked as the most accurate database.

Solar Resource Assessment Checklist

The checklist below provides the basic requirements for any solar resource assessment. It is intended to assist solar PV plant developers during the development phase of a PV project, and to ensure that suitable analysis has been completed to facilitate financing.

- [ ] A variety of solar resource datasets consulted with at least ten years of data.
- [ ] Satellite-derived data or data interpolated from ground-based measurements has been appropriately used.
- [ ] Site adaption (calibration) of satellite data has been used, where appropriate, to reduce the uncertainty in locations remote from a meteorological station.
- [ ] Algorithms have been used to convert global horizontal irradiation to irradiation on the tilted plane of the modules.
- [ ] A robust uncertainty analysis has been completed.

Energy Yield Prediction 5

To accurately estimate the energy produced from a PV power plant, information is needed on the solar resource and temperature conditions of the site in addition to the layout and technical specifications of the plant components.

5.1 ENERGY YIELD PREDICTION OVERVIEW

An important step in assessing project feasibility and attracting financing is to calculate the electrical energy expected from the PV power plant. The energy yield prediction provides the basis for calculating project revenue. The aim is to predict the average annual energy output for the lifetime of the proposed power plant, typically 25 to 30 years.

The accuracy needed for the energy yield prediction depends on the stage of project development. For example, a preliminary indication of the energy yield can be carried out using solar resource data and an assumed performance ratio (PR) from nominal values seen in existing projects. For a more accurate energy yield prediction, software should be used with detailed plant specifications as input, three-dimensional modelling of the layout and detailed calculation of shading losses with time-step simulation.

To accurately estimate the energy produced from a PV power plant, information is needed on the solar resource and temperature conditions of the site in addition to the layout and technical specifications of the plant components. Sophisticated software is often used to model the complex interplay of temperature, irradiance, shading and wind-induced cooling on the modules. While a number of software packages can predict the energy yield of a PV power plant at a basic level, financiers generally require an energy yield prediction carried out by a suitable technical expert.

Typically, the procedure for predicting the energy yield of a PV plant using time-step (hourly or sub-hourly) simulation software will consist of the following steps:

1. Sourcing modelled or measured environmental data, such as irradiance, wind speed and temperature from ground based meteorological stations or satellite sources (or a combination of both). This results in a time series of "typical" irradiation

on a horizontal plane at the site location along with typical environmental conditions.

2. Calculating the irradiation incident on the tilted collector plane for a given time step.
3. Modelling the performance of the plant with respect to varying irradiance and temperature to calculate the energy yield prediction in each time step.
4. Applying losses using detailed knowledge of the inverters, PV modules and transformers characteristics, the site layout and module configuration, DC and AC wiring, downtime, auxiliary equipment and soiling characteristics.
5. Applying statistical analysis of resource data and assessing the uncertainty in input values to derive appropriate levels of uncertainty in the final energy yield prediction.

A checklist covering the basic requirements of energy yield assessments has been included at the end of this chapter.

The following sections summarise the main steps required for calculating the electrical energy expected from a solar PV plant.

5.2 IRRADIATION ON MODULE PLANE

In order to predict the solar resource over the lifetime of a project, it is necessary to analyse historical data for the site. These data are typically given for a horizontal plane. The assumption is that the future solar resource will follow the same patterns as the historical values. Historical data may be obtained from land-based measurements or from data obtained from satellites as described in Section 4.3. Data in hourly or sub-hourly time steps are preferred. Statistical techniques can be used to convert average monthly values into simulated hourly values if these are not immediately available.

5.3 PERFORMANCE MODELLING

Sophisticated simulation software is used to predict the performance of a PV power plant in time steps for a set of conditions encountered in a typical year. This allows a detailed simulation of the efficiency with which the plant converts solar irradiance into AC power and the losses associated with the conversion. While some of these losses may be calculated within the simulation software, others are based on extrapolations of data from similar PV plants and analysis of the site conditions.

