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TRAINING OF TRAINERS MANUAL

Technical handbook on solar water pumps

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TRAINING OF TRAINERS MANUAL

Technical handbook on solar water pumps

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Contents

Abbreviations and acronyms

AC	Alternating Current
ANSI	American National Standards Institute
AWG	American Wire Gauge
DC	Direct Current
DP MCB	Double Pole Miniature Circuit Breaker
GHI	Global Horizontal Irradiation
GTI	Global Tilted Irradiation
HDPE	High-Density Polyethylene
HP	Horsepower
IP	Ingress Protection
LCC	Life Cycle Cost
LPL	Lightning Protection Level
LPS	Lightning Protection System
MCB	Miniature Circuit Breaker
MPPT	Maximum Power Point Tracking
NEC	National Electrical Code
NOCT	Nominal Operating Cell Temperature
PN	Pressure Nominal
PV	Photovoltaic
PWM	Pulse Width Modulation
SLD	Single-Line Diagram
SPD	Surge Protection Device
SP MCB	Single Pole Miniature Circuit Breaker
STC	Standard Test Conditions
SWPS	Solar Water Pumping Systems
TDH	Total Dynamic Head
Vac	Volts alternating current
Vdc	Volts direct current
VFD	Variable Frequency Drive

SECTION I

Introduction

In South Asia, solar water pumping systems (SWPS) are an emerging curiosity among farmers who are looking for better alternatives in reliable energy to pump water. Some applications where SWPS are gaining popularity are:

- Irrigation
- Drinking water
- Fish farming
- Livestock care
- Animal welfare

A well-designed SWPS is a reliable source of energy for water pumping for farmers throughout the year. Some of the benefits of SWPS are:

- A reliable energy source for pumping water throughout the year: SWPS does not require fuel or grid electricity. Therefore, it is not affected by fuel shortages and grid electricity outages. This is significant in the case of rural areas where the transport of fuel can be costly. Similarly, in some areas, the grid electricity voltage is too low to run electric pumps; these areas also suffer from frequent outages. Such problems can be disastrous for farmers who require timely water for irrigation or daily water for community drinking water supply. SWPS is immune to all these problems and its declining component costs over the years make it competitive against diesel pumps and also a reliable alternative to electric pumps.
- Harnessing renewable energy: SWPS, as opposed to diesel pumps, does not require fossil fuel for operation and is a clean technology for water-pumping purposes.

This handbook is aimed at young engineers to develop must-know knowledge about SWPS. The handbook walks you through the technical background, important concepts, survey, design, installation, and operation, as well as maintenance of SWPS, and covers the full spectrum of its technical aspect. The FAQ cited here are common and important questions that the author came across while working in the sector.

At the outset it has to be noted that the wide-scale implementation of SWPS still faces challenges in the form of lack of awareness about the technology, high upfront costs, and absence of facilities for technical repairs [1]. These challenges can be overcome through better technical understanding and effective implementation which this handbook aspires to achieve.

SWPS vary in size (as small as 120 Wp systems to greater than 50 kWp systems) and are designed for specific applications. This handbook serves as a stepping stone to the technical aspects of SWPS in order to equip young engineers with important theoretical and practical knowledge. The design walk-through described in this handbook is of a hypothetical project and does not serve as a standard since SWPS designs may have to be customised and altered reasonably according to site conditions.

SECTION II

Handbook overview

This handbook begins with the introduction of an essential background understanding of solar energy and its components. Next, the important concepts associated with SWPS are defined. Following these, a real-world example of an SWPS project is described by walking through the six technical steps of any such project. These steps have been broken down into:

- **Preliminary information:** In this phase, the purpose is to assess the technical feasibility and scale of the project. This includes the estimated size of the system and its cost, as well as the evaluation of any unique challenges that the project may face such as the high risk of flooding and land-permit constraints. The objective is to get an overview of the project requirements without investing significant time and money. The source of information may be limited at this stage, but engineers should be able to get critical information on the requirements and site conditions to enable them to create a preliminary design. Moreover, the information may be obtained remotely without visiting the site. There is also the fact that there can be significant uncertainties at the design stage.

Refer to the **Preliminary information** in Section VII for any critical information needed for any SWPS design.

- **Preliminary design:** After the preliminary information has been obtained, the engineers should be able to design a system that will then be the basis for the project cost. Remember, this is a preliminary design and some aspects of the design may only be an estimate. This is acceptable for this phase since the objective is to only understand the scale of the project. After the preliminary design has been done and the estimated cost calculated, the customer or the project developer can decide on whether the project is to be pursued or not.

Refer to the **Preliminary design** in Section VII for a walk-through of the preliminary design example.

- **Detailed survey:** The project will progress to the stage of a detailed survey once a collective decision has been made by the customer or the project developer to move ahead. In this phase, the engineers must properly assess the site and obtain accurate information on, but not limited to, the following aspects:
  - Vertical head
  - Water requirement and availability
  - Solar array location
  - Location of components
  - Distance measurements (cable distance, pipe distance, etc.)
  - Site conditions (risk of natural disasters, ease of logistics, etc.)

Refer to the **Detailed technical survey** in Section VII for a walk-through of the detailed survey procedures.

- **Detailed design:** The information from the detailed survey will be the basis of the SWPS design. All components of the SWPS must be properly defined and this handbook offers the requisite important technical information to make such definitions.

Refer to the **Detailed design** in Section VII for a walk-through of the detailed design example.

- **Installation:** After the design of the SWPS, the project moves towards construction, and at this stage, it is important to ensure that the system is properly installed as per the design in order to ensure reliability. Similarly, all aspects of the system (electromechanical and civil works) are systematically verified and their performance is monitored to ensure that the system (as a whole) performs as desired.

Refer to the **Installation and maintenance** in Section VII for a general overview of the installation procedures and recommendations.

- **Operation and maintenance:** After installation, it is vital to properly operate and maintain the SWPS so that it continues to benefit the user throughout its design life. Proper operation and maintenance have two aspects to them:
  - **User training:** It is the users who will be using the system on a day-to-day basis; therefore, they must be trained on the proper use of the system and whom they need to contact if any problems occur.
  - **Scheduled and unscheduled maintenance:** It is recommended that the project developers/installers/companies provide scheduled and unscheduled maintenance services. In the case of countries like Bhutan where SWPS components are not easily available, maintenance service is a valuable addition to the customer. Scheduled and unscheduled maintenance ensures that the system runs for its desired lifetime and this increases customer satisfaction.

Refer to the **Basic maintenance tips for users** in Section VII for general information on maintenance of SWPS for non-technical users.

SECTION III

Scope and limitations

The scope and limitations of this handbook are summarised below:

Irrigation water requirement calculations: As mentioned in the introduction, SWPS can benefit different types of water needs. Each application needs careful study to determine water requirements. For example, many variables affect the water requirement for irrigation, ranging from the type of crops to climatic conditions and soil types. These require careful calculations based on location and application. However, such discussions are out of the scope of this handbook; but note that there is software available such as CROPWAT which is designed to calculate the water requirement for the irrigation of crop fields.

Accurate water output simulation: Pump models from different manufacturers have different characteristics in terms of efficiency curve, power vs flow vs head curve, and the minimum input power required to reach a certain head. The design walk-through in this document estimates the water output but does not include a simulation of the hourly water output. Refer to the Pump selection section for more information.

Structural analysis of solar panels: The structure of solar panels should be designed to withstand maximum wind speed for the given location. Since this requires mechanical stress analysis, it is out of the scope of this handbook. There are various software tools such as SAP, ANSYS, and SolidWorks which can be used for structural design and analysis.

Distribution pipe layout and pressure regulation: This handbook does not include information on the layout design of distribution pipes and on the regulation of water pressure on the distribution side. The details of pipe layout as per terrain are best evaluated by civil engineers, but these are out of the scope of this handbook. The example design described in this handbook is mainly focused on the electromechanical and transmission pipe design.

Water intake structures: Water intake structures can vary based on different locations (river, canal, borewell, etc.). The design, construction, and protection discussions on water intake structures are not within the scope of this handbook.

Details of irrigation, drinking water, and other applications of SWPS: The application aspect of SWPS can be broad and its details can be part of another handbook specific to the applications. For example, methods of irrigation (surface irrigation, sprinkler irrigation, drip irrigation, etc.), their efficiencies, individual- and community-level water management, crop management, etc. are not within the scope of this handbook.

SECTION IV

System overview

SWPS consists of three main components:

- Solar panel
- Controller
- Pump

Solar panels capture radiation energy from the sun and convert it to electrical energy which is then directed to the controller. The controller regulates the power output from the panels to drive the pump. A standard SWPS does not include battery backup and runs only during the daytime when there is adequate solar radiation.

Battery backup can be an additional component if extra runtime of the pump is required, but then the system cost would be significantly more and thus, less affordable. Due to this reason, this handbook focuses on the standard SWPS, exclusive of battery backup. The general representation of submersible and surface SWPS exclusive of battery backup are shown in Figures 1 and 2.

FIGURE 1 **GENERAL REPRESENTATION OF SUBMERSIBLE PUMP SWPS**

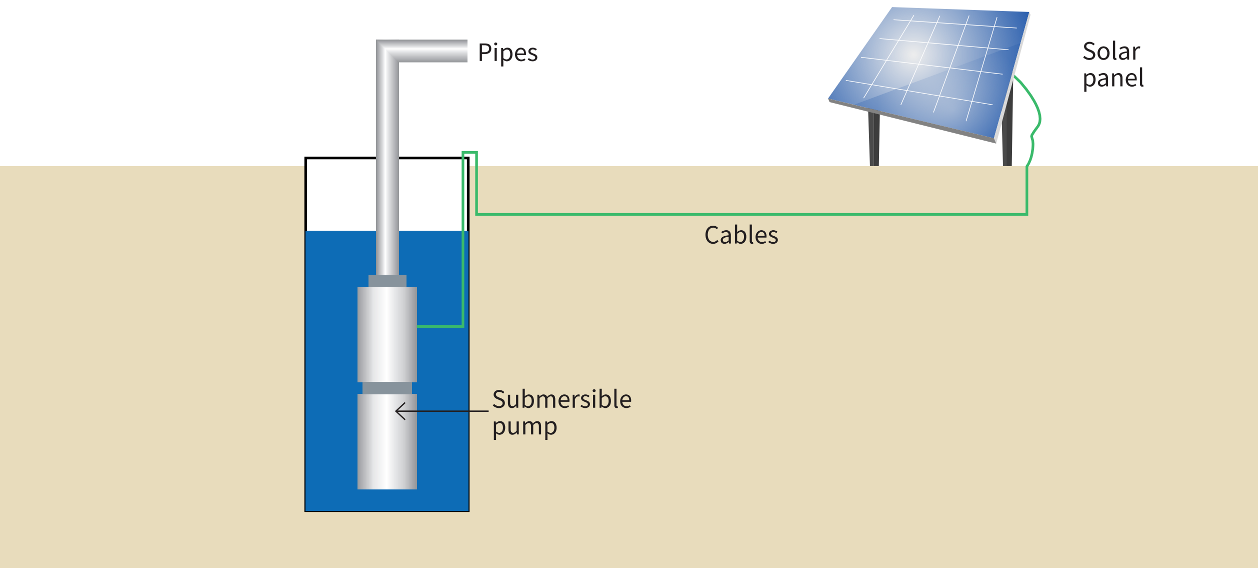
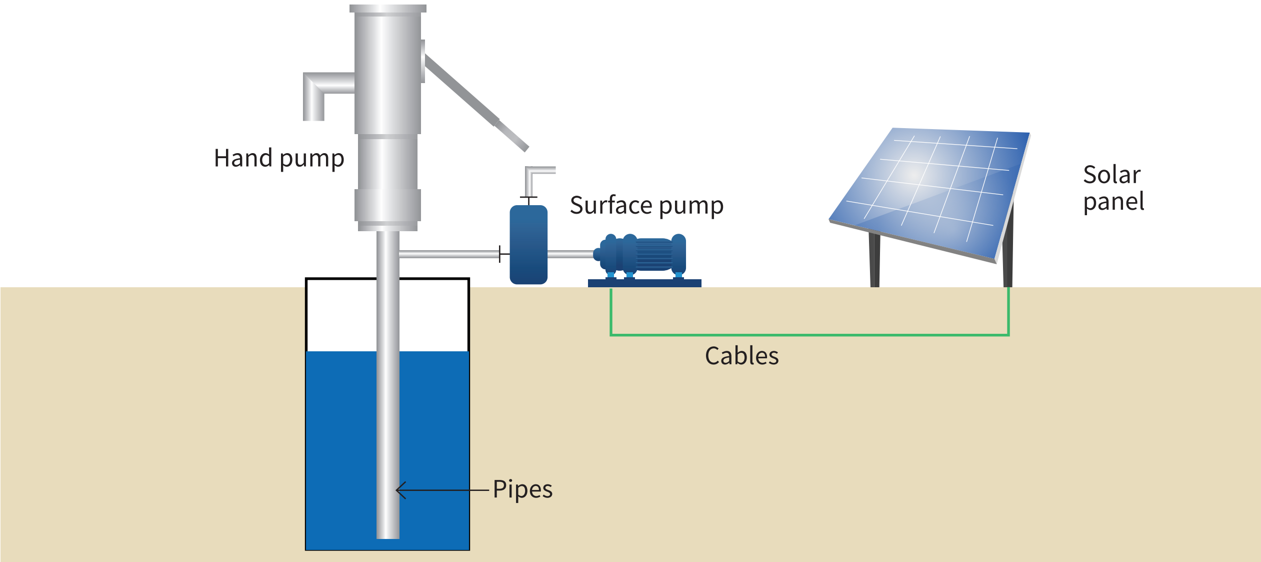


FIGURE 2 GENERAL REPRESENTATION OF SURFACE PUMP SWPS



SECTION V

Technical concepts

A. Solar radiation

Solar radiation is the key determinant of the performance of SWPS. Solar radiation is electromagnetic radiation that ranges from 0.25 to 0.45 µm in wavelength. This is the sun's radiant power measured in W/m^2 or kW/m^2. The typical peak value on the earth's surface facing the sun on a clear day at noon and at sea level is 1,000 W/m^2. This is also the standard condition for the ratings of solar modules.

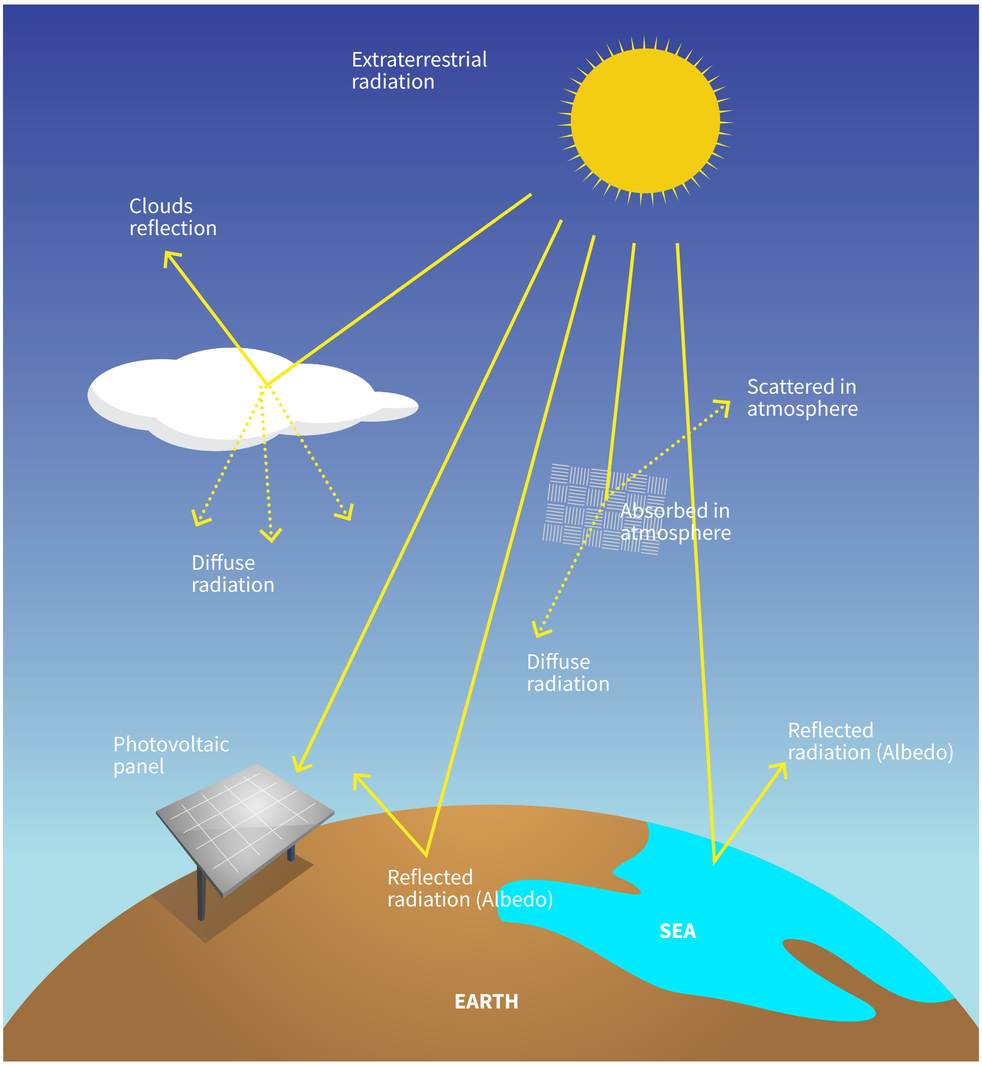
Direct radiation (also beam radiation or direct beam radiation): Direct radiation is the radiation travelling in a straight line to the earth's surface. This accounts for 70–80% of the total radiation.

Diffuse radiation: The sun rays that are scattered by the particles present in the atmosphere are called "diffuse radiation". Diffuse radiation does not have a straight path. In polluted areas, there is an increase in diffuse radiation. In terms of diffuse radiation on solar panels, these panels are installed horizontally

FIGURE 3 GLOBAL SOLAR RADIATION

Is 1,000 W/m^2 the absolute maximum?

No. Solar irradiance increases as we leave the earth's atmosphere. The average value of solar irradiance outside the earth's atmosphere is 1,366 W/m^2. This is because, approximately, 30% of extraterrestrial solar power is absorbed or reflected by the earth's atmosphere before it reaches the surface. This is due to the effects of altitude, latitude, time of day and year, air pollutants, weather patterns, and the wavelength of solar radiation.



Source: Image obtained from Souza, M. B. D., et al. (2019) [2]

to capture the maximum diffuse radiation. The panels are mostly kept at an angle to capture the direct radiation, but if the angle of the solar panel with the ground is lessened, then diffuse radiation increases.

Reflected/albedo radiation: Reflected radiation is radiation reflected from surfaces, not air particles. This is radiation reflected from hills, trees, houses, and waterbodies. Though the percentage of this radiation is very low compared to direct and diffuse radiation, this can contribute to as much as 15% in snowy regions.

MEASURING SOLAR RADIATION

Here are the descriptions of some devices used to measure solar radiation:

Pyranometer: Pyranometer is a device that measures global solar irradiance, both direct and diffuse. It is precise and used in laboratory measurements and weather stations. Its dual glass dome improves low incidence angle and thermal accuracy. However, these devices are expensive (estimated cost range of USD 785 to USD 1,482).

Pyrheliometer: Pyrheliometer measures the direct normal component of the total global radiation. This device always tracks the sun. Due to its high precision, accuracy, and tracking hardware, the pyrheliometer is also expensive (estimated cost above USD 3,000).

Handheld solar meter: Handheld solar meters use small photovoltaic (PV) cells to measure solar irradiance. For accurate measurement, the PV cell must be in careful alignment with the plane of the array. These meters are inexpensive (estimated cost range of USD 90 to USD 500) and good for basic field measurements (Figure 4).

