

Handbook for on-grid rooftop solar PV design optimisation



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Handbook for on-grid rooftop solar PV design optimisation

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Contents

PAGES v–vi

Scope

Structure of the handbook

How to use the handbook

Key terms and definition

What is an on-grid rooftop solar PV system?

System architecture

SECTION I | PAGES 1–3

A. Meteorology and solar geometry

Meteorology

Solar insolation data

Solar geometry

SECTION II | PAGES 4–11

B. Generation

Solar PV module

Bifacial solar panels

Module performance

IV curve

Solar PV modules arrangement

Categorisation of solar module quality

Reading the solar module datasheet

SECTION III | PAGES 12–16

C. Power conditioning unit

On-grid inverter

Reading the inverter datasheet

SECTION IV | PAGES 17–20

D. Balance of system

PV module mounting structure

Cables

SECTION V | PAGES 21–22

E. Metering

Net metering

Net billing

Gross metering

SECTION VI | PAGES 23–24

F. International standards

SECTION VII | PAGES 25–47

G. Design

Site audit

Design principles

Design flowchart

Design walkthrough – I

Comparison with simulated generation

Design walkthrough – II

Site audit outcomes

Shadings

Far shading

Near shading

Array row spacing

Orientation

H. Project packaging

Single line diagram

Bill of quantity

Financials

I. Case study

References

List of figures

Figure 1:	On-grid solar PV system	v	Figure 23:	Roof outside, roof purlin inside	26
Figure 2:	Typical on-grid solar PV system	vii	Figure 24:	Solar module rail mounting, array layout in the roof	26
Figure 3:	Normalised insolation curve to peak sun hour	1	Figure 25:	Solar modules arrangements	27
Figure 4:	Daily insolation snapshot of NASA POWER data access viewer	2	Figure 26:	Power logger	27
Figure 5:	Solar geometry	3	Figure 27:	Design principles	28
Figure 6:	On-grid solar PV system	4	Figure 28:	Solar modules in a typical rooftop – PVSyst model	29
Figure 7:	Visual comparison between monocrystalline and polycrystalline cells	5	Figure 29:	Irradiance data obtained from PVSyst software	30
Figure 8:	Bifacial solar modules	6	Figure 30:	Example of a 370Wp solar PV module parameters	30
Figure 9:	IV-curve of solar cells	6	Figure 31:	Types of losses in each major component	33
Figure 10:	Output IV characteristic of the PV module with different temperatures	7	Figure 32:	Bird's-eye view of Buildings A, B and C	35
Figure 11:	Solar panels wired in series	8	Figure 33:	Electricity usage of Hotels in Kathmandu (based on electricity bills)	36
Figure 12:	Solar panels wired in parallel	8	Figure 34:	Average daily energy consumption and peak demand of Hotels in Kathmandu	36
Figure 13:	Sample Longi PV module datasheet	11	Figure 35:	24-hour power consumption of Hotels in Kathmandu	37
Figure 14:	On-grid solar PV system i	12	Figure 36:	24-hr voltage profile of Hotels in Kathmandu	37
Figure 15:	Types of on-grid inverters	12	Figure 37:	3D modelling of Hotels in Kathmandu in PVSyst	39
Figure 16:	Maximum power point tracking	14	Figure 38:	Sun path with far shading (Solargis)	40
Figure 17:	Central and string inverter arrangements	14	Figure 39:	Near shading from trees and buildings	41
Figure 18:	Sample Sungrow inverter datasheet	16	Figure 40:	Example snapshots from a sun-path mobile app	41
Figure 19:	On-grid solar PV system	17	Figure 41:	Inter-row spacing	41
Figure 20:	Examples of solar module mounting structures on roofs	19	Figure 42:	Solar array placement 1	42
Figure 21:	Example of metering scenarios for customers	22	Figure 43:	Solar array placement 2	42
Figure 22:	Elements investigated and analysed during a site audit	25	Figure 44:	Solar array placement 3	43
			Figure 45:	Near shading analysis using a sun-path app	43
			Figure 46:	Solar module orientation	43
			Figure 47:	Energy production variation with change in Azimuth – Scenario 1	44
			Figure 48:	Energy production variation with change in Azimuth – Scenario 2	44
			Figure 49:	Energy production variation with change in tilt angle – Scenario 3	44
			Figure 50:	Energy production variation with change in tilt angle – Scenario 4	44
			Figure 51:	solar array configurations	45
			Figure 52:	Energy generation and penetration of Layout 3	46
			Figure 53:	General SLD of an on-grid solar PV system	49

Figure 54: Comparison of energy cost between grid and solar	51
Figure 55: Comparison of total lifetime expenses of grid and solar	51
Figure 56: Solar PV system in ICIMOD in Kathmandu, Nepal	52
Figure 57: Comparison of lifetime cost of grid electricity and solar PV system at ICIMOD	53

List of tables

Table 1: Sources of insolation data	2
Table 2: Comparison between different solar cells	5
Table 3: Tiered classification of solar modules	9
Table 4: Differences between micro-inverter, string inverter, and central inverter	13
Table 5: Description of the balance of systems	17
Table 6: Some relevant standards of major on-grid solar PV components	23
Table 7: Description of roof features	29
Table 8: Solar module parameters	31
Table 9: Options for on-grid inverters	32
Table 10: Assessing the compatibility of the on-grid inverter	32
Table 11: Recommended values of system losses	33
Table 12: Calculation of annual energy production	33
Table 13: Tariffs at different times of day	35
Table 14: Energy estimations of 50kWp and 100kWp system capacities	38
Table 15: Comparison of solar array configurations	46
Table 16: Major items in the BoQ of on-grid solar PV system	48
Table 17: Template of a the bill of quantity	50
Table 18: Key financial input parameters	50
Table 19: Key financial indicators	50
Table 20: Description of the on-grid solar PV system of ICIMOD, Kathmandu	52
Table 21: Energy production of ICIMOD's solar PV system	52

Scope

This handbook explains the design optimisation process for on-grid rooftop solar photovoltaic (PV) systems. It sheds light on the fundamentals of solar PV systems and presents detailed examples and scenarios to illustrate the optimal design of such a system. The handbook takes a practical approach to system design, focusing on the customer's needs and aspirations.

This handbook specifically focuses on solar PV grid-connected systems with rooftop installation. It does not include ground-mounted installation practices, storage-type solar PV systems and other solar PV applications such as off-grid solar PV, solar water pumping, or solar mini-grids. Similarly, it does not include solar on-grid PV with battery inverter(s) or diesel generator(s) synchronisation.

The handbook incorporates inputs from industry practitioners and the experience of the authors.

Structure of the handbook

The handbook is divided into the following sections:

- **Basics of generation, power conditioning unit and balance of systems** (Figure 1): These sections describe the fundamentals of the solar PV on-grid rooftop components.
- **Design:** This section describes the design optimisation process by walking the reader through different scenarios.
- **Project packaging:** This section discusses financial analysis and processes that will allow the customer to decide whether to implement the on-grid rooftop solar PV system in their facility.
- **Case study:** This section includes a case study of the on-grid rooftop solar PV system at ICIMOD's Kathmandu office.

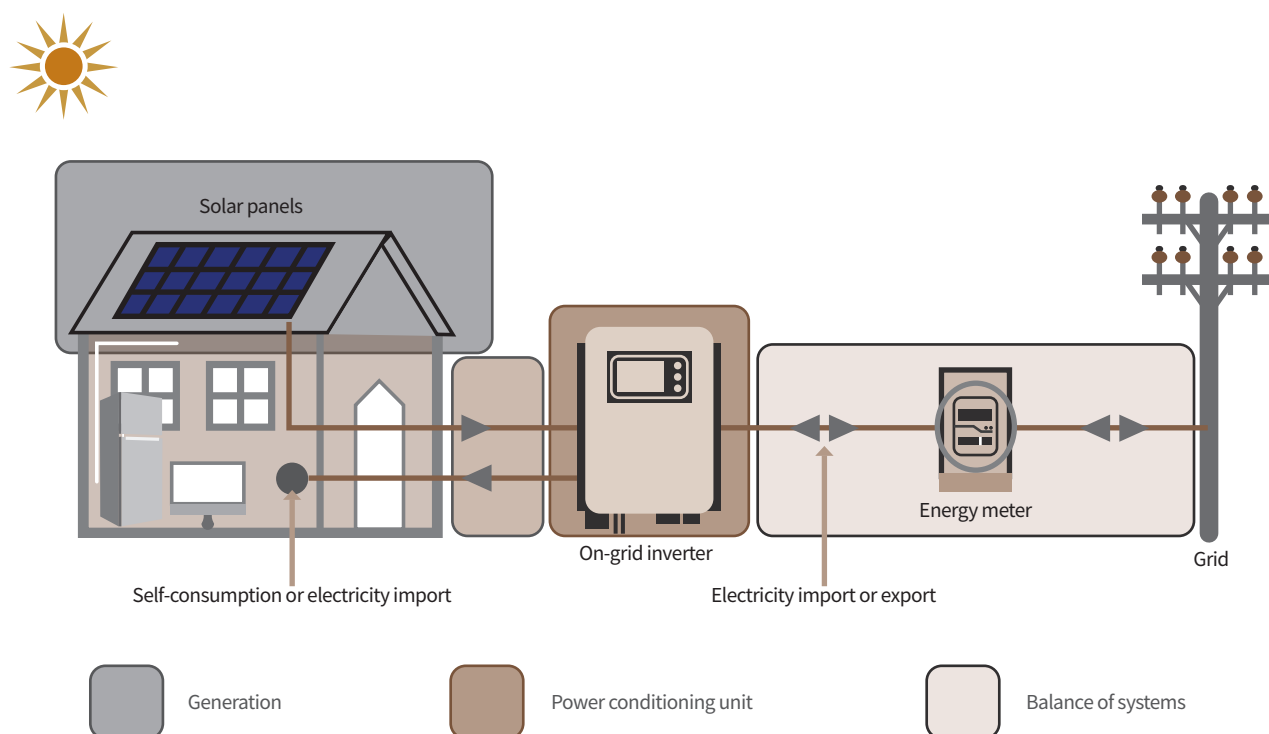
How to use the handbook

Practitioners can use the handbook for the following purposes:

- To understand the fundamentals of on-grid rooftop solar PV systems: Links to external resources are provided, where applicable, which will enable practitioners to deepen their theoretical understanding.
- To understand how critical solar PV system parameters influence the design and decision-making process: The main points of each section are summed up in brown boxes entitled 'Keeping it all together'.
- To grasp the fundamentals of on-grid rooftop solar PV design.

FIGURE 1

ON-GRID SOLAR PV SYSTEM



Key terms and definitions

Battery inverter	An off-grid battery-based inverter (not grid-tied)
Bus bar	A common connection point for one or more electrical cables
Current transformer	A device for measuring the current in a conductor
DC and AC	Direct Current (DC) and Alternating Current (AC)
Grid	National electricity grid
Irradiance	The amount of light energy from one thing hitting a square metre of another each second ^[1] ; it is typically expressed in W/m ² (watt per square metre) or kW/m ² (kilowatt per square metre)
On-grid solar PV or Solar PV system	These terms are used interchangeably and refer to on-grid rooftop solar PV systems in this handbook
PV array	A group of solar panels in single or multiple locations
PV modules or, Module(s) or, Solar PV modules	Solar PV panel(s)
Self-consumption	Energy consumed by the facility itself and not exported to the national grid
Utility-scale solar PV plants	Solar PV plants above 1MWac capacity

What is an on-grid rooftop solar PV system?

An on-grid rooftop solar PV system is a roof-mounted system that is tied to the local utility connection. The electricity generated from solar PV can be self-consumed and/or exported to the grid via a meter. These systems are commonly implemented in residential, commercial, and industrial facilities. This handbook focuses on battery-less on-grid rooftop solar PV systems.

1. When the solar PV electricity generation is adequate to power the loads, the electricity is not drawn from the grid.
2. When the solar PV electricity generation is not adequate to power the loads, the deficit power is drawn from the grid.
3. When the solar PV electricity generation is more than the load, the surplus electricity is exported to the grid.
4. When the grid is down, the solar PV on-grid system shuts down.

System architecture

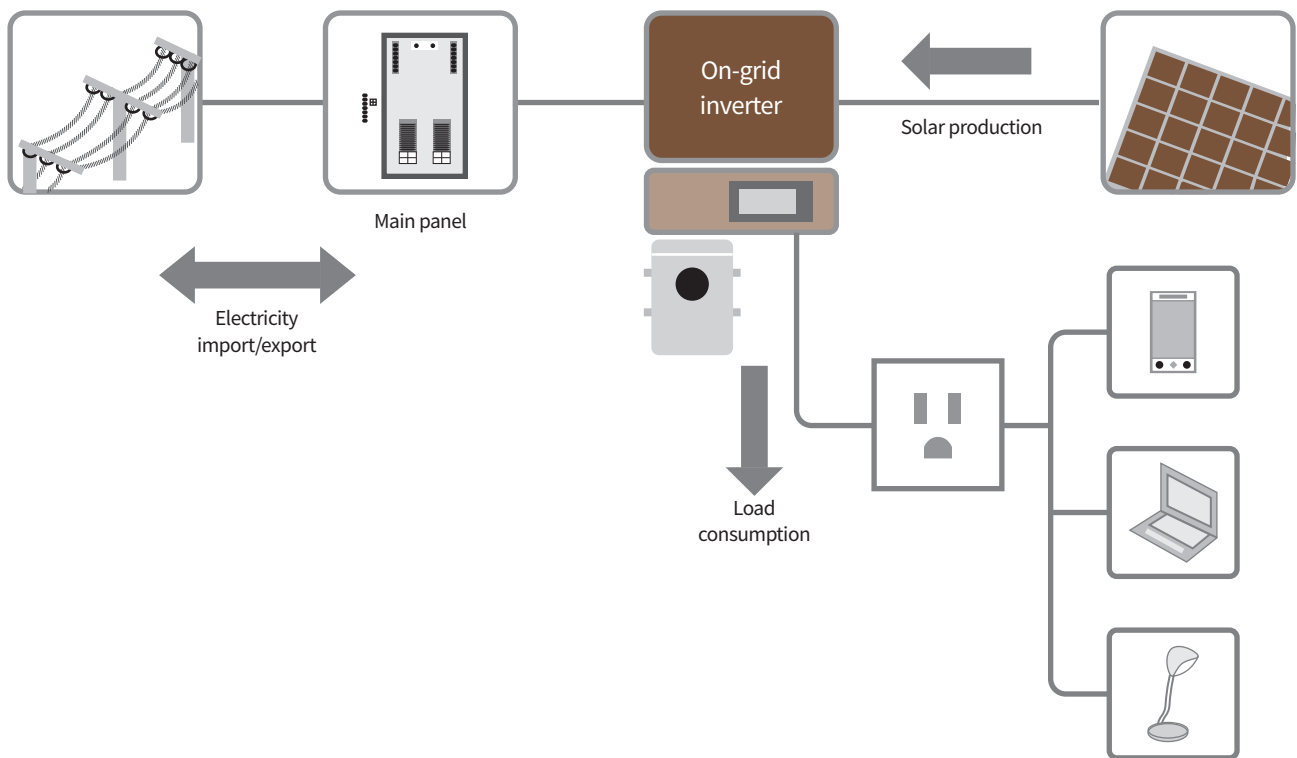
Figure 2 shows the architecture of a typical on-grid solar PV system, where the direct current (DC) electricity generated from solar PV modules is converted to alternating current (AC) electricity via the on-grid inverter. The electricity powers the local loads or is exported to the grid. The system has four modes of operation:

External resources

A brief overview of the on-grid rooftop solar PV system can be found [here](#).

FIGURE 2

TYPICAL ON-GRID SOLAR PV SYSTEM^[2]



A. Meteorology and solar geometry

Meteorology

The important meteorological parameters that influence solar PV generation are presented below. Let's start with some definitions.

Solar insolation: Solar insolation is the total amount of solar energy that is collected on a surface area within a given period. It is typically reported in kilowatt hour per square metre (kWh/m²). The total solar energy collected on a surface area over a day normalised at 1,000 watts per square metre (W/m²) is called 'peak sun hours'. It is typically expressed in kWh/m² day and depicted in Figure 3.

Ambient temperature: It is the air temperature of the surrounding environment and is reported in degrees centigrade (°C).

Wind speed: Wind speed or wind velocity is reported in metres per second (m/s).

Obtaining solar insolation data for a particular location is the first step in estimating the energy generation of a solar PV system.

Solar insolation data

Solar insolation data can be obtained from different sources. Some of the sources are shown in Table 1.

As an example, a snapshot from the NASA POWER data access viewer is shown in Figure 4.

Keeping it all together



A reliable source of insolation data is critical to solar PV system design because it serves as input data for energy generation projections. The insolation dataset must be specific to the project location, have historical averages and must be from a reliable source.

Lack of, or inaccurate insolation data can lead to unreliable energy generation estimates, resulting in financial losses and risk of customer dissatisfaction because the solar PV system fails to serve their needs.

FIGURE 3 NORMALISED INSOLATION CURVE (LEFT) TO PEAK SUN HOUR (RIGHT)

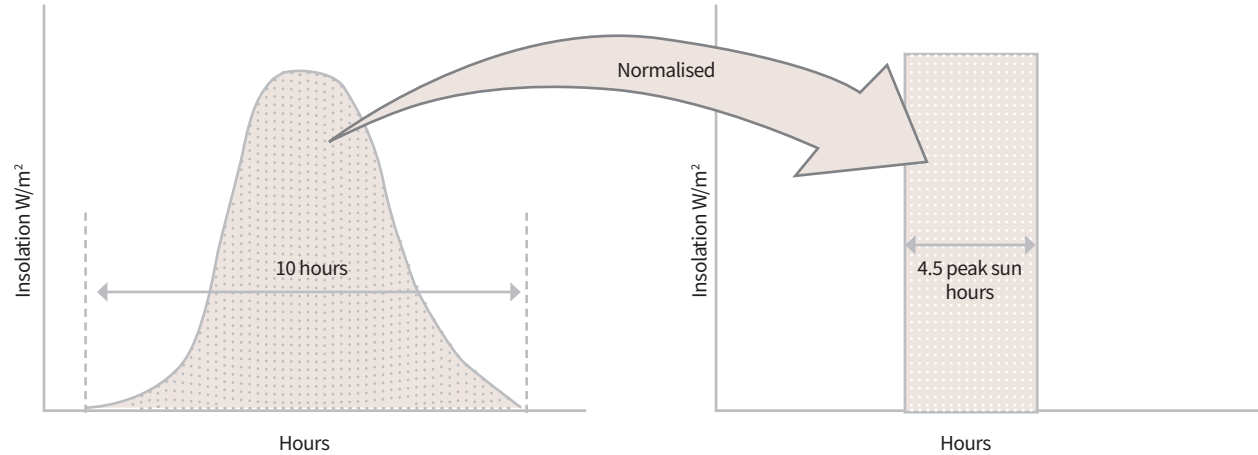
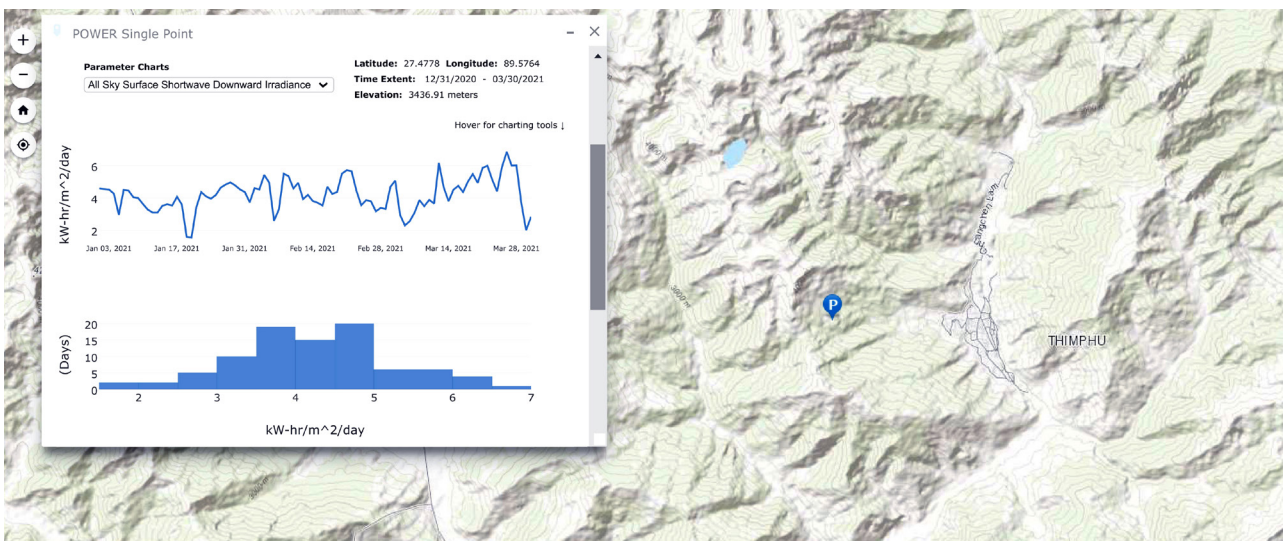


TABLE 1

SOURCES OF INSOLATION DATA

Source name	Access type	Hyperlinks
NASA POWER data access viewer	Free	https://power.larc.nasa.gov/data-access-viewer/
SolarGIS	Paid	https://solargis.com
Meteonorm	Paid	https://meteonorm.com/en/
Nearest weather stations, airport data and research data	Free or paid depending on the region	
REEECH Energy dashboard	Free	http://tethys.icimod.org/apps/reeech/dss/

FIGURE 4

DAILY INSOLATION SNAPSHOT OF NASA POWER DATA ACCESS VIEWER^[3]

Note regarding data accuracy: To factor in data uncertainty, it is advisable to check the ground data and use a correction factor to mitigate inaccuracies, unless specified by the data provider.

Solar geometry

Solar geometries are parameters and measurements of the position of the sun respective to a location. Solar geometry is important for calculating the irradiance captured on a surface (flat or tilted). Usually, the irradiance data is given at a horizontal plane because the optimal tilt angles will vary in different geographical locations. For example,

Keeping it all together



It is important to analyse solar geometry because it directly affects energy generation. For example, orientation of PV modules on the roof, tilt of the roof, etc.

some sources may only provide Global Horizontal Irradiance (GHI) and based on the optimal tilt angle for a specific location, the Global Tilted Irradiance (GTI) will have to be calculated.

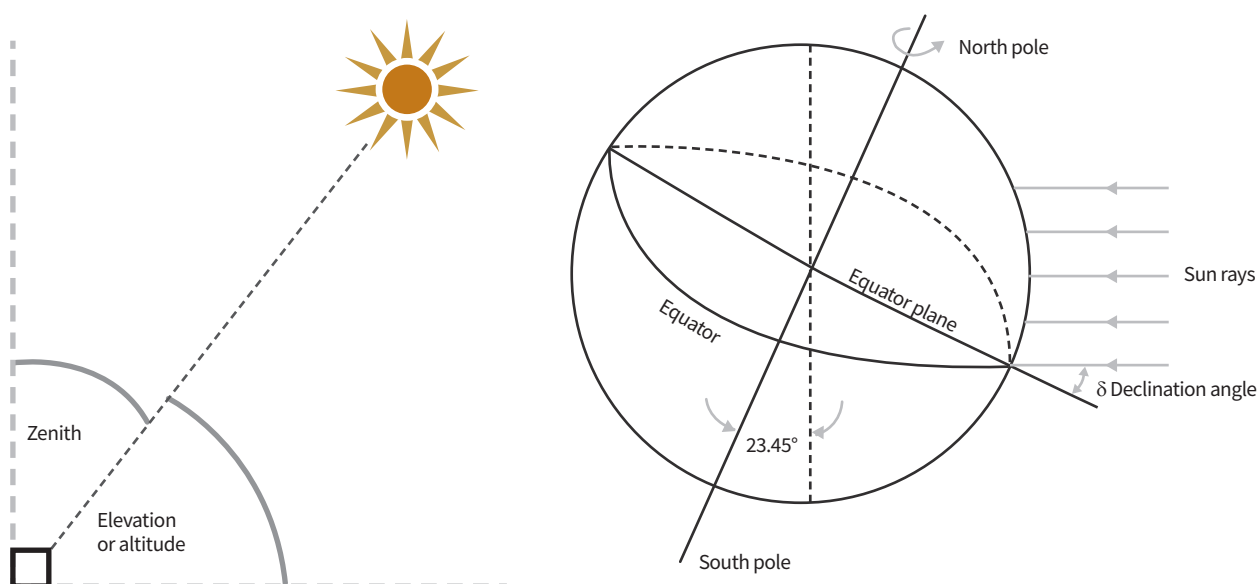
Some of the key terms of solar geometry are:

Zenith angle: The zenith angle is the angle between the sun and the vertical (imaging right above one's head). The zenith angle is similar to the elevation angle, but it is measured from the vertical rather than from the horizontal, as shown in Figure 5, i.e. $\text{Zenith angle} = 90^\circ - \text{elevation angle}$ ^[4].