There are several solar PV modelling software packages available on the market, which are useful analytical tools for different phases of a project's life. These packages include PVSyst, PV*SOL, RETScreen, HOMER, INSEL, Archelios and Polysun, among others. For bank-grade energy yield assessments, PVSyst has become one of the most widely used in Europe and other parts of the world due to its flexibility and ability to accurately model utility-scale PV plants.

Depending on specific site characteristics and plant design, energy yield losses may be caused by any of the factors described in Table 6. Energy yield prediction reports should consider and (ideally) quantify each of these losses.

5.4 ENERGY YIELD PREDICTION RESULTS

The predicted annual energy yield may be expressed within a given confidence interval. A P90 value is the annual energy yield prediction that will be exceeded with 90 percent probability; P75 is the yield prediction that will be exceeded with 75 percent probability; and P50 is the yield prediction that will be exceeded with 50 percent probability. Good quality "bank grade" energy yield reports will give the P50 and P90 energy yield prediction values as a minimum.

Projects typically have a financing structure that requires them to service debt once or twice a year. The year-on-year uncertainty in the resource is therefore taken into account by expressing a "one year P90." A "ten year P90" includes the uncertainty in the resource as it varies over a ten-year period. The exact requirement will depend on the financial structure of the specific plant and the requirements of the financing institution.

Table 6: Losses in a PV Power Plant	
Loss	**Description**
Air pollution	The solar resource can be reduced significantly in some locations due to air pollution from industry and agriculture. Air pollution reduces solar irradiance incident on the module and thereby reduces power output. This is more significant in urban and peri-urban locations, particularly in more recently industrialised nations.
Soiling	Losses due to soiling (dust and bird droppings) depend on the environmental conditions, rainfall frequency, and cleaning strategy as defined in the O&M contract. This loss can be relatively large compared to other loss factors. It has the potential to reach up to 15 percent[a] annually and potentially higher in deserts, but is usually less than 4 percent unless there is unusually high soiling or problems from snow settling on the modules for long periods of time. The soiling loss may be expected to be lower for modules at a high tilt angle as inclined modules will benefit more from the natural cleaning effect of rainwater. Tracking systems typically record similar soiling losses as fixed systems. As this loss can have an important impact on the PR, it is recommended that an expert is consulted to quantify the soiling loss.
Shading	Shading losses occur due to mountains or buildings on the far horizon, mutual shading between rows of modules and near shading due to trees, buildings, pylons or overhead cabling. To model near-shading losses accurately, it is recommended that a 3D representation of the plant and shading obstacles are generated within the modelling software. This loss can potentially be quite large, thus it is important that the plant is modelled accurately.
Electrical shading	The effect of partial shadings on electrical production of the PV plant is non-linear and is modelled through partitioning of the strings of modules. Modules installed in landscape configuration for an orientation towards the equator will typically experience less electrical shading losses than modules installed in portrait configuration due to the connection of diodes. Similarly, some types of thin-film technology are less impacted than crystalline PV modules. Electrical shading effects can typically be set within the modelling software. This will be quantified differently depending on module configuration, chosen technology and the system type (i.e., tracking or fixed).
Incident angle	The incidence angle loss accounts for radiation reflected from the front glass when the light striking it is not perpendicular. For tilted PV modules, these losses may be expected to be larger than the losses experienced with dual axis tracking systems, for example.
Low irradiance	The conversion efficiency of a PV module generally reduces at low light intensities. This causes a loss in the output of a module compared with the Standard Test Conditions (STC) (1,000W/m2). This “low irradiance loss” depends on the characteristics of the module and the intensity of the incident radiation. Most module manufacturers will be able to provide information on their module low irradiance losses. However, where possible, it is preferable to obtain such data from independent testing institutes.
Module temperature	The characteristics of a PV module are determined at standard temperature conditions of 25˚C. For every degree rise in Celsius temperature above this standard, crystalline silicon modules reduce in efficiency, generally by around 0.5 percent. In high ambient temperatures under strong irradiance, module temperatures can rise appreciably. Wind can provide some cooling effect, which can also be modelled.
Module quality	Most PV modules do not exactly match the manufacturer’s nominal specifications. Modules are sold with a nominal peak power and a guarantee of actual power within a given tolerance range. The module quality loss quantifies the impact on the energy yield due to divergences in actual module characteristics from the specifications. Typically, the module output power at STC is greater than the nominal power specified in the datasheets. As such, a positive quality factor can be applied to the energy yield.
Module mismatch	Losses due to "mismatch" are related to the fact that the real modules in a string do not all rigorously present the same current/voltage profiles; there is a statistical variation between them which gives rise to a power loss. This loss is directly related to the modules’ power tolerance.
Degradation	The performance of a PV module decreases with time (see Section 3.3.5). If no independent testing has been conducted on the modules being used, then a generic degradation rate depending on the module technology may be assumed. Alternatively, a maximum degradation rate that conforms to the module performance warranty may be considered as a conservative estimate.
Inverter performance	Inverters convert current from DC into AC with an efficiency that varies with inverter load. Manufacturers are usually able to provide an inverter’s efficiency profile for low, medium and high voltages; entering these into the modelling software will provide more accurate inverter losses.
MPP tracking	The inverters are constantly seeking the maximum power point (MPP) of the array by shifting inverter voltage to the MPP voltage. Different inverters do this with varying efficiency.