FIGURE 4 **INSTRUMENTS USED TO MEASURE SOLAR RADIATION**

Figure 4a) Pyaranometer

Figure 4b) Pyrheliometer

Figure 4c) Handheld solar meter

Image sources: [3], [4] and [5]

B. Solar panels

Solar panels capture the energy radiated by the sun. The energy is captured in the form of radiation and converted into electrical energy. Solar panels produce direct current (DC) which is supplied to the pump directly if the pump also runs on DC; else, it is supplied via a controller, converting the DC to alternating current (AC) if the pump runs on AC.

There are three main types of solar panels:

- Polycrystalline
- Monocrystalline – standard and PERC cells
- Thin film

The comparison between the different types of panels is shown in Table 1.

There are even bifacial solar panels that produce power from both sides of the panel. These cells typically use monocrystalline technology [8]. The 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 be as high as 27% [8].

The choice and specification of the solar panel are made based on the requirement of the site and system design. The higher the efficiency, the higher the cost of the solar panels. Hence, one needs to design the system by balancing the cost and efficiency to meet the requirement.

Open circuit voltage (V_{oc}) of 72-cell solar panel is given by:

V_{oc} = 0.58 V * 72 cells

V_{oc} = 41.8 V

Similarly, the open circuit voltage (V_{oc}) of 60-cell solar panel is given by:

V_{oc} = 0.58 V * 60 cells

V_{oc} = 34.8 V

TABLE 2 PROS AND CONS OF 60-CELL AND 72-CELL SOLAR PANELS

Panel	Pros	Cons
60 cells	More compact, can fit on smaller roof segments, harder to damage	Less output per panel (on average), installation requires more panels
72 cells	More output per panel, cheaper cost per watt	The larger size means it doesn't fit well on smaller roof segments and is heavier and difficult to handle

FAQ: Why are solar panels specified in Watt-peak (Wp) and not Watt (W)?

Solar panels are specified in watt-peak because the rated power of the panel is achieved only at "peak" when the standard conditions are met, i.e. at STC conditions (refer to the Solar module power ratings section about STC conditions). The peak power is also referred to as the nominal power of the panel. The actual power from the panel will be less due to temperature and environmental losses [56].

TABLE 1 COMPARISON BETWEEN DIFFERENT PANEL TYPES

Standard Polycrystalline	Standard Monocrystalline	PERC Cells Monocrystalline	Thin Film
Efficiency: 13–16% (medium)	Efficiency: 15–20% (medium)	Efficiency: Up to 25% (highest) [7]	Efficiency: 7–13% (lowest)
Requires more space	Smaller footprint	Smaller footprint	Requires more space
High durability	Relatively lower durability	Relatively lower durability	High durability
Cheaper than monocrystalline	Relatively expensive	Relatively expensive	Cheapest
Performs well at high temperature	Degrades faster at high temperatures	Degrades faster at high temperatures	Best performance at high temperature

Source: Figure obtained from Immadi, P. et al. (2015) [6]

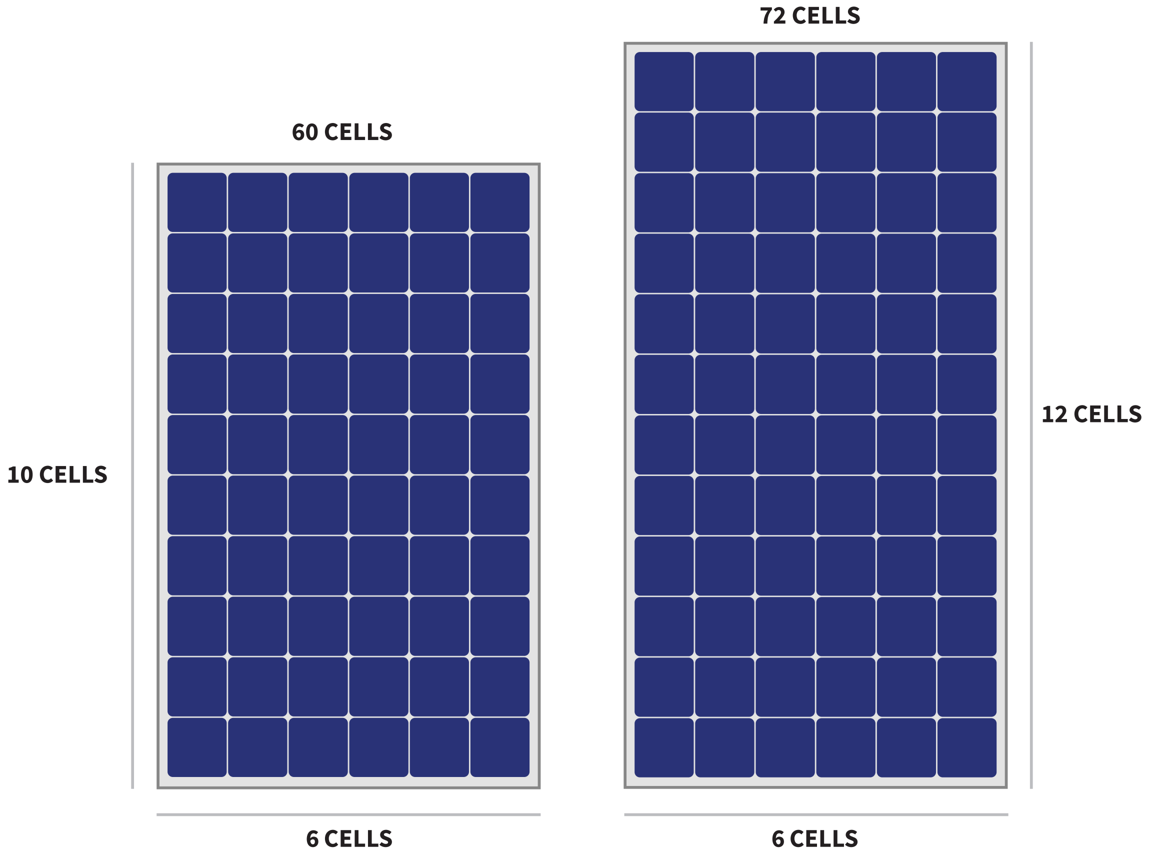
SOLAR CELLS

Most solar panels are made of a combination of 60 or 72 cells. Other cell arrangements are also available. The open circuit voltage of each cell is typically about 0.58 V [9]. The group connection of these cells makes the solar panel that we normally get in the market (Figure 5). Table 2 shows the pros and cons of the 60 and 72 cells solar panels.

MANUFACTURER AND ASSEMBLER CLASSIFICATION

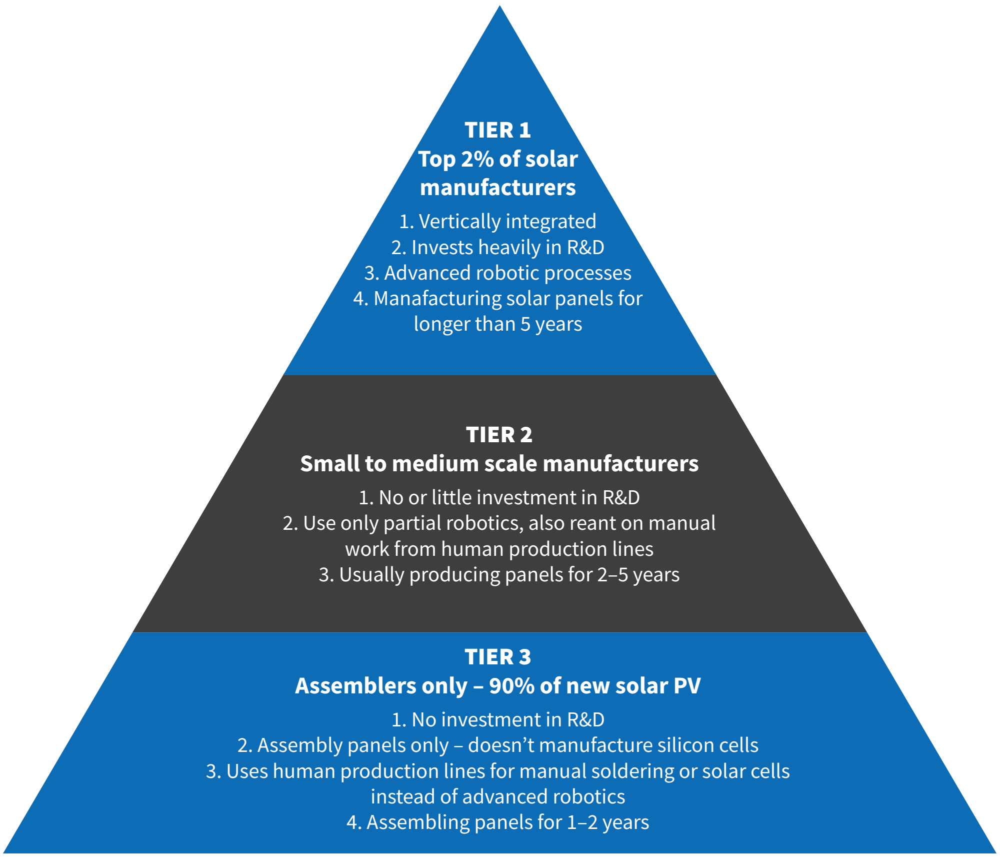
When choosing solar panels, suppliers may claim that they supply 1st Tier panels. Manufacturer and assembler classification is a system of ranking panel manufacturers as "good" and "bad" based on their panel-production quality. Figure 6 illustrates the difference between each.

FIGURE 5 60-CELL AND 72-CELL SOLAR PANELS



Source: Image obtained from Sendy, A. (2021) [10]

FIGURE 6 MANUFACTURER AND ASSEMBLER CLASSIFICATION



Source: Image obtained from Solar Choice [11]

1st Tier: These manufacturers make the panel from the ground up (vertical integration) without relying on the assembly of components from other manufacturers. This means they have control over the entire manufacturing quality and that most of the manufacturing process is automated. They also invest heavily in research and development (R&D) to innovate and improve upon their products. One of the qualifiers for 1st Tier panel manufacturers is that they need to have at least five years' experience in producing solar panels so that it instils trust in the buyers that they will be around for over 20 years to provide warranty [11].

2nd Tier: They invest relatively little money in R&D and only some of their manufacturing process is automated. They may not have five years' production experience, which makes them aspiring 1st Tier manufacturers [11].

3rd Tier: This type of panel manufacturers is the most common and comprises the bulk of the market share (90%). They have little experience and they assemble specific components manufactured by Tier 1 and Tier 2 to create panels with lower costs. The production is heavily dependent on manual labour with no R&D operations of its own [11].

A list of module makers in each tier is available to the subscribers of Bloomberg New Energy Finance's Solar Insight as part of the quarterly Bloomberg New Energy Finance PV Market Outlook [12].

FAQ: What are 12 V and 24 V solar panels?

Often, for someone new to solar, people talking about 12 V or 24 V solar panels will be confusing. The lower range of solar panels, for example, of 150 Wp and less, have a Vmp of around 17 V for 36-cell panels. The higher range of solar panels, for example, of 150 Wp and above, has a Vmp of 30 V and above. The 12 V and 24 V classifications are for panel ranges suitable for different system voltages.

For example, for a 12 V pump, it makes sense to connect the panel in the range of 17 V than of 30 V if the power requirements and other design parameters are met. Similarly, for a 24 V pump, a panel range of 17 V is not enough to meet the pump voltage; therefore, the nearest range of above 24 V is chosen, which will be 30 V.

SOLAR MODULE POWER RATINGS

FAQ: What is STC?

STC is the abbreviation for standard test conditions. It is an industry-wide standard to indicate the performance of solar panels at a cell temperature of 25°C and at an irradiance of 1,000 W/m^2 with an air mass of 1.5 (AM1.5) spectrum. These correspond to the irradiance and spectrum of the sunlight incident on a clear day upon a sun-facing 37°-tilted surface with the sun at an angle of 41.81° above the horizon [57].

This condition approximately represents the solar noon near the spring and autumn equinoxes in continental United States with the surface of the cell aimed directly at the sun. However, these conditions are rarely encountered in the real world [57].

What is NOCT?

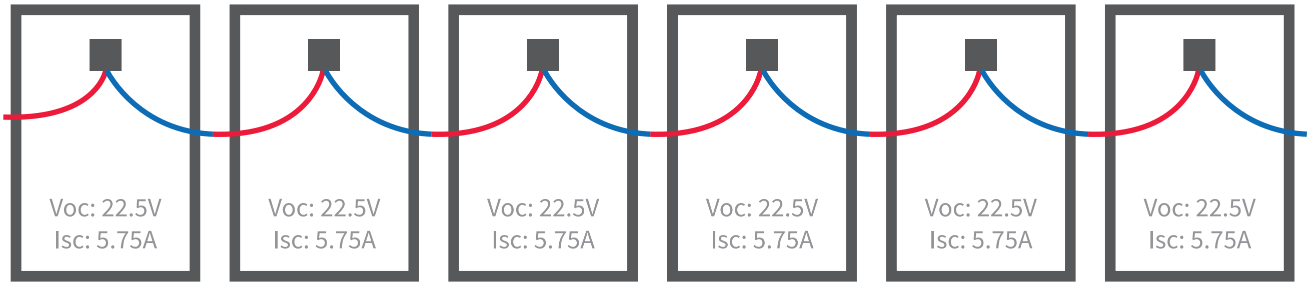
NOCT is the abbreviation for nominal operating cell temperature. Since the STC does not reflect the actual field conditions, NOCT aims to simulate this more closely. The NOCT indicates the performance of solar panels at an irradiance of 800 W/m^2 with 1 m/s velocity of wind at an air temperature of 20°C [58].

SERIES CONNECTION

In a series connection, the positive of one panel is connected to the negative of the other panel and so on. In a series connection, the voltage of each panel adds up but the current remains the same. In Figure 7, the output voltage and current from the 6 panels in series are:

22.5 V * 6 = 135 V

FIGURE 7 SERIES CONNECTION



Going to charge controller: 135 volts; 5.75 amps

Note: The current remains the same for each panel. Generally, this is called "1 string of 6".

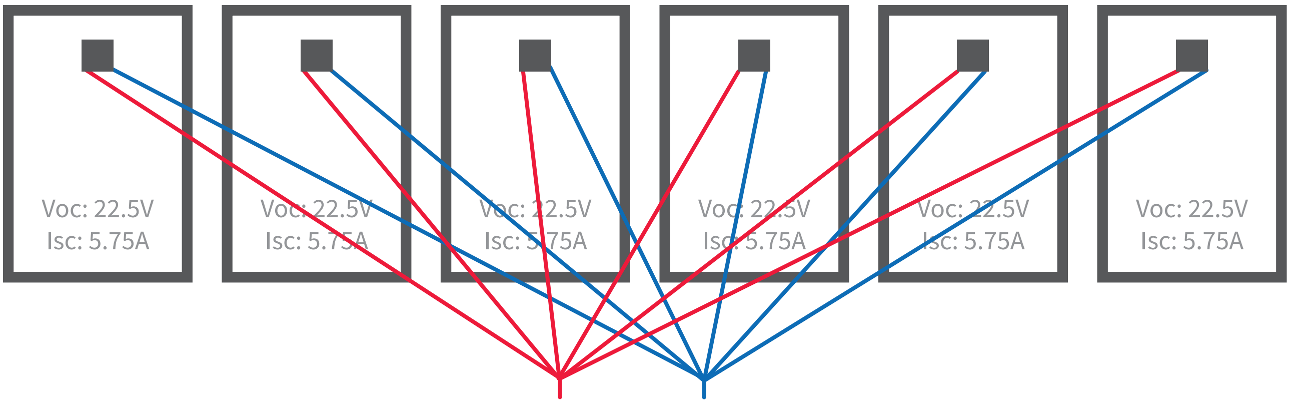
PARALLEL CONNECTION

In a parallel connection, all the positive terminals of the panels are connected as one, and the same with the negative terminals. The current of each panel adds up but the voltage remains the same. In Figure 8, the current and voltage from the 6 panels in the parallel connection are:

5.75A * 6 = 34.5A

During system design, the solar panels are configured in a combination of series and parallel connections to achieve the desired array voltage and current which is compatible with the controller's acceptable input DC voltage and current.

FIGURE 8 PARALLEL CONNECTION



Note: The voltage remains the same for each panel. Generally, this is called "6 strings of 1".

SERIES-PARALLEL CONNECTION

As the term suggests, the "series-parallel connection" has both combinations of panel arrangement. In Figure 9, the 6 panels are divided into 3 sets of series connections and the output of each is connected in parallel. In each set of series connection, the voltage is added, i.e. 22.5 V * 2 = 45 V, and when the 3 sets are connected in parallel, the current is added, i.e. 5.75 A * 3 = 17.25 A. Therefore, the output voltage and current are 45 V and 17.25 A, respectively.

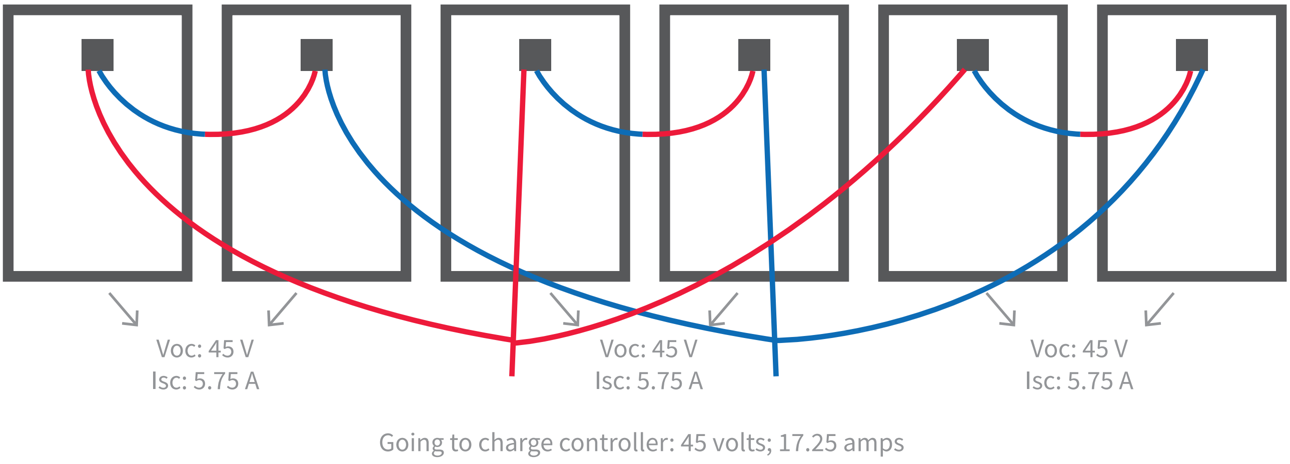
Generally, this is called "3 strings of 2".

LOSSES

The factors that cause losses in a solar panel power output are:

- Atmospheric loss of solar irradiance – depends on the local weather and climate.
- Power loss due to cell temperature – depends on the local weather, climate, and panel gaps.
- Nameplate DC rating – depends on manufacturing uncertainty.
- Diode and connection loss – depends on manufacturing uncertainty.

FIGURE 9 **SERIES-PARALLEL CONNECTION**



- Mismatch loss – depends on the uniformity of the panels in the array (uniform tilt angles, uniform azimuth, etc.).
- DC and AC wiring loss – depends on the appropriate sizing of cables to minimise the losses.
- Sun-tracking loss – due to changing sun position and the irradiance angle striking the solar panels over the day.
- Shading loss – depends on the site conditions (near and far shading).
- Soiling loss – depends on the site conditions (a clean environment means less soiling/dust deposited in the panels, which, therefore, lowers system loss, whereas a dirty environment means more soiling and therefore, higher system loss).
- Controller loss – depends on the electrical conversion efficiency of the controller.