Solar altitude angle: The solar altitude angle is the angular distance between the sun and the imaginary horizontal plane on which the observer is standing. The altitude angle is negative when the sun drops below the horizon^[5].

Declination angle: The declination of the sun is the angle between the equator and a line drawn from the centre of the Earth to the centre of the sun^[6].

FIGURE 5

SOLAR GEOMETRY^[4]

Solar azimuth: The azimuth angle is the compass direction from which the sunlight is coming. At solar noon, the sun is always directly south in the northern hemisphere and directly north in the southern hemisphere. The azimuth angle is like a compass direction with North = 0° and South = 180° . Other authors use a variety of slightly different definitions (i.e. angles of $\pm 180^\circ$ and South = 0°)^[7].

Summer and winter solstice: Solstice is the time or date (twice each year) at which the sun reaches its maximum or minimum declination, marked by the longest and shortest days (about 21 June and 22 December).

Based on the parameters of the solar geometry, the orientation of the PV modules is decided.

Keeping it all together



Understanding solar geometry is crucial for optimising the solar PV system design because it is used to make decisions regarding:

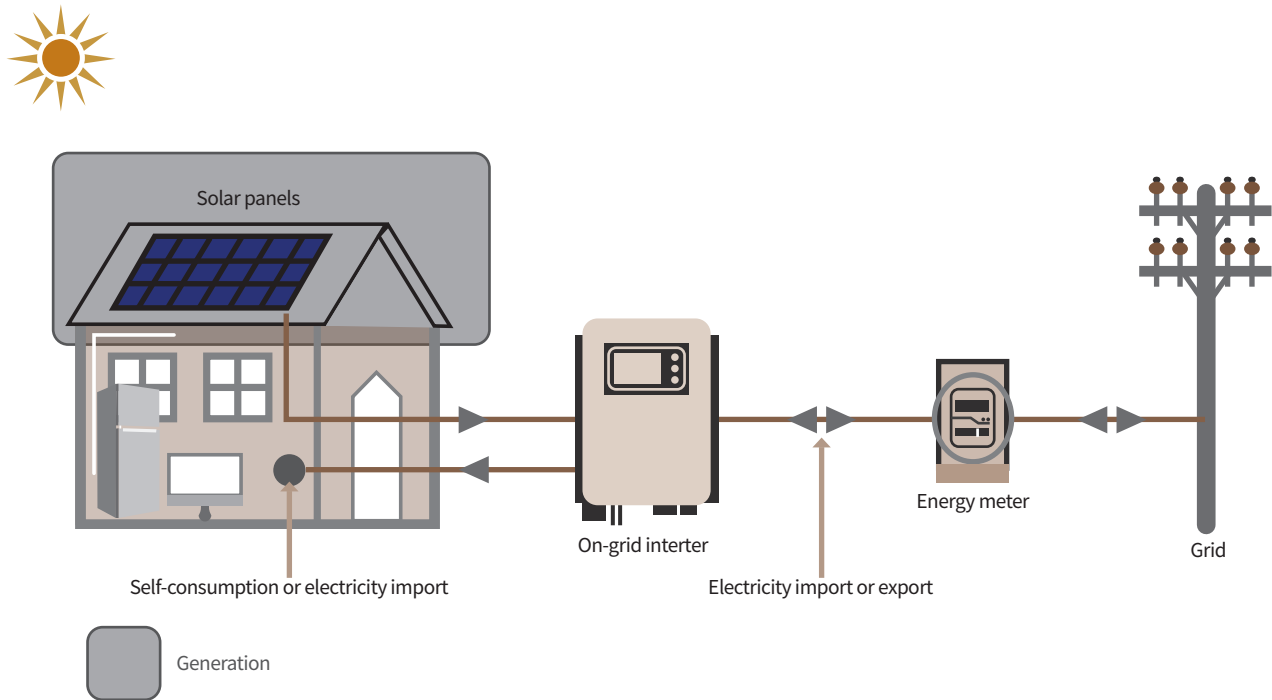
- Tilt angle and azimuth placement of PV modules on rooftops
- Evaluation of trade-off between energy and cost in relation to different orientations of photovoltaic modules

B. Generation

Generation includes all aspects of electricity production as shown in Figure 6.

a) **Monocrystalline PERC cells:** PERC stands for Passivated Emitter and Rear Cell.

FIGURE 6 ON-GRID SOLAR PV SYSTEM



Solar PV module

Solar PV modules capture the radiation energy from the sun and convert it to electrical energy.

External resources

For more background on solar energy, refer to:

- i) [Solar energy I](#)
- ii) [Solar energy II](#)

There are various types of solar PV modules available in the market. Some of the most popular types of solar modules are:

1. **Monocrystalline:** Monocrystalline cells are an extremely pure form of silicon. These are highly efficient and cost-competitive, which is why most manufacturers are now focusing on the production of monocrystalline cells only.

PERC monocrystalline cells are growing in popularity. It achieves higher efficiency than standard solar cells as the passivation layer added to the solar panels acts as a mirror and reflects light that passes through the solar panel the first time^[8]. The layers improve the efficiency of the panels by:

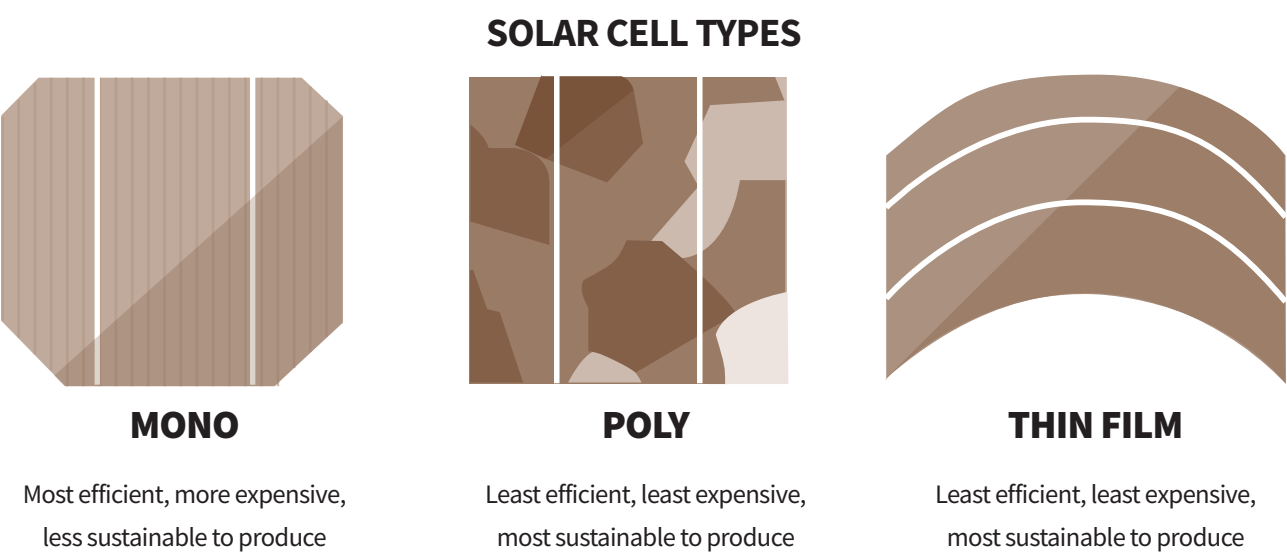
- i) **REDUCING ELECTRON COMBINATION:** It reduces the losses due to electron recombination in the solar cell by ensuring a more steady and consistent flow of electrons.
- ii) **INCREASING THE SOLAR CELL'S ABILITY TO CAPTURE LIGHT:** The unabsorbed light is reflected by the passivation layer back to the solar cell.
- iii) **REFLECTING SPECIFIC WAVELENGTHS THAT NORMALLY GENERATE HEAT:** Since the increase in heat results in increased losses in solar panels, the passivation layer helps reflect certain wavelengths that would otherwise convert to heat^[9].

2. **Polycrystalline:** Instead of a single uniform crystal structure, polycrystalline (or multi-crystalline) cells contain many small grains of crystals (see Figure 7). A cheaper but less efficient alternative, polycrystalline silicon PV cells dominated the world market in the earlier decade, representing about 70% of global PV production in 2015^[10].

Bifacial solar panels

Bifacial solar panels produce power from both sides of the solar panel as shown in Figure 8. These cells typically use monocrystalline technology^[14]. Solar cells on top of the solar panel gather direct sunlight, whereas the cells on the bottom collect reflected light. The efficiency of bifacial solar panels can reach up to 27%^[14].

FIGURE 7 VISUAL COMPARISON BETWEEN MONOCRYSTALLINE AND POLYCRYSTALLINE CELLS^[11]



3. **Thin-film amorphous:** Amorphous silicon (a-Si) is produced by depositing thin layers of silicon onto a glass substrate. The result is a very thin and flexible cell which uses less than 1% of the silicon needed for a crystalline cell. Due to this reduction in raw material and a less energy-intensive manufacturing process, amorphous silicon cells are much cheaper to produce. Their efficiency, however, is greatly reduced because the silicon atoms are much less ordered than in their crystalline forms^[10].

Table 2 shows a comparison between different types of solar cells.

Module performance

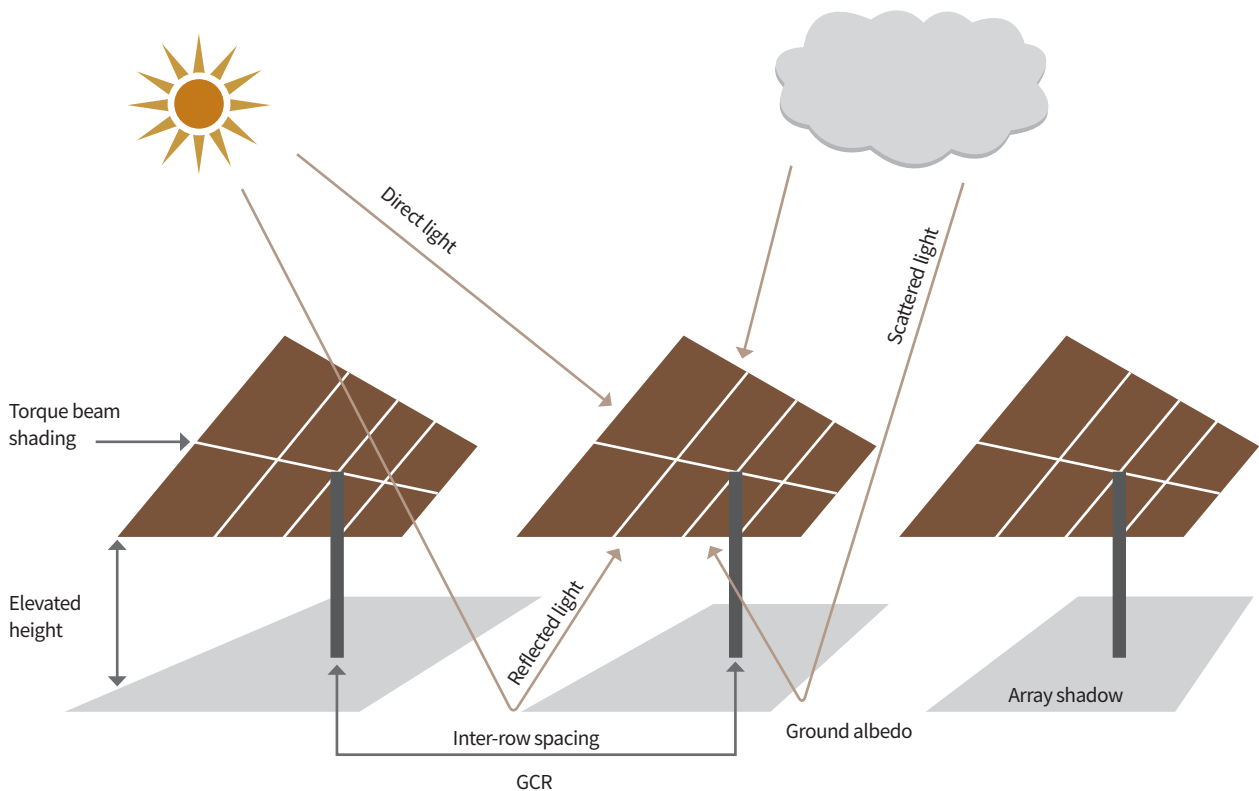
Multiple individual cells are combined to form solar modules. The commonly available solar modules are composed of 60 or 72 cells. Other cell configurations are also possible. Each cell typically has an open-circuit voltage of 0.58 V^[16]. The solar modules available on the market are made from these cells joined together.

The required wattage and voltage of the panel determine the arrangement of the series and parallel configuration of the cells.

TABLE 2 COMPARISON BETWEEN DIFFERENT SOLAR CELLS^[12]

Standard monocrystalline	PERC cells monocrystalline	Standard polycrystalline	Thin film
Efficiency: 15–20% (medium)	Efficiency: Up to 25% ^[13] (highest)	Efficiency: 13–16% (medium)	Efficiency: 7–13% (lowest)
Smaller footprint	Smaller footprint	Requires more space	Requires more space
Relatively expensive	Relatively expensive	Cheaper than monocrystalline	Cheapest among available options
Degrades faster at high temperatures	Degrades faster at high temperatures	Performs well at high temperature	Best performance at high temperature

FIGURE 8

BIFACIAL SOLAR MODULES^[15]

Keeping it all together



- Solar PV modules are the most important component of an on-grid rooftop solar PV system, as this component converts solar energy to electrical energy.
- The choice of solar PV modules is based on factors such as site conditions (such as roof space availability), cost of PV modules and design preferences.

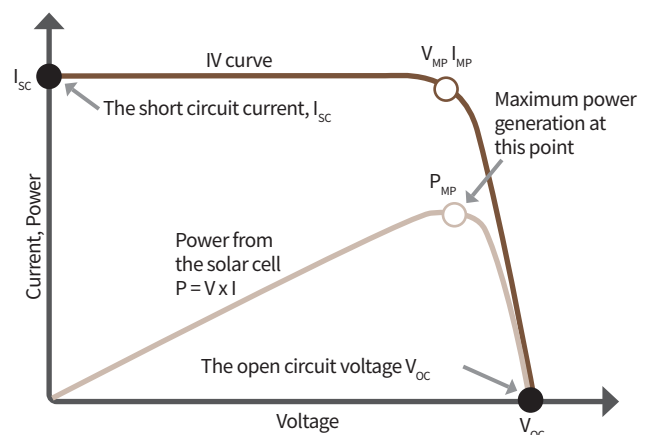
For example, PERC monocrystalline can be a practical option for rooftop installations given its availability in the market, decreasing costs, and higher efficiency compared to standard polycrystalline PV module. However, in ground-mounted applications where solar modules are mounted vertically in rows to allow for agricultural activity, bifacial modules can be used as it can convert energy from both faces of the PV module.

IV Curve

The characteristics of a solar cell are defined by its current (I) and voltage (V), also called the IV curve. The IV curve shows the current and voltage characteristics of a solar cell, which ultimately define the maximum power of the cell (see Figure 9).

In the Figure 9, the 'brown' curve shows the relationship between current (I) and voltage (V). The area under the light brown curve represents the instantaneous power at the respective values of I and V (power = voltage * current).

FIGURE 9

IV-CURVE OF SOLAR CELLS^[17]

When the current (I) is zero, the voltage (V) is known as open-circuit voltage (V_{oc}). This can be measured when the PV module is not connected to the circuit.

Similarly, when voltage (V) is zero, the current (I) is known as short-circuit current (I_{sc}). This can be measured when the positive and negative terminals of the PV module are short-circuited.

External resources

More on IV curve [here](#).

Keeping it all together



Understanding the IV curve is a prerequisite for understanding the performance of PV modules and optimising the solar on-grid design.

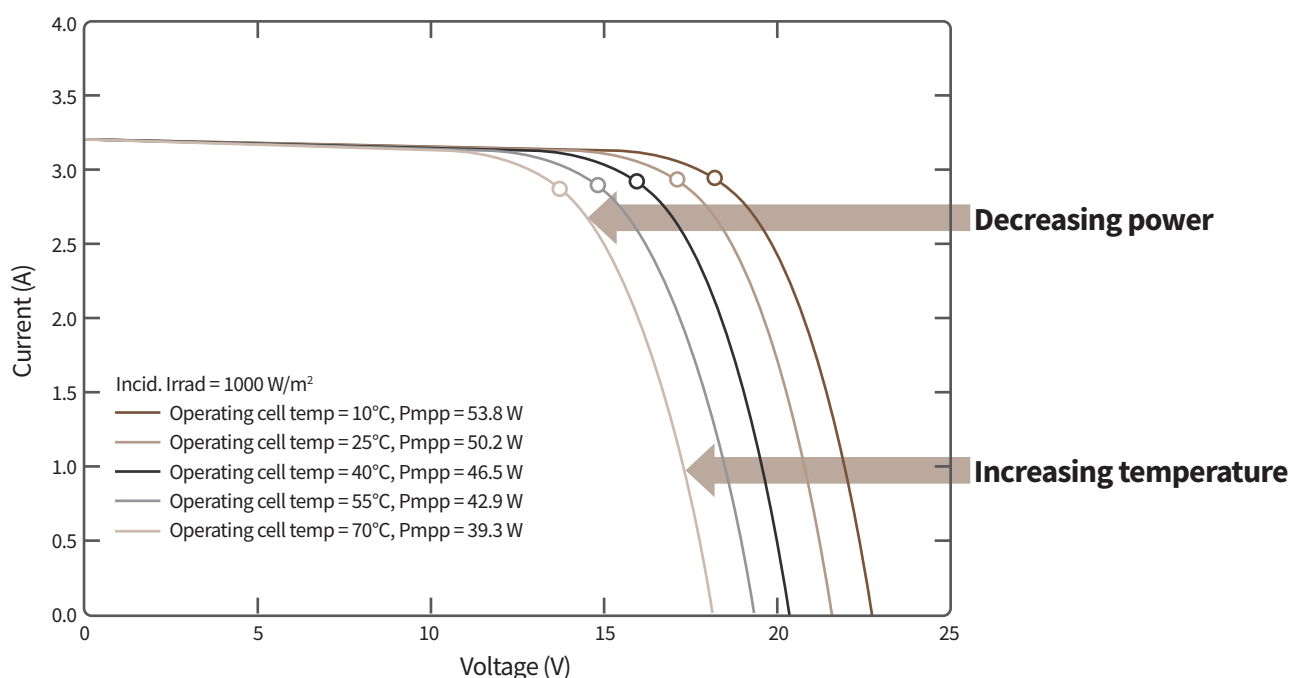
As you will see in Section C, the IV curve is directly related to Maximum Power Point Tracking (MPPT).

The IV curve of a PV module varies based on external environmental and meteorological conditions such as temperature, insolation, soiling, etc. One such important factor is the PV module temperature. Solar PV cells are sensitive to temperature. An increase in temperature decreases the cell voltage and vice versa. Due to this, the power output of the module also decreases. Figure 10 shows the variation in power output due to the change in temperature for a silicon-based solar cell.

As the standard performance values of a PV module are given at 25°C, every degree increase or decrease from this standard temperature will lead to losses or gain in power. This is determined by the temperature coefficients provided by the PV module manufacturer and specified as the temperature coefficient of I_{sc} , temperature coefficient of V_{oc} , and temperature coefficient of $Power_{max}$.

For example, for a 285Wp module, if the temperature coefficient of $Power_{max}$ is specified as $-0.350\%/^{\circ}C$ and the PV module temperature is 27°C, then a power loss with a temperature rise of 2°C is -0.70% ($-0.350 \times 2^{\circ}C$). This relates to a $-2W$ watt power loss ($-0.007 \times 285Wp$). Thus, under this condition, the rated 285Wp module will be producing 283Wp.

FIGURE 10 OUTPUT IV CHARACTERISTIC OF THE PV MODULE WITH DIFFERENT TEMPERATURES^[18]



Solar PV modules arrangement

Quickly covering the basics, the PV modules are arranged in a combination of series and parallel connections.

Keeping it all together



Analysis of temperature coefficient helps us to understand power gain and losses and thus improve the accuracy of energy generation projections. This is important while designing and selecting the

system components in colder regions where low temperature can significantly affect voltage.

Note: PV module temperature can be higher or lower than the ambient temperature.

Series connection

In a series connection, the solar modules are connected in a manner where the positive terminal of each module is connected to the negative terminal of the adjacent module as shown in Figure 11. In a series connection, the voltage of each solar module is added. Thus, the number of modules in series is determined by the desired voltage. In an on-grid PV system, the number of modules in series is often defined by the inverter's voltage input range.

Parallel connection

In a parallel connection, the solar modules are connected in such a way that they have a common positive terminal, meaning that all the positive terminals are connected to each other, and a common negative terminal, as shown in Figure 12. In a parallel connection, the current of each solar module is added, thus the number of modules in parallel is determined by the design current. In an on-grid solar PV system, the number of modules in parallel is often defined by the inverter's current input range.

FIGURE 11 SOLAR PANELS WIRED IN SERIES^[19]

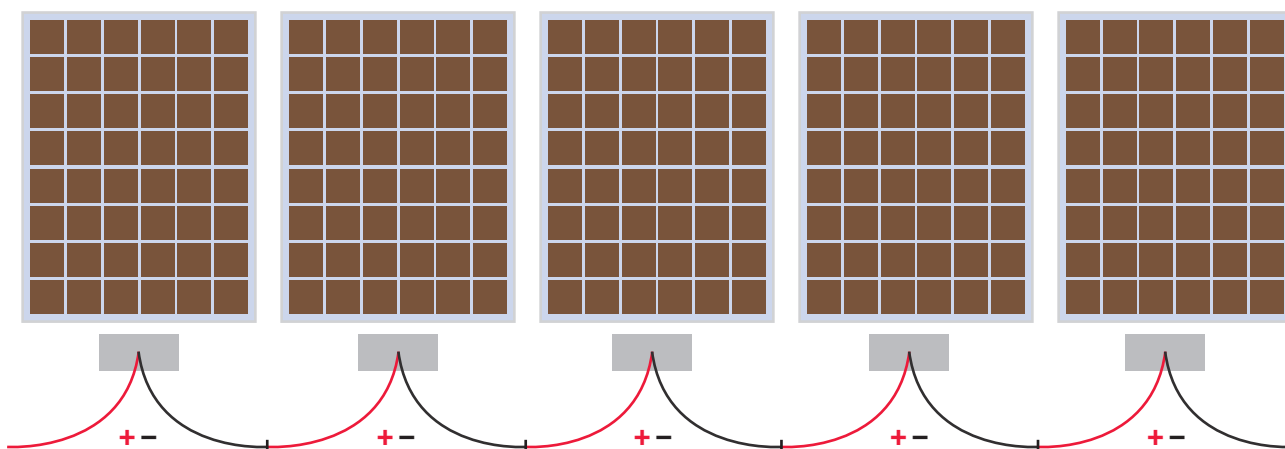
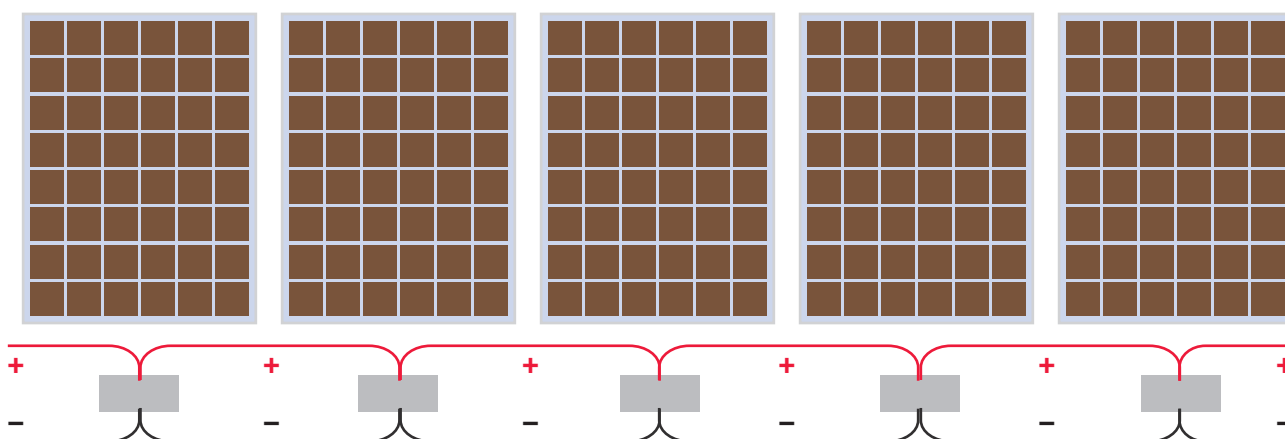


FIGURE 12 SOLAR PANELS WIRED IN PARALLEL^[19]



External resources

More on series and parallel connections [here](#).