(Continued)

a S. Canada, “Impacts of Soiling on Utility-Scale PV System Performance,” Issue 6.3, Apr/May 2013, http://solarprofessional.com/articles/operations-maintenance/impacts-of-soiling-on-utility-scale-pv-system-performance (accessed April 2014).

Table 6: Losses in a PV Power Plant *(Continued)*	
Loss	Description
Curtailment of tracking	Yield losses can occur due to high winds enforcing the stow mode of tracking systems so that the PV modules are not optimally orientated.
Transformer performance	Transformer losses are usually quantified in terms of iron and resistive/inductive losses, which can be calculated based on the transformer's no-load and full-load losses.
DC cable losses	Electrical resistance in the cable between the modules and the input terminals of the inverter give rise to ohmic losses (I^2R).[b] These losses increase with temperature. If the cable is correctly sized, this loss should be less than 3 percent annually.
AC cable losses	AC cable losses are the ohmic losses in the AC cabling. This includes all cables post inverter up to the metering point. These losses are typically smaller than DC cable losses and are usually smaller for systems that use central inverters.
Auxiliary power	Power may be required for electrical equipment within the plant. This may include security systems, tracking motors, monitoring equipment and lighting. Plants with string inverter configurations will typically experience smaller auxiliary losses than central inverter configurations. It is usually recommended to meter this auxiliary power requirement separately. Furthermore, care should be taken as to how to quantify both daytime and nighttime auxiliary losses.
Downtime	Downtime is a period when the plant does not generate due to failure. The downtime periods will depend on the quality of the plant components, design, environmental conditions, diagnostic response time, and repair response time.
Grid availability and disruption	The ability of a PV power plant to export power is dependent on the availability of the distribution or transmission network. The owner of the PV plant relies on the distribution network operator to maintain service at high levels of availability. Unless detailed information is available, this loss is typically based on an assumption that the local grid will not be operational for a given number of hours/days in any one year, and that it will occur during periods of average production.
Grid compliance loss	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 can have serious impacts on project economics.

b Ohmic Loss is the voltage drop across the cell during passage of current due to the internal resistance of the cell.

5.5 UNCERTAINTY IN THE ENERGY YIELD PREDICTION

The uncertainty of energy yield simulation software depends on each modelling stage and on the uncertainty in the input variables. Modelling software itself can introduce uncertainty of 2 percent to 3 percent.

The uncertainty in the daily aggregated values of irradiation measured by ground based pyranometers (depending on the accuracy class) is in the range of ± 2 percent to ± 8 percent. This represents the upper limit in accuracy of resource data obtained through meteorological stations. However, in many cases, the presence of a ground-based pyranometer at the project location during preceding years is unlikely. If this is the case, solar resource data will likely have been obtained using satellites or by interpolation as described in Section 4.3. This will increase the uncertainty in the resource data, depending on the quality of the data used. In general, resource data uncertainty in the region of 5 percent to 8 percent or higher may be expected, depending on the region.