Major losses need to be taken into account during the design stage in order to accurately estimate the usable energy in the system which directly affects the water output. The procedure to account for losses in the system is explained in **System design** in Section VII, under **Panel selection**.

FAQ: Does panel efficiency increase with decrease in temperature?

Yes. Panel performance increases with decrease in temperature below 25°C (rated temperature) [59]. This can also be seen from temperature coefficient calculations specified as negative in the data sheet of panels which adds power to the rating below 25°C.

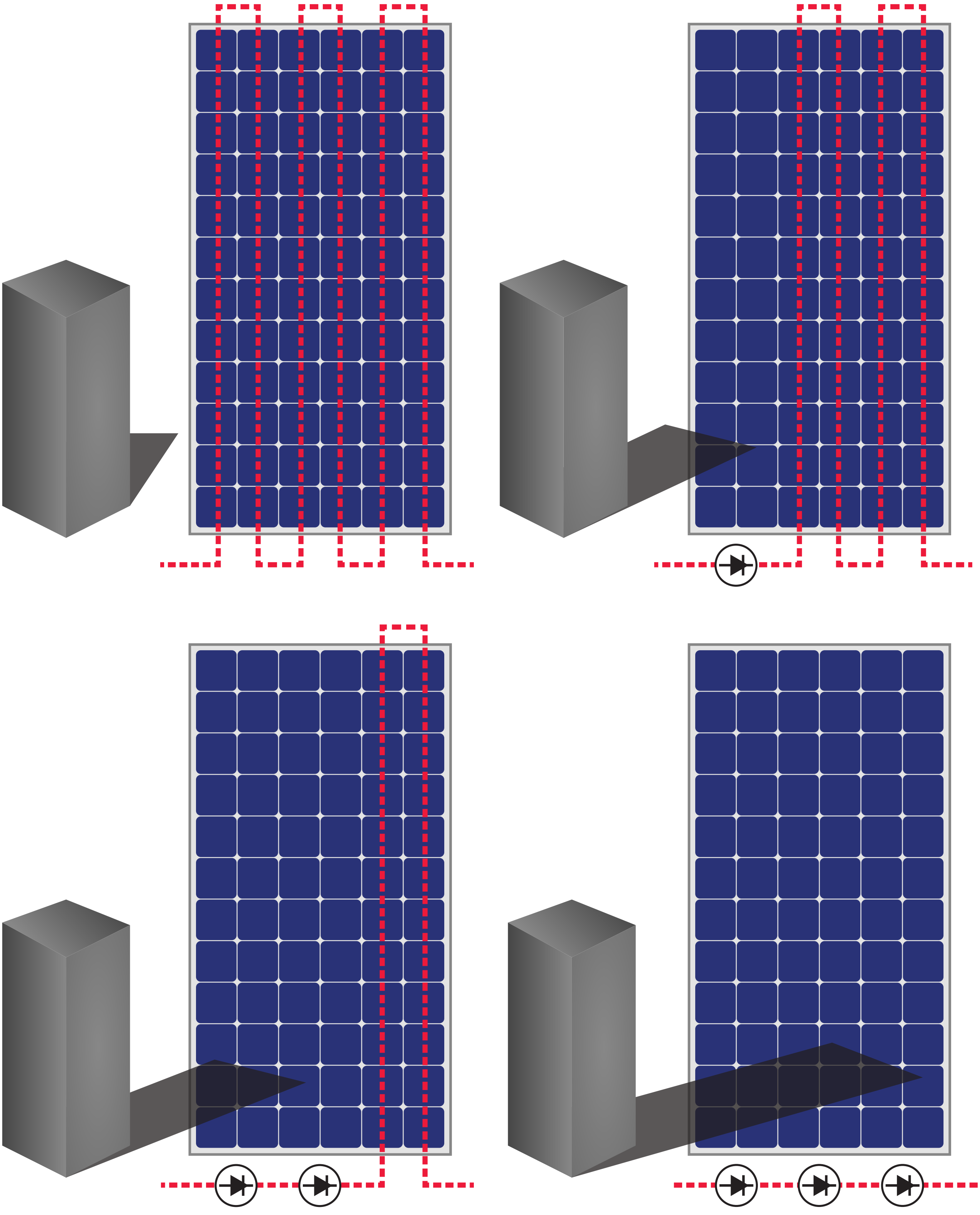
EFFECTS OF SHADING

Shading on a solar panel can dramatically affect its power output. Also, the type of shading can have a drastic impact on the panel's output. If panels are partially or completely shaded, the shaded parts can act as a resistance agent, causing power to be dissipated as heat, thereby creating "hot spots" which can lead to a dangerous deterioration of the cell and module back sheet; in the worst-case scenario, it may even catch fire. Therefore, in order to reduce power loss and prevent hot spots, bypass diodes are used in modules to route current around the shaded areas [14].

In the figure below, a 72-cell solar panel with 3 bypass diodes is shown, each bridging a series of 24 cells. Each diode bypasses the series it is connected to when shading occurs.

Therefore, partial shading can have a significant effect on power production since the whole set of cells in a series can be affected (Figure 10).

FIGURE 10 SHADING EFFECTS



Emerging trend: Agrivoltaics

As solar PV systems begin to scale, ground-based solar PV systems will cover a significant amount of land area. A 1 MWp ground-based solar PV system will, on average, require 2.5 acres of land. For agriculture-driven economies, the large area required for solar panel installations comes in direct conflict with land use for agriculture.

While in the past, technologies for energy and food had been seen as independent of each other, now methods have been developed to integrate both. Agrivoltaic is a concept that co-develops the same area of land for both solar PV power as well as for conventional agriculture [67] (Figure 11).

A study from the United States shows that the value of solar-generated electricity coupled with shade-tolerant crop production created over 30% increase in the economic value of farms deploying agrivoltaic systems instead of practising conventional agriculture [67].

FIGURE 11 EXAMPLE OF AN AGRIVOLTAIC SYSTEM

Source: Image obtained from Rodriguez, L. (2021) [68]

Another study from North Italy ran long-term simulations comparing the yield of maize from an open field to the yield of maize obtained by following an agrivoltaic model. The results showed that while the yield under the agrivoltaic model was slightly lower when water was a non-limiting factor, it was higher during drought. Similarly, the average rain-fed maize yield was higher and more stable under the agrivoltaic model than in full-light conditions [69].

These studies show that the agrivoltaic system, by supporting crop yield, clean energy production, and water saving, can play a significant role in the energy–food–water nexus [69].

PANEL GAPS

Rooftop installation: For rooftop installation, especially when panels are installed on rails parallel to the roof slope, the air gap between the roof and the panel must be between 100 mm to 110 mm [15]. A smaller air gap will increase module temperature and hence, increase power loss. A greater air gap will have a negligible cooling impact and the structure moments may increase [15].

Ground installation: The ground installation gap depends on the site and should be determined during the survey. In some sites, the ground where the panel is to be installed may be used for vegetation which could be a land-use concern for the owner. Therefore, in some circumstances, the height of the structure may be raised to allow the owners to grow vegetables below the panels; however, safety must be ensured (such as neatly tied cables) behind the panels to: i) reduce the risk of electrocution; and ii) prevent damages to the electrical cables.

Informing farmers about the dangers and training them to properly operate SWPS is crucial for health and safety, as well as for the smooth running of the system.

Inter-row spacing: The inter-row spacing of the panel array must be evaluated to avoid shading from one row to the other which affects system performance. This is calculated based on the altitude and the azimuth angles of the sun. The altitude and the azimuth angles of the sun for a given location can be obtained online and via software. For example, the sun-path with altitude and azimuth angles for a given location is shown in Figure 12.

The minimum inter-row spacing can be calculated by the following equation:

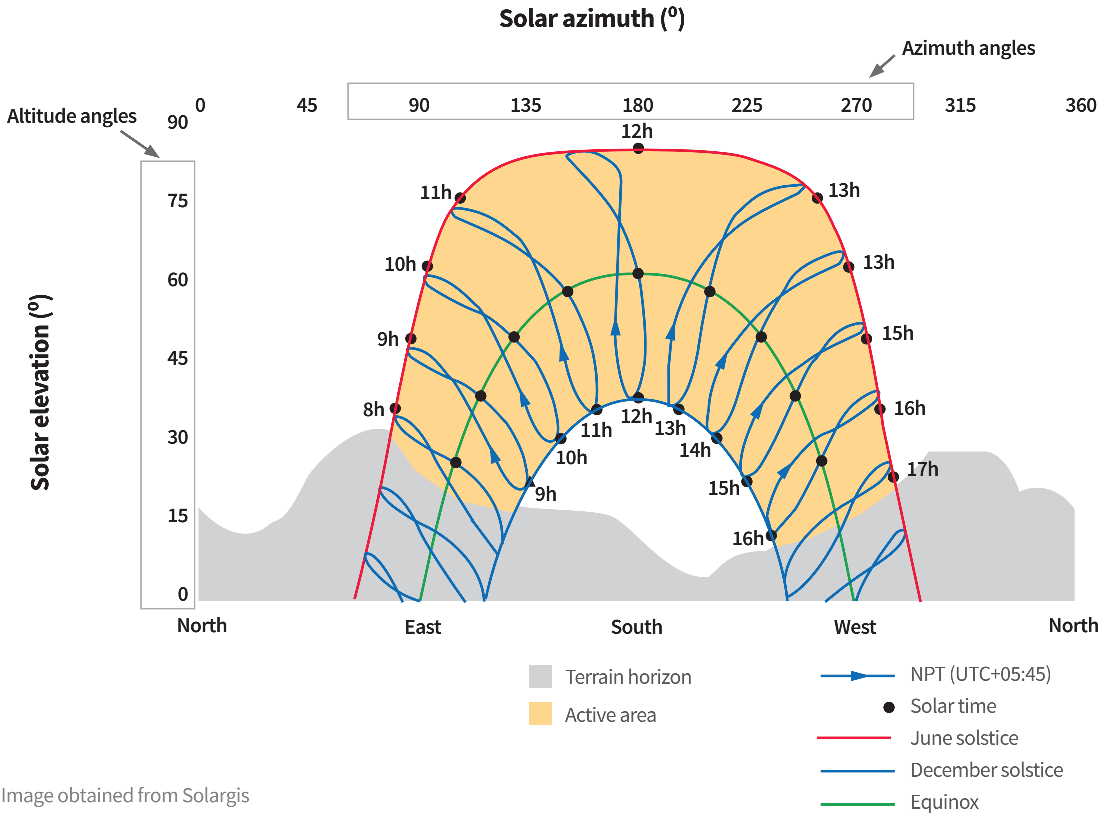
$$d = h \text{ x } \frac{\text{cox}\ (\theta)}{\tan\ (\alpha)} \qquad \text{Eq. 2}$$

where,

d = Minimum inter-row spacing in m;
h = Vertical height of panel in m;
θ = Azimuth angle; and
α = Altitude angle

Adjacent panel gap: Adjacent panel gap depends on metal expansion tolerances, mounting type, clamp sizes, etc. Due to these factors, the minimum gap that is to be maintained between adjacent panels is hard to prescribe. However, in practice, for structures without clamps, a gap of at least 20 mm

FIGURE 12 EXAMPLE OF ALTITUDE (VERTICAL AXIS) AND AZIMUTH (HORIZONTAL AXIS) ANGLES



Source: Image obtained from Solargis

allows for the panels to be easily positioned during installation.

CERTIFICATIONS

Solar panels from recognised manufacturers conform to international certifications. These certifications include:

- IEC 61215:2016
- IEC 61730-1/-2:2016
- ISO 9001:2015 Quality Management System
- ISO 14001:2015 Environmental Management System
- ISO 45001:2018 Occupational Health and Safety Management System
- UL 61730
- TS62941: Guideline for module design qualification and type approval

Although a few certifications may vary depending on the country of origin, it is important to check the certifications of solar panels so as to ensure product quality. The certifications are usually listed in the solar panel data sheet or on the website of the manufacturer.

It is important to note that the acceptable standards may differ from country to country and the choice of solar panels must be compliant with the country where the SWPS is to be implemented. Some country-specific national standards are: Nepal Photovoltaic Quality Assurance (Nepal); and the Bureau of Indian Standards (India).

C. VFD controller

The variable frequency drive (VFD) controller regulates DC power from the panels to produce AC power to drive the pump. The VFD is a type of motor controller that drives an electric motor by varying the frequency and voltage of its power supply. The controller discussed in this section focuses on SWPS. The other charge controllers for off-grid or on-grid systems are not covered here. However, it is important to know about two main types of controllers.

PWM CONTROLLERS

The pulse width modulation (PWM) controllers bring down the input voltage from the panels to the desired voltage of the output. The PWM circuit in the controllers turns on and off to give an average voltage output matching the desired voltage. The ratio of “on” time to the total period, also known as the “duty cycle”, determines the output voltage.

Let’s take an example of a DC pump and its specifications specifications as shown in Table 3.

TABLE 3 POWER RATINGS OF DC PUMP

Rated power	120 W
Rated voltage	12 V
Rated current	10 A

To power this pump, a 150 Wp module is connected to a PWM controller that connects to the pump. The specifications of the 150 Wp panel are shown in Table 4.

TABLE 4 ELECTRICAL PARAMETERS OF 150 WP PANEL

Parameters	Values
Wattage	150 Wp
V_{mp}	18.6 V
V_{oc}	22.4 V
I_{mp}	8.06 A
I_{sc}	8.53 A

Now, it seems that 150 Wp is a good size to power the 120 W pump; however, the use of the PWM controller shows otherwise.

When the panel is connected to the pump, the voltage of the panel drops to match the voltage of the pump, but the current Imp of the panel is the maximum current it can supply while running the load.

Therefore, now the maximum power available to the pump is:

12 V * 8.06 A = 96.7 W

This shows that the actual power available to the pump is less than its rated power. Assuming that the panel is generating power in ideal conditions, the rest of the power (53.3 W) is wasted as heat [6].

If there is no other option than to use a PWM controller, then another 150 Wp panel will be needed in parallel to double the available current from the panels, i.e. 8.06 A * 2 = 16.12 A. Since the pump is rated at 10 A, it has the required voltage and current to run at its rated power.

The disadvantage of adding another panel even though the pump is running at its rated power is that the system is oversized and its power capacity is underutilised. For example, when a 300 Wp array capacity is powering a 120 Wp pump, i.e. the panel size is 150% bigger than the rated power of the pump, it is significantly oversized even if other environmental and cable losses are taken into account.

There is an alternative to this approach which will be discussed in the next section on the maximum power point tracking (MPPT) controllers.

MPPT CONTROLLERS

While PWM controllers provide a direct connection between the panel and the load, MPPT controllers have an indirect connection. The algorithm in the MPPT circuit in the controller tracks the maximum power available from the panels.

Note: MPPT controllers also have PWM circuits. However, MPPT is an algorithm that tracks the maximum power available from the panel at any point in time.

Figure 13 shows the IV (current-voltage) and power curves of a solar panel. Starting from the left and moving to the right of the graph, the Isc of the panel is fairly constant while the voltage increases. Towards the right of the graph, the Isc decreases significantly as the voltage reaches Voc. The maximum power in the path of the curve is shown by the black line and is marked Pmp by the dotted lines. This is where the panel yields the maximum power.

The MPPT controller tracks this point of the panel to extract the maximum power available.

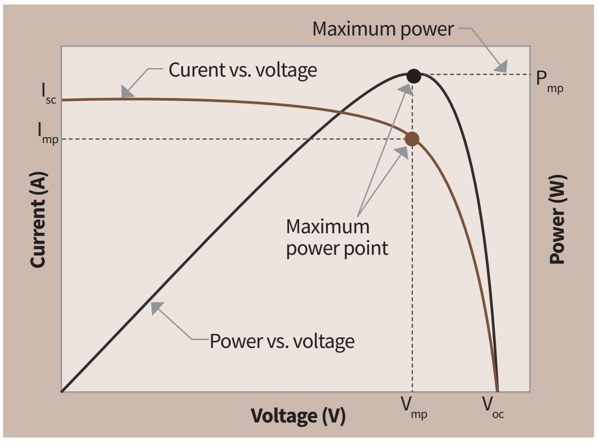
CHOOSING THE RIGHT CONTROLLER

Before choosing the best controller that would fit the application, Table 5 describes the pros and cons of each.

TABLE 5 COMPARISON BETWEEN MPPT AND PWM CONTROLLERS

PWM	MPPT
Can be one-third or half the cost of MPPT controllers	Can be two to three times more expensive than PWM controllers
30% less efficient than the MPPT controller	90–98% efficiency
The PV array size is larger to compensate for the greater loss of the controller	The PV array size can be reduced due to the higher conversion efficiency of the controller
Longer lifespan due to fewer electronic components and less thermal stress	Lesser expected lifespan due to more electronic components and greater thermal stress
PWM controllers are physically smaller than MPPT controllers	MPPT controllers are physically larger than PWM controllers

FIGURE 13 PV PANEL IV CURVE AND MPPT TRACKING



Source: Image obtained from Mayfield, R. (2012) [16]

To choose the best controller for the application, the following points should be considered:

- If the distance between the panel and the load is high, then it is better to go with the MPPT controller since it accepts higher voltage than the PWM controller, which means lower loss over higher distances. The decision is up to the designer after evaluating the voltage loss, cable size, and costs for both options.
- **Cost:** Taking the example of running a 120 Wp pump as described in the PWM controller section above, there are two choices:
  – **PWM option:** This will require adding another 150 Wp panel to reach the pump's rated power. Therefore, the cost comparison should take into account this additional panel (Table 6).

TABLE 6 EXAMPLE OF COST OF A PWM CONTROLLER

PWM controller	USD 28
Additional 150 Wp panel	USD 82
Total	**USD 110***

* Costs are estimates only.

- **MPPT option:** With the MPPT controller, an additional 150 Wp panel is not needed, but the cost of the controller is greater (Table 7).

TABLE 7 **EXAMPLE OF COST OF AN MPPT CONTROLLER**

MPPT controller	USD 126*

* Costs are estimates only.

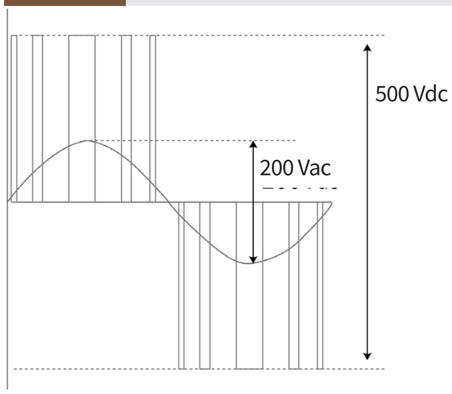
Now, looking only at efficiency, the MPPT controller is better, but comparing the cost of the two systems, the PWM controller makes more sense since it is cheaper by a significant amount.

That means, choosing between PWM and MPPT controllers is based on the cost and site requirements. There will also be systems, mostly in the kW range of panel array, wherein MPPT controllers become an efficient and cost-effective option compared to PWM controllers. After all, loss of power in PWM controllers is loss of money, which becomes significant in the case of larger systems, making MPPT controllers a better option.

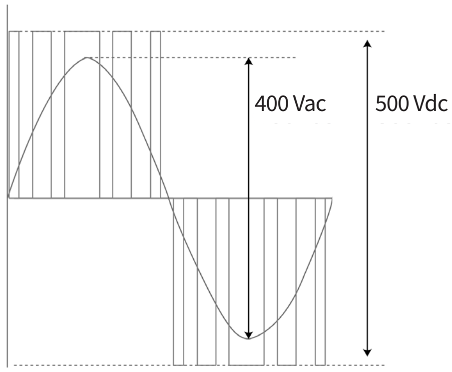
BRIEF ON VFD

VFD stands for "variable frequency drive", while some call it "AC drives". In most SWPS, the DC voltage from solar panels as input is inverted to AC voltage as output. The AC voltage is not sinusoidal, but rather a high-frequency PWM square wave that mimics a sinusoidal wave. Figure 14 shows the pulse output from VFD.