Keeping it all together



The understanding of series and parallel connections is fundamental to the design of on-grid solar PV systems. Based on the technical parameters of the chosen inverter, the PV modules need to be arranged in a

combination of series and parallel connection to achieve the desired system voltage and current requirements.

TABLE 3

TIERED CLASSIFICATION OF SOLAR MODULES^[21]

Tier 1	<ul style="list-style-type: none">• Vertically integrated• Invest heavily in R&D• Advanced robotic processes• Manufacturing solar panels for longer than 5 years
Tier 2	<ul style="list-style-type: none">• No or little investment in R&D• Use only partial robotics, also reliant on manual work from human production lines• Usually producing panels for 2–5 years
Tier 3	<ul style="list-style-type: none">• No investment in R&D• Assembly panels only – don't manufacture silicon cells• Use human production lines for manual soldering of solar cells instead of advanced robotics• Assembling panels for 1–2 years

Categorisation of solar module quality

When choosing PV modules, one often comes across tier ratings. Tier rating is a hierarchical system for rating the quality of PV modules. It indicates the credibility of the manufacturer and provides product performance assurance.

Solar modules are categorised into three tiers (see Table 3). [Bloomberg New Energy Finance](#) has set the following criteria for Tier 1 modules:

Tier 1 module manufacturers are those which have provided own-brand, own-manufacture products to at least six different projects, which have been financed non-recourse by six different commercial banks (i.e. not development, not export-import) in the past two years. The earlier financing or commissioning date counts for tiering, i.e. refinancing of old projects does not count^[20].

Keeping it all together



While selecting the type of PV modules, the customer's decision can be influenced by market availability, cost constraints and quality standards of the region.

However, most decision makers choose Tier 1 modules to ensure performance and durability. Furthermore, Tier 1 manufacturers provide better service compared to Tier 2 and Tier 3 manufacturers.

External resources

You can find a secondary source of Tier 1 list [here](#).

Reading the solar module datasheet

On the solar module specifications sheet, the solar module is rated against Standard Test Conditions (STC). This means, for example, a 255Wp module will produce this power when the irradiance is 1000W/m², the Air Mass is 1.5 spectrum, and the cell temperature is 25°C^[22]. Similarly, the same module is also rated in Normal Operating Cell Temperature (NOCT) which tries to model the site conditions where the solar module will produce 184Wp at an irradiance of 800W/m², an ambient temperature of 20°C and wind speed of 1m/s^[23].

While selecting a solar panel, one should carefully check the following information on the datasheet:

1. Manufacturer and model number
2. Most datasheets have two separate tables for electrical parameters – for STC and NOCT conditions
3. Power, voltage, current, efficiency and other electrical parameters under STC conditions
4. Power, voltage, current, efficiency and other electrical parameters under NOCT conditions
5. The temperature coefficient of open-circuit voltage is important for determining the voltage loss
6. The temperature coefficient of power is important for determining the power loss
7. Dimensions of solar panel
8. Number of cells
9. Warranty information

An example of a PV module datasheet is shown in Figure 13.

Relevance for system design



Technical information on the PV module datasheet will serve as input parameters during the design of a solar PV system. For example, information from the datasheet will be used for the following

during system design:

- Arrangement of series and parallel connections compatible with inverter(s)
- Energy generation projections
- Generation losses
- Design of PV module mounting structures

Note: It is also important to go through the datasheets of other components of the solar PV system.

FIGURE 13 SAMPLE LONGI PV MODULE DATASHEET^[24]

Hi-MO O 4m

LR4-72HPH 445~465M

21.4%
MAX MODULE
EFFICIENCY

0~3%
POWER
TOLERANCE

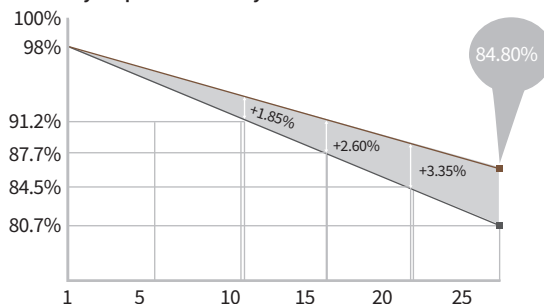
< 2%
FIRST YEAR POWER
DEGRADATION

0.55%
YEAR 2~25 POWER
DEGRADATION

HALF-CELL
LOWER OPERATING
TEMPERATURE

Additional value

25-year power warranty

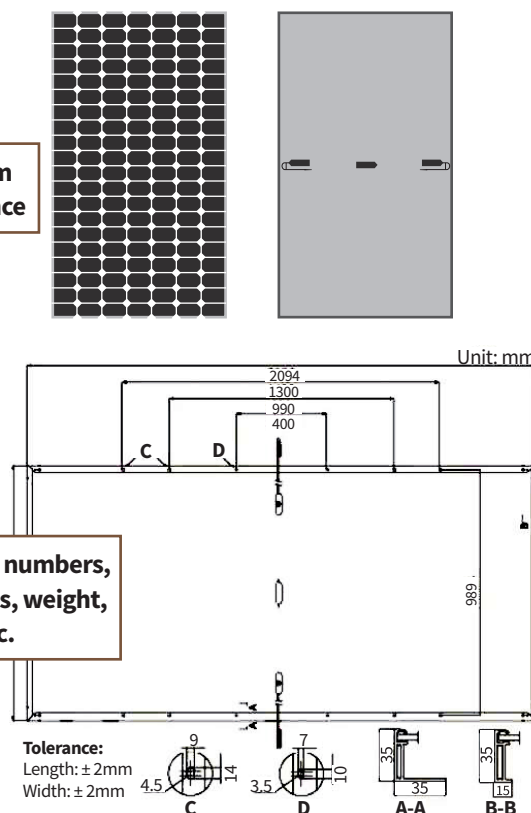


Long-term
performance

Mechanical parameters

Cell orientation	144 (6 x 24)
Junction box	IP 68, three diodes
Output cable	4mm ² , +400, -200mm/±1400mm length can be customised
Glass	Single glass, 3.2mm coated tempered glass
Frame	Anodized aluminum alloy frame
Weight	24.3 kg
Dimension	2094 x 1038 x 35mm
Packaging	30 pcs per pallet/150 per 20' GP/600 per 40' HC

Info on cell numbers,
dimensions, weight,
etc.



Electrical characteristics STC: AM1.5 1000W/m² 25°C NOCT: AM1.5 800W/m² 25°C 1m/s Test uncertainty for P_{max}: ±3%

Module type	LR4-72 HPH 445M		LR4-72 HPH 450M		LR4-72 HPH 455M		LR4-72 HPH 460M		LR4-72 HPH 465M	
Testing condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum power (P _{max} /W)	445	334.3	450	336.1	455	341.8	460	345.5	465	349.3
Open circuit voltage (V _{oc} /V)	49.1	46.2	49.3	46.3	49.5	46.4	49.7	46.7	49.9	46.9
Short circuit current (I _{sc} /A)	11.53	9.35	11.60	9.38	11.68	9.43	11.73	9.51	11.79	9.56
Voltage at maximum power (V _{mp} /V)	41.3	38.4	41.5	38.6	41.7	38.8	41.9	39.0	42.1	39.2
Current at maximum power (I _{mp} /A)	10.78	8.70	10.85	8.70	10.92	8.75	10.98	8.86	11.05	8.91
Module efficiency (%)	20.5		20.7		20.9		21.2		21.4	

STC parameters

NOCT parameters

Operating parameters

Operating temperature	-40°C ~ +85°C
Power output tolerance	0 ~ 3%
V _{oc} and I _{sc} tolerance	±3%
Maximum system voltage	DC1500V (IEC/UL)
Maximum series fuse rating	20A
Normal operating cell temp.	45 ± 2°C
Protection class	Class II
Fire rating	UL type 1 or 2 IEC Class C

Mechanical loading

Front side maximum static loading	5400 Pa
Rear side maximum static loading	2400 Pa
Hailstone test	25mm hailstone at the speed of 23m/s

Temperature rating (STC)

Temperature coefficient of I _{sc}	+0.050%/°C
Temperature coefficient of V _{oc}	-0.265%/°C
Temperature coefficient of P _{max}	-0.340%/°C

Temperature
coefficient
parameters

Manufacturer

LONGi

No.8369 Shangyuan Road, Xi'an Economic and Technological Development Zone, Xi'an, Shaanxi, China.

Web: en.longi-solar.com

Specifications included in this datasheet are subject to change without notice. LONGi reserves the right of final interpretation. (20211101V14)

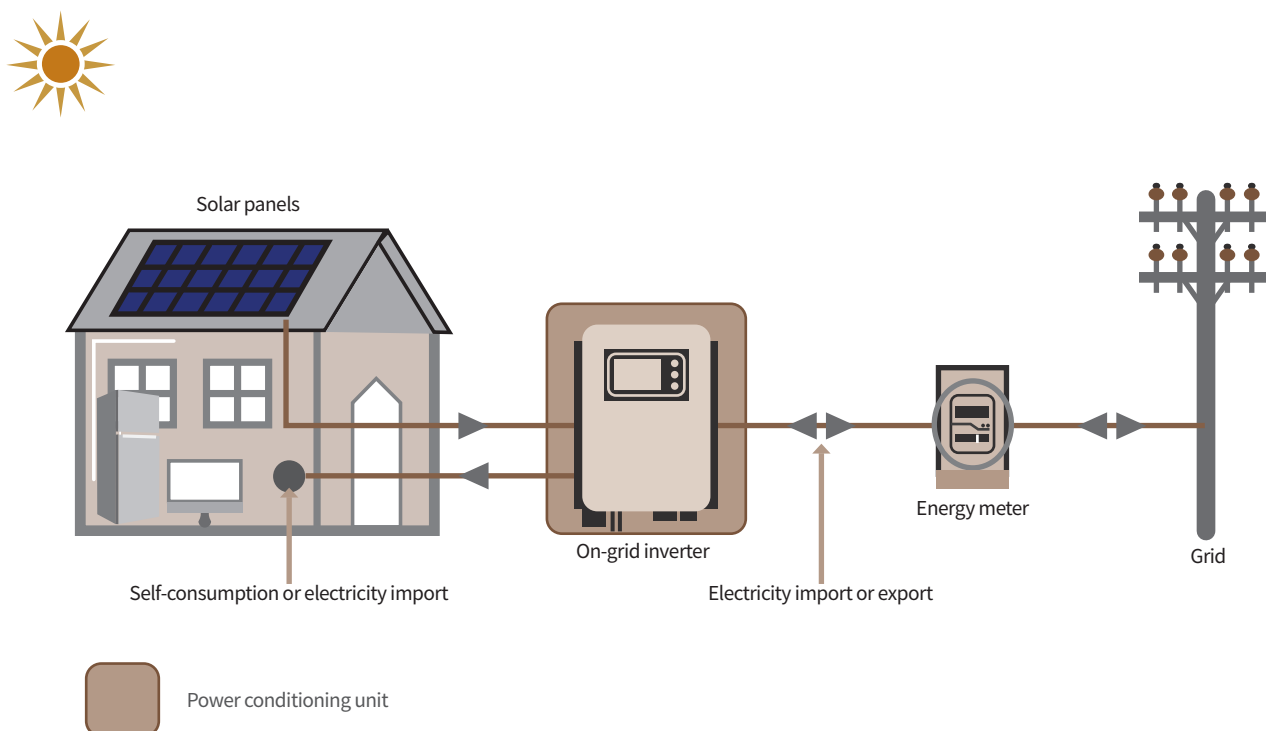
C. Power conditioning unit

The power conditioning unit includes devices such as an inverter that converts and regulates energy as shown in Figure 14.

On-grid inverter

On-grid inverters convert DC from solar PV input to AC and are synchronised with the grid for power ejection.

FIGURE 14 ON-GRID SOLAR PV SYSTEM



External resources

Basics of inverter is explained [here](#).

There are three main types of inverters: micro inverters, string inverters, and central inverters as shown in Figure 15.

FIGURE 15 TYPES OF ON-GRID INVERTERS



Image sources from left to right: ^[25], ^[26], ^[27]

Maximum power point tracking

Before we compare and contrast the three inverters, we should understand the concept of maximum power point tracking (MPPT).

MPPT is an algorithm that tracks the maximum power point in the IV curve at any given instance. Remember that the IV curve changes with external factors such as insolation and temperature. In Figure 16, each curve shows the IV characteristics at different irradiance and the peak of each curve represents the maximum power point. However, MPPT ensures that maximum power from the PV array is always extracted, thus maximising energy generation.

The differences between micro-inverter, string inverter, and central inverter are presented in the Table 4.

Keeping it all together



Almost all on-grid inverters have the MPPT feature with one or more MPPT independent inputs. The inverter datasheet specifies the working voltage range of the MPPT (e.g. 200 V to 1000 V) between which the MPPT algorithm best tracks the maximum power output from the PV array. This comes in handy while assessing the compatibility between the inverter and the configuration of the PV array.

TABLE 4 DIFFERENCES BETWEEN MICRO-INVERTER, STRING INVERTER, AND CENTRAL INVERTER

Micro-inverter	String inverter	Central inverter
Connected to each module's backside.	A series of string inverters can either be located centrally or spread over the PV array area connecting to different sections as shown in Figure 17.	Located centrally where large numbers of PV arrays connect as shown in Figure 17. For ease, imagine a container with all essential power conditioning units inside.
Capacity range in watts (W).	Capacity range in kilowatts (kW).	Capacity ranges from kilowatts to megawatts (MW).
Improved MPP tracking because each module is independently tracked.	Has several MPPT inputs that connect different PV array strings.	Has several MPPT inputs that connect different PV array strings, and houses several safety components as well as transformers in some cases.
Reduces DC cabling and other components (such as junction boxes, etc.) because each micro inverter outputs AC power.	Higher DC cabling compared to micro inverters because the PV strings need to be routed to the nearest inverter location.	High DC cabling because the PV strings need to be routed to a central location.
Modular and most reliable because if one micro-inverter fails, only one PV module is affected.	Modular and reliable because if one string inverter fails, others continue to generate power.	Less reliable than micro-inverters and string inverters because if the central inverter fails, the solar PV plant cannot generate power.
Having micro inverters over the whole array is more expensive than having string and central inverters.	Is cheaper than micro inverters.	Can be cheaper than string inverters due to pre-assembled components but need to keep in mind the practicality of on-site transportation and installation.
Micro inverters are very easy to monitor as they have panel-level monitoring capabilities.	Since there are multiple inverters in a system and they might be at different locations on any given site, it might require more maintenance than a single inverter.	Easy to monitor as only a few inverters are used, unlike multiple string inverters that require a sophisticated surveillance system.
Micro inverters are easier to transport because they are small.	Can be transported fairly easily.	Transporting it requires careful planning because of its larger physical footprint.

FIGURE 16 MAXIMUM POWER POINT TRACKING^[28]

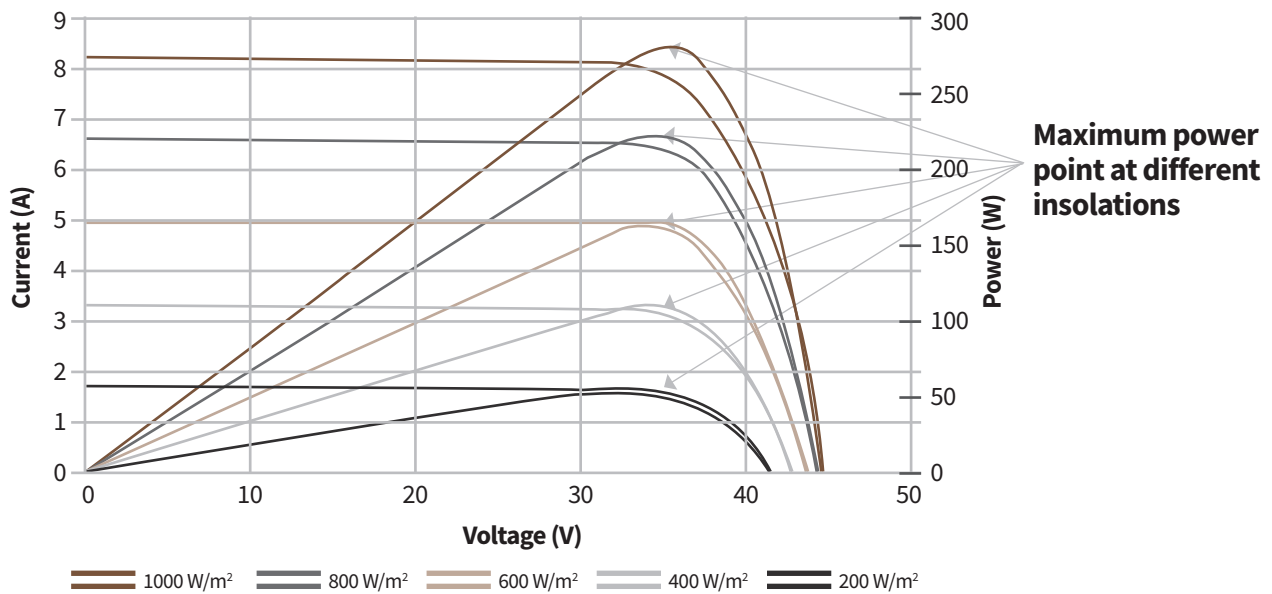
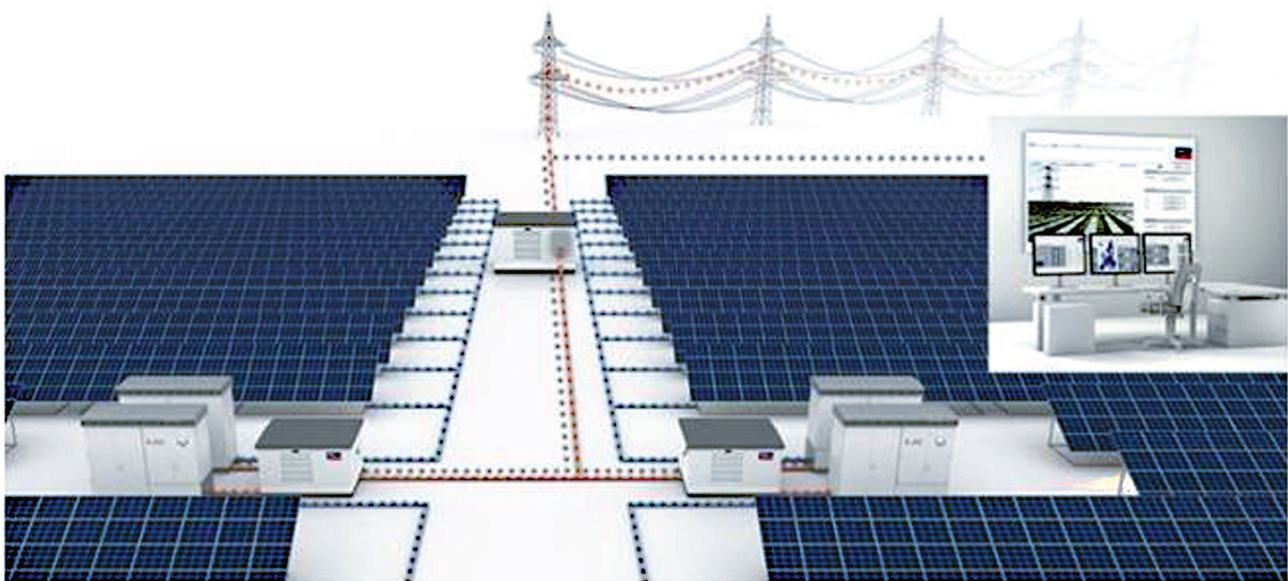
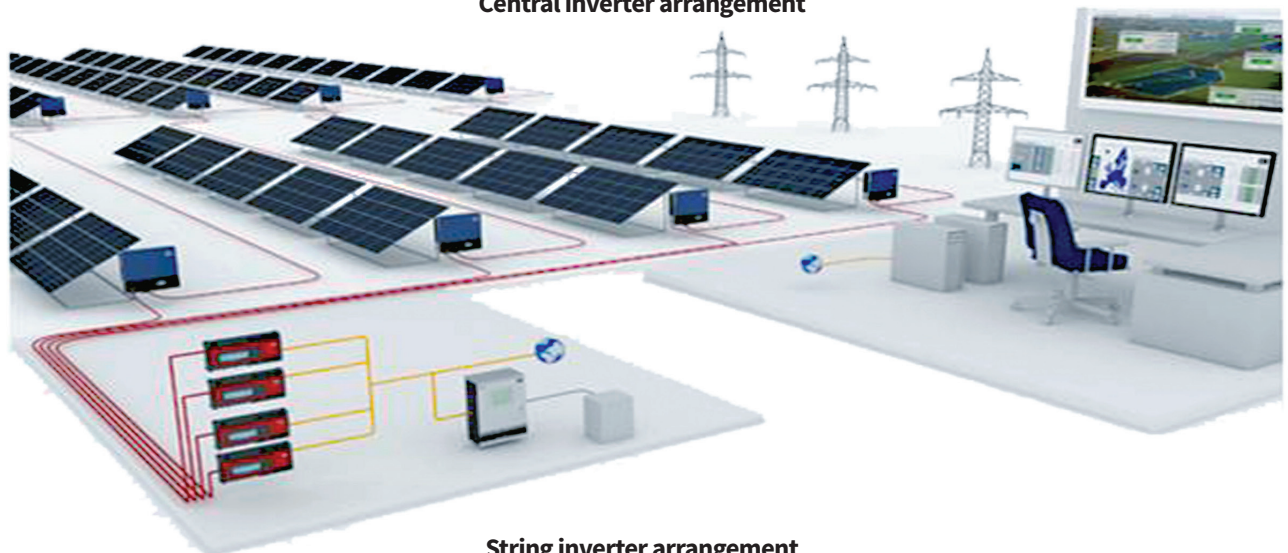


FIGURE 17 CENTRAL AND STRING INVERTER ARRANGEMENTS^[29]



Central inverter arrangement



String inverter arrangement

Reading the inverter datasheet

While selecting an inverter, you should check the following information on its datasheet:

1. Manufacturer and model number
2. Rated power capacity
3. Start-up and maximum input DC voltages
4. Optimal input DC voltage respective to output AC voltage
5. MPPT voltage range
6. Number of independent MPPT trackers and number of strings per MPPT tracker
7. Nominal output AC voltage
8. Operating temperatures
9. Standard protection features of the inverter
10. Inverter efficiency
11. Real-time communication options for on-site and remote monitoring
12. Warranty information

An example of an inverter datasheet is shown in Figure 18.

Keeping it all together



Imagine installing solar array on a facility with rooftops that have different orientations and also shading issues that are unavoidable. In this case, optimal operation of each PV module is needed to

maximise energy generation. Micro-inverters will maximise power generation because each PV module is independently tracked.

If you are installing a PV array on a facility with rooftops that have different orientations but no shading issues, groups of PV modules may be oriented differently. In this case, string inverters would be appropriate because strings from different PV groups and orientations can be connected to separate independent MPPT inputs in string inverters.

Now, think of utility-scale solar PV plants installed over several factory buildings with flat roofs. Here, central inverters would be appropriate because the inverters, along with other electrical components, can be centrally located and controlled.