Uncertainty in other modelling inputs include estimates in downtime, estimates in soiling, uncertainty in the inter-annual variation in solar resource and errors due to module specifications not accurately defining the actual module characteristics.

The energy yield depends linearly, to a first approximation, on plane of array irradiance. Therefore, uncertainty in the resource data has a strong bearing on the uncertainty in the yield prediction. Total uncertainty figures in the region of 8 percent to 10 percent may be expected, depending on the region. A good energy yield report will quantify the uncertainty for the specific site location.

Figure 15: Uncertainty in Energy Yield Prediction

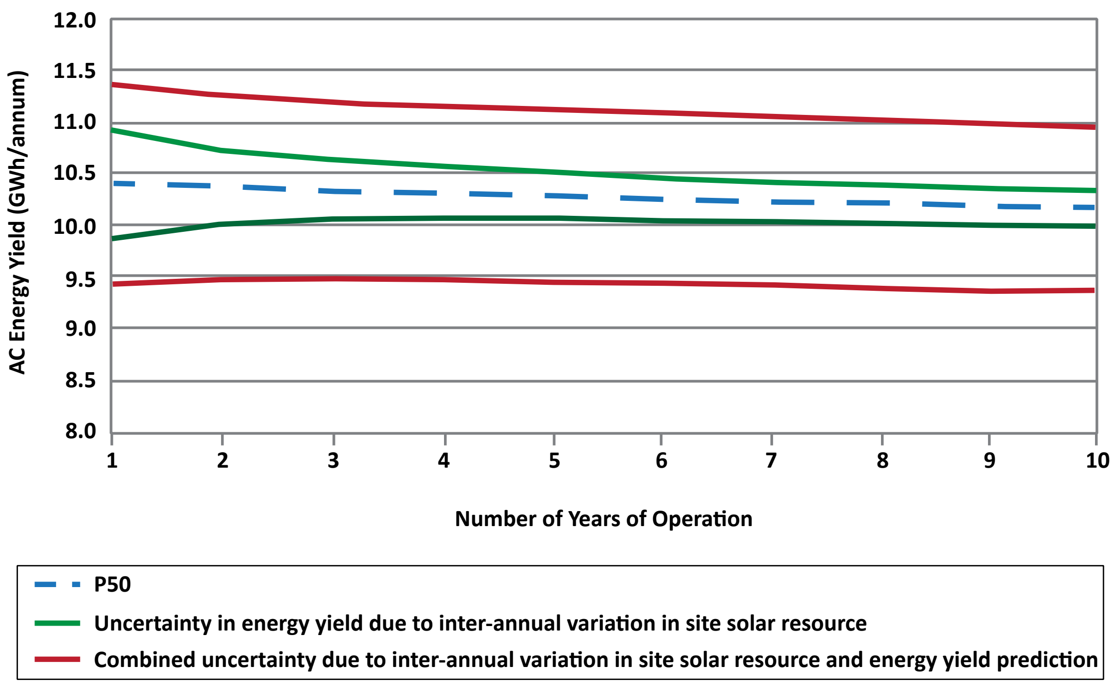


Figure 15 represents the typical combined uncertainties in the yield prediction for a PV power plant. The dashed blue line shows the predicted P50 yield. The green lines represent uncertainty in energy yield due to inter-annual variability in solar resource. The solid red lines represent the total uncertainty in energy yield when inter-annual variability is combined with the uncertainty in the yield prediction. The total uncertainty decreases over the lifetime of the PV plant. The lower limit on the graph corresponds to the P90 and the upper limit corresponds to the P10.

Box 3: Energy Yield Prediction Case Study in India

The developer of a 5MW plant in Tamil Nadu, India, required a solar energy yield prediction to confirm project feasibility and assess likely revenues. In this instance, the developer was either not aware of or did not consider a number of additional losses and did not calculate a long-term yield prediction over the life of the project with uncertainty analysis. Both of these would have been essential for potential project financiers.