FIGURE 14 **PWM PULSE OUTPUT OF VFD**



Shorter 'ON' duration resulting in lower voltage amplitude



Longer 'ON' duration resulting in higher voltage amplitude

Source: Image obtained from Laxmi Hydraulics [17]

OUTPUT VOLTAGE LIMITATION OF VFD

VFD without boost circuit: Some VFD controllers designed for solar water pumps mention that the output AC voltage depends on the DC input voltage. This is because:

- When the maximum input DC voltage is higher than the required output AC voltage (rated motor voltage), the VFD controller can better control the motor because it adjusts the PWM frequency to match the rated motor voltage.
- When the maximum input DC voltage is lower than the required output AC voltage (rated motor voltage), the VFD controller has no means to meet the rated motor voltage. Therefore, the pump will not run at its optimum.

So, when the DC voltage of the solar input changes, the AC voltage in the output also changes. Therefore, VFD controllers for SWPS without a boost circuit specify a higher DC input voltage than the AC output required to run the pump.

VFD with boost circuit: When it comes to smaller systems, meeting the high DC input voltages from a series arrangement of solar panels to run relatively small AC pumps (for example: >400 Vac input voltage to run a 400 Vac rated 1 HP pump) can cause difficulty in design. The designer may have to add additional solar panels in series just to meet the DC input voltage which can lead to oversized solar array capacity.

Therefore, some manufacturers have external or internal DC boost circuits that boost the DC input voltage to a higher level than the required AC output voltage. This allows for lower DC input voltage acceptance, making it easier to meet the optimal system size for relatively smaller SWPS.

OUTPUT LOAD REACTOR

The output wave form of VFD are high-frequency square waves resulting from the PWM circuit. This high frequency results in sharp changes in voltage over a short time (dv/dt). When motor impedance is higher than the conductor-cable impedance, the voltage wave form will reflect at the motor terminals and is known as a "standing wave" [18]. The longer

FAQ: Is there a difference between standard VFD drives and VFD controllers for SWPS?

There is no hardware difference between a normal VFD and an SWPS VFD except that the input in SWPS is already DC and doesn't require a rectifier. However, some VFD manufacturers add a feature of MPPT to standard VFD drives which may not be optimised and thus may not be of a high quality. Whereas, VFD controllers for SWPS are designed specifically for solar applications and have a high-quality MPPT control card that makes the system reliable and more efficient. It is recommended that the VFD controllers be of the same manufacturer as that of the solar pump since they will be tested and optimised for their products.

What is soft-start function?

When induction motors are given their full voltage at start, the motors can draw 2–3 times its rated current to reach its rated speed. This is called the initial surge of the motor. When operating large pumps, usually of above 5 HP, a direct online start can cause the voltage in the supply line to drop as the pump draws higher than the rated current; this may affect other equipment [70]. For solar water pumps, such a surge means the solar array has to be oversized to provide that initial high power to the pump; and the controller too needs to be oversized. This makes the design inefficient during normal operation.

To control the initial surge of the motor, the starting voltage of the pump is lowered to limit the current flow until the motor ramps up near to its rated speed. This method does not cause the initial surge and thus the system can be sized more efficiently.

Are there solar pumps that can directly be connected to solar panels without any controller in the system?

Yes, there are pumps in solar applications which have a controller built into the pump body and so do not require an external controller. The cables from the panels can directly be connected to the pump.

What is the difference between inverter and controller?

Devices that convert DC to AC are called "inverters". In SWPS, there are added control algorithms such as MPPT to make the system more "intelligent". Therefore, generally, the term "controller" is used in SWPS.

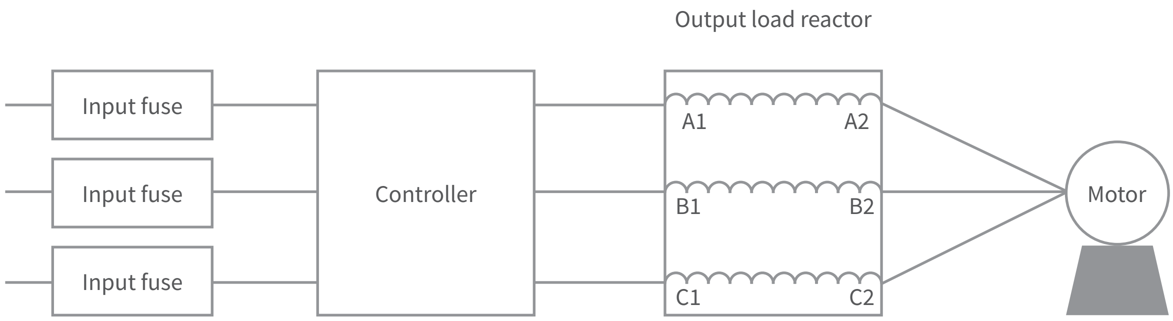
the cable between the VFD controller and the pump, the larger the amplitude of the standing wave. Voltage spikes can reach up to 2,150 V in a 480 V system operating at 10% overvoltage [18]. These voltage spikes on the motor side can over time break the insulation of the motor coil and short circuit the coil, causing damage and also tripping the VFD controller due to overcurrent.

To reduce the voltage spikes, load reactors or dv/dt (resistance, inductance, and capacitance) filters should be placed at the inverter output (Figure 15). The reactor is a coil which acts as an inductor. We know that inductors are reluctant to change current. Whenever there is a sudden change in current due to a voltage spike, the induced voltage opposes the voltage spike. Therefore, the voltage spike will be reduced.

The reactor should be installed close to the VFD controller. As a rule of thumb, if the cable distance between the VFD controller and pump is:

- >30 m (>100 ft), use output reactor [19].
- >150 m <300 m (>500 ft <1,000 ft), use dv/dt filter [19]

FIGURE 15 **OUTPUT LINE REACTOR**



Source: Image obtained from RAE [19]

Note: The distance above is a rule of thumb only. If the cable length between the VFD controller and the pump is higher than mentioned, refer to the manufacturer manual for the type of reactor to be used or contact the manufacturer for recommendation.

CERTIFICATIONS

Similar to solar panels, controllers for solar water pumps are certified based on certain quality standards. These certifications may include:

- CE certification (Europe)
- ISO 9001:2015 Quality Management System
- ISO 14001:2015 Environmental Management System
- ISO 45001:2018 Occupational Health and Safety Management System

Although a few certifications may vary depending on the country of origin, it is important to check the certifications of controllers to ensure product quality.

The certifications are usually listed in the controller data sheet or on the website of the manufacturer. If these are not available, the manufacturer must be contacted directly.

Similar to solar panels, the standards of SWPS controllers may be country-specific and must be checked during design and component selection.

D. Pumps

DIFFERENCE BETWEEN A PUMP AND A MOTOR

A motor is a device that converts electrical energy into mechanical energy. The most common type of motors are the ones that operate through rotary motion when it receives power via the current passing through a magnetic field [20]. A pump is a mechanical device that forces the liquid to move forward in a pipeline or uses suction (partial vacuum) to draw the liquid to a certain height [21].

Motors are of two types: AC and DC (Figure 16).

PUMP TECHNOLOGIES

There are different types of pump technologies. The choice of a pump depends on its application. Figure 17 shows the type of pump to be used for different head and water flows.

FAQ: Can VFD controllers work for all standard AC motors?

Earlier, VFD controllers were marketed as being compatible with all standard AC motors. However, due to high-frequency PWM controllers causing voltage spikes, motor manufacturers started designing motors specially for VFD controllers. These “inverter-ready” motors are wound with spike-resistance insulation systems. Some use inverter-grade magnet wire to minimise the adverse effects of the wave forms produced by VFDs. Other designs are wound with adjacent coils that are separated to minimise voltage potential [18]; this reduces the degradation of motors and increases pump life.

Note: NEMA MG 1-2011, Part 30 (US), provides performance standards for general-purpose motors used with VFDs [18]. It is worthwhile to check whether the motor of the pump complies with this standard.

SURFACE CENTRIFUGAL PUMPS

Surface centrifugal pumps are mostly used where the dynamic water level of the source is less than 6 metres (slight changes may occur in the suction head, depending on the pump manufacturer). The suction head of these pumps is limited (this will be explained later).

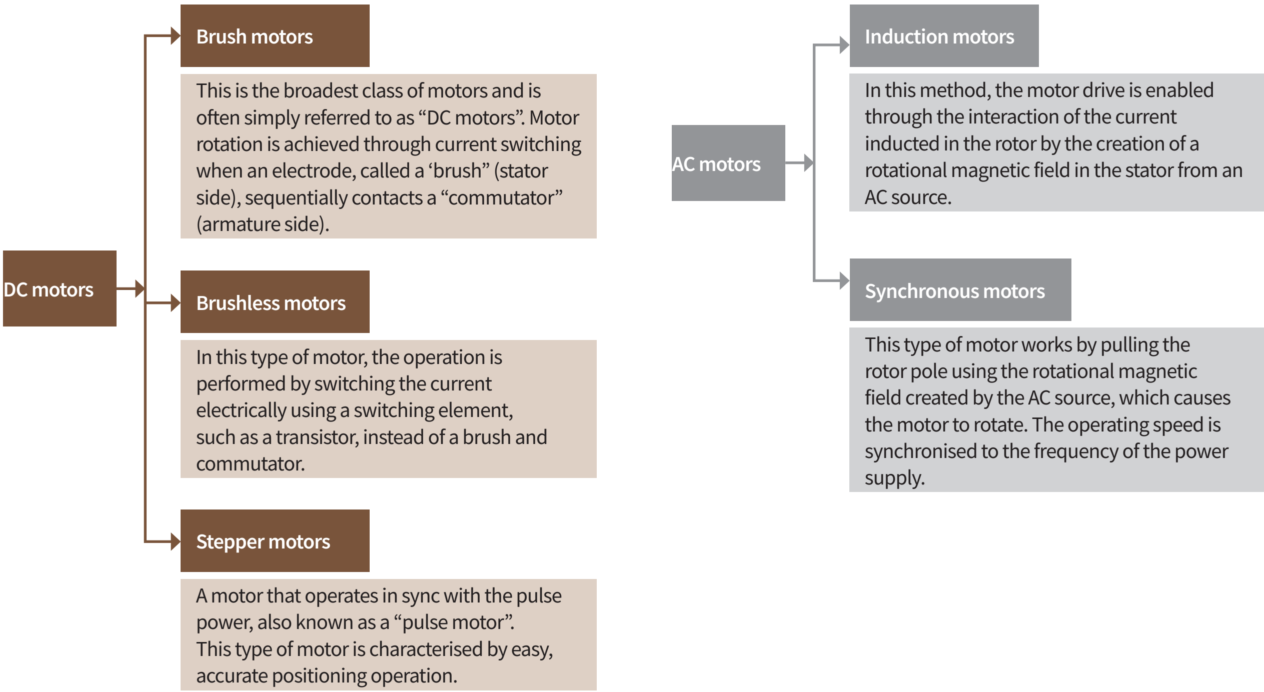
Centrifugal pumps are efficient for low-lift and high-discharge rates. They need to be carefully maintained and protected from external water and dirt. However, the pump may get damaged if run dry for a long time. These pumps are relatively cheap and are readily available in the market.

SELF-PRIMING CENTRIFUGAL PUMP

Air is the main enemy of a standard (non-self-priming) centrifugal pump (Figure 18). When a standard centrifugal pump encounters air, the pump can no longer push water since air is harder to pump than water. This is called “air bound”.

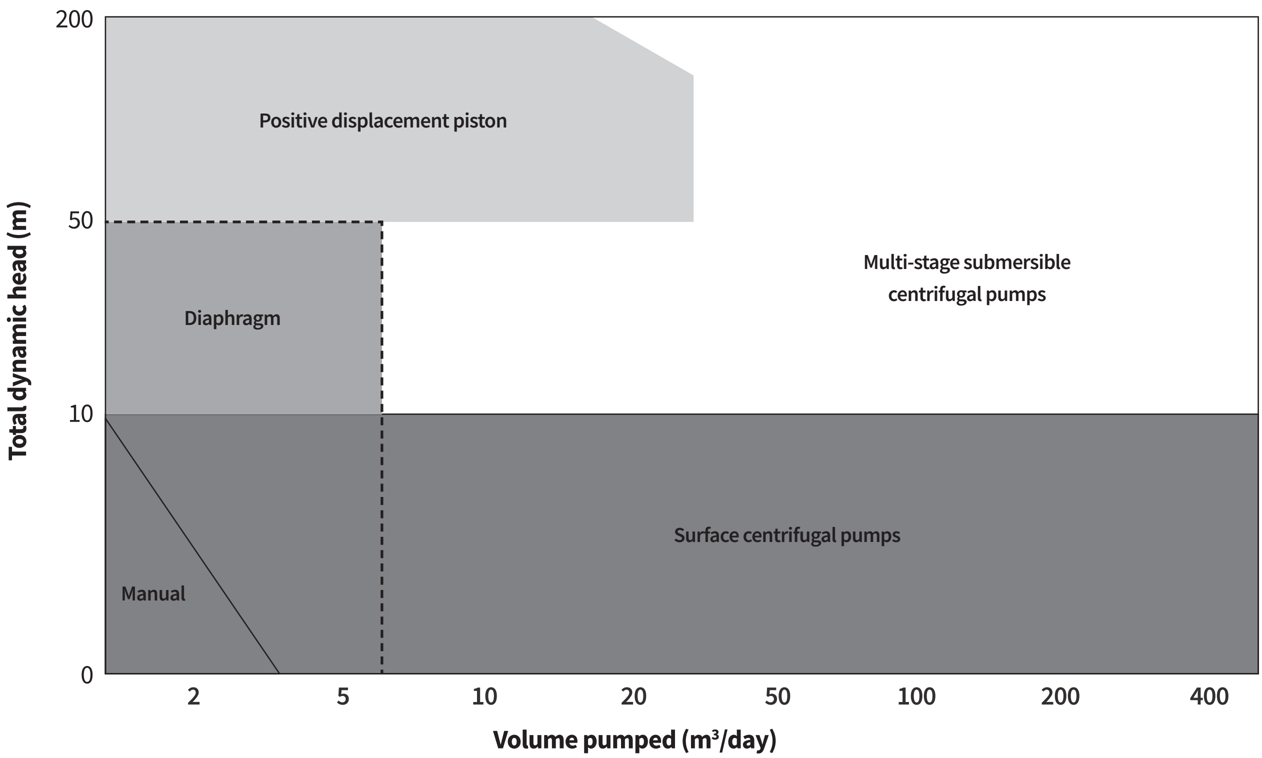
Non-self-priming pumps do not operate until the air is removed. A self-priming centrifugal pump overcomes the problem of air binding by mixing air with water to create a fluid with pumping properties much like those of regular water. The pump then gets rid of the air and moves water only, just like a standard centrifugal pump (Figure 19).

FIGURE 16 DIFFERENT TYPES OF MOTORS



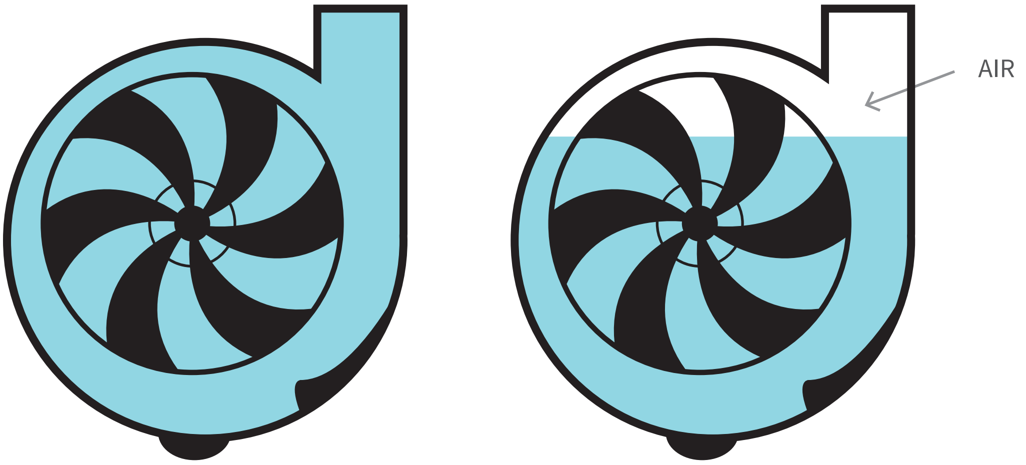
Source: Image obtained from ROHM Semiconductor [20]

FIGURE 17 GUIDE TO PUMP SELECTION ADAPTED FROM RESEARCH REPORT



Source: Figure obtained from Immadi, P. et al. (2015) [6]

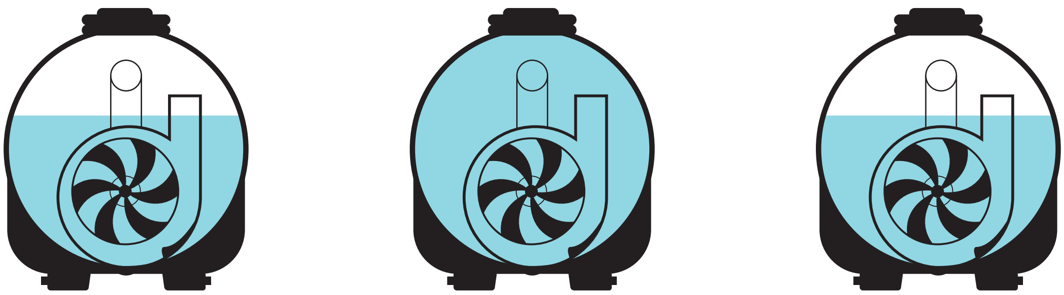
FIGURE 18 **AIR BINDING IN CENTRIFUGAL PUMPS**



Normal operation of centrifugal pumps

When air gets inside, the pump gets air-bound

FIGURE 19 **CASING OF SELF-PRIMING CENTRIFUGAL PUMPS**



During priming

While pumping

At rest

Source: Images obtained from Gorman-Rupp Company [22]

Note: A self-priming centrifugal pump must have water in the casing to operate. You cannot pull any self-priming pump right out of the box, turn it on, and expect it to pump.

SUBMERSIBLE PUMPS

"Submersible pumps", as the name suggests, are installed submerged in water. They do not require priming to operate and have better reliability than surface pumps since they are submerged and outside of other environmental harms.

MULTISTAGE CENTRIFUGAL SUBMERSIBLE PUMPS

Submersible pumps with multiple impellers mounted on a single shaft are called "multistage submersible pumps". Virtually, all submersible pumps are multistage pumps. Each impeller passes the water to the eye of the next impeller through a diffuser. The diffuser is shaped to slow down the flow of water and convert velocity into pressure. Each impeller and matching diffuser are called "stages". As many stages are used as necessary to push the water out of the well at the required system pressure and capacity. Besides, each time the water is pumped from one impeller to the next, its pressure is increased.

To get more flow, the exit width of the impeller is increased and there will then be less pressure (or head) that the pump will develop because there will be fewer impellers on a given HP size of the pump. Remember, the pump will always trade off one for the other (pressure and flow) depending on the demand of the system. If the system demands more than the pump can produce, it will be necessary to go up in horsepower, thereby allowing to stack more impellers or go to a different design pump with wider impellers.

FAQ: Why do surface pumps have limited suction head?

Fluid flows from high-pressure areas to low-pressure areas. Surface pumps create low pressure at the inlet which causes relatively high pressure of water to flow in this area due to atmospheric pressure acting on other areas.