FIGURE 18 SAMPLE SUNGROW INVERTER DATASHEET^[30]

SUN2000-100KTL-M1
Technical specification

Technical specification	SUN2000-100KTL-M1	Model
Efficiency		
Max efficiency	98.8% @480 V, 98.6% @380 V / 400 V	Efficiency of inverter
European efficiency	98.6% @480 V, 98.4% @380 V / 400 V	
Input		
Max. input voltage ¹	1,100 V	Max. DC input voltage
Max. current per MPPT	26 A	Input DC current
Max. short circuit current per MPPT	40 A	
Start voltage	200 V	MPPT operating range Optimal DC input voltage in respect to nominal output AC voltage
MPPT operating voltage range ²	200 V ~ 1,000 V	
Nominal input voltage	720 V @480 Vac, 600 V @ 400 Vac, 570 V @380 Vac	
Number of MPP trackers	10	No. of independent MPPT trackers and no. of string inputs per MPPT tracker
Max. input number per MPP tracker	2	
Output		
Normal AC active power	100,000 W	Rated power output
Max. AC apparent power	110,000 VA	
Max. AC active power (cosφ =1)	110,000 W	Voltage and frequency operating ranges
Nominal output voltage	480 V / 400 V / 380 V, 3W + (N) + PE	
Rated AC grid frequency	50 Hz/ 60 Hz	
Normal output current	120.3 A @480 V, 144.4 A @400 V, 152.0 A @380 V	
Max. output current	133.7 A @480 V, 160.4 A @400 V, 168.8 A @380 V	
Adjustable power factor range	0.8 leading... 0.8 lagging	
Max. total harmonic distortion	< 3%	
Protection		
Input-side disconnection device	Yes	Types of protections in the inverter
Anti-islanding protection	Yes	
AC overcurrent protection	Yes	
DC reverse-polarity protection	Yes	
PV-array string fault monitoring	Yes	
DC surge arrester	Type II	
AC surge arrester	Type II	
DC insulation resistance detection	Yes	
Residual current monitoring unit	Yes	
Arc fault protection	Optional	
Communication		
Display	LED indicators; WLAN adaptor + fusionSolar APP	Communication options for real-time monitoring
RS485	Yes	
USB	Yes	
Small dongle-4G	4G / 3G / 2G via smart dongle – 4G (Optional)	
Monitoring BUS (MBUS)	Yes (isolation transformer required)	
General data		
Dimensions (W x H x D)	1,035 x 700 x 265 mm	Dimensions, weight and operating temperatures
Weight (with mounting plate)	90 kg	
Operating temperature range	-25°C ~ 60°C	
Cooling method	Smart air cooling	
Max. operating altitude	4,000 m (13,123 ft.)	
Relative humidity	0 ~ 100%	
DC connector	Staubli MC4	
AC connector	Waterproof connector + OT/DT terminal	
Protection degree	IP66	
Topology	Transformerless	
Night time power consumption	< 3.5 W	
Standard compliance (more available upon request)		
Certificate	EN 62109-1/-2, IEC 62109-1/-2, EN 50530, IEC 61727, IEC 60068, IEC 61683	International standards compliances
Grid connection standards	VDE-AR-N4105, EN 50549-1, EN 50549-2, RD 661, RD 1699, C10/11	

* 1 The maximum input voltage is the upper limit of the DC voltage. Any higher input DC voltage would probably damage inverter.

*2 Any DC input voltage beyond the operating voltage range may result in inverter improper operating

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D. Balance of system

The balance of system encompasses all components of a complete on-grid solar PV system as shown in Figure 19.

The Table 5 describes the major components of the balance of systems.

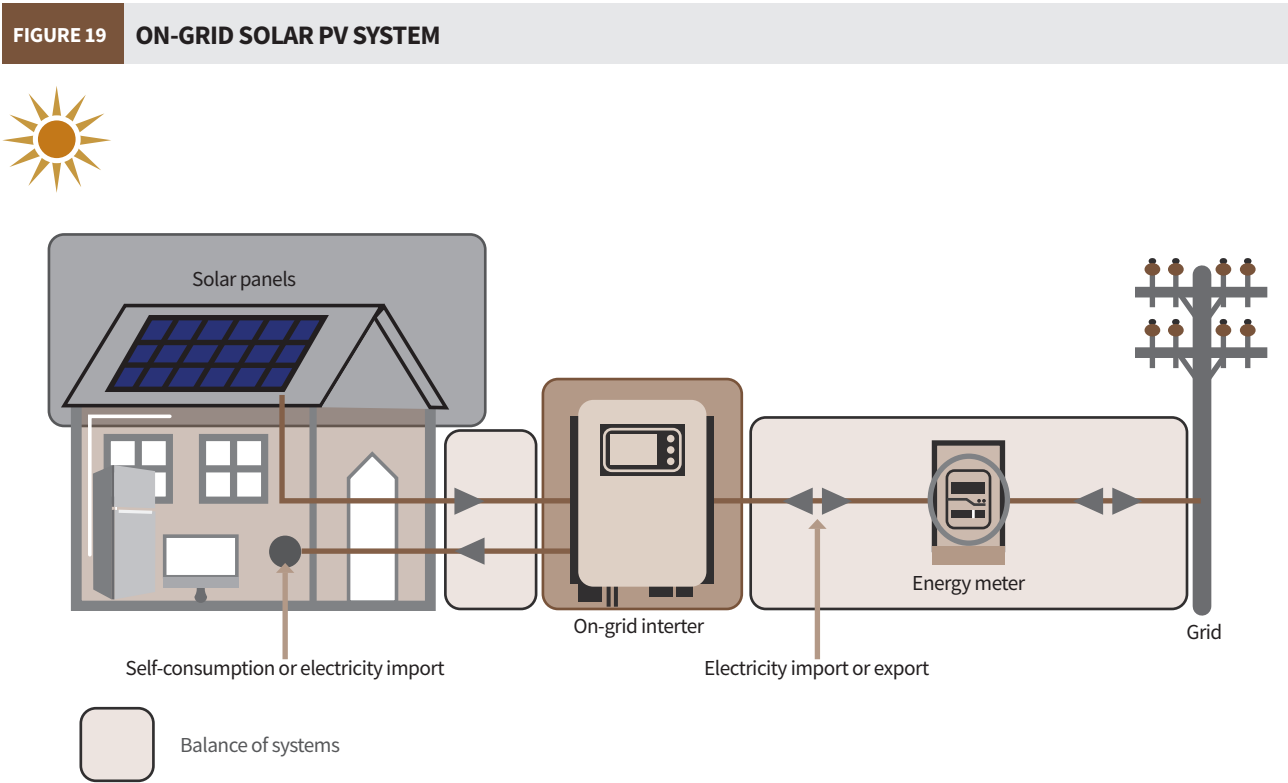


TABLE 5 DESCRIPTION OF THE BALANCE OF SYSTEMS			
Component	Description	Examples	Reference of images
MC4 connectors	MC4 connectors are standard PV module DC connectors that make it easy to secure a connection with the positive and negative terminals of a PV module.		[31]
PV array mounting structures	PV array mounting structures fix the PV modules in their desired locations.		[32]

Component	Description	Examples	Reference of images
Distribution boxes	Distribution boxes enclose smaller components of the system such as miniature circuit breakers, moulded case circuit breakers, and surge protection devices.		[33]
Junction boxes	<p>Junction boxes help connect multiple cables from different parts of the system to a few cables.</p> <p>For example, DC cables from multiple PV strings enter the junction box where they are connected to a common bus bar and only one set of cables is output from the junction box to the inverter.</p> <p>Junction boxes should be fire-proof and have an adequate IP rating, e.g. at least an IP65 rating for junction boxes installed outdoors.</p>		
Inverter and distribution box mounting structures	The inverters and distribution box mounting structures fix the inverters and distribution boxes in their desired locations (e.g. wall mount, floor mount, etc.). These structures need to be fabricated or assembled based on site conditions.		[34]
DC and AC cables	The DC and AC cables are used for the electrical interconnection of the various components.		[35]
Earthing and grounding cables	Earthing and grounding cables protect the system against current leakages and faults by providing a low resistance path for electricity to be dispersed on earth, ensuring safety for living bodies.		[36]
Surge protection devices	Surge protection devices protect the solar PV system against high electrical surges that can arise due to faults or lightning strikes. Surge protection devices then ground the electrical surge.		[37], [38], [39]
Miniature circuit breakers, moulded case circuit breakers and similar protection devices	Miniature circuit breakers (MCBs) and moulded case circuit breakers (MCCBs) protect the solar PV system against high currents and can also serve as an operating switch.		
Lightning air terminals	Lightning air terminals protect the PV array and its components against lightning strikes. The electrical surge attracted by the air terminals is grounded.		[40]
Remote monitoring systems	Remote monitoring systems enable solar PV system performance monitoring, data logging and fault identification.		[41]

Keeping it all together



For the solar PV system to function, various small components of the system need to come together and run properly. The two main components of the balance of system are power generation and power conditioning.

All components of the balance of system should be carefully selected to:

- Reduce system losses and optimise cost
- Ensure secure and reliable installation

Lack of attention to the balance of systems can increase failure points in the system, which adversely affects system performance.

PV module mounting structure

The mounting structure for fixing the solar modules should be chosen carefully as it influences some important aspects of the project. These include:

1. **Project cost:** It can be less than 5% of the project cost or higher.
2. **System performance:** The mounting arrangements lead to how the module will perform as the orientation and angle of tilt play a vital role in project economics, generation, and cost.
3. **Roof fixture:** The fixture for mounting needs to be carefully selected with appropriate design ratings and penetration, meaning how the mounting structure will be attached to the roof structure. For example, some options include fixing the structure to the purlin, gluing the structure to the roof sheet using appropriate adhesives, etc.

Some examples of roof mounting structures are shown in Figure 20.

Cables

Appropriate sizing of DC and AC cables is critical for ensuring the reliable performance of solar PV systems.

Keeping it all together



The selection of cable is directly related to the following:

- Power loss – undersizing cables can lead to high power losses while oversizing cables can lead to high system costs
- System reliability – cables of inadequate size, for example, cables that are undersized and too thin, can lead to fire hazards due to cable overheating

FIGURE 20

EXAMPLES OF SOLAR MODULE MOUNTING STRUCTURES ON ROOFS^[42]



Cables for DC and AC power are different. Some of the major parameters for cable selection are:

- **Material of the cable:** Common materials are copper and aluminium.
- **The cross-sectional area of the cable:** Increasing the cross-sectional area of the cable decreases resistivity.
- **Rated voltage:** Cables have a rated voltage to limit insulation breakdown.
- **Ampacity:** Ampacity is the current carrying capacity of the cable that needs to match the maximum current that will flow in the specific part of the solar PV system.

Note: Detailed sizing and selection of cables are beyond the scope of this handbook.

External resources

More on PV module mounting structure [here](#).

More about system protection [here](#).

One of many online tools for DC and AC cable sizing is [here](#).

E. Metering

There are various metering mechanisms adopted in different regions. Some of the tried and tested mechanisms are described below.

Net metering

In a net metering system, power exports are offset by imports, decreasing the electricity bill by deducting electricity generated from the total electricity consumed over a set period. The adjustments might be made on a monthly, half-yearly, or annual basis. A bidirectional 'net meter' typically accounts for both power import and export.

Net billing

In net billing, consumers are compensated for net excess electricity that is generated and exported to the grid under net metering laws. End-users can utilise net billing to offset retail electricity purchases, like net metering. The primary difference between net billing and net metering is that there are different rates used to value the excess energy fed into the grid and energy received from the grid under net billing^[43].

Gross metering

In gross metering, the consumer is compensated for all the solar electricity generated, which is exported to the grid at a fixed feed-in tariff rate. The consumer must pay the retail supply tariff to the power distribution company for the power consumed from the grid. Tariffs for feed-in and retail supply are rarely the same.

Figure 21 presents customer-end payment scenarios of the different types of metering if a customer consumed 150kWh of energy over a month (import) and exported 100kWh of energy from the solar PV on-grid rooftop system. The per kWh cost used in the scenarios is for example only. Actual rates will vary depending on the region.

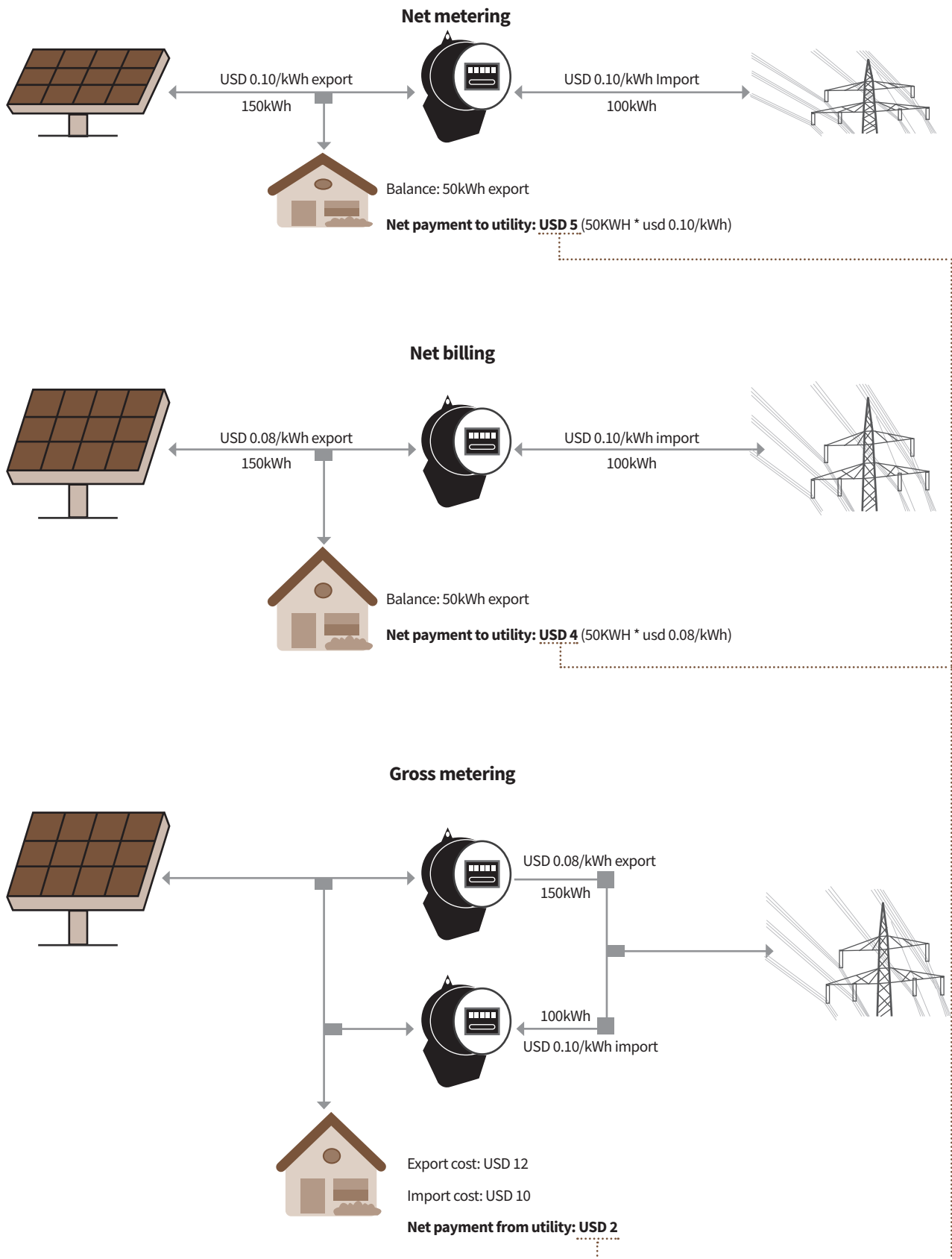
Keeping it all together



From the customer's perspective, return on investment is important. Thus, metering regulations must be carefully analysed to maximise financial benefits.

FIGURE 21 EXAMPLE OF METERING SCENARIOS FOR CUSTOMERS

Customer-end scenarios assuming 100kWh import and 150kWh export



Observe how the net payment to or from the utility can vary depending on the type of metering used.

F. International standards

All components of on-grid solar PV systems should meet national and international standards to ensure quality performance and results. A major international organisation that sets such standards is the International Electrotechnical Commission (IEC), a global, not-for-profit membership organisation whose work underpins quality infrastructure and international trade in electrical and electronic goods^[44].

Table 6 defines the standards of the major components of an on-grid solar PV system.

Note: The standards presented in the table below are by no means exhaustive because the relevance of standards is specific to the region. These standards are described for general guidance purposes.

TABLE 6 SOME RELEVANT STANDARDS OF MAJOR ON-GRID SOLAR PV COMPONENTS

Component	Key description of the component	Reference international standards
Solar module		Some of the major conformity include: IEC 61215-1:2016 and IEC 61215-2:2016 for Terrestrial photovoltaic (PV) modules - Design qualification and type approval – Part 1: Test requirements and Part 2: Test procedures. IEC 61730 for PV module safety qualification. IEC 62804 for detection of potential induced degradation (PID).
Solar mounting structure	- Aluminum adhesive-type structure or steel components with antirust coating - Designed for wind speeds of up to 47.2m/s or as per regional standards (subjected to regional standards)	Subjected to specific regions.
DC cables		UV-protected copper cables, voltage rating of 1500V depending on maximum DC system voltage
DC breakers		IEC 60947 - Low-voltage switchgear and control gear
DC SPD	Type I + II	IEC 61643-1 - Low-voltage surge protective devices – Part 1: Surge protective devices connected to low-voltage power distribution systems – Requirements and tests
DC MCBs		IEC 60947 - Low-voltage switchgear and control gear
On-grid inverter	String inverters	IEC 61683 - Photovoltaic systems - Power conditioners - Procedure for measuring efficiency IEC 62116 - Utility-interconnected photovoltaic inverters - Test procedure of islanding prevention measures IEC 61727 - Photovoltaic (PV) systems - Characteristics of the utility interface EN 50530 - Overall efficiency of grid-connected photovoltaic inverters IEC 60068-2 - Environmental testing IEC 62109-1/2 - Safety of power converters for use in photovoltaic power systems
AC cables	Armoured or unarmoured, copper or aluminium cables	
AC breakers		IEC 60947 - Low-voltage switchgear and control gear
AC SPD	Type I + II	IEC 61643-1 - Low-voltage surge protective devices – Part 1: Surge protective devices connected to low-voltage power distribution systems – Requirements and tests
Energy meter	Accuracy Class I + II	-

Component	Key description of the component	Reference international standards
Earthing		IS 3043 - Code of practice for earthing IEC 60364-7 - Low voltage electrical installations - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems
Lightning protection system		IS 3043 - Code of practice for earthing IEC 62305 - Protection against lightning
Monitoring system		CE-certified product is a product that has been assessed by the manufacturer and meets EU safety, health, and environmental protection requirements.
Outdoor mounted boxes (e.g. junction boxes)	At least IP65, UV stabilized	IEC 60529 - Degrees of protection provided by enclosures (IP Code)

External resources

Benefits of IEC standards are described [here](#).

G. Design

Beginning from this section, the handbook will focus on on-grid rooftop solar PV design. Before delving into the design process, it is important to understand the site audit process.

Site audit

It is customary for a solar PV system designer to conduct a site survey and gather information about local conditions and issues. The project begins with a site audit – a detailed examination of how a facility consumes power. A site audit answers critical questions regarding how much the facility will pay for power, what information and tools are required, and the processes to be followed on the site. Information collected during a site audit broadly relates to one of the following:

- Environmental and meteorological conditions
- Technical - Installation area, load patterns, energy metering, energy expenses
- Local regulations/compliances

A site study allows us to analyse the feasibility of installing an on-grid solar PV system that meets the customer's needs. A site study is therefore necessary for developing a correct and cost-effective solar energy production system.

Keeping it all together



Site audit is critical for achieving an optimal design that meets the customer's needs. Think of site audit as an 'input', and customer needs as the 'output'. If the input is incorrectly carried

out, then it will reflect on the output, i.e. the design will not be properly carried out and customer aspirations may not be fulfilled.

Environmental and meteorological conditions

When you start investigating the site, observe and record its environmental and meteorological conditions. The tasks include, but are not limited to, the following:

- Identify how dusty or clean the site is. This is needed to estimate the energy production of the solar PV modules and make improvements if necessary.
- Identify possible risks to the components of the solar PV system such as weak structures of the roof, non-ventilated room for placement of inverters, etc.
- Record GPS locations of the potential solar PV installation area to later extract meteorological data specific to the site.
- Identify the magnitude of shading in the potential solar PV module installation area.

Technical

Figure 22 broadly lists the kinds of information collected during a site audit and the kinds of analysis conducted based on this information.

FIGURE 22

ELEMENTS INVESTIGATED AND ANALYSED DURING A SITE AUDIT

Investigation	Analysis
What do we look for?	What do we extract?
<ul style="list-style-type: none">• Site location• Facility operation• Site layout• Building information• Electrical infrastructure• Energy audit	<ul style="list-style-type: none">• Load analysis• Meteorology• Solar array positioning• Mounting requirements• Shading sources identification• Cable conduit and routing• Positioning of components (e.g., inverter)• Communication

Investigation of the electrical layout

The steps for investigating the existing electrical layout are described below.

Step 1	Request the electrical layout of the facility from the contact person. If it is not available, draw a generalised layout including the incoming connection from the utility and how power has been regulated and distributed throughout the facility with their respective ratings (i.e. kV, kVA, KVAR, A, V).
Step 2	Identify the building that has the main distribution board and verify the connection type (voltages, 1 phase/3 phase).
Step 3	Record the existing wire or bus bar size at the main electrical point of the facility (for later selection of a current transformer) for inverter output connection and record the ratings of existing protection devices (such as MCCB rating).
Step 4	Record other backup systems such as generators and UPS inverters along with their switching and protection systems. Also, make note of major electrical infrastructure components such as capacitor banks, stabilisers, etc.

Investigation of site layout

Below are the steps for investigating the site layout.

Step 1	Request a layout of the facility from the contact person. If it is not available, draw a generalised layout presenting all the buildings and roofs with their proper azimuth orientation. Take 360° videos/pictures from each roof and mark the point on the layout from where it has been taken.
Step 2	Once all the information has been collected, summarise the information on panel placement, structure type, and roof type. Make a detailed diagram to clearly illustrate the information. The diagram should have at least three views (top, front and side view) of the roof, and in some cases, it may require additional views. The diagram should contain information about the dimensions of the roof, net available panel area, type of shading structures and skylights, cable route on each roof, purlin type and its spacing.

Purlin type and spacing should be properly assessed before laying out PV modules on the roof as shown in Figure 23.

Once the strength of the purlins is assessed, the mounting points of the solar module rails are defined. As an example, the resulting layout of the solar array on a rooftop is shown in Figure 24.

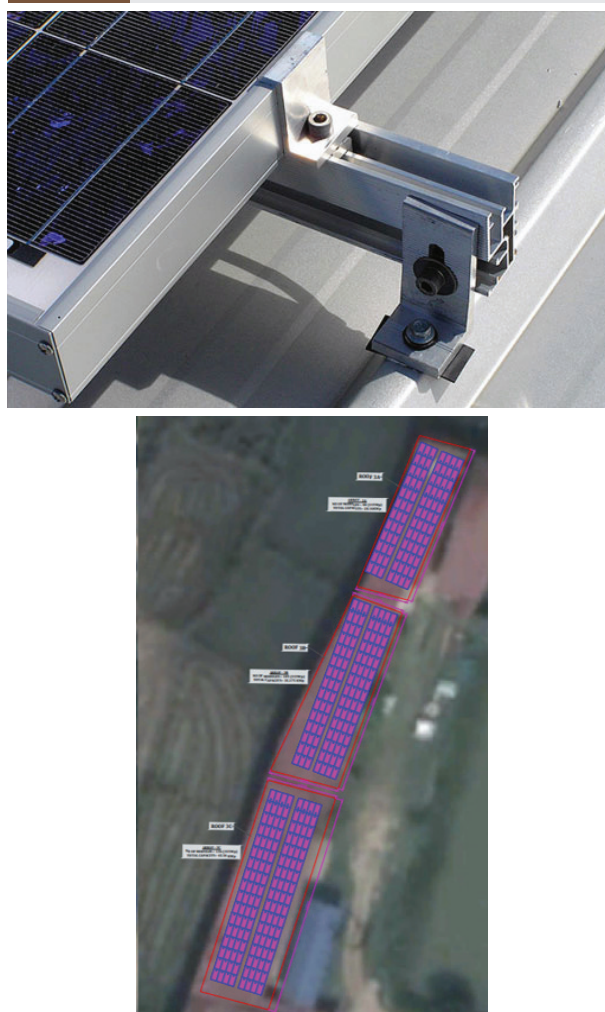
FIGURE 23

ROOF OUTSIDE, (TOP) ROOF PURLIN INSIDE (BOTTOM)



FIGURE 24

SOLAR MODULE RAIL MOUNTING^[32], (TOP) ARRAY LAYOUT IN THE ROOF (BOTTOM)



Module layout optimisation

The number of modules that can fit on a roof depends on whether the modules are mounted in landscape or portrait arrangement. Although this does not affect energy generation because the number of modules installed is the same, the choice of module arrangement impacts the cost of the system as a whole. For example, as shown in Figure 25, for the same length of the solar mounting rail, four modules can be installed in portrait orientation, whereas only two modules can be installed in landscape orientation. Therefore, for a narrow-length roof, portrait orientation may be the best option.