The developer sourced global horizontal irradiation data for the site location. Commercially available software was used to simulate the complex interactions of temperature and irradiance impacting the energy yield. This software took the plant specifications as input and modelled the output in hourly time steps for a typical year. Losses and gains were calculated within the software. These included:

- Gain due to tilting the module at 10°.
- AC losses. Reflection losses (3.3 percent).
- Losses due to a lower module efficiency at low irradiance levels (4.2 percent).
- Losses due to temperatures above 25°C (6 percent).
- Soiling losses (1.1 percent).
- Losses due to modules deviating from their nominal power (3.3 percent).
- Mismatch losses (2.2 percent).
- DC Ohmic losses (1.8 percent).
- Inverter losses (3.6 percent).

The software gave an annual sum of electrical energy expected at the inverter output in the first year of operation. Although this is a useful indicative figure, an improved energy yield prediction would also consider:

- Inter-row shading losses (by setting up a 3D model).
- Horizon shading, if any.
- Near shading from nearby obstructions, including poles, control rooms and switch yard equipment.
- Downtime and grid availability.
- Degradation of the modules and plant components over the lifetime of the plant.

This analysis modelled energy yield for one year, however lifetime analysis is typically required. In order to clearly show the expected output during the design life of the plant and assess the confidence in the energy yield predictions, it is necessary to analyse the level of certainty in the data and processes used for this analysis, including:

- Level of accuracy of solar resource data used.
- Reliability/accuracy of modelling process.
- Inter-annual variation of the solar resource.

The energy yield prediction for the 5MW plant was provided as a first-year P50 value (the yield that will be exceeded with 50 percent probability in the first year), excluding degradation. An investor will usually look for a higher level of confidence in the energy yield prediction, typically expressed as the P90 value, or the annual energy yield prediction that will be exceeded with 90 percent probability.

Energy Yield Assessment Checklist

The following checklist covers the basic requirements and procedures for energy yield assessments. It is intended to assist solar PV power plant developers during the development phase of a PV project.

- [ ] A variety of judiciously-selected solar resource datasets consulted.
- [ ] Hourly generation profile obtained or synthetically generated.
- [ ] Plant design basic information detailed (plant capacity, tilt and shading angles, orientation, number of modules per string, total number of modules and inverters).
- [ ] Module, inverter and transformer datasheets available.
- [ ] 3D shading model generated using modelling software.
- [ ] Horizon and near-shading obstacles detailed and implemented in 3D model.
- [ ] DC and AC cable losses calculated.
- [ ] Soiling losses assessed based on precipitation profile, environmental conditions and cleaning schedule.
- [ ] Auxiliary losses broken down and assessed.
- [ ] Availability losses based on grid and plant availability assessed.
- [ ] Essential module characteristics available (degradation, low light performance, tolerance, temperature coefficient).
- [ ] Essential inverter characteristics available (including Maximum Power Point Tracking capability, efficiency profile for three voltages).
- [ ] Overall energy yield loss calculated.
- [ ] P50 calculated monthly and for project duration.
- [ ] PR calculated monthly and for project duration.
- [ ] Specific yield calculated for year 1 of operation.
- [ ] Inter-annual variation obtained.
- [ ] Solar resource measurement uncertainty obtained.
- [ ] Overall uncertainty assessed.
- [ ] P90 calculated for years 1, 10 and 20.

6 Site Selection

6.1 SITE SELECTION OVERVIEW

In general, the process of site selection must consider the constraints of each site and the impact it will have on the cost of the electricity generated. "Showstoppers" for developing a utility-scale PV power plant in a specific location may include constraints due to a low solar resource, low grid capacity or insufficient area to install modules. However, a low solar resource could be offset by high local financial incentives that make a project viable. A similar balancing act applies to the other constraints. A Geographical Information System (GIS) mapping tool can be used to assist the site selection process by assessing multiple constraints and determining the total area of suitable land available for solar PV project development.

The checklist at the end of the chapter lists the basic requirements and procedures necessary to assist developers with the site selection process.