However, even with a perfect vacuum at the pump inlet, atmospheric pressure limits how high the pump can lift a liquid.

The calculation below shows why there is a limitation to the suction head of a surface pump:

$$h = \frac{p * 10.197}{SG} \qquad \text{Eq. 3} \quad [60]$$

where,

h = Water head in m; p = Standard atmospheric pressure at sea level = 1.01 bar
10.197 is the conversion factor of 1.01 bar to water column in m
SG = Specific gravity of water at 25°C = 0.999
Now, solving the equation for h,
h = 10.34 m

This means that, for water at 25°C, the suction head of the pump is limited to 10.3 m in ideal conditions and at this point, the weight of the water in the suction pipe equals the force exerted by the atmospheric pressure.

In reality, the suction head of surface pumps will be lower at around 6 to 7 m due to pipe losses.

HELICAL ROTOR SUBMERSIBLE PUMPS

A helical pump is a type of positive displacement pump. The rotor has an eccentric movement which when rotating inside the stator, effectively squeezes water through the pump on every rotation. This positive displacement action means that the water is pumped when the pump is running at very low speeds; this also means that high pressure can be created in order to pump water to high lifts [23].

COMPARISON BETWEEN SURFACE AND SUBMERSIBLE PUMPS

The comparison between surface and submersible pumps are shown in Table 8.

CERTIFICATIONS

Pumps are certified according to certain quality standards. These certifications may include:

- UL
- CE certification (Europe)
- EN 60335-1
- EN 60034-1
- IEC 60335-1
- IEC 60034-1
- ISO 9001:2015 Quality Management System
- ISO 14001:2015 Environmental Management System
- ISO 45001:2018 Occupational Health and Safety Management System

TABLE 8 **COMPARISON OF SURFACE AND SUBMERSIBLE PUMPS**

Surface pump	Submersible pump
Needs to be primed	Doesn't need to be primed
More prone to theft	Less prone to theft
More prone to wear and tear due to environmental effects	Less prone to wear and tear due to environmental effects
Easy to access	Difficult to remove once installed
Pipework doesn't have to be removed and any maintenance can be done locally in a workshop	Requires major overhaul maintenance and possible rewind approximately every 5 years

FAQ: What is the difference between oil-filled and water-filled submersible pumps?

In terms of operation, there is no difference between oil-filled and water-filled submersible pumps. Basically, for submersible motors which are enclosed in casing, fluid needs to be filled in the motor to allow for heat dissipation from the shaft to the water outside.

Standard submersible pumps are filled with water and the following factors differentiate water and oil-filled pumps:

- **Environment:** Water-filled pumps eliminate environmental hazards while not all oil-filled pumps use biodegradable oil.
- **Lubrication and cooling:** Water-filled pumps have simple drainage channels inside the pump that allows the water to cool the stator and rotor efficiently. They also transfer frictional energy from the bearings to motor housings well. Oil-filled pumps need a dedicated oil line to provide lubrication and if that line is not clear throughout its operational life, then the pump will not offer improved lubricity and good thermal conductance. As long as the motor is properly insulated, water-filled pumps are better at lubrication and cooling.
- **Real-world considerations:** Since water is not a viscous liquid, a water-filled motor may lose its lubricating film if load spikes and thrust loads occur. However, oil is more viscous and will maintain its lubricating film at load spikes. Moreover, water-filled motors require a better design consideration since the motor needs to be properly insulated.

Although a few certifications may vary depending on the country of origin, it is important to check the certifications of pumps to ensure product quality.

The certifications are usually listed in the pump data sheet or on the website of the manufacturer. If these are not available, the manufacturer must be contacted directly.

Similar to solar panels, the standards of pumps may be country-specific and must be checked during design and component selection.

E. Balance of systems

Balance of systems includes:

- Cables
- Protection equipment such as miniature circuit breakers and surge protectors
- Grounding
- Lightning protection system

FAQ: What is the acceptable DC and AC voltage loss?

According to BS 7671 (UK):

- The overall DC voltage drop between the solar array and the controller should be <3%.
- It is recommended that the AC voltage drop between the controller and the load (pump) be <1%.

Cable

VOLTAGE LOSS

To calculate the size of the cables, the following equation can be used:

$$\Delta U = b * (\rho * \frac{L}{S} * \cos\emptyset + \lambda * \sin\emptyset) * I_B \qquad \text{Eq. 4}$$

ΔU is voltage drop in volts

b is the cable length factor

ρ is resistivity in ohm.mm²/m of the conductor for a given temperature

L is the single length of cable in metres

S is the cross-sectional area of cable in mm²

cosØ is a power factor

λ is reactance per length unit in ohm/m

sinØ is sinus (acos[cosØ])

IB is current in ampere

Note: For DC circuit, cosØ=1, so sinØ=0.

AMPACITY

Ampacity is defined as the maximum current-carrying capacity of any conductor under certain cable properties, installation conditions, and surrounding environment [24]. If the conductor carries a continuous current of more than the ampacity of the conductor, it heats up and can cause cable damage and fire hazard.

A reference for copper and aluminium cable ampacity is given in the **Appendix** on **Cable ampacity and size conversion**.

FAQ: What are armoured and unarmoured cables?

Armoured cables have an extra protection layer to protect the cable from damage. Armoured cables are used in applications where the cable is exposed to a harsh environment. A feature of armoured cable is its lack of flexibility due to the additional metallic layer. In SWPS, armoured cables can be used for underground wiring from the controller to the pump.

Unarmoured cables do not have the extra protection layer and so have more flexibility. In SWPS, unarmoured cables can be used for solar panel inter-wiring which requires cable flexibility; they are also relatively more protected behind panels and conduits.

Choosing between aluminium and copper cables

Copper cables have a higher ampacity compared to an equivalent size of aluminium cables because of the former's greater material conductivity [25]. However, since both copper and aluminium cables can be sized for a given voltage and current, how do we choose between the two? To answer this, the following aspects have to be looked into:

Cost: Aluminium cables are cheaper than copper cables [25]. The cost difference becomes significant with increasing length, so the decision can be based on the budget.

Dimension restrictions: For a given copper cable, the equivalent size of an aluminium cable will be larger in diameter. This could affect ducting and conduit-fitting sizes, as well as respective costs.

Weight restrictions: Aluminium cables are lighter than their copper counterpart [25]. This can be an advantage if many cables have to run in cable trays. However, this may not be significant when it comes to small solar water pumping systems.

Availability: Due to production cost and demand, some manufacturers do not manufacture some sizes of aluminium cables; so, the designer has to choose their copper equivalent.

Miniature circuit breakers

Miniature circuit breakers (MCBs) can function as a switch in SWPS and protect against any surges. They are usually connected on the DC side as PV disconnectors/isolators. The number of MCBs depends on the number of string inputs. A disconnector MCB has to be installed for each input string and the current rating of the MCB should be at least 1.56 times the Isc current output of the string [26].

FAQ: What is SP and DP MCB?

A single pole (SP) MCB is connected only to the positive "hot wire". A double pole (DP) MCB is used to isolate both positive and negative wires. AS/NZS5033:2005 requires a double-pole disconnection device on the PV array cable on the DC side to isolate the array from the rest of the system [62].

Also, be careful while wiring the DC MCB. A common mistake made is that the connection of source (solar panels) is made at the top of the MCB and the load (to inverter) is made at the bottom. The manufacturer will have a circuit drawing in the MCB indicating "+" and "–", which respectively stand for where the source is to be connected and the direction of the current. This must be followed.

What is polarized and non-polarized breaker?

Polarized DC circuit breakers use a small magnet to direct the arc away from the contacts and up into the arc shoot and arc disrupter cage [62]. Any incorrect wiring of a polarized MCB, resulting in reversed current flow, may destroy it.

Non-polarized circuit breakers operate safely as load-breaking isolators and as a fault current protection mechanism regardless of the direction of current flowing through them [62].

> **FAQ: Can AC MCB be used in a DC connection?**
>
> No. AC and DC MCBs are distinctly different. In AC circuits, the voltage wave form changes polarity 100 times every second (for 50 Hz) and so does the direction of the current. The changing current passing frequently through zero in AC circuits means that the arcs do not sustain for a long time when physical contact is opened. However, in DC circuits, the current is unidirectional and the voltage polarity is constant [63]. Due to this, the arcs sustain for a longer time when physical contact is opened. These are the features of difference in design between AC and DC MCBs.
>
> Installing an AC MCB in a DC circuit can be a safety hazard because an AC MCB for a given rating may not be able to handle the arc generated during the DC switching, leading to a breakdown or fire.

Grounding

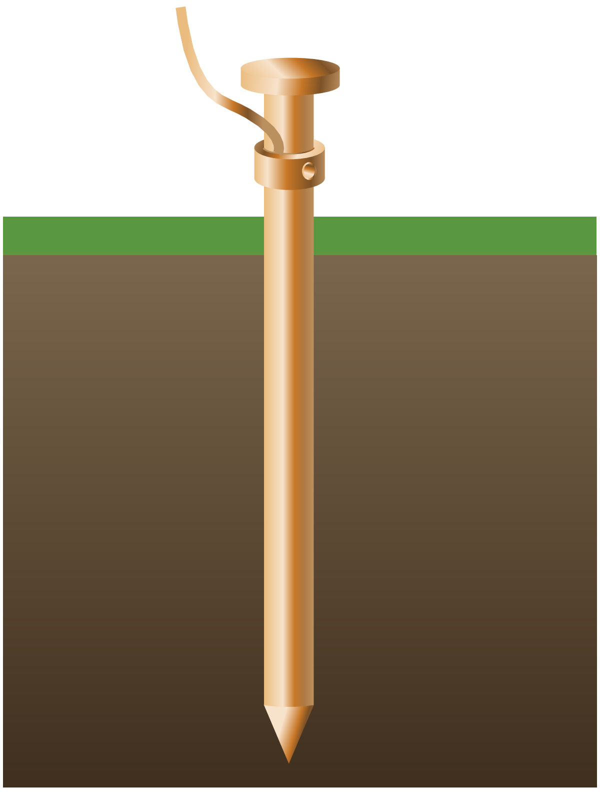
Grounding must be given to the pump, controller, panel, panel structure, and the controller body. Grounding protects humans and electronics from unwanted issues such as insulation cuts in the cable touching a conducting surface. It also provides a low-resistance path to the unwanted current directly to the earth. A ground rod of high-conductivity/low-resistance material such as steel or copper is to be used (Figure 20).

Now to an important question: what affects the ground resistance? The answer involves the following aspects:

- **Length and depth of the ground electrode:** The NEC code (1987, 250-83-3) requires a minimum ground electrode length of 2.5 metres (8.0 feet) to be in contact with the soil. Generally, by doubling the length of the ground electrode, the resistance level can be reduced by an additional 40% [27].
- **Diameter of the ground electrode:** Increasing the diameter of the ground electrode has very little effect on lowering the resistance. For example, you could double the diameter of a ground electrode but your resistance would only decrease by 10% [27].

The number of ground electrodes: Another way to lower ground resistance is to use multiple ground electrodes. For these additional electrodes to be effective, the spacing of the additional rods needs to be at least equal to the depth of the driven rod. Without proper spacing of the ground electrodes,

FIGURE 20 SINGLE GROUND ELECTRODE



Source: Image obtained from Fluke [27]

their spheres of influence will intersect and the resistance will not be lowered. To assist in installing a ground rod that will meet specific resistance requirements, see Figure 21 which can be used as a reference for ground resistances. Remember, this is to be used as a rule of thumb only because soil layers are rarely homogenous – the resistance values will vary greatly [27].

- **Ground system design:** Simple grounding systems consist of a single ground electrode driven into the ground. The use of a single ground electrode is the most common form of grounding in SWPS [27].

Lightning protection system

A direct lightning strike on the SWPS – an unlikely scenario – can destroy and melt solar panels and controllers (Figure 22); while indirect strikes can induce high voltage which can again damage electrical components. Direct lightning strikes can be thwarted by air terminals, while indirect strikes can be foiled by the surge protection devices explained in the **Surge protection device** section. It has to be noted that there are higher chances of lightning in open fields which are far from high buildings and trees.

FIGURE 21 GROUNDING RESISTANCE RULE OF THUMB

Type of soil	Soil resistivity	Earthing resistance					
		Ground electrode depth (m)			Earthing strip (m)		
	M	3	6	10	5	10	20
Very moist soil, swamplike	30	10	5	3	12	6	3
Farming soil, loamy and clay soil	100	33	17	10	40	20	10
Sandy clay soil	150	50	25	15	60	30	15
Moist standy soil	300	66	33	20	80	40	20
Concrete 1:5	400	-	-	-	160	80	40
Moist gravel	500	160	180	48	200	100	50
Dry sandy soil	1,000	330	165	100	400	200	100
Dry gravel	1,000	330	165	100	400	200	100
Stoney soil	30,000	1,000	500	300	1,200	600	300
Rock	10^7	-	-	-	-	-	-

Source: Figure obtained from Fluke [27]

FIGURE 22 DAMAGE CAUSED BY A LIGHTNING STRIKE

Source: Image obtained from Pickerel, K. (2015) [28]

FAQ: Is there a difference between earthing and grounding?

No, the terms "earthing" and "grounding" mean the same and opting for one or the other is dependent on the region. "Grounding" is used in North American standards (such as IEEE, NEC, ANSI, and UL), whereas "earthing" is used in European standards (such as IEC and IS) and Commonwealth regions [64].

Lightning protection levels (LPLs) are based on the strength of the lightning strike and can be divided into four different levels as shown in Table 9.

TABLE 9 LIGHTNING CURRENT FOR EACH LPL BASED ON 10/350 M S WAVE FORM [29]

LPL	I	II	III	IV
Max current (kA)	200	150	100	100
Min current (kA)	3	5	10	16

Note: Each LPL also corresponds to the respective class of lightning protection, i.e. I, II, III, and IV.

The LPS is installed near the SWPS to divert lightning energy surges to the ground. The LPS consists of three main components: air terminal; down conductor; and lightning ground electrode.

The recommended methods for determining the position of the air terminals are:

- Protective angle method
- Rolling sphere method
- Mesh method

Protective angle method

The protective angle method is a simplified version of the rolling sphere method and could be more applicable to the SWPS. The height of the air

FAQ: What is the desired ground resistance?

According to the BS EN/IEC 62305 Lightning Protection Standard, the desired grounding resistance should be 10 ohms or less [29].

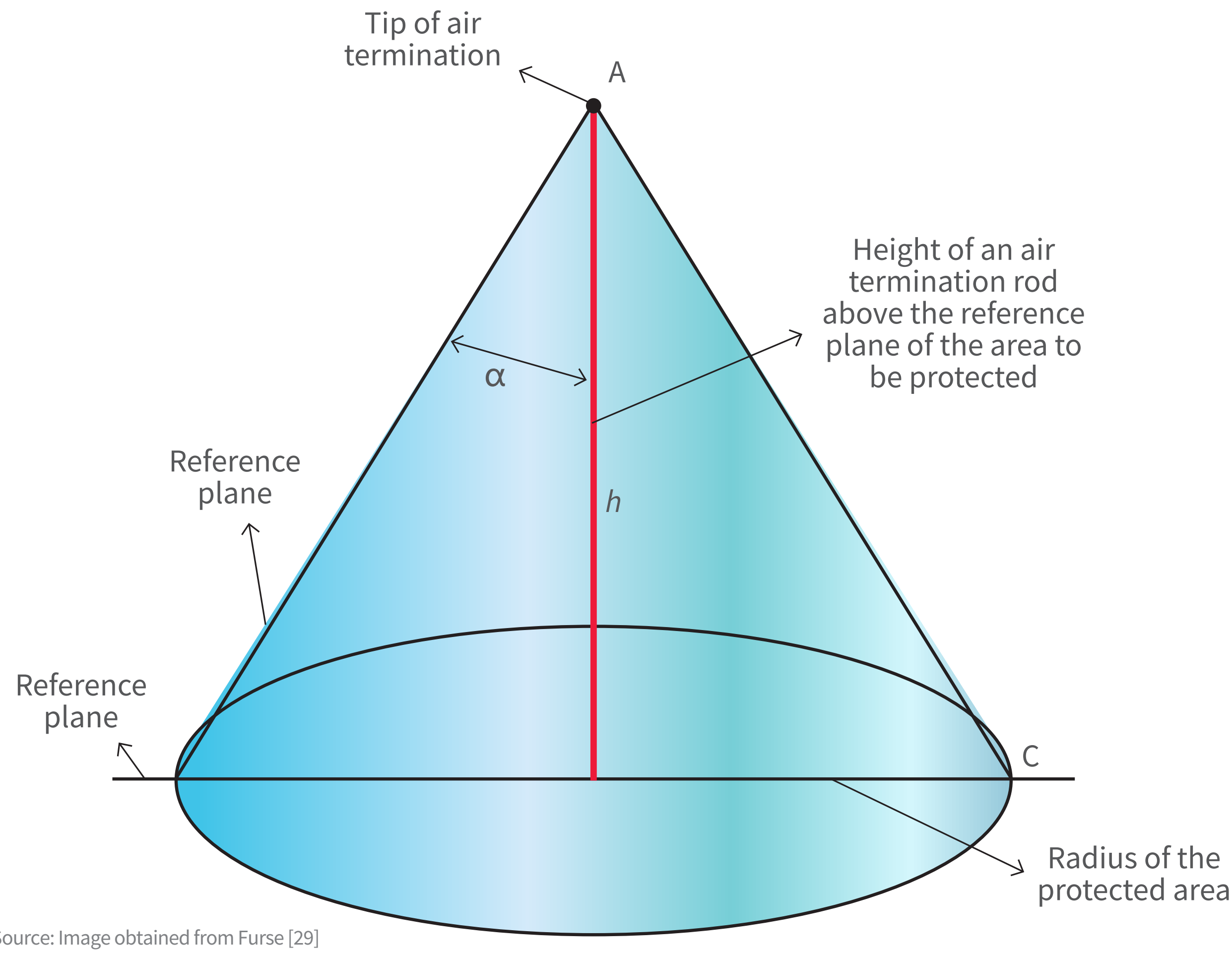
terminal defines a cone with the protection angle starting from its tip. The objects inside the cone, also known as the "zone of protection", are protected by the air terminal as shown in Figure 23.

The protective angle differs with the change in height of the air terminal and the protection class as shown in Figure 24.

and ridges with a pitch of more than 5.7 degrees. A mesh of air terminals is connected to protect the entire plain surface. The size of the mesh is determined by the class of protection (Figure 26).

The air terminal and down conductor must not touch any part of the SWPS; if they do so, the system will be damaged. However, the ground electrode for lightning protection must be connected to the ground electrode of the SWPS for equipotential bonding.

FIGURE 23 **PROTECTIVE ANGLE OF A SINGLE AIR TERMINAL**



Source: Image obtained from Furse [29]

Rolling sphere method

The rolling sphere method is more suitable for protecting structures of complex geometry. This method takes into account the probability of lightning strikes. The different radii of the rolling sphere correspond to a different class of protection (Figure 25) [29].