Note: This is just one case presented as an example. The best type of orientation depends on the roof type.

Historical audits in the past

To understand the load and energy consumption pattern of the facility, it is recommended to ask for electricity bills for at least one year before the date of the audit. The bills should indicate the units

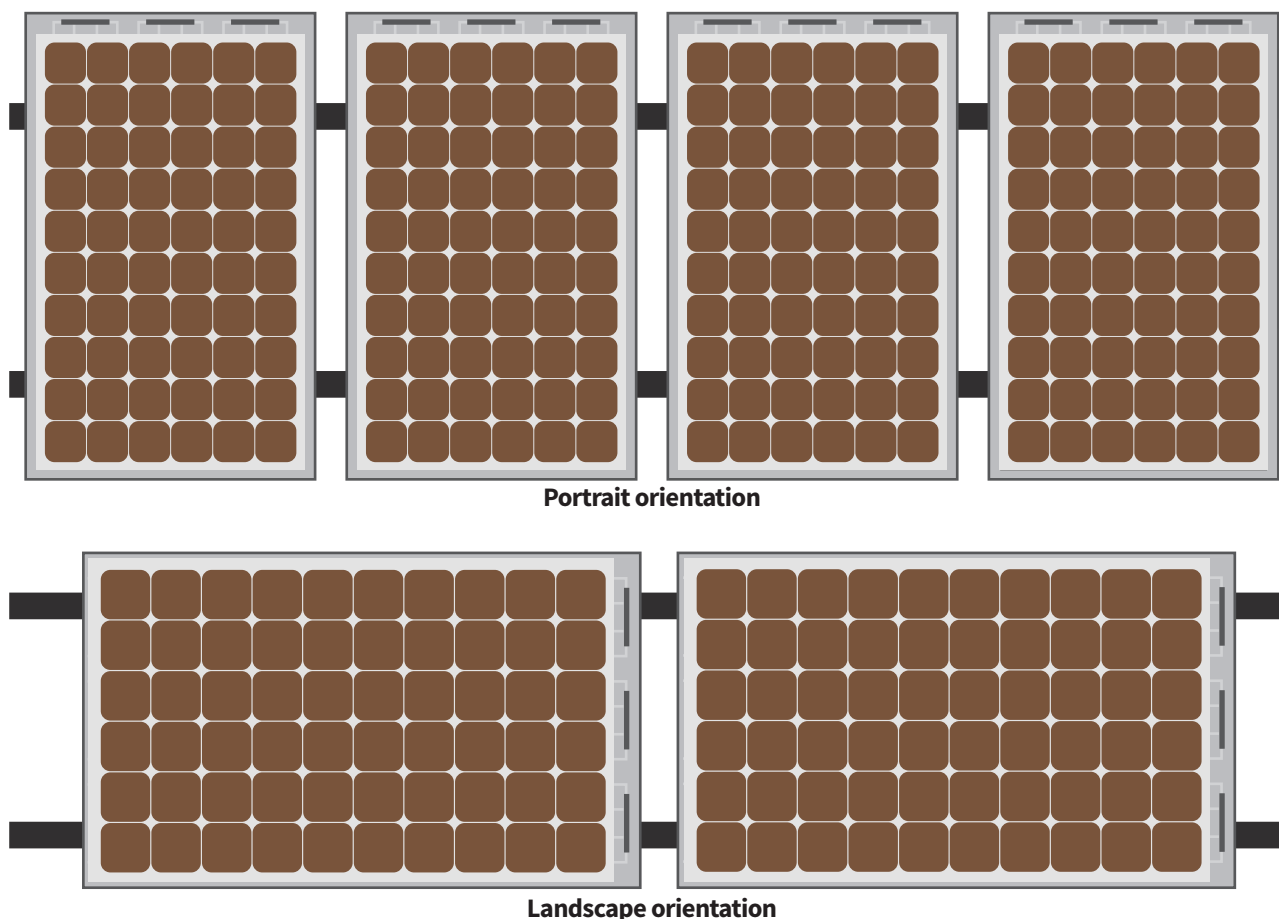
consumed and electricity tariff for all the hours (peak, off-peak and normal) as well as the demand charge.

Power loggers as shown in Figure 26 can be used to measure electrical parameters for a period.

FIGURE 26 POWER LOGGER^[45]



FIGURE 25 SOLAR MODULES ARRANGEMENTS



Keeping it all together



1. Power logger
2. Multimeter
3. Laser distance measure
4. Compass (available on phone)
5. Measuring tapes
6. Inclinator
7. Sun-path app (available on phone)

Local regulations/compliances

It is important to understand the local regulations to ensure that the solar PV system complies with regulatory requirements. For example, local regulations may require specific protection systems for safety, voltage, frequency tolerances, etc.

Upon completion of the site audit, a decision will be made on whether to go ahead with the further design of the solar PV system. If the site audit reveals that the customer aspirations cannot be met, say, because of a small roof area, high shading, maximum load use at non-sunshine hours, etc., then the customer may not find it worthwhile pursuing a detailed design.

However, upon site audit, if the site is feasible for an on-grid solar PV system and shows promise to meet the customer's aspirations, information from the site audit is used to prepare the design.

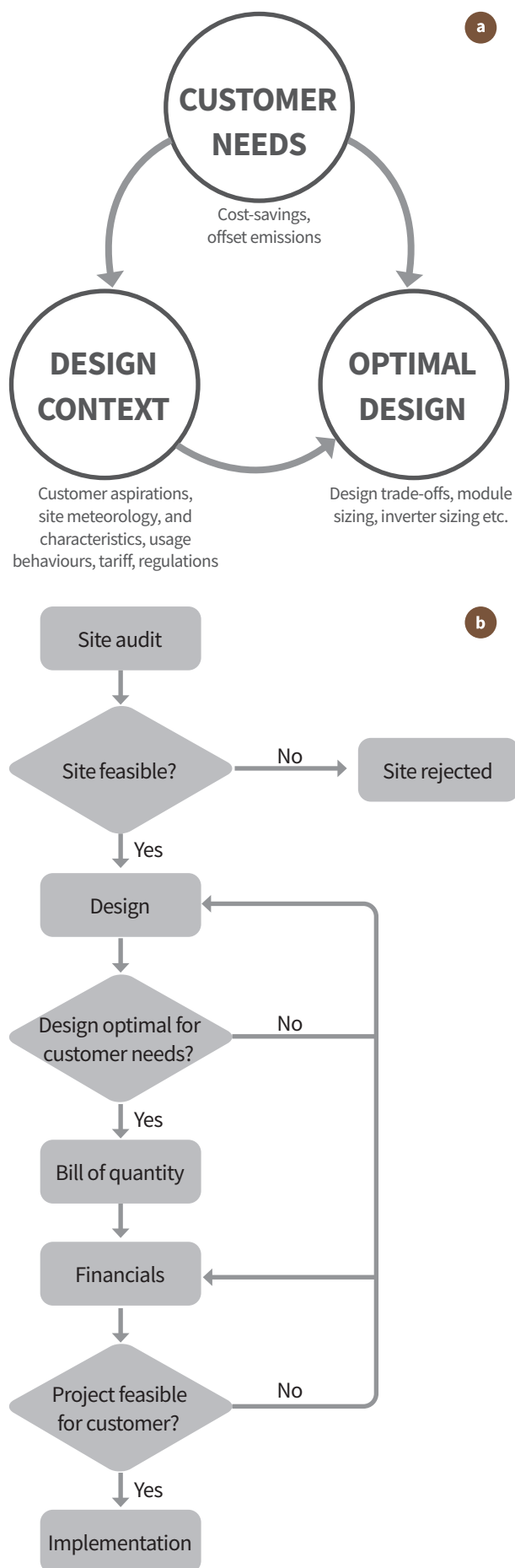
Design principles

This handbook takes a demand-side approach to designing a solar PV on-grid system. First, understanding the customer/beneficiary's needs is paramount. Second, the designer needs to understand the local context, and constraints such as metering regulations, meteorological conditions, roof space, load usage, etc. Third, based on the customer need and the local context, the designer has to design an appropriate system through an iterative optimisation process. Figure 27a depicts this process.

Design flowchart

Now, with the design principles established, the flowchart in Figure 27b shows the general steps in the design process.

FIGURE 27 DESIGN PRINCIPLES



The design process is described in detail in the following sections.

Design walkthrough – I

In this design case, a simple manual calculation for a quick (back-of-the-envelope) energy estimation is presented. To validate the estimation, a comparison with simulated energy production is performed.

Manual calculations allow us to get a quick snapshot of the solar PV system features before we dive into the detailed design process, which requires more resources and time.

As we move on to the design phase, remember the design principles: customer needs, design context, and optimal design.

Customer needs

A customer wants to install a 3kWp on-grid solar PV system on the roof of their house that will be net-metered. The solar PV subsidy scheme for a standard 3kWp capacity for the region allows customers to get the best value for money.

To quantify their earnings from net metering and before deciding whether to install the system, the customer wants to know how much energy the system will produce in a year.

Design context

STEP 1: SITE FEATURES

Figure 28 shows the customer’s rooftop that is in ideal condition. Let us assume that this site is in the northern hemisphere; PV modules will hence be installed only on the south-facing roof.

The objective here is to estimate the annual energy generation of a 3kWp on-grid solar PV using a quick and easy method.

The features of the roof are described in Table 7.

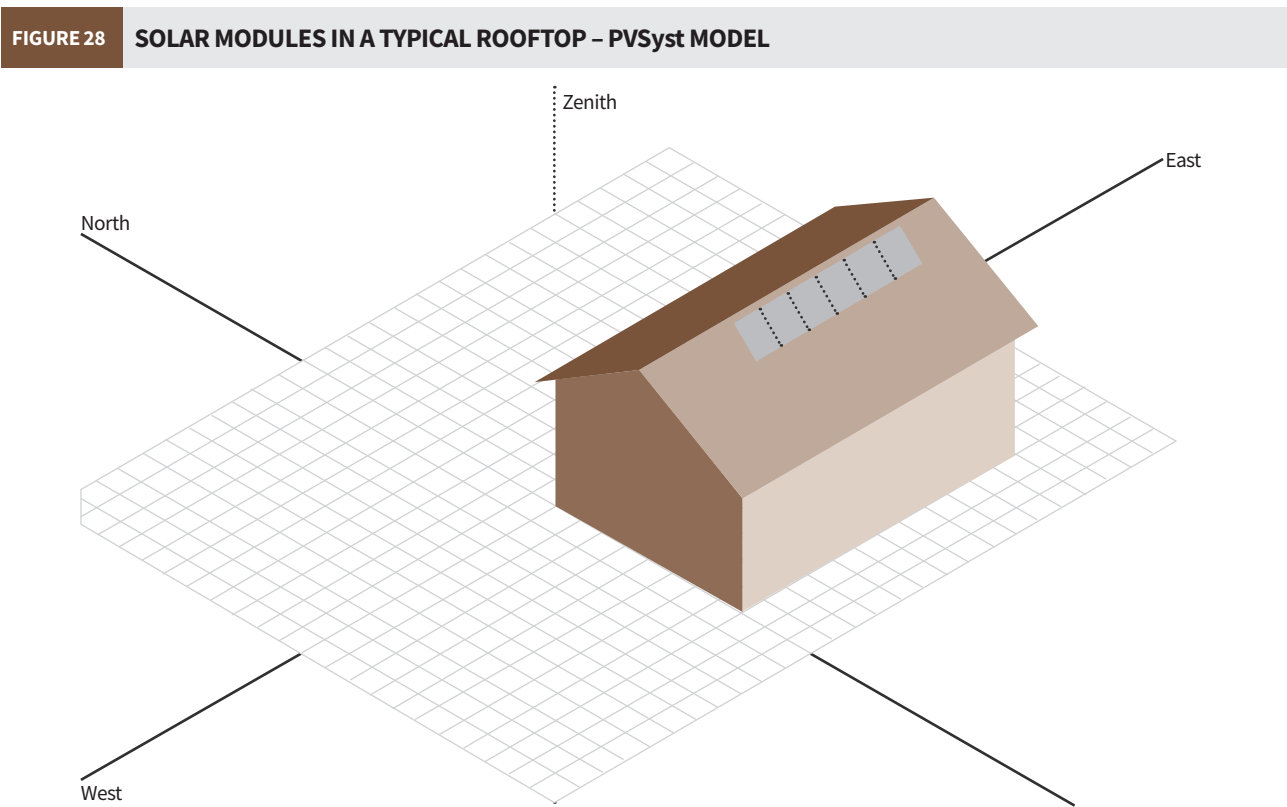
TABLE 7	DESCRIPTION OF ROOF FEATURES
Roof inclination	30° (both sides)
Roof direction	North-south
Azimuth	0°
Available roof area	15m length x 4m breadth
Grid connection	230Vac, 50Hz

Optimal design

STEP 2: METEOROLOGICAL INFORMATION

Let us assume that the site audit has been completed and the process has reached the design stage.

Remember that meteorological information from the site is needed to estimate energy generation. After



the site audit, the following irradiance data were extracted for the facility.

In this case, the meteorological data, especially the irradiance data, is obtained from PVSyst software.

The categories in the column of Figure 29 are defined below:

GlobHor – global horizontal irradiance in kWh/m²

DiffHor – diffuse horizontal irradiance in kWh/m²

T Amb – ambient temperature in °C

GlobInc – global inclined irradiance in kWh/m²
(optimal tilt for a specific location)

FIGURE 29 IRRADIANCE DATA OBTAINED FROM PVSyst SOFTWARE				
	GlobHor kWh/m ²	DiffHor kWh/m ²	T Amb °C	Globinc kWh/m ²
January	130.6	28.97	16.94	194.6
February	122.5	46.90	19.53	155.9
March	150.4	74.54	23.14	168.1
April	150.6	88.70	24.70	149.1
May	168.9	90.69	27.25	155.4
June	162.7	92.16	27.96	145.1
July	161.4	90.94	28.87	146.5
August	137.6	95.48	28.97	131.4
September	127.8	76.61	27.79	132.2
October	122.9	63.42	26.21	144.4
November	122.4	39.73	22.02	170.3
December	123.3	25.98	18.53	192.3
Year	1681.2	814.11	24.35	1885.2

↑
Annual global irradiance
in an inclined plane

Keeping it all together



There are various software for meteorological data and solar PV system design simulations, such as:

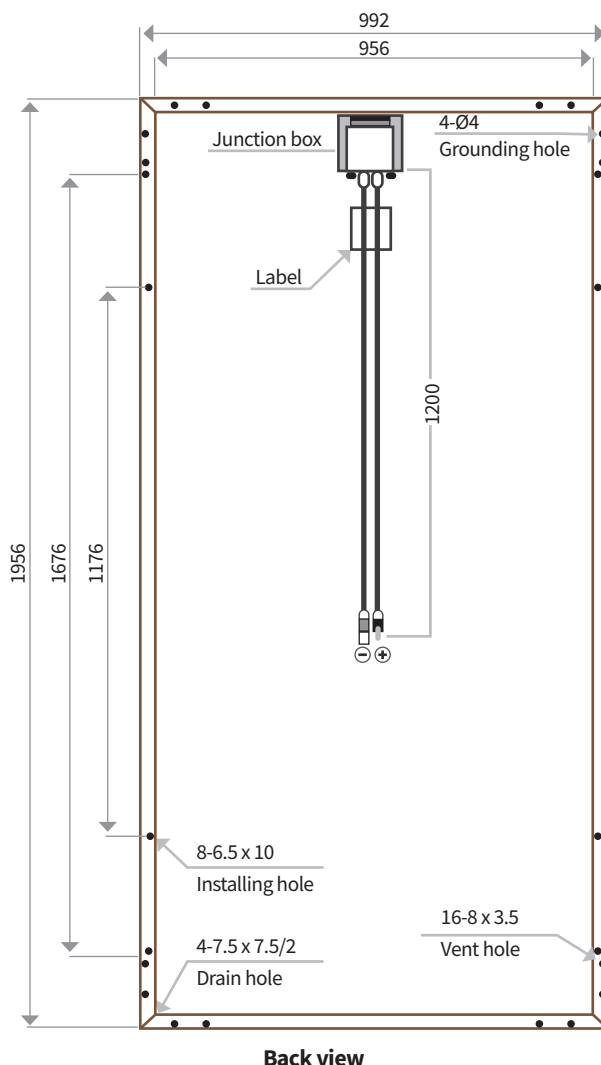
- PvSyst
- Pvsol
- Homer
- SAM
- SolarGIS apps
- HelioScope

STEP 3: SYSTEM SIZE AND ENERGY GENERATION ESTIMATIONS

Now, let us assume that the area of each solar module is 2m² for a 370Wp module (see Figure 30 for dimensions). At least eight modules are needed for a 3kWp (2.96kWp) system.

FIGURE 30 EXAMPLE OF A 370WP SOLAR PV MODULE PARAMETERS

Electrical data ^{1,2} All data refers to STC			
Peak power P _{max} (Wp) (0 ~ +4.99Wp)	365	370	
Maximum voltage V _{mpp} (V)	39.8	40.0	
Maximum current I _{mpp} (A)	9.17	9.26	
Open circuit voltage V _{oc} (V)	48.3	48.5	
Short circuit current I _{sc} (A)	9.73	9.84	
Modul efficiency η (%)	18.81	19.07	



Source: Vikram Solar

Similarly, taking an average module efficiency of 19% (monocrystalline modules) and total system efficiency of 80%, the average annual energy generation is calculated as follows:

$$2\text{m}^2 * 8 \text{ modules} * 0.191 \text{ module efficiency} * 0.8 \text{ system efficiency} * 1,885.2 \text{ global inclined irradiance} = \mathbf{4,608 \text{ kWh}} \text{ (annual).}$$

These types of calculations are known as manual calculations.

Comparison with simulated generation

To validate the annual energy generation of a 3kWp (2.96kWp to be precise) on-grid solar PV calculated in the previous section, the energy generation value is compared with the simulated energy generation via PVsyst software.

In this section, the same design example is used to determine the sizing of the major components and calculate the energy generation via software.

STEP 1: PV MODULE

For example, the available solar PV module is 370Wp and its technical parameters are given in Table 8.

For a 3kWp solar PV system, eight 370Wp solar modules are used with a cumulative capacity of 2.96kWp.

TABLE 8 SOLAR MODULE PARAMETERS		
Testing condition	STC	NOCT
Maximum power (Wp)	370	274.1
Open circuit voltage (Voc)	48.3	45.1
Short circuit current (Isc)	9.84	7.93
Voltage at maximum power (Vmp)	39.4	36.4
Current at maximum power (Imp)	9.39	7.53
Module efficiency (%)	19.1	19.1
Temperature coefficient of Isc	+0.057%/C	
Temperature coefficient of Voc	-0.286%/C	
Temperature coefficient of Pmax	-0.370%/C	

STEP 2: ON-GRID INVERTER

The next step is to select a solar on-grid inverter. Some options are presented in Table 9.

Among the three options, the appropriate inverter for a 2.96kWp solar array is Option 2. This is because considering DC to AC conversion losses, the nearest

AC power rating is 2kVA while accommodating a solar PV array of 2.96kWp (max. PV array power is 3kWp).

STEP 3: COMPATIBILITY CHECKS

Now, the solar modules should be arranged to meet the technical parameters of the on-grid inverter and the electrical parameters must be compatible with the electrical features of the site.

From the compatibility checks shown in Table 10, it can be concluded that the inverter is compatible with the system and the solar PV array arrangement is defined (all modules in series).

STEP 4: EFFICIENCIES AND ENERGY GENERATION SIMULATION

Next, before calculating energy generation, we need to learn about system efficiencies.

EFFICIENCY

Every electrical system incurs losses. Similarly, in an on-grid solar PV system, as energy is converted and transmitted via different components and materials, there are losses incurred in each step. Figure 31 shows the types of losses in each major component of on-grid solar PV systems.

Table 11 describes the recommended values for the losses.

Soiling effect: The glass of the solar PV modules can accumulate dust, bird droppings, etc. over time. These obstructive layers reduce the transmission of solar incident rays to the solar cells, thus reducing solar irradiation and power output. Soiling can significantly reduce the solar module's performance; thus, regular cleaning is very important.

The system efficiency of an on-grid solar PV system with no storage can be calculated using this formula:

System efficiency (η) = PV side efficiency (soiling, array mismatch, temperature losses, etc.) * inverter efficiency * DC power efficiency * AC power efficiency

Table 12 shows the calculation of monthly and average annual energy generation.

The average annual generation of the system is **4,739 kWh**. Comparing this detailed calculation with the back-of-the-envelope calculation (**4,608 kWh**), the variation is 2.8%. This shows that back-of-the-envelope calculation can provide a quick estimation of energy generation. However, a detailed estimate is important if the project is to be implemented.