Selecting a suitable site is a crucial component of developing a viable solar PV project.

6.2 SITE SELECTION CRITERIA

Selecting a suitable site is a crucial component of developing a viable solar PV project. There are no clear-cut rules for site selection. Viable projects have been developed in locations that may initially seem unlikely, such as steep mountain slopes, within wind farms and on waste disposal sites. In general, the process of site selection must consider the constraints and the impact the site will have on the cost of the electricity generated. The main constraints that need to be assessed include:

- Solar resource.
- Available area.
- Local climate.
- Topography.
- Land use.
- Local regulations/land use policy or zoning.

- Environmental designations.
- Geotechnical conditions.
- Geopolitical risks.
- Accessibility.
- Grid connection.
- Module soiling.
- Water availability.
- Financial incentives.

It can be useful to use GIS mapping tools to aid in the process of site selection to visually display constraints, enable consideration of multiple constraints to a particular site, and determine the total land area available for development.

As mentioned before, "showstoppers" for developing a utility-scale PV power plant in a specific location may include constraints due to a low solar resource, low grid capacity or insufficient area to install modules. However, constraints can sometimes be offset; for example, high local financial incentives can offset a low solar resource and make a project viable. Similar considerations apply to other constraints, which are discussed in further detail below.

6.3 SITE SELECTION CONSTRAINTS

6.3.1 *SOLAR RESOURCE*

A high average annual GTI is the most basic consideration for developing a solar PV project. The higher the resource, the greater the energy yield per kWp installed. When assessing the GTI at a site, care must be taken to minimise any shading that will reduce the irradiation received. Shading could be due to mountains or buildings on the far horizon, mutual shading between rows of modules, or shading near the location due to trees, buildings or overhead cabling. Particular care should be taken to consider any shading that could occur due to future construction projects or by growth of vegetation.

Avoiding shading is critical, as even small areas of shade may significantly impair the output of a module or string of modules. The loss in output could be more than predicted by simply assessing the proportion of the modules that are shaded.

When assessing shading, it must be remembered that the path the sun takes through the sky changes with the seasons. An obstacle that provides significant shading at mid-day in December may not provide any shading at all at mid-day in June. The shading should be assessed using the full sun path diagram for the location.

6.3.2 *AREA*

The area required per kWp of installed capacity varies with the technology chosen. The distance between rows of modules (the pitch) required to avoid significant inter-row shading varies with the site latitude. Sites should be chosen with sufficient area to allow the required capacity to be installed without having to reduce the pitch to levels that cause unacceptable yield loss.

For example, depending on the site location (latitude) and the type of PV module selected (efficiency), a well-designed PV power plant with a capacity of 1MWp developed in India is estimated to require between one and two hectares (10,000 to 20,000 m^2) of land. A plant using lower efficiency CdTe thin-film modules may require approximately 40 percent to 50 percent more space than a plant using multi-crystalline modules. Table 7 lists the approximate area required for plants in five different countries.

6.3.3 *CLIMATE*

In addition to a good solar resource, the climate should not suffer from extremes of weather that will increase the risk of damage or downtime. Weather events that may need consideration include:

- **Flooding:** May cause damage to electrical equipment mounted on or close to ground level. Also increased risk of erosion of the support structure and foundations, depending on geotechnical conditions.

Table 7: Area Required for Megawatt-scale Solar Power Plant		
Country	Technology	Approximate Area (ha/MWp)[a]
South Africa	c-Si	0.9 – 1.4
	CdTe	1.5 – 2.0
Chile	c-Si	1.0 – 1.5
	CdTe	1.7 – 2.2
Thailand	c-Si	0.8 – 1.2
	CdTe	1.3 – 1.8
India	c-Si	1.0 – 1.5
	CdTe	1.6 – 2.0
Indonesia	c-Si	0.8 – 1.2
	CdTe	1.3 – 1.8

a Exact area will vary according to the tilt angles and pitch.