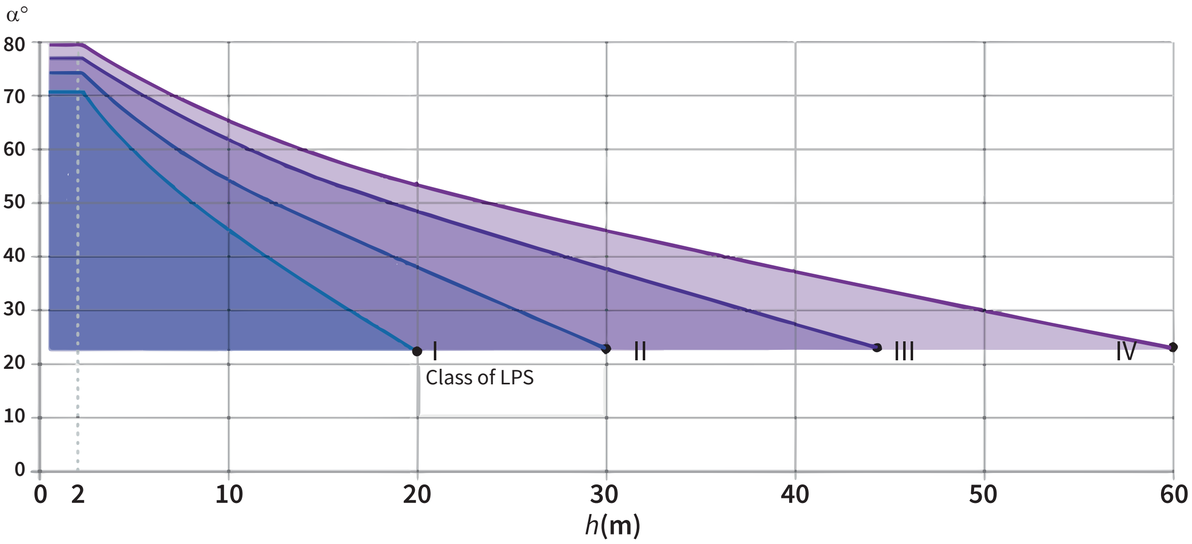
Mesh method

The mesh method is commonly used to protect against lightning in plain surfaces where the air terminal is positioned on roof edges, roof overhangs,

Direct strike: When there is a direct lightning strike, the air terminal, which is made of copper, attracts the strike onto itself due to its high conductivity. The lightning current is then diverted to the ground via the down conductor which is also made of copper.

Indirect strike: When lightning strikes near the SWPS, the potential difference between the SWPS ground electrodes and the strike area can result in current flowing into the SWPS. This surge of current is protected by the surge protection device (SPD, see Figure 28).

FIGURE 24 DETERMINATION OF THE PROTECTIVE ANGLE OF A SINGLE AIR TERMINAL



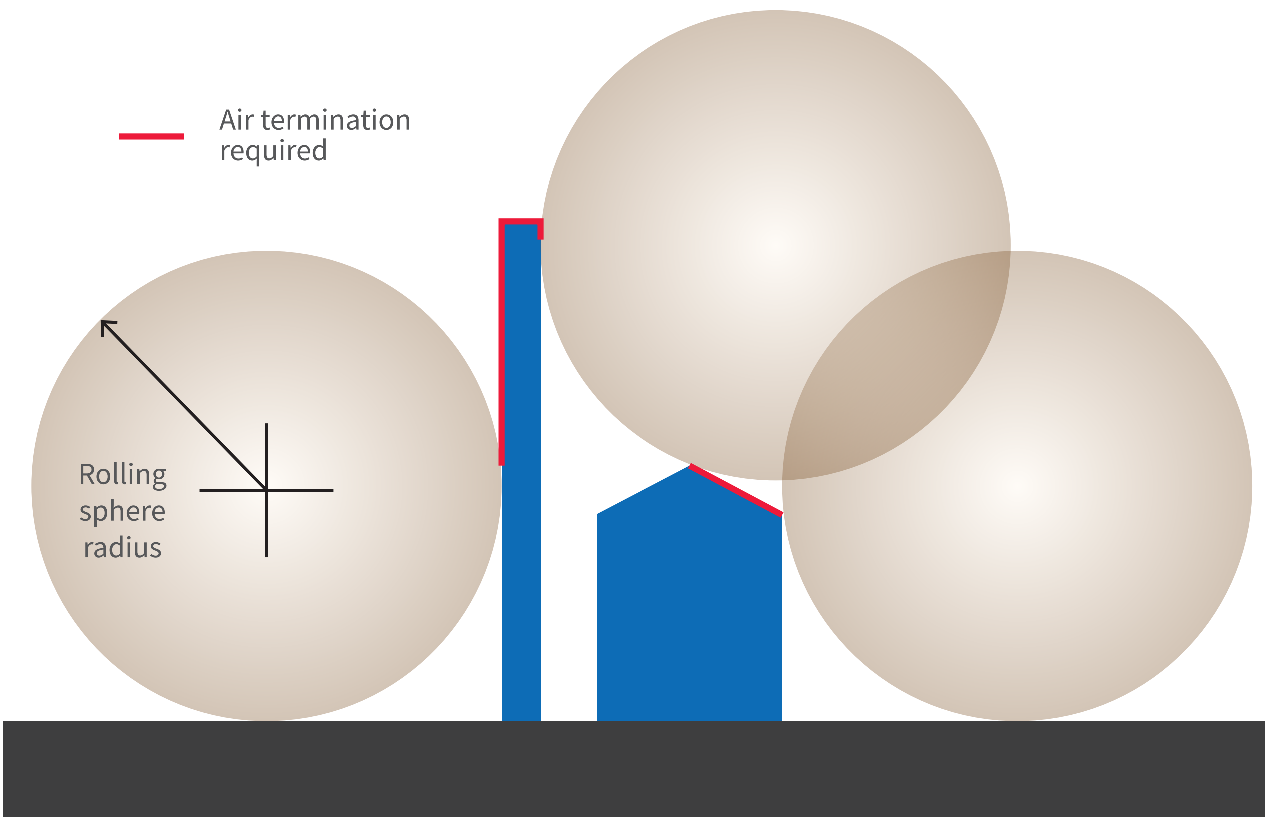
Note 1: Not applicable beyond the values marked with
Only rolling sphere and mesh methods apply in these cases

Note 2: *h* is the height of all termination above the reterence plane of the area to be protected

Note 3: The angle will not change for values of *h* below 2m

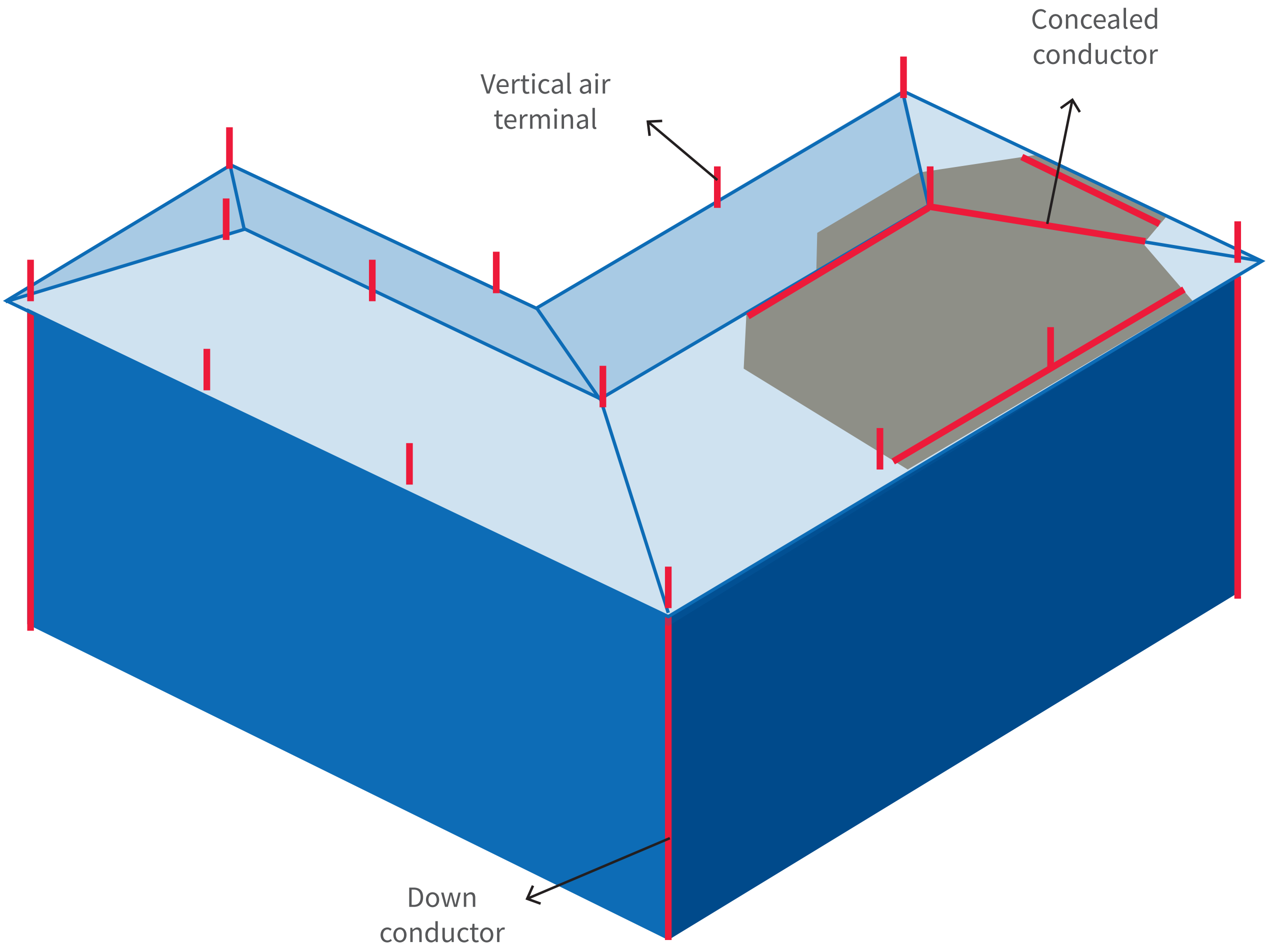
Source: Image obtained from Furse [29]

FIGURE 25 ROLLING SPHERE METHOD



Source: Image obtained from Furse [29]

FIGURE 26 **MESH METHOD. IMAGE OBTAINED FROM FURSE**



Source: Image obtained from Furse [29]

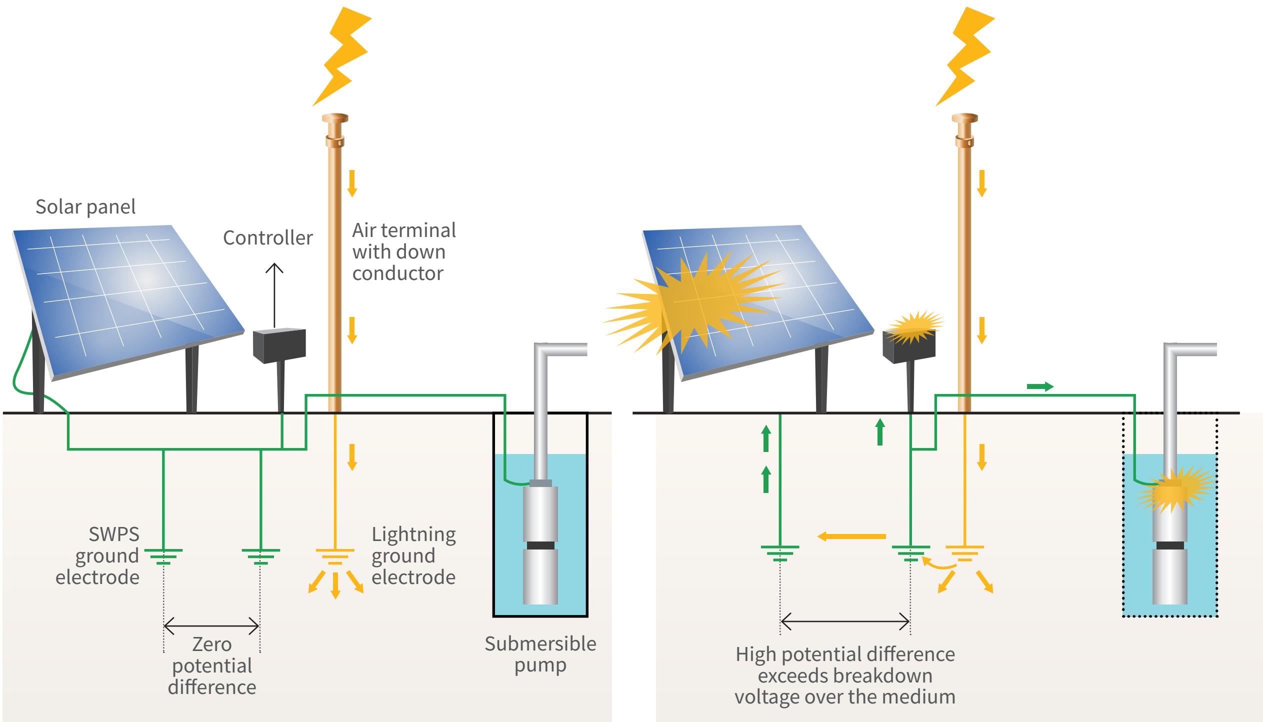
FAQ: Why equipotential bonding?

Let's say there is an SWPS with an isolated SWPS ground electrode, i.e. there's no equipotential bonding. When there is a lightning strike, the voltage at the lightning ground electrode can be high, i.e. of 1,000 volts. This voltage is huge in reference to the SWPS ground electrode. The potential difference between the two electrodes and other metallic objects near the lightning ground electrode will be high. If the distance between the lightning ground electrode and the SWPS ground electrode and other metallic components are near enough to cause a voltage breakdown, the surge current will flow back to the SWPS and thus cause damage. The voltage breakdown distance depends on the strength of the lightning strike and soil properties.

Now, let's consider the same scenario of lightning strike, but with equipotential bonding, i.e. the SWPS ground electrode are connected together. When lightning strikes, the voltage at the lightning ground electrode increases and so does the voltage at the SWPS ground electrode (which is connected to the rest of the SWPS). That means, the potential difference between the lightning ground electrode and the SWPS ground electrode is zero; therefore, no current flows through the SWPS and it is absorbed by the earth.

This is shown in Figure 27.

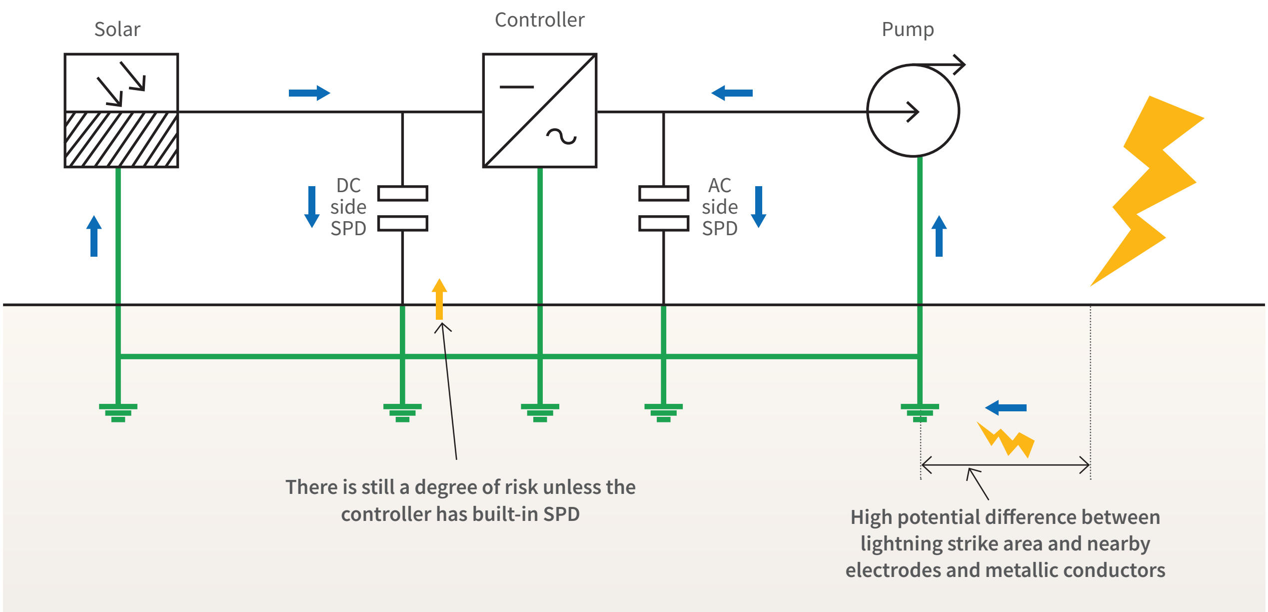
FIGURE 27 LEFT: LPS AND SWPS WITH EQUIPOTENTIAL BONDING; RIGHT: LPS AND SWPS WITHOUT EQUIPOTENTIAL BONDING



All metallic objects are at the same potential, therefore, lightning current discharges to the ground

LPS and SWPS are at different potential, therefore, current travels into the SWPS

FIGURE 28 SPD PROTECTION OF INDIRECT LIGHTNING STRIKE



Surge protection device

The surge protective device is designed to protect electronic devices, appliances, and equipment from a sudden burst of energy known as a "power surge". In many cases, a power surge is caused by a bolt of lightning that sends an abnormally high level of current through an electrical system using nearby metallic conductors [30]. In SWPS, these metallic conductors can be ground electrodes, the metal structure of solar panels, GI pipes, and pumps. Such high currents can damage any electronic circuitry and cause heat damage.

As per the National Electrical Code® (NEC) and ANSI/UL 1449, the SPDs for any facility not exceeding 1,500 Vdc in PV applications are designated as follows:

Type I: Permanently connected and intended for installation between the secondary coil of the service transformer and the line side of the service disconnect overcurrent device (service equipment). Its main purpose is to protect the insulation levels of the electrical system against external surges caused by lightning or utility capacitor bank switching.

Type II: Permanently connected and intended for installation on the load side of the service disconnect overcurrent device (service equipment), including brand panel locations. Their main purpose is to protect the sensitive electronics- and microprocessor-based loads against residual lightning energy, motor-generated surges, and other internally generated surge events.

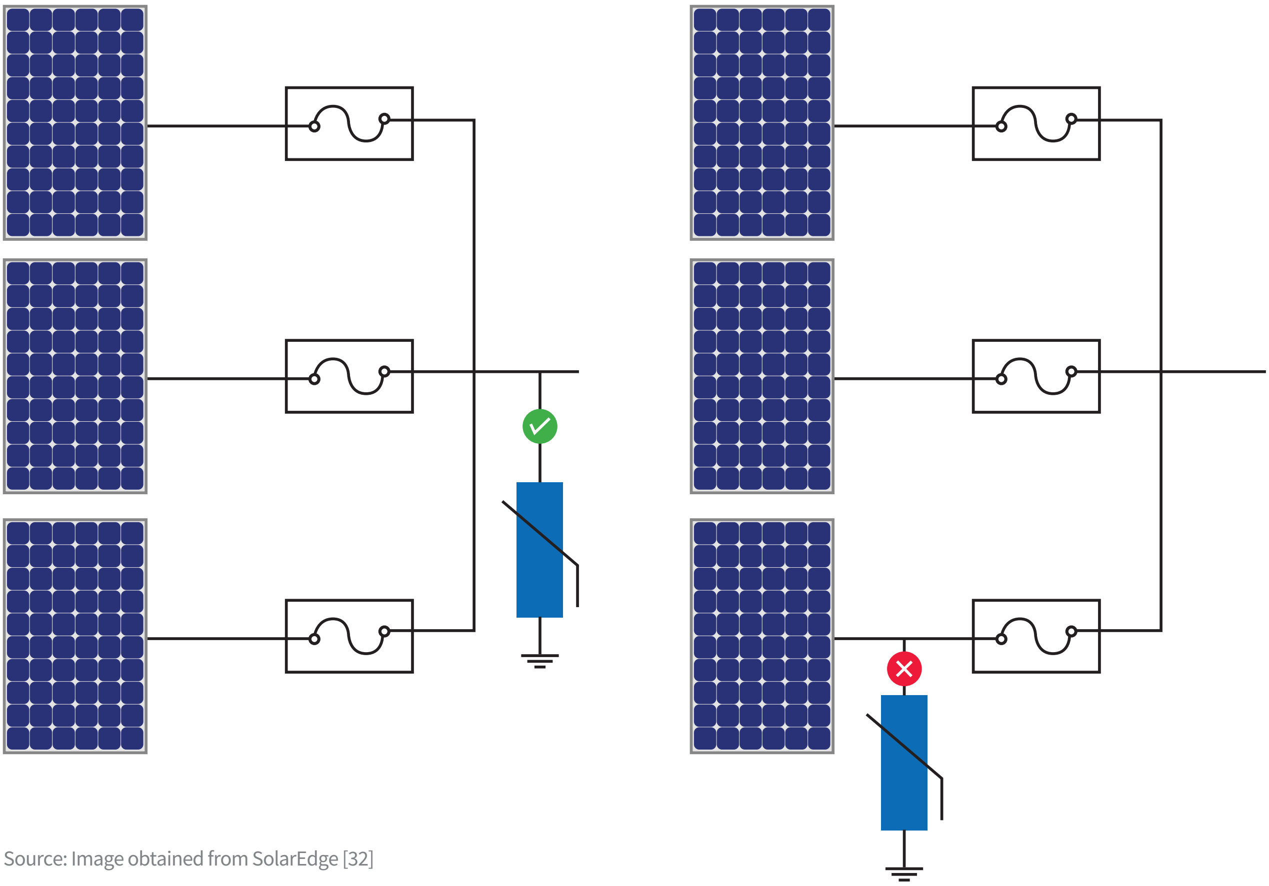
Type III: Point-of-utilisation SPDs are installed at a minimum conductor length of 10 metres (30 feet) from the electrical service panel to the point-of-utilisation. Examples include cord-connected, direct plug-in, and receptacle-type SPDs [31].