TABLE 9 **OPTIONS FOR ON-GRID INVERTERS**

	Option 1	Option 2	Option 3
Input DC			
Max. PV array power (Wp)	2250	3000	3750
Max. DC voltage (V)	450	450	550
Nominal DC operating voltage (V)	360	360	360
Max. input current (A)	14	14	14
Max. short circuit current (A)	16	16	16
MPPT voltage range (V)	50-430	50-430	55-530
Start operating voltage (V)	50	50	70
No. of MPP trackers	1	1	1
Stings per MPP tracker	1	1	1
Output AC			
Nominal AC power (VA)	1500	2000	2500
Max. AC power (VA)	1650	2200	2750
Nominal grid voltage (AC voltage range) (V)	220/230/240; 180~280		
Nominal grid frequency/range (Hz)	50/60; +/-5		
Nominal AC current (A)	8.7	8.7	10.8
Max. AC current (A)	9.6	9.6	11.9
Displacement power factor	0.8 leader ~ 0.8 lagging		
THDi, rated power (%)	<3		
Efficiency			
MPPT efficiency (%)	99.9		
Euro efficiency (%)	96.5	96.5	96.5
Max. efficiency (%)	98.0	98.0	98.0

TABLE 10 **ASSESSING THE COMPATIBILITY OF THE ON-GRID INVERTER**

	Inverter parameter	Actual system design parameter	Check
Max. PV array power (Wp)	3000	2960	OK
Max. DC voltage (V)	450	386.4 (eight 370Wp modules in series)	OK
Max. short circuit current (A)	16	9.84 (one string/parallel arrangement of modules)	OK
MPPT voltage range (V)	50-450	315.2 (eight 370Wp modules in series)	OK
Nominal grid voltage (AC voltage range) (V)	220/230/240; 180~280	230	OK
Nominal grid frequency/range (Hz)	50/60; +/-5	50	OK

FIGURE 31 TYPES OF LOSSES IN EACH MAJOR COMPONENT

Solar module	Inter-cable connection	Inverter	Cables	Injection point loss
Environmental loss (temperature, convection, etc.) Array mismatch, soiling, snow, shading, etc.	Wire loss (voltage drop)	Inverter efficiency (at load, altitude, temperature)	Wire loss (voltage drop)	Voltage drops

TABLE 11 RECOMMENDED VALUES OF SYSTEM LOSSES

Parameters	Equation/Range /Value	Symbol	Recommended values
Soiling de-rating	Site dependent	S_D	• Site dependent, normally 1–3% or more
Temperature coefficient of maximum power output	Refer to the manufacturer specifications sheet	T_p	• Refer to the manufacturer specifications sheet
Average PV module operating temperature	Site dependent	T_{OP}	• 20–30°C above average ambient temperature
Module power de-rating	$1+(T_p/100*(T_{OP}-25^{\circ}\text{C}))$	T_D	–
DC interconnection wire loss		W_L	• Normally less than 3%, depending on financial optimisation
Array mismatch		A_M	• 2% for most modules and systems with long strings • 1% for modules that have low wattage tolerances • 0% is automatically used on modules with DC optimisers or microinverters

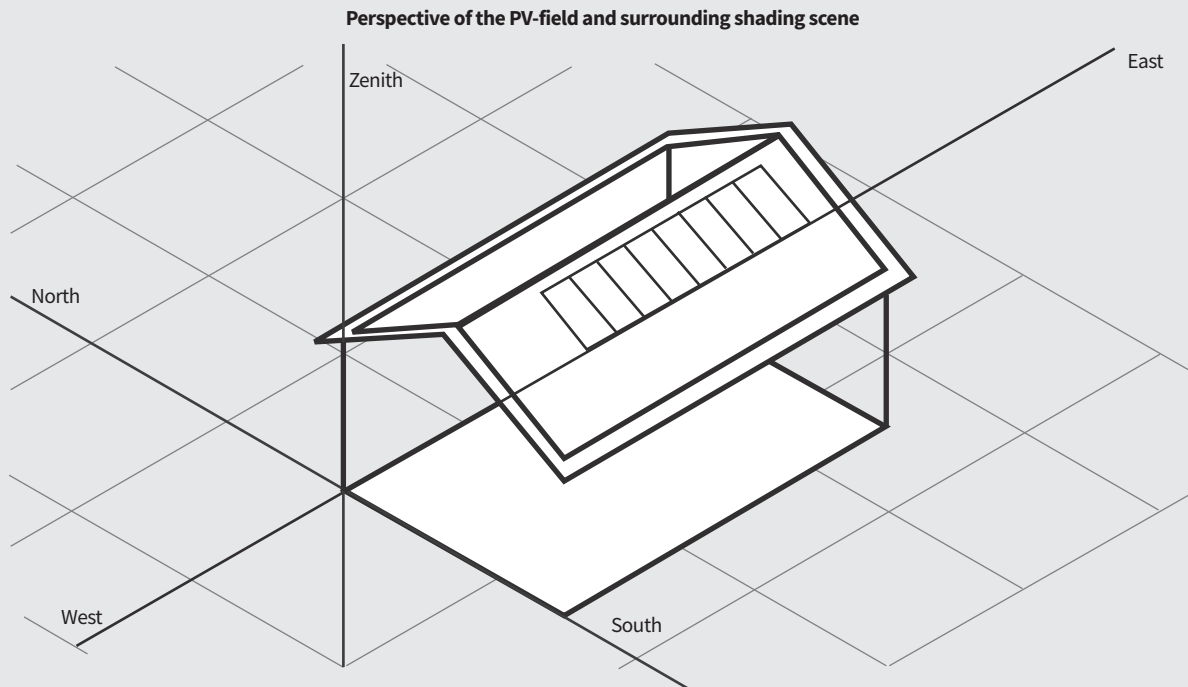
TABLE 12 CALCULATION OF ANNUAL ENERGY PRODUCTION

Months	PVSyst data Global incident (kWh/m ²) [A]	PVSyst data Avg. ambient temp (°C) [B]	Converted to days Daily global incident (kWh/m ²) [B = A ÷ month days]	Losses due to temperature Eff (temp) % [C]	Overall system efficiency Total system eff % [D]	Converted to months Avg. daily production (kWh) [E = B * C * D * 2.96kWp]	Avg. monthly production (kWh) [F = E * month days]
Jan	194.6	16.9	6.3	96%	87%	16	503
Feb	155.9	19.5	5.6	95%	86%	14	399
Mar	168.1	23.1	5.4	93%	85%	14	424
Apr	149.1	24.7	5.0	93%	85%	12	374
May	155.4	27.3	5.0	92%	84%	12	385
Jun	145.1	28	4.8	91%	84%	12	359
Jul	146.5	28.9	4.7	91%	83%	12	361
Aug	131.4	29	4.2	91%	83%	10	324
Sep	132.2	27.8	4.4	92%	84%	11	327
Oct	144.4	26.2	4.7	92%	84%	12	360
Nov	170.3	22	5.7	94%	86%	14	431
Dec	192.3	18.5	6.2	95%	87%	16	494
Total							4,739

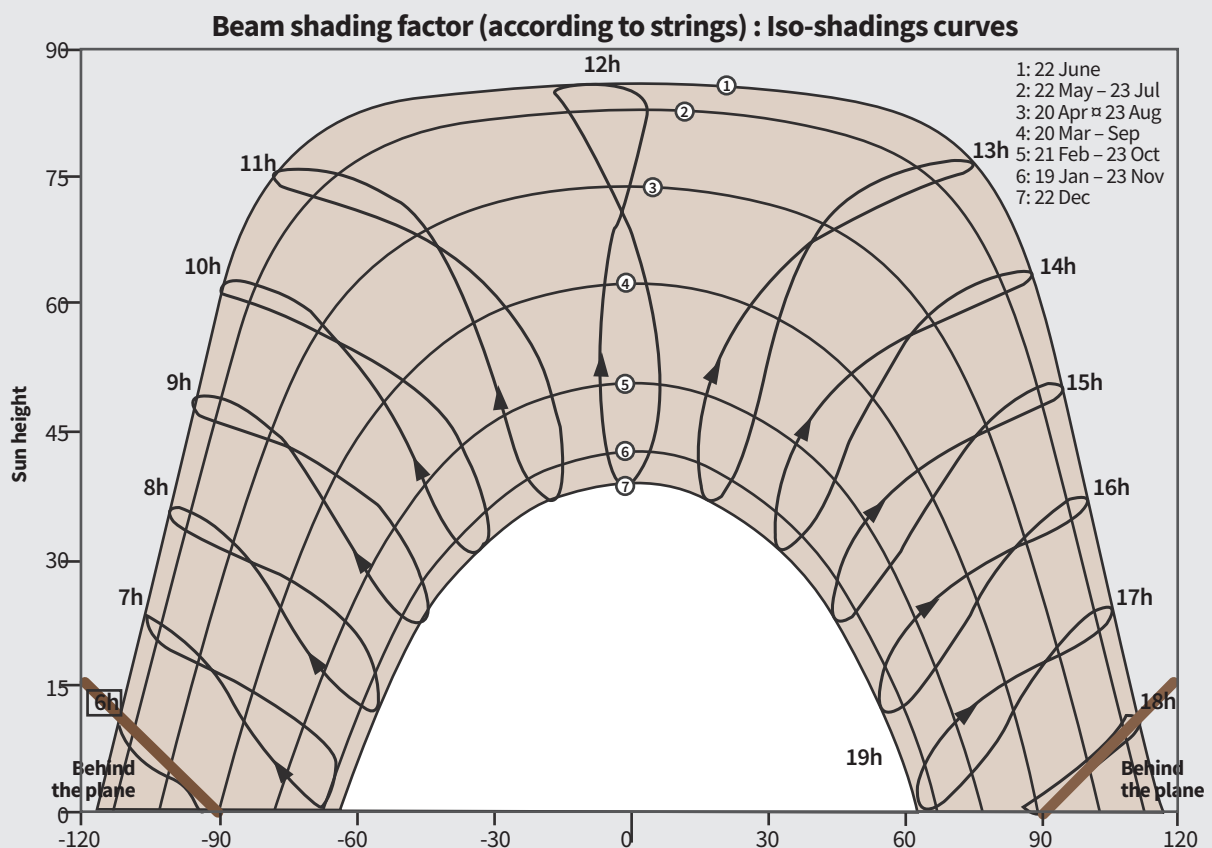
Just so you know!

Modelling and far-shading analysis features in PVSyst

For simulations, PVSyst software has advanced features such as 3D modelling of buildings with solar PV array arrangements and location-specific far shading analyses, as shown in the figures below.



Iso-shadings diagram



Keeping it all together



Keep in mind that Design Walkthrough 1 has ideal roof conditions, i.e. zero azimuth, 30° sloped roof optimal for the site location, and no shading effects. Real-life situations rarely match this scenario. Next up, we will look at an example with a more complex roof structure.

Design walkthrough – II

In the example presented in the previous section, the site features were convenient for solar array arrangement and did not require complex design decisions. For example, the roof faced south (optimal for regions such as Nepal and Bhutan), its inclination was 30°, and there were no near and far shadings.

However, given that solar PV rooftops must be designed according to site conditions, the roof conditions may present a challenge to system design. In this section, system design in a more complex building structure is presented.

Customer needs

In this hypothetical scenario, the owner of Hotel Kathmandu aspires to install an on-grid solar PV system to reduce the cost of electricity, expecting investment returns of 30% and marketing as a green hotel. The owner is interested in leveraging maximum debt, which can be financed through savings made by solar PV-generated electricity cashflows.

Design context

Hotel Kathmandu has 67 rooms, and the historical average occupancy is 70%, with a similar year-on-year consumption pattern. The facility has recently invested in a new building so there is no expansion plan for the next 10 years. The power quality in the facility has been stable, with no recorded incidents of equipment damage. The facility operates 365 days a year.

The hotel has three buildings (Figure 32):

FIGURE 32 BIRD'S-EYE VIEW OF BUILDINGS A, B AND C



Source: Image obtained from Google Earth

Building A: Accommodation and conference halls

Building B: Accommodation, restaurant and admin

Building C: Store and staff rooms

The hotel is connected at 11kV with a transformer of 200kVA which steps down to 440V 3-phase and is centrally distributed with the main distribution board located in Building C.

There are two back diesel generators of 62kVA and 125kVA each that are operated via a manual changeover switch. The facility has no alternative backups, capacitor banks or stabilising units.

The facility is connected with a Time of Day (ToD) Meter and there are three tariffs during the day (Table 13).

TABLE 13 TARIFFS AT DIFFERENT TIMES OF DAY

Time	Tariff (USD)
T1 - 5 PM to 11 PM	0.10/kWh
T2 - 5 AM to 5 PM	0.088/kWh
T3 - 11 PM to 5 AM	0.055/kWh

The hotel has an approved load of 200kVA.

The utility has a net billing regulation with a tariff of USD 0.058/unit.

Note: These example conditions are for Nepal. Electricity metering and tariffs may vary across countries.

Site audit outcomes

It is known that no energy audit has previously been carried out in the facility. However, electricity bills from one year have been obtained and the average daily consumption of the hotel is 964 units (kWh).

Monthly energy consumption based on the electricity bills is shown in Figure 33.

The minimum monthly electricity consumption of 16,900 units was recorded in October and the maximum monthly electricity consumption of 37,590 units was recorded in July. This is largely due to summer air-conditioning loads.

In T2 hours, the electricity consumption ranges from 8,750 units to 19,225 units in October and July respectively.

respectively. The maximum consumption is during the day which is almost 50% of the total daily energy consumption.

Similarly, the average daily consumption trend over the year is shown in Figure 34.

The average daily consumption in T2 is 494 units with a maximum of 624 units in June and a minimum of 282 units in October. The recorded peak demand reached a maximum of 107kVA and a minimum of 53kVA in September and October respectively.

During the audit, peak demand for T2 was found to be maximum during the early hours due to the kitchen and bakery unit loads, while for the rest of the day, the load normally ranged from 25 to 50kW depending on the occupancy.

FIGURE 33 ELECTRICITY USAGE OF HOTELS IN KATHMANDU (BASED ON ELECTRICITY BILLS)

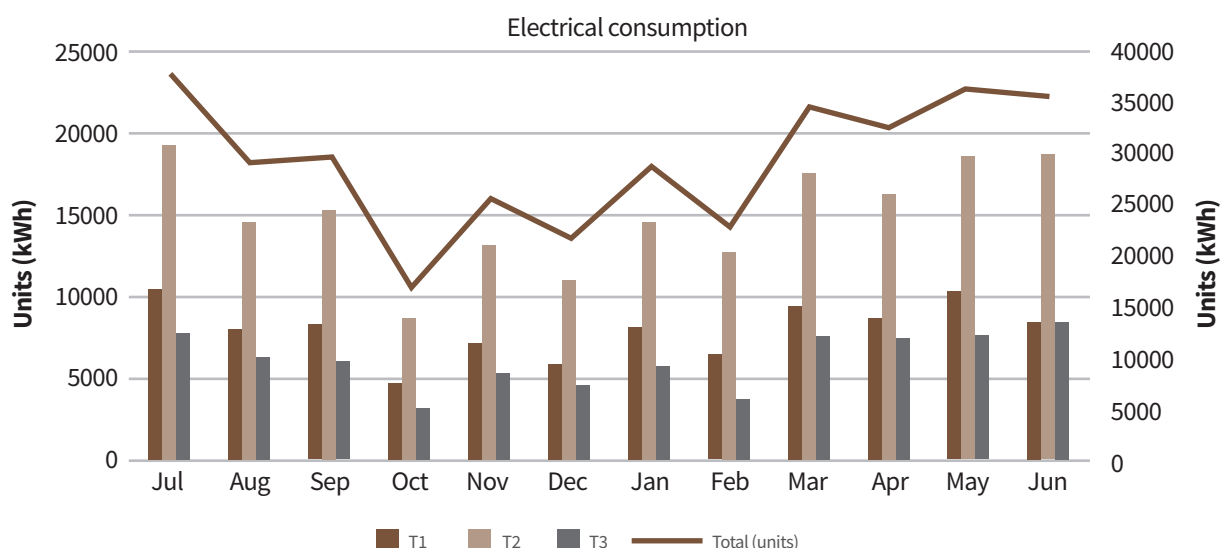
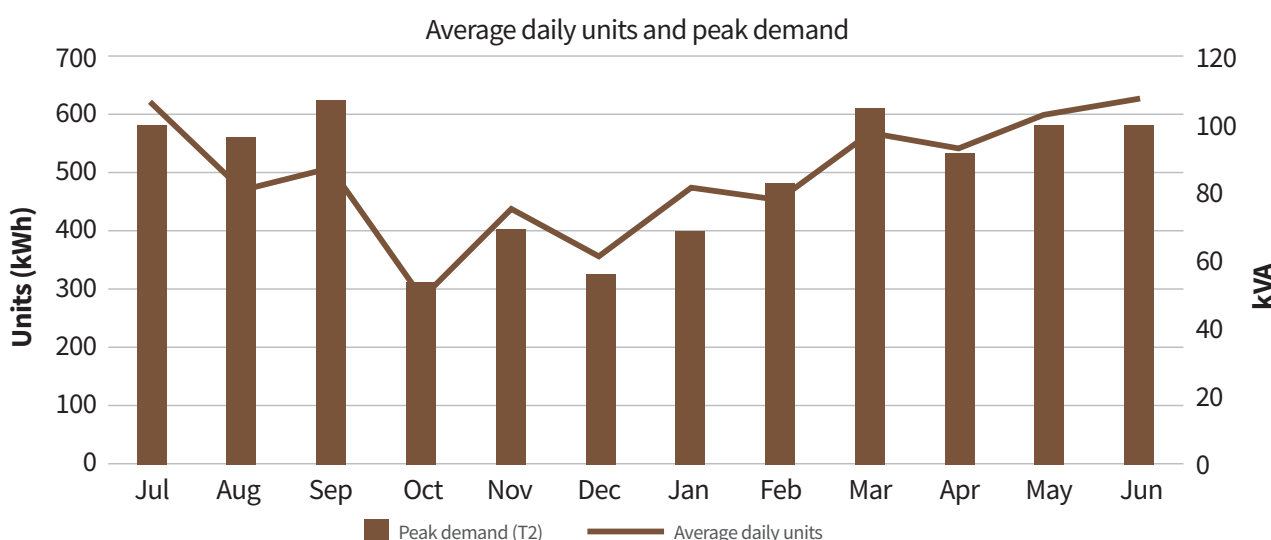


FIGURE 34 AVERAGE DAILY ENERGY CONSUMPTION AND PEAK DEMAND OF HOTELS IN KATHMANDU



Next, to confirm the electricity features and daily load pattern, a power logger was installed that recorded real-time electricity consumption over three days (with a data resolution of 5 minutes that was averaged hourly).

After analysis, the daily electricity consumption pattern was plotted, as shown in Figure 35.

Note: The power logger recorded data while the facility was in full operation and occupancy was 60%. The instantaneous loads during T2 hours were in the range of 20–50kW.

Similarly, from Figure 36, the voltage was found to be within tolerance. The voltage is seen to have fluctuated from a maximum of 243V to a minimum of 219V at certain points during the day. This analysis is important for ensuring that the voltage fluctuations are within the tolerance range of the on-grid inverter and that the electrical parameters are within the tolerance of the grid code. If the voltage level is erratic, the inverter will not function.

FIGURE 35 24-HOUR POWER CONSUMPTION OF HOTELS IN KATHMANDU

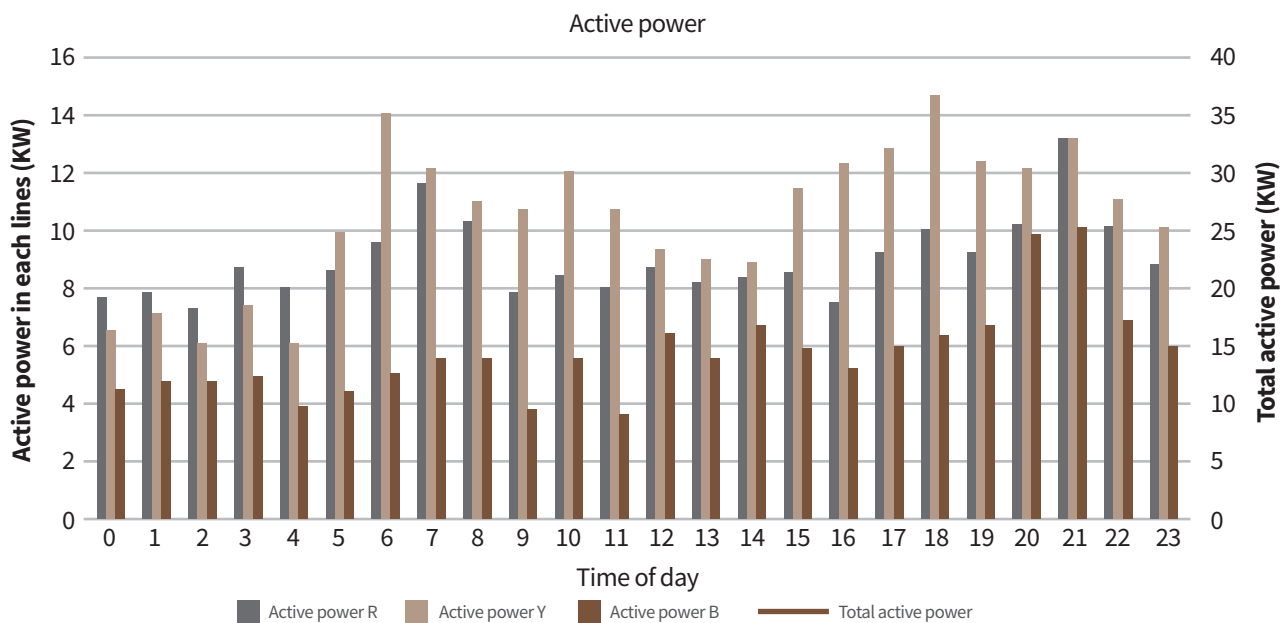
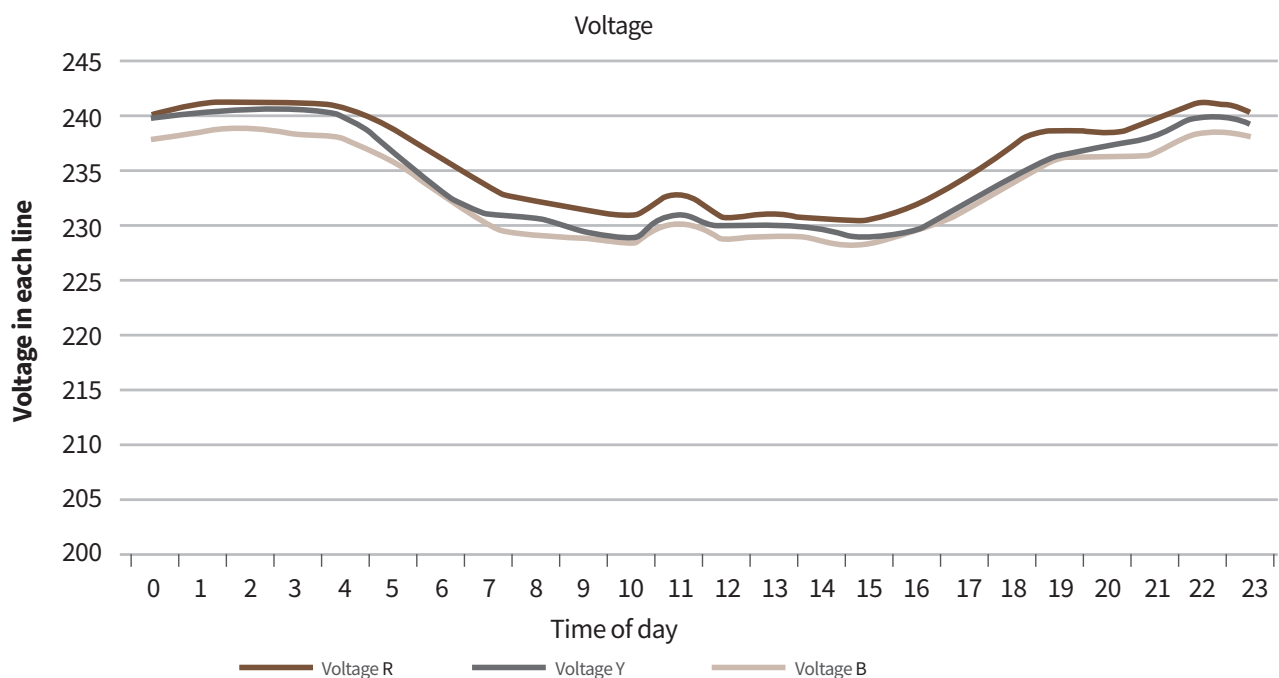


FIGURE 36 24-HR VOLTAGE PROFILE OF HOTELS IN KATHMANDU



Keeping it all together



The results of the site audit and power logger information are provided below:

- According to the logger data, the total average power is 25kW and the total energy consumed between 7 am and 5 pm is 278kWh. The recorded maximum power is 36.5kW.

- Based on the walkthrough audit, historical bills, and real-time measurements, it is estimated that the average power during T2 hours is in the range of 20kW to 50kW with monthly and occupancy variations.

Optimal design

A quick manual calculation (also carried out in Design Walkthrough-I) can help us get a suitable size range for the site.

Almost all energy generated is self-consumed if the solar PV system is less than 50kW, while if the system is greater than 100kW, then the daytime power production will be more than the consumption. It is preferable that energy is consumed in the facility itself because this directly offsets the import of grid electricity and thus reduces the cost of electricity. Therefore, the system size should be between 50kW and 100kW.

Table 14 shows the estimated energy production from a 50kWp and 100kWp system capacity with their respective percentage of penetration, i.e. the percentage of solar PV in the total energy mix consumed by the facility.