- **High wind speeds:** The risk of a high wind event exceeding the plant specifications should be assessed. Locations with a high risk of damaging wind speeds should be avoided. Fixed systems do not shut down at high wind speeds, but tracking systems must shut down when high wind speeds are experienced.
- **Snow:** Snow settling on modules can significantly reduce annual energy yield if mitigating measures are not incorporated. If the site is prone to snow, then one has to consider factors such as the extra burden on the mounting structures, the loss in energy production, and the additional cost of higher specification modules or support structures. The cost of removing the snow needs to be weighed against the loss in production and the likelihood of further snowfall. The effects of snow can be mitigated by a design with a high tilt angle and frameless modules. The design should also ensure that the bottom edge of the module is fixed higher than the average snow level for the area. Most importantly, a site that that has regular coverings of snow for a long period of time may not be suitable for developing a solar PV power plant.
- **Temperature:** The efficiency of a PV power plant reduces with increasing temperature. If a high temperature site is being considered, mitigating measures should be included in the design and technology selection. For instance, it would be better to choose modules with a low temperature coefficient for power.
- **Air pollutants:** The location of the site in relation to local air pollution sources must be considered. Local industrial atmospheric pollution may reduce the irradiation received or contain significant levels of airborne sulphur or other potentially corrosive substances. Similarly, the distance to the sea (coastline) should be considered as this may lead to elevated levels of salts in the atmosphere. All these conditions could lead to accelerated corrosion of unprotected components. PV modules to be used in highly corrosive atmospheres such as coastal areas must be certified for salt mist corrosion as per standard IEC 61701. Further information on the impact of air pollution can be found in Section 5.3.

6.3.4 *TOPOGRAPHY*

Ideally, the site should be flat or on a slight south-facing slope in the northern hemisphere or north-facing slope in the southern hemisphere. Such topography makes installation simpler and reduces the cost of technical modifications required to adjust for undulations in the ground. With additional cost and complexity of installation, mounting structures can be designed for most locations. In general, the cost of land must be weighed against the cost of designing a mounting structure and installation time.

6.3.5 *LAND USE*

Solar PV power plants will ideally be built on low value land. If the land is not already owned by the developer, then the cost of purchase or lease needs to be considered. The developer must purchase the land or use rights for the duration of the project. Section 8 (Permits and Licensing) provides further details. Besides access to the site, provision of water, electricity supplies and the rights to upgrade access roads must be considered along with relevant land taxes.

Since government permission will be required to build a solar power plant, it is necessary to assess the site in line with the local conditions imposed by the relevant regulatory bodies. See Section 12 for further information on regulations.

If the land is currently used for agricultural purposes, then it may need to be re-classified for "industrial use," with cost and time implications. The best locations for solar plants are usually previously developed lands or brownfield sites because they often have existing energy use nearby. Use of high-quality agricultural land should be avoided if possible. In some instances, due to the spacing between modules and their elevation, some agricultural activity such as sheep grazing can remain.

The future land use of the area must also be taken into account. It is likely that the plant will be in operation for at least 25 years. Furthermore, external factors also need to be considered to assess the likelihood of their impact on energy yield. For example, the dust associated with building projects or vehicular traffic could have significant soiling effect and associated impact on the energy yield of the plant. Any trees on the project site and surrounding land may need to be removed, with cost implications.

Clearances from the military may be required if the site is in or near a military-sensitive area. Glare from solar modules can affect some military activities.

6.3.6 LOCAL REGULATIONS / LAND USE POLICY

Any planning restrictions for the area of the development should be taken into consideration. These will differ from country to country, but may include land use zoning regulations or constraints to a particular type of development. These issues are discussed further in Section 8 (Permits and Licensing).

It is advisable to contact the relevant government department in the first instance to ascertain any specific restrictions on the area in question.