For SWPS, since the controller electronics are to be protected, Type II SPDs are used.

Connection of SPD

When string protectors are used, such as fuses or DC breakers, the SPD must be installed between the fuses and the controller; otherwise, the PV strings would be unprotected if the fuse is triggered (Figure 29) [32].

FIGURE 29 CONNECTION OF SPD



Source: Image obtained from SolarEdge [32]

Important concepts

Total dynamic head

The total dynamic head (TDH) is the total vertical height that the pump has to push water which takes into account all losses. The vertical head is the 90° height difference from the water level to the maximum delivery point.

The vertical measurements of the submersible and surface pump systems are shown in Figures 30 and 31.

The TDH of any system is given by: Vertical head + Major loss + Minor loss

Major loss

When water flows through any passage, it loses a certain head due to the friction in the passage, change in shape, bends, and several other factors. The loss due to friction makes for the major loss, whereas other losses make for minor ones.

FIGURE 30 VERTICAL MEASUREMENTS OF THE SUBMERSIBLE PUMP SYSTEM

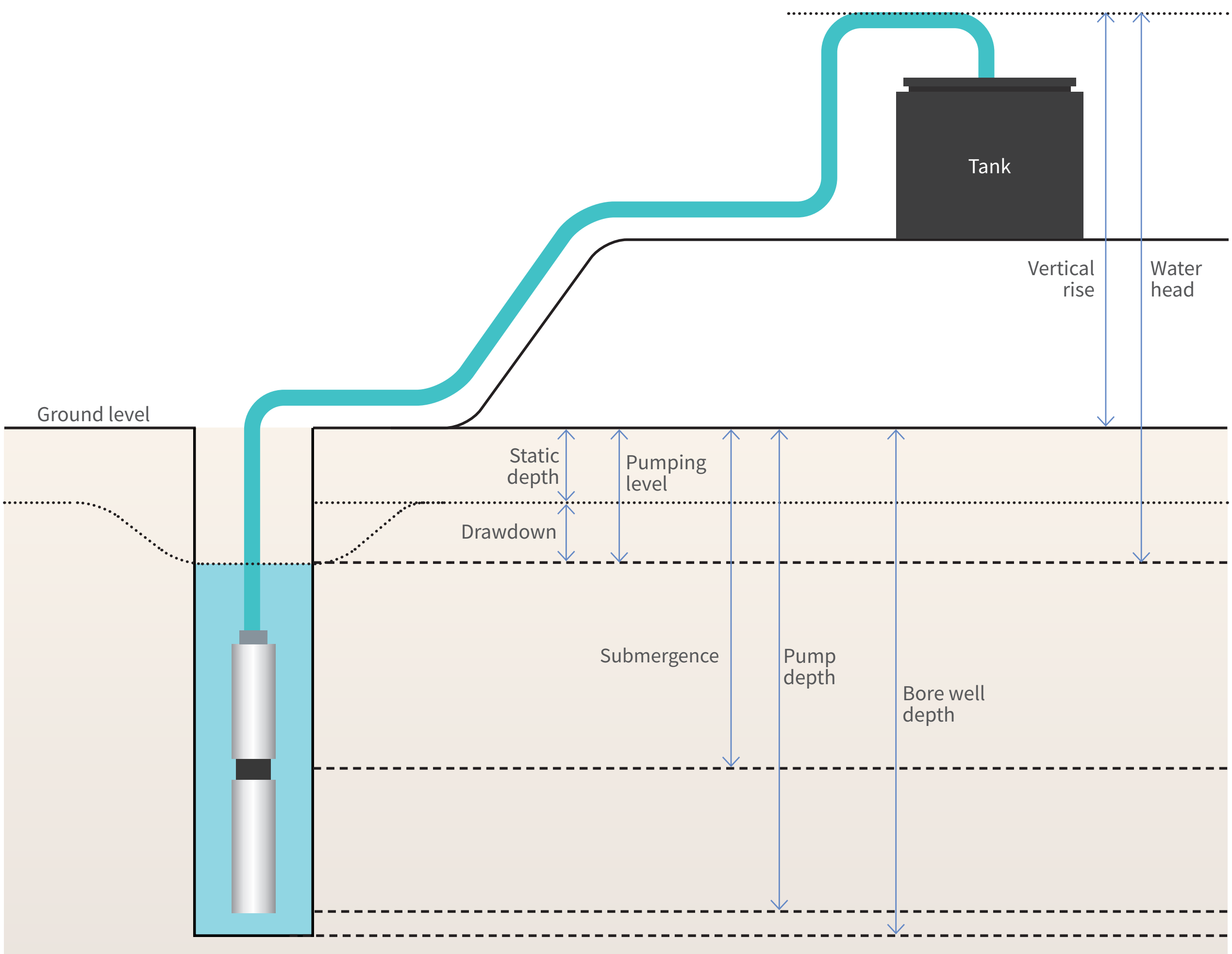
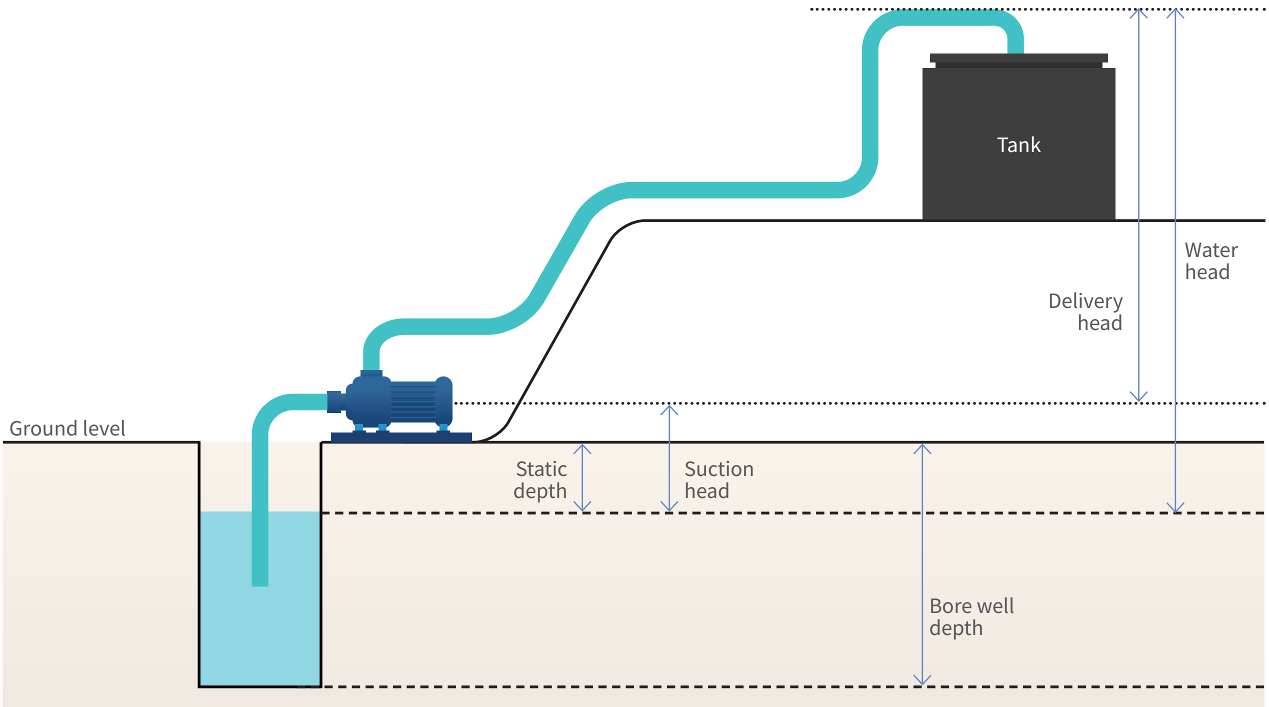


FIGURE 31 VERTICAL MEASUREMENTS OF THE SURFACE PUMP SYSTEM



The major loss is calculated using the Darcy-Weisbach equation:

$$h_1 = f * \frac{L * v^2}{2 * d * g} \qquad \text{Eq. 5}$$

Where,

h_1 is Major friction loss

f is Darcy-Weisbach friction coefficient

l is Length of pipe

v is Velocity of fluid

d is Internal diameter of the pipe

g is Acceleration due to gravity (m/s^2)

Note: The diameter of the pipe is not known initially, i.e. in the process of designing an SWPS, the diameter of the pipe is to be determined by evaluating the friction loss in different sizes of pipes. So, the process is iterative.

Iteration process:

- Assume a value for the major head loss and calculate the total dynamic head.
- For the pump selected, use equation 5 to calculate the major head loss. The f friction coefficient is dependent on the laminar or the turbulent flow given by Reynold's number (Re).
  - Re is Reynold's number, given by:

$$Re = \frac{\rho * v * D}{\mu} \qquad \text{Eq. 6}$$

where, Re is dimensionless, ρ is the density of the fluid (kg/m^3), v the velocity of the fluid (m/s), D the internal diameter of the pipe (m), and μ the dynamic viscosity (Ns/m^2).

  - If Re is <2,000, then the flow is laminar; if Re is >4,000, then the flow is turbulent [33].
  - For laminar flow:

$$f = \frac{64}{Re} \qquad \text{Eq. 7}$$

  - For turbulent flow, f can be estimated by the Moody diagram (Appendix).
  - Now use equation 5 to determine the major friction loss.
- Compare it with the assumed major head loss.
- If the calculated head loss is less than the assumed head loss, move forth with the design; if not, change the value of the assumed head loss and repeat the process till the values are close to a decimal.

Minor loss

"Minor loss", as the term suggests, is minor compared to a major loss. Minor loss is the result of loss in pipe fittings and components.

Minor loss can be calculated by:

$$h_m = \varepsilon * \frac{v^2}{2 * g} \qquad \text{Eq. 8}$$

Where,

h_m is minor friction loss (m)

ε is a minor loss friction coefficient (dimensionless)

v is velocity of the fluid (m/s)

g is acceleration due to gravity (m/s²)

ε is the sum of all minor loss coefficients in the system. See the Appendix on Minor loss coefficients for the reference table.

G. Theoretical pump size

It is a good practice to calculate the theoretical pump size (in watts, kilowatts, HP) of the system to verify whether the pump selected in any SWPS design is optimal. Before jumping right into the manufacturer catalogue of pumps, it is advised to do a theoretical pump-sizing exercise.

To calculate the theoretical pump size, the water requirement and TDH must be known through:

$$P_H = \frac{q * \rho * g * h}{3.6 * 10^6} \qquad \text{Eq. 9}$$

Where,

P_H is hydraulic power (kW)

q is fluid flow (m^3/hr)

ρ is the density of the fluid (kg/m^3)

g is acceleration due to gravity (m/s^2)

h is the total dynamic head (m)

$3.6*10^6$ is the conversion of an hour into seconds (3,600) and is multiplied by 1,000 in the denominator to convert watts into kilowatts

Equation 9 gives the hydraulic power, but the efficiency of the pump is not taken into account. Therefore, the theoretical pump size is given by the shaft power:

$$P_S = \frac{P_H}{\eta} \qquad \text{Eq. 10}$$

Where,

P_S is the shaft power (kW)

η is the efficiency of a pump which can be obtained from the pump efficiency curve

The shaft power is the final estimation of the required pump size. The actual pump size may be lower or higher than estimated depending on the manufacturer's product design.

SECTION VII

System design

Need assessment

The motivation behind designing a solar water pump is to cater to the need of the user. Therefore, the first step of the preliminary design would be to assess the need of the individual or the community. Some of the needs for SWPS may be:

- Irrigation
- Drinking water
- Livestock care

In each case, the water requirement pattern will be different as described below:

- **Irrigation:** For irrigation, the water requirement will vary from day to day, week to week, and month to month. This is due to factors such as climatic conditions, soil characteristics, cultivation seasons, crop water requirements, and the frequency of water requirement per crop. For example, paddy requires intensive water in the initial stage of plantation and this need decreases over the season. Therefore, the water requirement for irrigation should consider these factors in addition to alternative water sources (rainwater, canals, etc.), and the requirement should be based on the maximum water that is needed for a full-year crop cycle.
- **Drinking water:** Compared to irrigation, the water requirement for drinking water can be averaged over the year considering a certain set of population, annual population growth rate, and average water use per capita.
- **Livestock care:** Similar to drinking water, the water requirement for livestock care can be averaged over the year considering a certain set of livestock population, annual population growth rate, and average water requirement per livestock.

In an SWPS project, different steps follow before a final electromechanical design is prepared. The main steps are:

- Preliminary site information on the key technical parameters
- Preliminary design
- Detailed survey
- Detailed design

In this section, an example site has been chosen and the SWPS design process is described that covers the above design steps in their respective order. The location and site information has been chosen for design walk-through only.

Preliminary information

Preliminary information and the succeeding preliminary design are crucial to define a project. Before significant resources and budget are allocated for the detailed design, it's essential to gather preliminary information for the project.

In this hypothetical situation, the site information is as follows:

- **Site location:** Hypothetical location in Bhutan
- **Application:** Drinking water
- **Population served:** 250
- **Number of households:** Around 50
- **Vertical head from the pump to tank:** Around 150 m
- **Existing electric pumps, pipelines, etc.:** No
- **Access to grid electricity:** No
- **Open location for installation of solar panels:** Yes
- **Estimated distance from potential pump location to distribution point:** 700–800 m

These few pieces of information may be all that the customer provides for cost estimation. However, the designers need to get critical information to come up with a preliminary design. From the information above, the two key inputs for the preliminary design are:

- Population size, which can help in arriving at an estimate of the minimum water requirement; and,
- The vertical head.

A preliminary survey template form is provided in the Appendices.

Preliminary design

WATER REQUIREMENT

According to the World Health Organization (WHO), the minimum water that is required for drinking, cooking, personal washing, washing clothes, cleaning the home, and sanitation is 70 litres per person per day [34]. From this, taking the maximum population to be 250, the total water requirement per day is 17,500 litres.

Note: The per capita water requirement cited above is a general estimation and has been taken as a reference for this design example only. In a real-case scenario, the per capita water requirement will differ based on several factors such as rural or semi-urban area, typical user livelihood, existing water source available, and local climate; these must be verified during and after the site survey.

THEORETICAL PUMP SIZE

The theoretical pump-sizing process has been explained in **Theoretical pump size** in the previous section.

The average peak sun hours taken is 4.32 kWh/m²/day (average taken from Figure 34).

$Q = 17{,}500/4.32 = 4{,}051$ litres/hr $= 4.05\ m^3$/hr

$\rho = 1{,}000\ kg/m^3$ for water

$h = 150$ m, neglecting the TDH as this will require accurate information

Using equation 9:

$$P_H = \frac{q * \rho * g * h}{3.6 * 10^6}$$

$P_H = 1.66$ kW

Note that the efficiency of the pump is dependent on the manufacturer. For preliminary estimation, a motor shaft efficiency of 60% will be taken.

$$P_S = \frac{P_H}{\eta}$$

$P_S = 1.66 \div 0.6 = 2.78$ kW

Therefore, the theoretical pump size is 2.78 kW. The actual pump size may differ slightly due to the different efficiency points at a given head and flow.

FAQ: What is the conversion between kW to HP?

1 kW = 1.34 HP

1 HP = 0.75 kW

Kilowatt (kW) is an SI unit and is adopted by most countries, while horsepower (HP) is still commonly used to specify pump sizes. However, HP has not been properly defined as it depends on the application and geography (for example, brake horsepower, metric horsepower, boiler horsepower, etc.) [65]. Therefore, in this handbook, kW is used to maintain consistency.

Estimated array size and footprint

It will be useful to obtain an estimate of the required panels and of their footprint. To obtain this, the theoretical pump size is multiplied by a factor to account for system losses.

As a rule of thumb, this factor is 1.3.

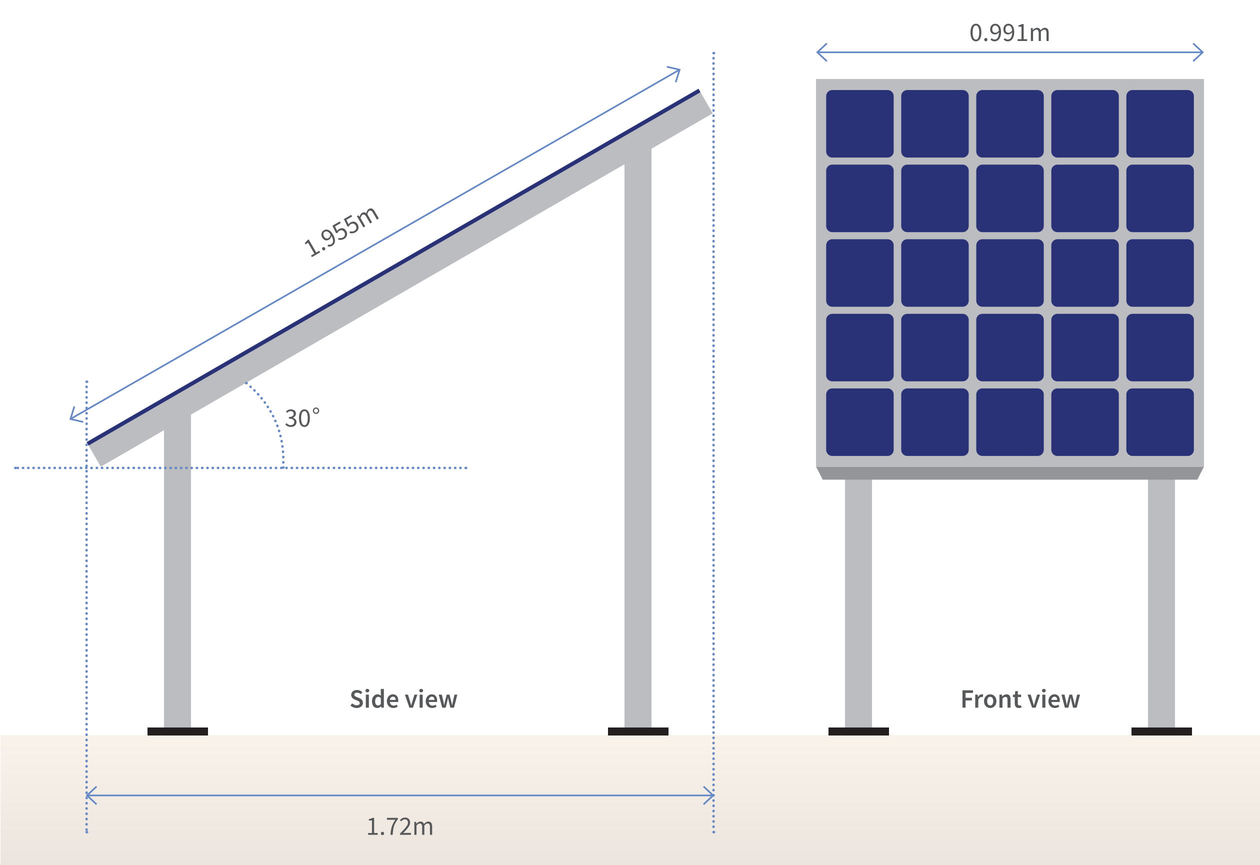
Therefore, the preliminary array capacity is 3.6 kW (2.78 kW * 1.3).