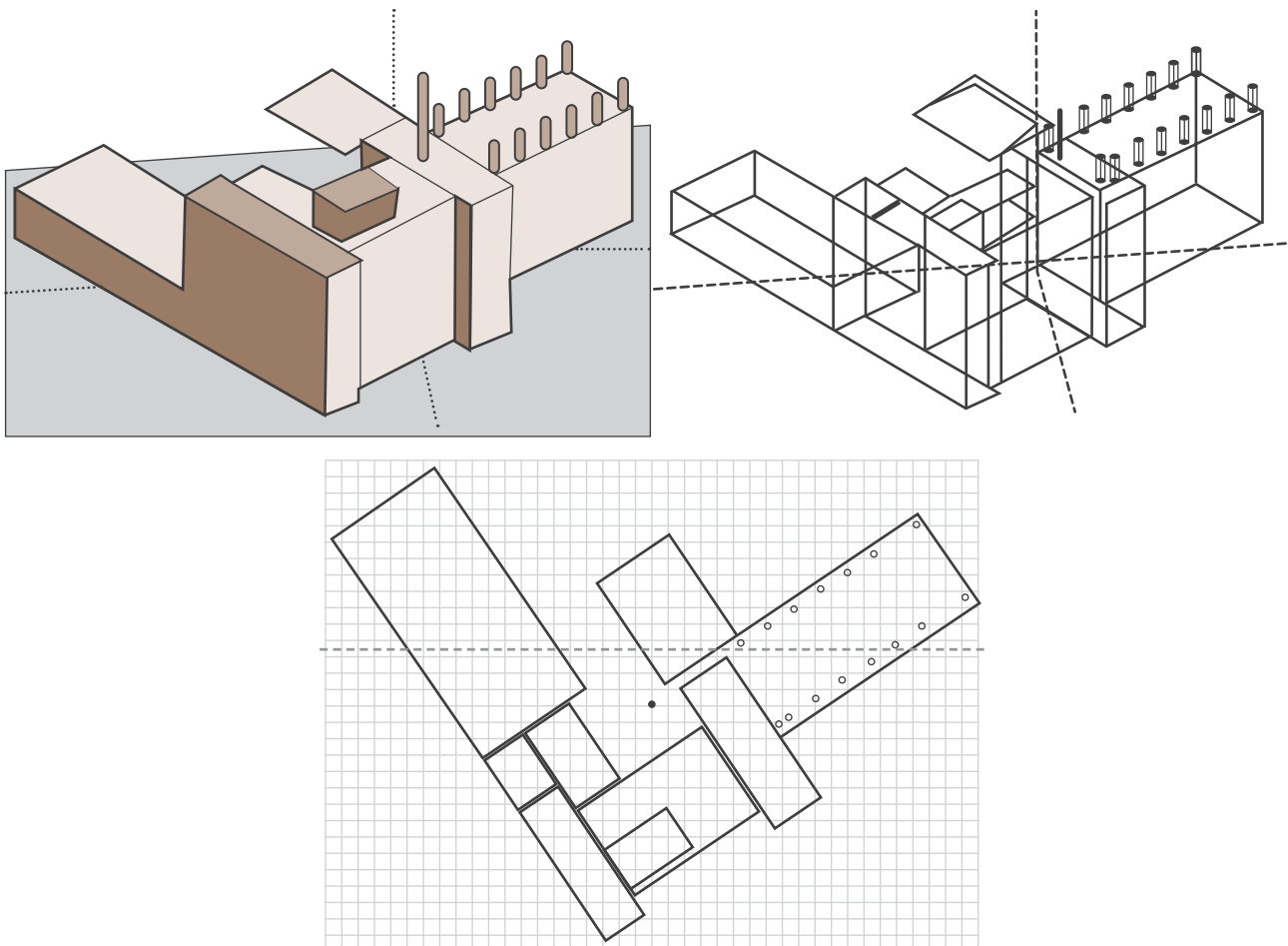
TABLE 14 ENERGY ESTIMATIONS OF 50KWP AND 100KWP SYSTEM CAPACITIES

Months	Avg. amb temp (°C)	Daily global incident (kWh/m ²)	Eff (temp) %	Total system eff %	Avg. daily T2 units [A]	Daily energy production of 50kWp system		Daily energy production of 100kWp system	
						Avg. daily prod kWh (50kWp) [B]	% of self-consumption by the facility % Penetration (50kWp) [C = B ÷ A]	Avg. daily prod kWh (100kWp) [D]	% of self-consumption by the facility % Penetration (100kWp) [E = D ÷ A]
Jan	14.96	4.7	0.97	88%	472	207	44%	413	88%
Feb	19.43	5.2	0.95	87%	454	223	49%	446	98%
Mar	24.95	6.3	0.93	85%	567	266	47%	533	94%
Apr	29.62	6.2	0.91	83%	541	259	48%	518	96%
May	31.04	6.0	0.91	83%	602	251	42%	501	83%
Jun	30.14	5.3	0.91	83%	624	222	35%	443	71%
Jul	29.39	4.7	0.91	84%	620	197	32%	393	63%
Aug	29.27	4.6	0.92	84%	470	192	41%	383	82%
Sep	28.31	5.2	0.92	84%	507	218	43%	437	86%
Oct	26.43	5.3	0.92	84%	282	222	79%	444	157%
Nov	21.57	5.2	0.94	86%	437	222	51%	444	102%
Dec	17.14	4.7	0.96	87%	360	205	57%	410	114%

Now the question is how much space is available in the building and how many solar modules can be accommodated.

To design the arrangement of solar modules on the hotel roof, a 3D model of the hotel is designed in PVsyst software using measurements recorded during the site survey, as shown in Figure 37.

FIGURE 37 3D MODELLING OF HOTELS IN KATHMANDU IN PVSYST



Keeping it all together



The roof structure of Hotel Kathmandu is much more complicated than Design Walkthrough I. Notice that the roof has pillars, uneven dimensions and height that will cause shading in the PV modules if their placement is not properly planned. Let's learn more about shading.

Shadings

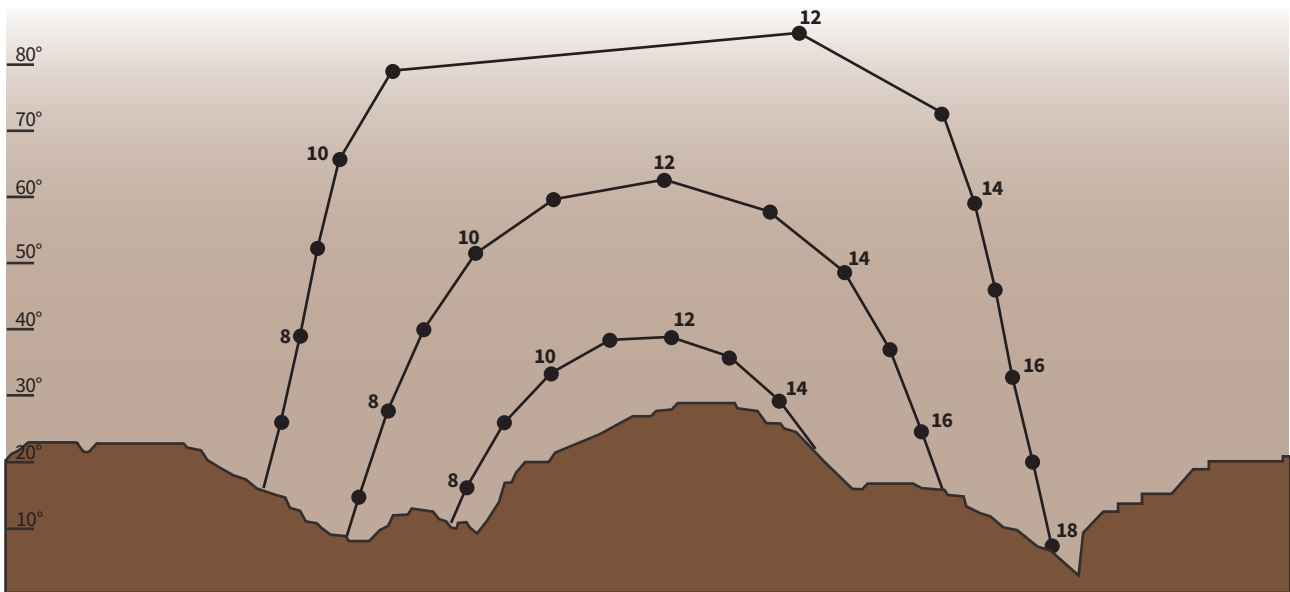
Shading is a very important factor as it directly affects energy generation. Shading can be from distant (far shading) and/or near objects (near shading), e.g. trees, buildings, hillsides, and the solar array itself in case of multiple rows.

Far shading

Far shading, such as shading from surrounding hills, can be analysed from sun path tools.

The sun's path for a given latitude and longitude is the relative position (elevation and azimuth) of the sun in the sky for the months and the time of day. Figure 38 shows an example of the sun's path with a horizon of surrounding hills obtained from Solargis.

FIGURE 38 SUN PATH WITH FAR SHADING (SOLARGIS)



Note: The sun is lowest in the sky during December and highest during June. The shortest day in December is known as the winter solstice and the longest day in June is known as the summer solstice.

In the figure above, the sun rises around 7:30 am in December and sets around 3 pm. In June, the sun rises around 6 am and sets around 6 pm. This variation of sun hours across seasons is directly related to the daily solar insolation.

Near shading

Near shading is caused by nearby objects surrounding the PV array, e.g. trees, neighbouring buildings, chimneys, etc. as shown in Figure 39.

Keeping it all together



It is recommended to avoid near and far shadings altogether. However, this may not always be possible when there is a PV array of fixed capacity and no room for module adjustments. In such cases, the designer will have to use software simulated models to determine potential energy losses caused by the shading(s) and make an informed decision based on that.

Far and near shading can also be analysed using sun path mobile apps, as shown in Figure 40.

External resources

One of many sun-path apps can be downloaded [here](#) for Android.

Next, for PV modules that are to be installed with a tilt on a horizontal surface, each row of PV modules can cast a shade over the row behind it. Therefore, array row spacing has been calculated.

Array row spacing

When there are more than two rows of solar PV array, the inter-row spacing must be calculated to ensure that the front row doesn't cast a shade upon the back rows. The required inter-row spacing can be calculated manually or with simulation software.

For the northern hemisphere, the inter-row distance shall be calculated for the winter solstice (21 December) when the sun is lowest in the sky.

Using the sun path diagram for the given site, the sun altitude angle (β) and azimuth (θ) at 7:30 am and 3 pm can be estimated (Figure 41).

Using the selected solar module length and the tilt angle (α), the height differential (h) between the top of one row and the bottom of the row to the north can be estimated.

FIGURE 39 NEAR SHADING FROM TREES AND BUILDINGS^[46]

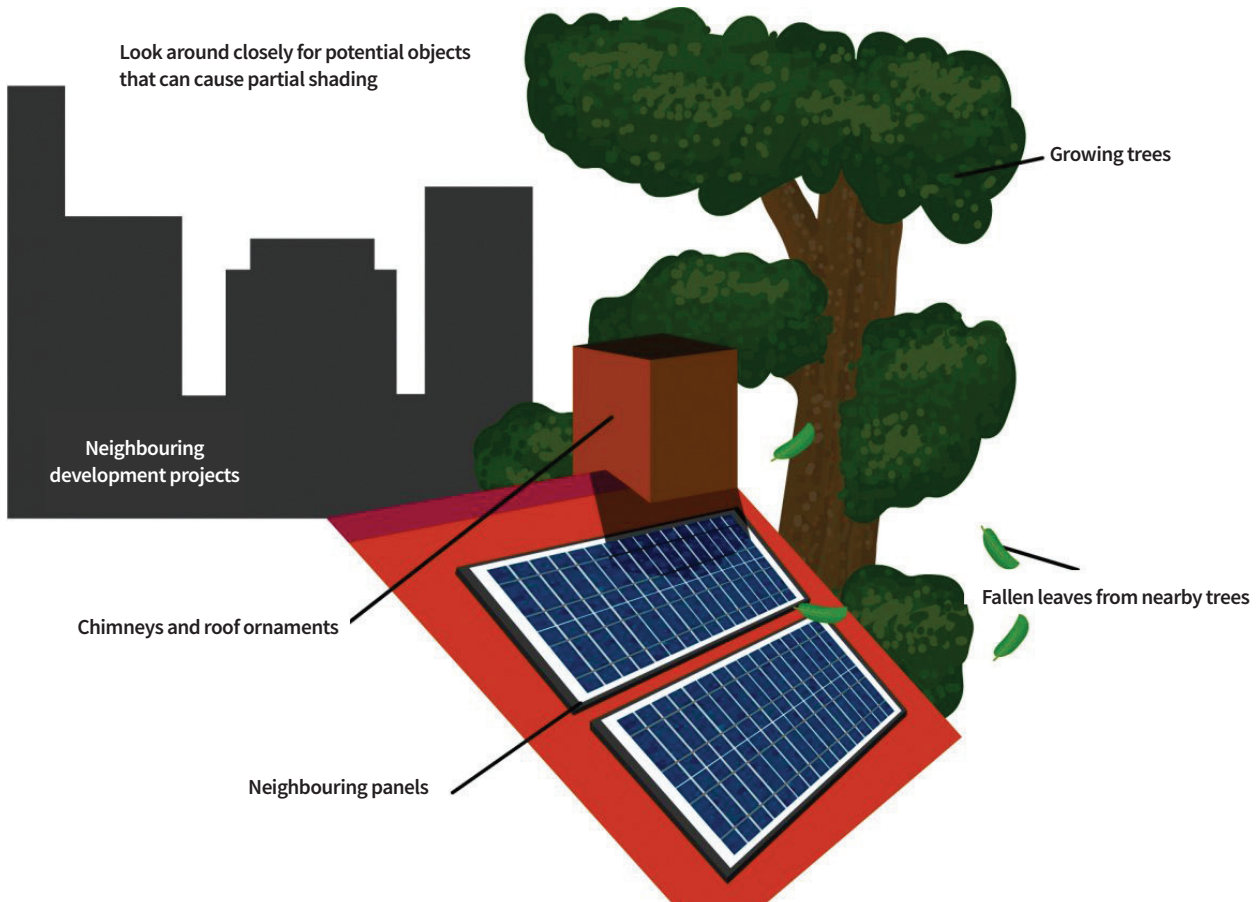
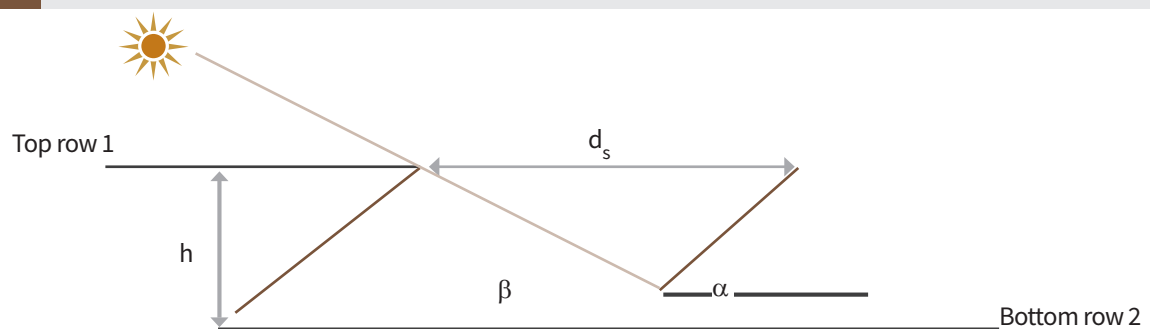


FIGURE 40 EXAMPLE SNAPSHOTS FROM A SUN-PATH MOBILE APP



FIGURE 41 INTER-ROW SPACING



The inter-row shadow length (d_s) can be calculated using the mathematical equation below:

$$d_s = \frac{h}{\tan b}$$

The minimum inter-row distance (d_{min}) can be calculated using the following mathematical equation below:

$$d_{min} = d_s \times \cos i$$

As the tilt angle is reduced, the shadow length also decreases. This means more rows of panels can be accommodated (this may favour energy production in certain seasons, for example, when the sun is at a high angle during summer to increase energy penetration for self-consumption, and also

depending on metering regulations to increase financial benefits).

For a site, for example, a higher tilt may accommodate 5kW, whereas a lower tilt angle may accommodate 10kW. Though the energy generation may be low for a lower tilt angle, the loss can be accounted for if the net metering/feed-in-tariff rates are attractive. Furthermore, increasing the system size reduces the overall cost per Wp of the system.

Getting back to the design of Hotel Kathmandu, the 3D model allows the designer to iterate the best configuration of solar arrays considering the obstructions and the near shadings on the hotel roof. The different solar array placement options on the hotel roof are shown in Figures 42, 43, and 44.

FIGURE 42 SOLAR ARRAY PLACEMENT 1

Array 1: Facing south-east (-40° azimuth)

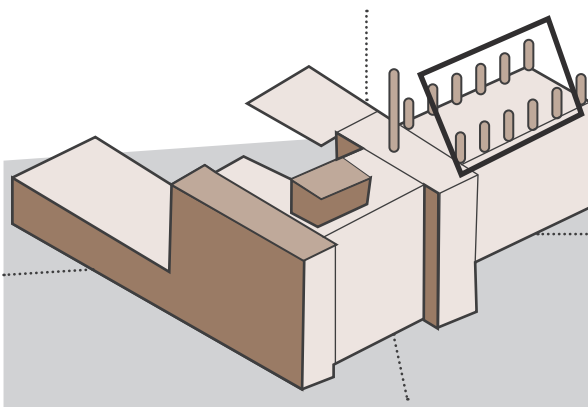


FIGURE 43 SOLAR ARRAY PLACEMENT 2

Array 2: Facing south-west (+54° azimuth)

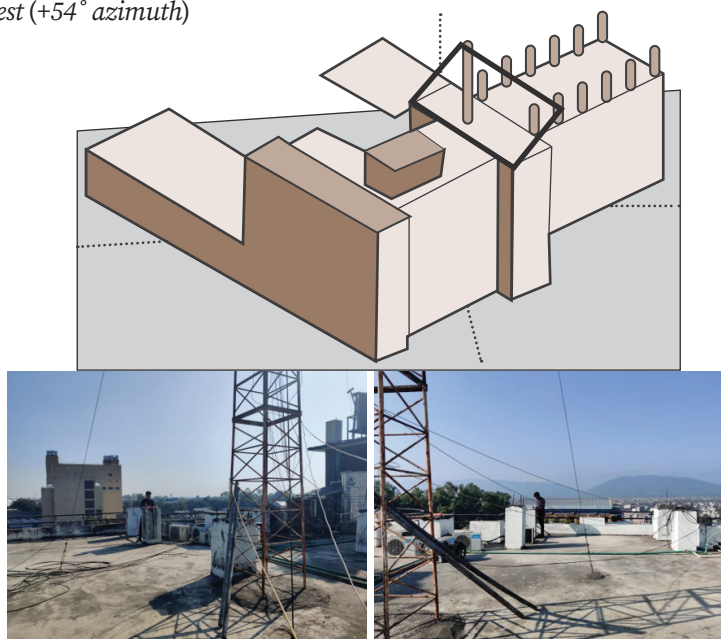


FIGURE 44 SOLAR ARRAY PLACEMENT 3

Array 3: Facing south-west (+54° azimuth)



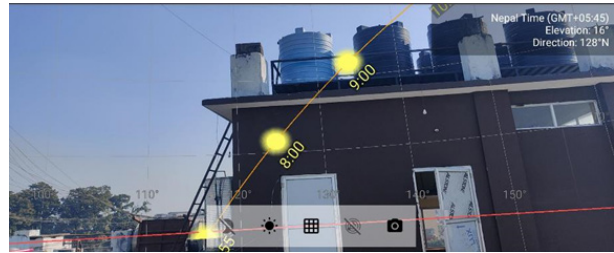
Decisions about solar array placement depend on the facility owner and the technical aspects of the roof (near-shadings, walkways, etc.).

The analysis of near shading using the sun path app is shown in Figure 45.

Orientation

Each roof can have different orientations. In the given example, the roof has two orientations – southeast and southwest. Aspects of solar module orientation

FIGURE 45 NEAR SHADING ANALYSIS USING A SUN-PATH APP



Keeping it all together

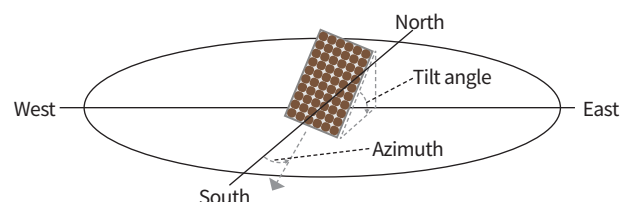


Notice that the PV arrays are placed in different orientations. Array 1 is facing south-east while Array 2 and 3 are facing south-west (both are non-zero azimuths). We know that optimal energy generation will be achieved in zero azimuth for the specific location at an optimal tilt angle but let's first learn how different orientations can affect energy generation.

is shown in Figure 46. In the morning hours, the southeast (−40° azimuth) face will get sunlight while the southwest (+54° azimuth) face will be shaded. At noon, both faces may get equal sunlight while in the evening, the southwest will get more. It is important to separate these arrays respective to their orientation for maximum energy generation because the mismatch between the shaded array voltage (remember the shading effect on cells) and the non-shaded array voltage causes system inefficiencies and production loss. To maximise energy production, arrays of different orientations are connected to separate MPPT inputs of the on-grid inverters. Therefore, in these cases, string inverters are preferable.

To determine the optimal orientation of solar PV arrays for maximum energy generation, different scenarios of varying azimuths are evaluated. In

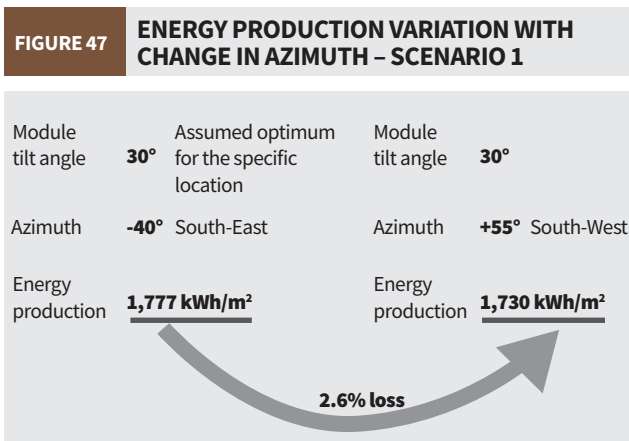
FIGURE 46 SOLAR MODULE ORIENTATION^[47]



addition, the scenarios also show the effect of varying tilt angles to demonstrate both factors: i) varying azimuth and ii) varying tilt angle. The global irradiance on the PV module plane has been generated from PVSyst software.

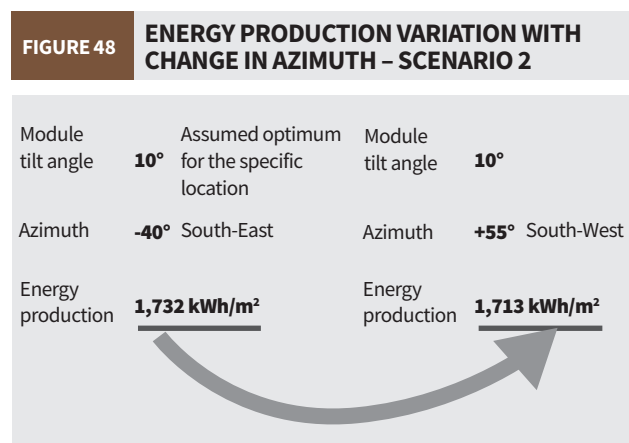
Scenario 1: Varying the azimuth with a constant tilt angle (30°)

In Figure 47, keeping the tilt angle constant at 30°, the azimuth is varied from -40° to +55°. In this case, energy production per m² decreases by 2.6% (decrease from 1,777kWh/m² to 1,730kWh/m²).



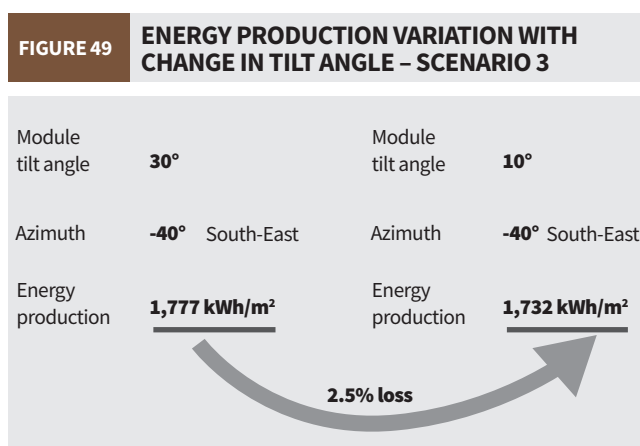
Scenario 2: Varying the azimuth with a constant tilt angle (10°)

In Figure 48, keeping the tilt angle constant at 10°, the azimuth is varied from -40° to +55°. In this case, the energy production per m² decreases by 1.1% (decrease from 1,732kWh/m² to 1,713kWh/m²).



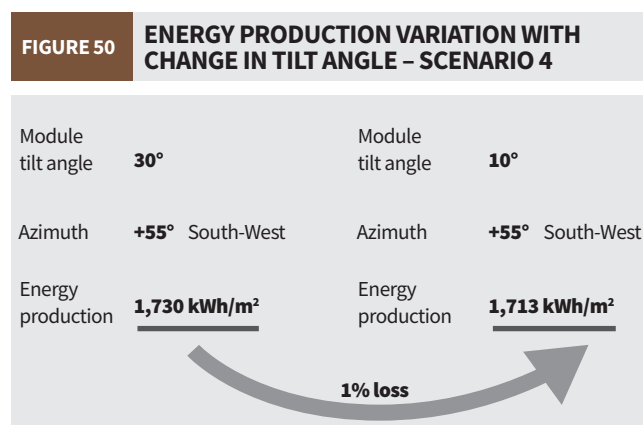
Scenario 3: Varying the tilt angle with a constant azimuth (-40°)

In Figure 49, as the tilt angle changes away from the optimum while the azimuth is constant at -40°, energy production per m² decreases by 2.5% (decrease from 1,777kWh/m² to 1,732kWh/m²).