6.3.7 ENVIRONMENTAL & SOCIAL CONSIDERATIONS

Most regulatory regimes require some sort of Environmental Impact Assessment (EIA) or Environmental and Social Impact Assessment (ESIA), or an environmental scoping document which screens for any significant issues so that a decision can be made by the relevant authorities as to whether a full-blown assessment is required. However, there may be some countries where no such regulatory requirements exist. In either case, the siting process should consider the following key environmental and social criteria:

- **Biodiversity:** Avoiding sensitive or critical habitats and species is crucial. Construction and operation of solar PV power plant sites and ancillary infrastructure (access roads, transmission lines) leads to clearing of existing habitats and disturbance to fauna and flora. Facilities, including ancillary infrastructure, should be sited away from ecologically sensitive areas, e.g., protected areas and those with high biodiversity value such as wetlands, undisturbed natural forests and important wildlife corridors. Ideally, solar PV power plants should be built on sites that are either open or barren (e.g., desert or semi-desert locations) or that have previously been disturbed, e.g., farmland, industrial land, abandoned land or existing transportation and transmission corridors. Impacts on designated conservation or biodiversity protection sites should be avoided wherever possible, in particular those with national or international significance.
- **Land acquisition:** Avoiding or minimizing involuntary resettlement is a key concern. Installation of solar PV plants results in long-term land acquisition and conversion. If involuntary resettlement (i.e., physical or economic displacement of households) is necessary, this may complicate and slow project development and give rise to possible project delays later in the development cycle, particularly where land tenure and ownership laws are tenuous and/or customary land tenure exists. Sites that would require physical displacement (relocation of residences) should be avoided wherever

possible; site selection should furthermore aim to avoid or minimize economic displacement (e.g. loss of croplands, businesses or other livelihood sources).

- **Other social impacts:** Avoiding cultural heritage, visual impacts and indigenous peoples (IPs) is another critical concern. Besides involuntary resettlement, solar PV projects and their ancillary infrastructure may adversely impact cultural heritage or IPs, may result in visual impacts to nearby communities and may require establishment of worker accommodation camps involving an influx of outsiders into a local community, with attendant social risks. Sites should be selected in such as manner as to avoid close proximity to settled areas, to avoid cultural heritage (e.g., graves, sacred sites) and to avoid or minimize adverse impacts on IPs' lands or properties.

6.3.8 GEOTECHNICAL

A geotechnical survey of the site is recommended prior to final selection. Its purpose is to assess the ground conditions in order to inform the foundation design approach and right of way (ROW) to ensure that the mounting structures will have adequately designed foundations. The level of detail required in the geotechnical survey will depend on the proposed foundation design.

Best practice dictates that either boreholes or trial pits are made at regular intervals, along with soil sampling and in-situ testing, at a depth appropriate for the foundation design. This is usually around 2.5m to 3m below ground level. The boreholes or trial pits would typically assess:

- The groundwater level.
- The resistivity of the soil.
- The load-bearing properties of the soil.
- The presence of rocks or other obstructions.
- Suitability of chosen foundation types and drivability of piled foundations.
- The soil pH and chemical constituents in order to assess the degree of corrosion protection required and the adequate specification of cement properties to be used in foundation concrete.
- The degree of any ground contaminants present which may require special consideration during detailed design or special measures to be undertaken during construction.

Depending on the actual site location, the geotechnical study may also be expected to include an assessment of the risk of seismic activity, land slip, ground subsidence, historical mining or mineral extraction activity and the susceptibility of the soil to frost or clay heave, erosion and flooding.

6.3.9 GRID CONNECTION

A grid connection of sufficient capacity is required to enable the export of power. The viability of the grid connection will depend on factors such as capacity, proximity, ROW, grid stability and grid availability. These factors should be considered at an early stage of the project development process. If the grid connection study is neglected, unforeseen grid connection costs could seriously impact the viability of the project.

- **Proximity:** A major influence on the cost of connecting to the grid will be the distance from the site to the grid connection point. In order to ensure the grid connection does not adversely affect project economics, it is necessary to carry out a feasibility study to assess power evacuation and transmission line routes at the planning stage of the project.
- **Availability:** The grid availability is the percentage of time that the network is able to accept power from the solar PV plant. The annual energy yield from a plant may be significantly reduced if the grid has significant downtime. This may have adverse effects on the economics of the project. In developed areas, the availability of the grid is usually very high. In less developed and rural areas, networks may suffer from