Scenario 4: Varying the tilt angle with a constant azimuth (+55°)

In Figure 50, as the tilt angle changes away from the optimum while the azimuth is constant at +55°, energy production per m² decreases by 1% (decrease from 1,730kWh/m² to 1,713kWh/m²).



Keeping it all together



The scenarios above indicate that although there is a loss of energy production when the tilt angle and azimuth is deviated away from optimal site conditions, the loss of energy is likely within an acceptable range. Therefore, by comparing different energy loss scenarios, the designer can plan whether the energy loss is acceptable.

After learning about orientations, the designer may come up with a few options for solar array configurations as shown in Figure 51.

Note: These simulations are created from PVSyst software.

FIGURE 51 SOLAR ARRAY CONFIGURATIONS

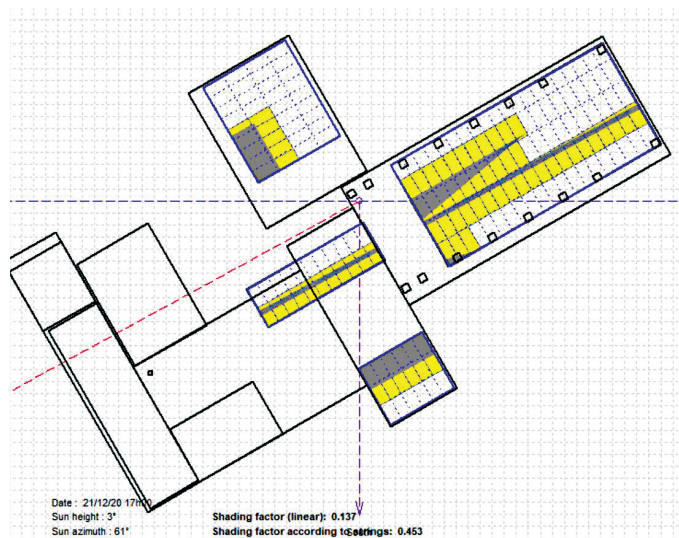


Layout 1

Total capacity = **57.2kWp**

No. of panels: **176**

Module: **325Wp**

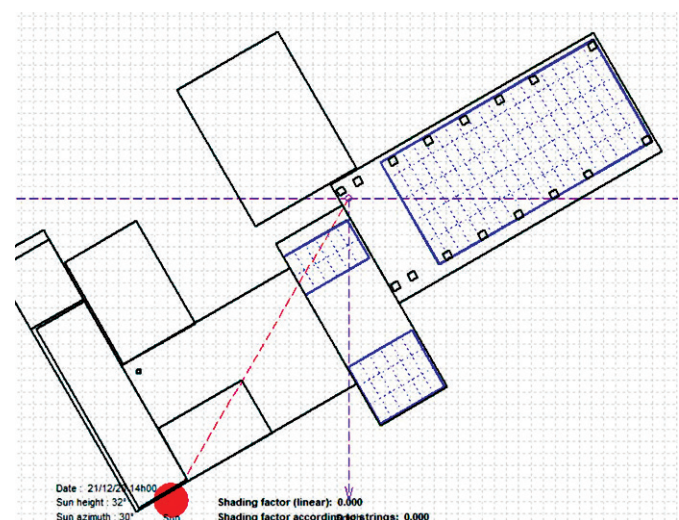


Layout 2

Total capacity = **57.2kWp**

No. of panels: **176**

Module: **325Wp**



Layout 3

Total capacity = **57.2kWp**

No. of panels: **130**

Module: **440Wp**

The summary of the three different layouts is described in Table 15.

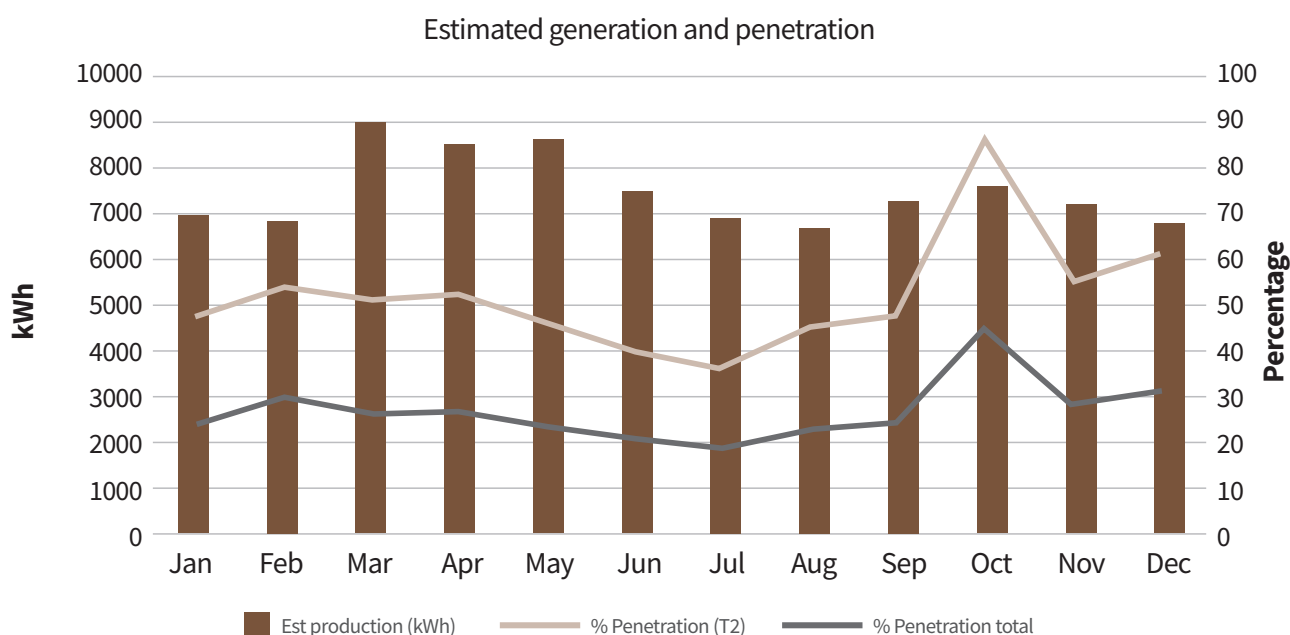
TABLE 15 COMPARISON OF SOLAR ARRAY CONFIGURATIONS			
Description	Layout 1	Layout 2	Layout 3
Total capacity	57.2kWp	57.2kWp	57.2kWp
No. of modules	176	176	130
Wattage per module	325Wp	325Wp	440Wp
Annual production	61MWh	73MWh	90.1MWh
Specific production	1,095kWh/ kWp	1,314kWh/ kWp	1,576kWh/ kWp
Cost (USD/Wp)	0.29	0.33	0.36
Project IRR	21%	25%	33%

As shown in Table 15, although all three layouts have the same solar array capacity, they produce different amounts of energy. The highest amount of energy is generated in Layout 3 with an annual production of 90.1MWh. The graph shown in Figure 52 for Layout 3 shows the percentage of penetration (self-consumption) during the T2 period (day) and the overall percentage of penetration of the facility's energy consumption.

Note: Loss considerations for this simulation are: panel back temperature 20 °C (-0.35% power loss per °C), soiling 2%, DC cable loss 2%, AC cable loss (1%), inverter efficiency 97%, array mismatch 1%, and combined efficiency of 91.3%.

Based on the historical units consumed, the energy generated from Layout 3 is almost entirely self-consumed.

FIGURE 52 ENERGY GENERATION AND PENETRATION OF LAYOUT 3



Keeping it all together



We have identified the PV capacity and its layout for Hotel Kathmandu. We can now progress towards sizing and selection of the inverter and the balance of systems.

Although detailed sizing of individual components is beyond the scope of this handbook, the above section has shown the basic steps for optimal selection and placement of the solar on-grid rooftop PV system.

After determining the PV array layout, the designer will continue with the following steps:

- Inverter sizing
- Defining the balance of systems
 - o Selection of PV module mounting structure design
 - o DC and AC cable sizing
 - o Defining the numbers and ratings of protection systems, which include, but are not limited to, the following:
 - DC MCBs and MCCBs
 - AC MCCBs
 - DC SPDs
 - AC SPDs
 - Lightning air terminal
 - Earthing pits
 - Grounding cables
 - o Defining the numbers and technical requirements of junction boxes and distribution boxes
 - o Connectors and accessories (e.g. MC4 connectors, cable trays, etc.)
 - o Monitoring system

H. Project packaging

Once the technical design of the solar PV system is completed, the project moves to the packaging phase. The term ‘project packaging’ suggests that the project is ‘packaged’ with information that will allow the customer to decide whether to implement the project.

To make a decision, the customer needs to understand two aspects of the project:

- Technical feasibility
- Financial feasibility

At this stage, we have assessed the technical feasibility and we will now generate a single-line diagram (SLD) and a detailed bill of quantity (BoQ).

Single-line diagram

A single-line diagram (SLD) is an engineering drawing that shows all components of the on-grid solar PV system. The designer may choose to create different versions of the SLD with varying levels of detail. An example of an SLD is shown in Figure 53.

Bill of quantity

After the on-grid solar PV system design is complete, a bill of quantity (BoQ) is created. The BoQ provides a detailed list of components and materials required to make a complete system. The BoQ is further elaborated with the cost of each item to calculate the total cost of the system. The total cost will then serve as input to the financial analysis.

Items in the BoQ are highly dependent on the particular site and country standards. Table 16 provides an example of a BoQ with major components.

A template of a bill of quantity is shown in Table 17.

Financials

The decision-makers of Hotel Kathmandu evaluate the technical and financial feasibility to decide whether to implement an on-grid solar PV system.

TABLE 16 MAJOR ITEMS IN THE BOQ OF ON-GRID SOLAR PV SYSTEM

SN	Material	Description to include in the BoQ
1	Solar PV module	Type, capacity, standards, and quantity
2	On-grid inverter	Capacity, voltage, 1ph/3ph and quantity
3	Monitoring device	Details of compatibility with the inverter, standards and quantity
4	Mounting frames	Material, type, compatibility with purlin & modules, standards, and quantity
5	AC MCCB box (near evacuation point)	IP protection, description of each protection device, standards, and quantity
6	AC MCCB box (near inverter output)	IP protection, description of each protection device, standards, and quantity
7	DC cables	Size, number of cores, standards, and length
8	AC cables	Size, number of cores, standards, and length
9	Cable for body earthing (structure, inverter, and lightning arrester)	Size, number of cores, standards, and length
10	Communication cable	Size, number of cores, standards, and length
11	PVC conduit	Material, size, standards, and length
12	Flexible conduit	Material, size, standards, and length
13	Installation accessories (MC4 connections, tapes, nuts and bolts, etc.)	Standards and quantity
14	Human resources	All human resources requirements in the project (including project manager, technical team, administrative and management team)
15	Health & safety accessories (signages, fire extinguishers, etc.)	Template and quantity
16	Transportation	Modes of transport

FIGURE 53

GENERAL SLD OF AN ON-GRID SOLAR PV SYSTEM

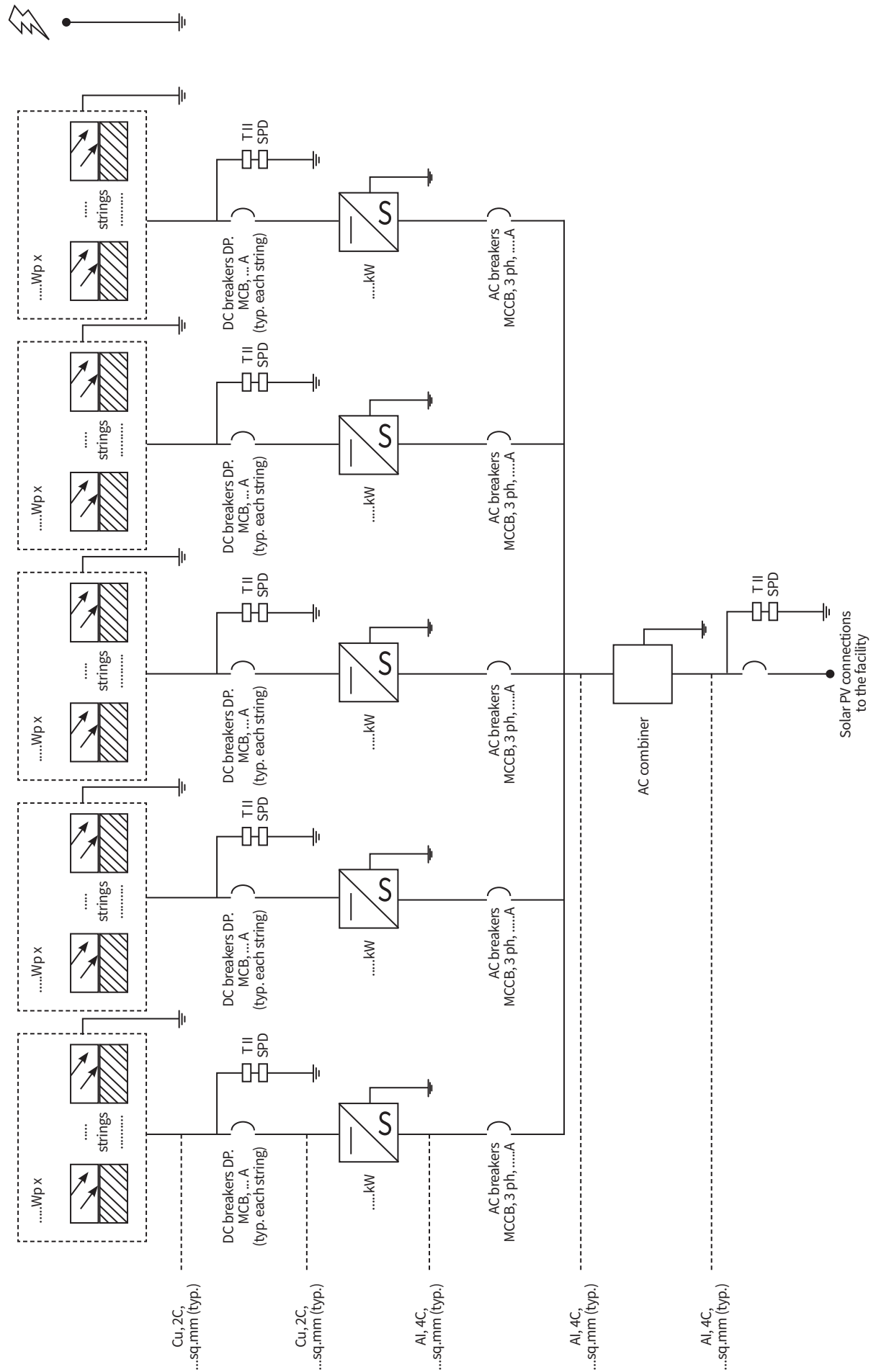


TABLE 17 **TEMPLATE OF A BILL OF QUANTITY**

SN	Item	Specifications	Quantity	Unit	Rate (USD)	Total amount (USD)
1	Solar modules	325Wp, monocrystalline	50	pieces		
...	...					
...	...					
...	...					
					Sub-total (USD)	
					Taxes	
					Total (USD)	

The previous sections of the handbook discussed the technical analysis. An overview of financial indicators is also necessary to demonstrate the overall feasibility of the system.

Although the detailed financial calculation is beyond the scope of this handbook, the following Table 18 shows the key financial indicators that will guide the customer's decision.

TABLE 18 **KEY FINANCIAL INPUT PARAMETERS**

System size (kWp)	57.2
Capital investment	USD 32,063
Estimated annual generation (MWh)	90.1
Financial assumptions	
Project life	25 years
Debt	80%
Interest rate	10%
Tenure (years)	10
Depreciation rate	50% in 1st year
Tax rate	20%
Inflation rate	5%
Discount rate	12%
Tariff rate	USD 0.09/kWh
Tariff escalation	3%

These inputs will then be analysed to create a financial model with key indicators. Based on the model, the management team of Hotel Kathmandu will make a go or no-go decision.

Each of the indicators is defined below.

Key definitions:

NPV: Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period. NPV is used in capital budgeting and investment planning to analyse the profitability of a projected investment or project^[48].

IRR: The internal rate of return (IRR) is a metric used in financial analysis to estimate the profitability of potential investments. IRR is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis^[49].

LCOE: The levelised cost of energy (LCOE), also referred to as the levelised cost of electricity or the levelised energy cost (LEC), is a measurement used to assess and compare alternative methods of energy production^[50].

Breakeven on equity: The breakeven of equity is the period over which the net profit is equal to the initial equity investment.

The key financial indicators for the solar on-grid rooftop PV system in Hotel Kathmandu are given in Table 19.

TABLE 19 **KEY FINANCIAL INDICATORS**

Key financial indicators

NPV	USD 30,460
IRR	33%
LCOE	USD 0.022/kWh
Breakeven on equity	~1.5 years

Keeping it all together



The IRR is attractive, indicating a 33% profitability over the project duration. Similarly, the positive NPV indicates that the projected earnings generated by the solar PV system or its investment exceeds the anticipated costs^[51]. Finally, the breakeven on equity is approximately 1.5 years, i.e. in 1.5 years, the net profit will equal the initial equity investment.

Furthermore, to assess the financial feasibility of solar against grid electricity, the cost of energy over 15 years is plotted in Figure 54.

Here, the cost of energy (USD/kWh) of the grid is higher than the cost of energy from solar, thus making solar energy financially attractive.

Finally, for a more direct comparison, the expense of solar is compared with the expenses of grid electricity over the project lifetime. The comparison, shown in Figure 55, suggests that expenses for grid electricity can be up to 4 times higher than solar energy expenses.

Keeping it all together



The management team of Hotel Kathmandu is encouraged by the financial indicators. After all, expenses for solar energy can be four times less than expenses for grid electricity over the project lifetime.

The Hotel Kathmandu management have given the go-ahead and they are excited to harness renewable energy from the sun to serve their hotel guests!

FIGURE 54 COMPARISON OF ENERGY COST BETWEEN GRID AND SOLAR

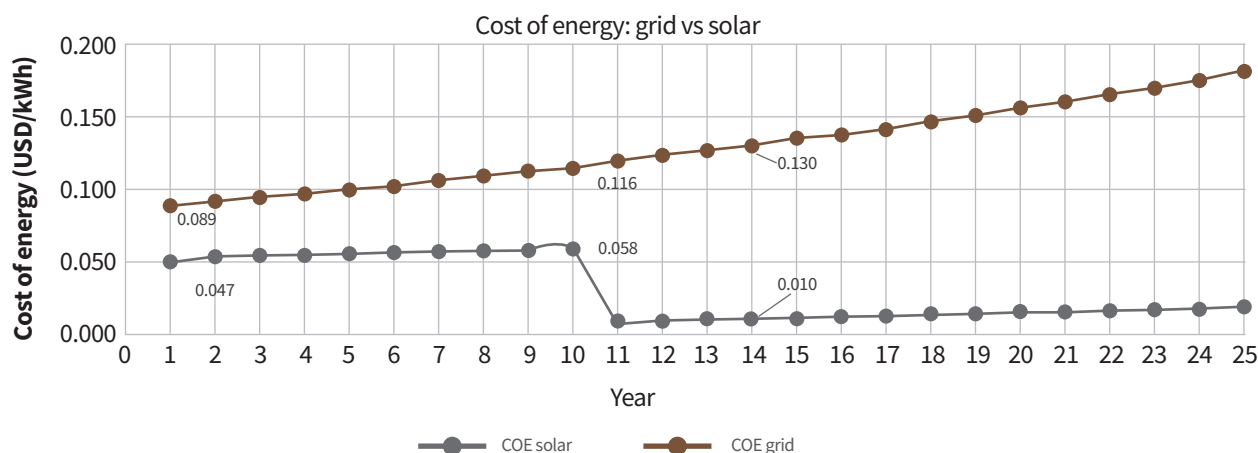
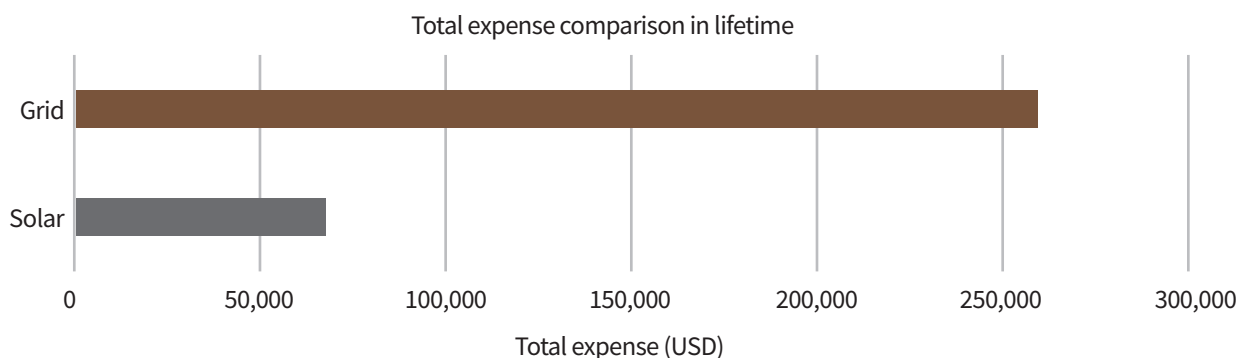


FIGURE 55 COMPARISON OF TOTAL LIFETIME EXPENSES OF GRID AND SOLAR



I. Case study

This section presents a case study of the 146.6kWp solar on-grid rooftop PV system at the International Centre for Integration Mountain Development (ICIMOD), Kathmandu (Table 20 and Figure 56).

The on-grid solar PV is equipped with a remote monitoring system that monitors and records real-time parameters of the system including energy generation, export, import and system parameters (input voltages, input current, frequency, faults, etc.).

The annual energy generation data (including downtime) of the solar PV system is shown in Table 21.

The average daily generation per kW is **3.4kWh/kWp/day**.

If we compare the financial returns from the solar PV on-grid rooftop system to the grid electricity cost over the system lifetime of 25 years, the cost of the solar PV system is one-third of the grid electricity cost (Figure 57).

TABLE 20

DESCRIPTION OF THE ON-GRID SOLAR PV SYSTEM OF ICIMOD, KATHMANDU

System description	
DC Capacity	146.57kWp (92.61kWp and 53.96kWp)
Commissioning date	92.61kWp – May 2016 53.96kWp – January 2020

TABLE 21

ENERGY PRODUCTION OF ICIMOD'S SOLAR PV SYSTEM

	92.61kWp						53.96kWp	
Year	2016	2017	2018	2019	2020	2021	2020	2021
Energy (kWh)	47,497	121,733	100,849	109,756	64,736	98,633	74,812	67,868

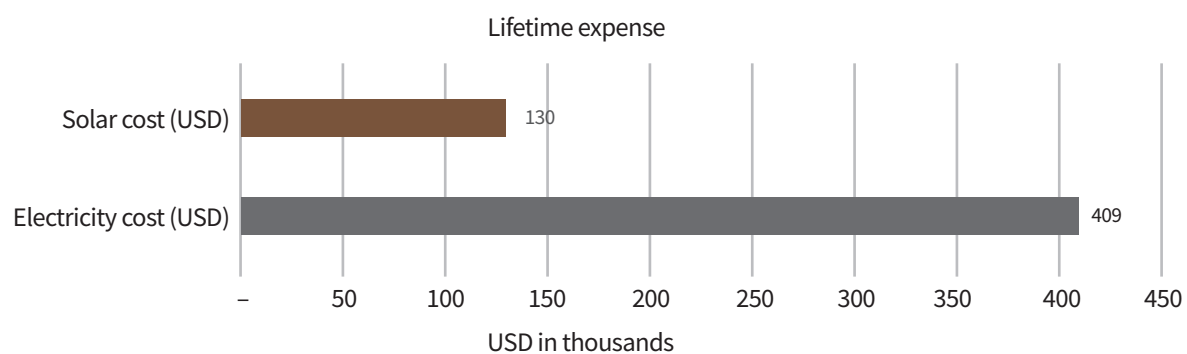
FIGURE 56

SOLAR PV SYSTEM AT ICIMOD IN KATHMANDU, NEPAL



FIGURE 57

COMPARISON OF LIFETIME COST OF GRID ELECTRICITY AND SOLAR PV SYSTEM AT ICIMOD



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