Now the individual panel capacity of 370 Wp will be taken for reference. For a 3.6 kWp array capacity, 10 pieces of 370 Wp panels will be required. For this example, the optimal direction and tilt angle of the array for Bhutan is true south and 29° (~30°) (Solargis data).

Figure 32 shows the ground footprint (length and breadth) of a single 370 Wp panel.

Assuming that the panels are installed in one row and taking 20% as a contingency for panel gaps, the ground footprint area of the array is 17.6 m²
(1.72 m * 0.991 m * 10 panels * 1.03).

FIGURE 32 GROUND FOOTPRINT OF A SINGLE 370 WP PANEL



Note: If fencing is required on the site, add additional area accordingly.

The estimation of the array footprint can be helpful in the detailed site survey to secure the adequate panel area.

System cost

Similarly, it may also be helpful to obtain a tentative cost of the SWPS.

To carry out a back-of-the-envelope calculation, the per Wp cost of a 3.6 kWp SWPS system is USD 1.12 based on the market cost in Bhutan. **However, it is important to note that the cost is subject to market changes and that the values taken are for the sole purpose of illustrating the concept.**

Estimated system cost: USD 4,032 (3.6 kWp * USD 1.12 * 1,000)

Finally, the cost estimation of the key system components can help make technical and financial decisions on "go" or "don't go" for the detailed technical survey without investing any significant resource.

Some guiding questions to the decision makers can be:

- Is the estimated cost of the SWPS affordable and can the financial resources be arranged for the SWPS?
- Is the SWPS technically feasible? If there are risks in the project, how can they be mitigated?

Detailed technical survey

The detailed technical survey follows after the project is qualified as feasible and worth pursuing. The following areas must be evaluated during the survey (which is limited to electromechanical systems):

- **Statutory requirements:** Before proceeding with the project activities, it is essential to fulfil the statutory requirements related to SWPS projects. This will require coordination with the local community, local government authorities, and other stakeholders. Some general statutory requirements are:
  - Land acquisition permits (for both private and public land) relating to:

- Solar array location
- Collection tank location
- Distribution tank location
- Transmission line path
- Distribution line path

– Environmental and social risk assessment

- **Water source:** There will be no SWPS if there is not enough water in the source. This should be the first point of evaluation. The water should be from a perennial source, clear with no debris, and with an adequate natural or artificial filtration system to secure the intake. The flow of water and its recharge rate should be measured to make sure the pump does not run dry after emptying the source. For example, the bucket test method or salt dilution method can be used for flow measurements, whereas the recharge rate can be measured by measuring the time to fill up a fixed volume of water in the water source. This is an important part of the survey and the intake location must be carefully chosen. Though civil engineers will be responsible for this evaluation, it is important to ensure that the pump is installed in a secure location and won't run dry any time of the year. Talking to the local community about the reliability of the water source will be helpful. Here are some pointer questions for water-source evaluation:
  - Is the water naturally or artificially filtered and is it clean of debris? If not, what is the solution before the pump is installed?
  - If the water source is from a natural spring, does it go dry any time of the year?
  - Is there any risk of natural disasters (such as floods) that could damage the source or the SWPS site?
  - Is the water source sustainable, i.e. ensuring that the flow rate (in the case of surface water sources) is higher than the pumping flow rate during daily use and throughout the year or ensuring that the recharge rate (in the case of groundwater sources) is sufficient to support drafting the required water?
  - Is there enough room for the pump to be in a secure position?
  - Is there enough room for easy access to the pump for maintenance purposes?
  - Is the site safe from vandalism or wildlife encounters?

Advice: Choosing riverside intake location

If water is to be pumped from a river and a water intake is to be constructed on the riverside, it is advised that the intake be naturally protected. The unpredictable nature of rivers and the water force can damage the intake structure during floods or bring in debris that can spoil the pump. This is further explained in the Site information section.

- **Vertical head:** The vertical head must be verified as this is critical for system design. In some projects, civil engineers perform land mapping and determine the vertical head accurately using instruments such as Total Station. However, this may not always be the case, so the next option is to mark the pumping area and the highest point with GPS.

- **Water requirement:** Always verify the water requirement of the location. For irrigation, land size and crop patterns are the primary parameters; for drinking water, it is the population coverage; for fish farms, it is the number of ponds and their dimensions.

- **Solar array location:** The panel array must be installed where there is little to no shading throughout the day. To aid in the selection of such areas, mobile apps such as "Sun Paths"[1] are available for sun-path tracking.
  - **Roof mount:** Measure the area available, record potential shading, consider the roof construction material, and account for slope (if any) and slope direction (for example, 10° slope facing south-west).
  - **Ground mount:** Record ground conditions (sandy/clay loam, etc.), waterlogging possibility, and potential shading.

- **Location of components:** The location of the components must be determined during the survey. This includes the pump installation point, solar array installation area, controller access point, transmission pipe path, and distribution path. Though the transmission and distribution paths fall more on the civil survey side, it is important to see them through and complete them on-site. The reason behind finalising the location of components on-site is because of the permission that has to be granted by the

[1] Link to Google Play Store: https://play.google.com/store/apps/details?id=jp.gr.java_conf.siranet.sunshine&hl=en&gl=US&pli=1

land owners and the community. All these components have a footprint and the best option does not necessarily get permission. Sometimes, the community or the land owner may verbally give consent for their land use, in which case it must be documented. Failure to finalise and document component placement while on location can lead to confusion over construction and also to disputes with the community or owner during or after the construction. Some matters to consider are:

- Ground distance of cabling from the pumping area to the controller
- Ground distance of cabling from the controller to the panel array
- Ground distance of the transmission pipe from the pumping area to the distribution tank
- Ground distance of the distribution pipe from the distribution tank to customer locations

- **Existing pumping mechanisms:** Make note of the existing pumping mechanisms on-site if there are any. This will help to consider the integration of SWPS into the existing mechanism or to evaluate SWPS's advantage over it.
- **Community interview:** The community has more knowledge about the location. It is advised to ask the community members regarding any frequent natural disasters on that site, about the ease or difficulty of logistics in the area, about similar projects in the past that have failed and the reason for the failure, as well as about any community concerns. Their information may bring to light any details that may have to be considered during the design stage. Remember, for any project to be successful, community participation is the key (read more on "Gender equality and social inclusion" in the following section).
- **Photos:** Take photos of the site and of every important structure on the site. This will help in analysing and making decisions remotely without having to travel.

A detailed survey template form is provided in the Appendices.

Before diving into the detailed design aspect, it is important to understand the gender equality and social inclusion (GESI) perspective that will inform certain decisions during the survey and system design stage; these decisions will be gender inclusive and accommodative of marginalised groups. For example, for a community-owned solar water pumping system, encouraging the participation of women and other marginalised groups in the management committee of the project from the very beginning will pave way for design and operational decisions that are friendly to different societal groups. For example, in this case, water distribution can be scheduled with equal justice to the marginalised groups who may otherwise be left out from having equal water access during the SWPS operation.

Gender equality and social inclusion (GESI)

GESI is a concept that addresses the unequal power relations experienced by people on the grounds of gender, wealth, ability, location, caste/ethnicity, language, and agency or a combination of these dimensions. It focuses on the need for action to rebalance these power relations, reduce disparities, and ensure equal rights, opportunities, and respect for all individuals regardless of their social identity [35].

Some of the GESI issues to be addressed in the renewable energy sector are:

- Access to information on energy and on the emerging opportunities in the sector
- Low levels of disaggregated data/evidence
- Inclusive policies/plans/mechanisms
- Accessibility to renewable energy technologies and skills [36]

Owing to the common practice of division of labour along gender lines, women have special technology needs that have to be met to reduce their drudgery and increase their productivity. Mostly, technology-transfer institutions are male dominated and have tended to address male technology needs only [37]. For instance, in the case of the indigenous women of Nepal – representing more than 18% of the population and playing a key role in providing for their families and communities – they suffer from the double discrimination of being marginalised because of their indigenous status and of being disempowered because of their gender in a society that is steeped in patriarchy [38].

Across Nepal, there is both lack of information and opportunities in the renewable energy sector. In the country's rural areas, when people think of solar energy, they usually have a picture of a solar home system in mind which powers only a few lights and charges mobiles. The user misconception that large- and wide-scale applications of solar PV energy have to be treated differently than the utility grid is still present. Besides, in this age of technology, there are still pockets of population without electricity and internet access, which places constraints on both women and men from gaining information.

Furthermore, in Nepal, the research conducted on renewable energy has been highly skewed towards pure science. So, there's a need to strike a balance between pure and applied sciences. By "pure science" or "basic research", what is meant is a method of investigating nature by experimental means in an attempt to satisfy the need to know. But many activities in pure science are not experimental; however, it can always be shown that in such cases, the activities are ancillary to the experiment [39]. As for "applied science", it involves the use of pure science for some practical human purposes [39]. Specifically, science serves two human purposes: to know and to do. Pure science is a matter of understanding, while applied science is a matter of action [39]. In Nepal's context, since there is a general need to fulfil basic facilities (such as cent per cent access to electricity, proper sanitation, and organised urban development), applied science should be given more priority. The practical approach of applied science can catalyse economic development and thus uplift society as a whole. Generally, in Nepal, men take the major household decisions, while most women are overburdened with household chores and have limited or no say on household decisions. The transition towards women having an equal say in such decisions will come through cultural and generational shifts catalysed by inclusive policies and capacity-building programmes.

In Nepal, the lack of accessibility to renewable energy technologies and skills is both a result of poor quality of education and an absence of basic connectivity (such as roads and internet). In such a context, students grow up with limited knowledge and skills, thereby impeding local development and perpetuating the vicious cycle of unskilled manpower (both among men and women).

Therefore, making the operation of SWPS women friendly and promoting the inclusion of women and other marginalised groups in the decision-making process in the energy sector will enable them to improve their livelihoods, gain confidence, and achieve overall independence.

Detailed design

SITE INFORMATION

The location of the site is an example of where the SWPS for drinking water is to be established. The SWPS location with pins in pump, panel and distribution tank locations are shown in Figure 33.

FIGURE 33 SITE MAP

Source: Image obtained from Google Earth [40]

GLOBAL HORIZONTAL IRRADIATION PROFILE

The global horizontal irradiation (GHI) profile (Figure 34) has been obtained for Bhutan.

For a conservative estimate, the general uncertainty of the data is: ± 10% [41].

The system design for drinking water is more sensitive than designing for irrigation systems. For irrigation, supplementary rainfall adds to the water output of the SWPS, whereas for drinking water systems, the demand is constant throughout the year and must be fulfilled by the SWPS. To reduce the risk of non-availability of water, storage tanks have to be constructed. The capacity of these storage tanks can be larger than the total daily water requirement which then provides 'autonomy' to the system. Autonomy is the time during which the water needs can be fulfilled by the storage tank without any water supply from the SWPS. For example, if the capacity of the storage tank is double that of the total daily water need, then the storage tank has an autonomy of two (if it is full, it can supply water for two days without the operation of the SWPS). This stabilises the water supply during days of low irradiance and any SWPS downtime.

Furthermore, to gain higher confidence in water output from the SWPS, the minimum average GHI is taken as the basis of peak sun hours. From the above figure, an average GHI of 4.32 kWh/m²/day has been taken near Thimphu. In addition, the maximum uncertainty (10%) of data has been further factored in for safety.

The daily average GHI (kWh/m²/day) can also be interpreted as "peak sun hours" since the accumulation of total irradiation over a day represents equivalent hours of rated radiation, i.e. 1,000 W/m².

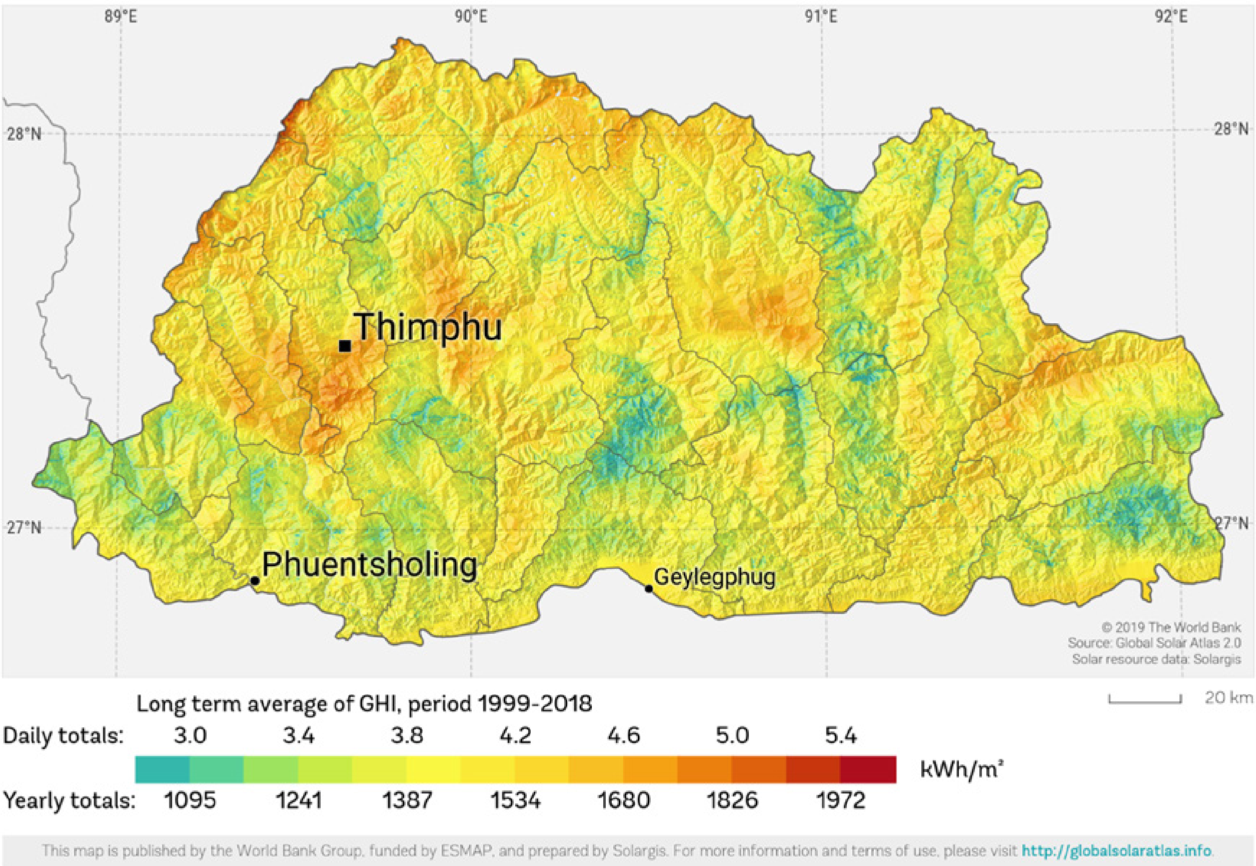
In other words, 4.32 kWh/m²/day can be interpreted as 1,000 W/m² of radiation over 4.32 hours (1,000 W/m² * 4.32 hours = 4,320 Wh/m² = 4.32 kWh/m²).

Thus, the peak sun hours for the design basis is: 4.32 * (1 – 10%) = 3.89 kWh/m²/day. By ensuring that the system can deliver on a water demand of 3.89 kWh/m²/day, the demand for water can be met for any month of the year.

PUMP INTAKE LOCATION

The pump intake location is near a village and within the inward curvature of a riverbank. The

FIGURE 34 GHI OF BHUTAN



Source: Image obtained from Solargis

inward curvature and the downstream flow of the river means that the intake location will be naturally protected during the rainy season when the force of the river will be high as shown in Figure 35.

Though this won't guarantee absolute protection due to the unpredictable nature of the river-flow path and the volume of water in different seasons, the geographic protection will break the high-speed currents of river water which would otherwise destroy the pump intake structure as shown in Figure 36.

Therefore, the infrastructure for pump intake must be a subject of careful study so that it is designed in

FIGURE 35 NATURAL PUMP INTAKE PROTECTION

FIGURE 36 PUMP INTAKE VULNERABILITY DUE TO CHANGES IN RIVE PATH

Source: Images obtained from Google Earth [40] such a way that it can withstand the natural forces specific to the site location. For example, some studies can include geological and geotechnical aspects in order to determine the suitable location of the pump intake.

VERTICAL HEAD

Figure 37 shows the elevation profile from the pump intake location to the distribution tank.

Intake elevation: 1,288 m

Distribution tank elevation: 1,419 m

Vertical head: 131 m

WATER REQUIREMENT

From the site survey, the number of households and population have been corrected:

Number of households: 45

The average number of people per household: 5

Current population: 225

Annual population growth rate: 10%

Total population: ~247.5–250

Now, taking into account the 70 litre-per-day average for individual water needs, we have:

Total water required per day: 17,500 litres

SOLAR ARRAY LOCATION

The location of the solar array is shown in Figure 38.

FIGURE 37 ELEVATION PROFILE

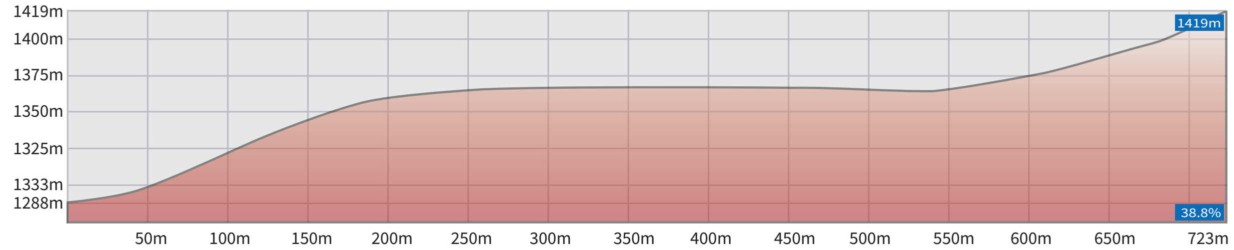


FIGURE 38 SOLAR ARRAY SITE

Source: Images obtained from Google Earth [40]

The array will be a ground mount fixed structure. For this example, the optimal direction and tilt angle of the array for Bhutan is true south and 29° (~30°) (Solargis data). A horizon analysis through the solargis software shows the sun paths during the winter solstice, spring/autumn, and summer solstice respective to the panel orientation.

In Figure 39, for the worst-case scenario during the winter solstice, the sunrise takes place around 08:30 and the sunset around 16:00. Designing a system that can successfully satisfy the water requirement during the winter solstice will ensure that the demand for water is met throughout the year.

DISTANCE MEASUREMENTS

Ground distance of cabling from the pumping area to the controller: 185 m

Ground distance of cabling from the controller to the panel array: The controller will be installed in the structural frame of the panel array; the distance between the +ve and -ve connections of the array are estimated to be less than 10 m.

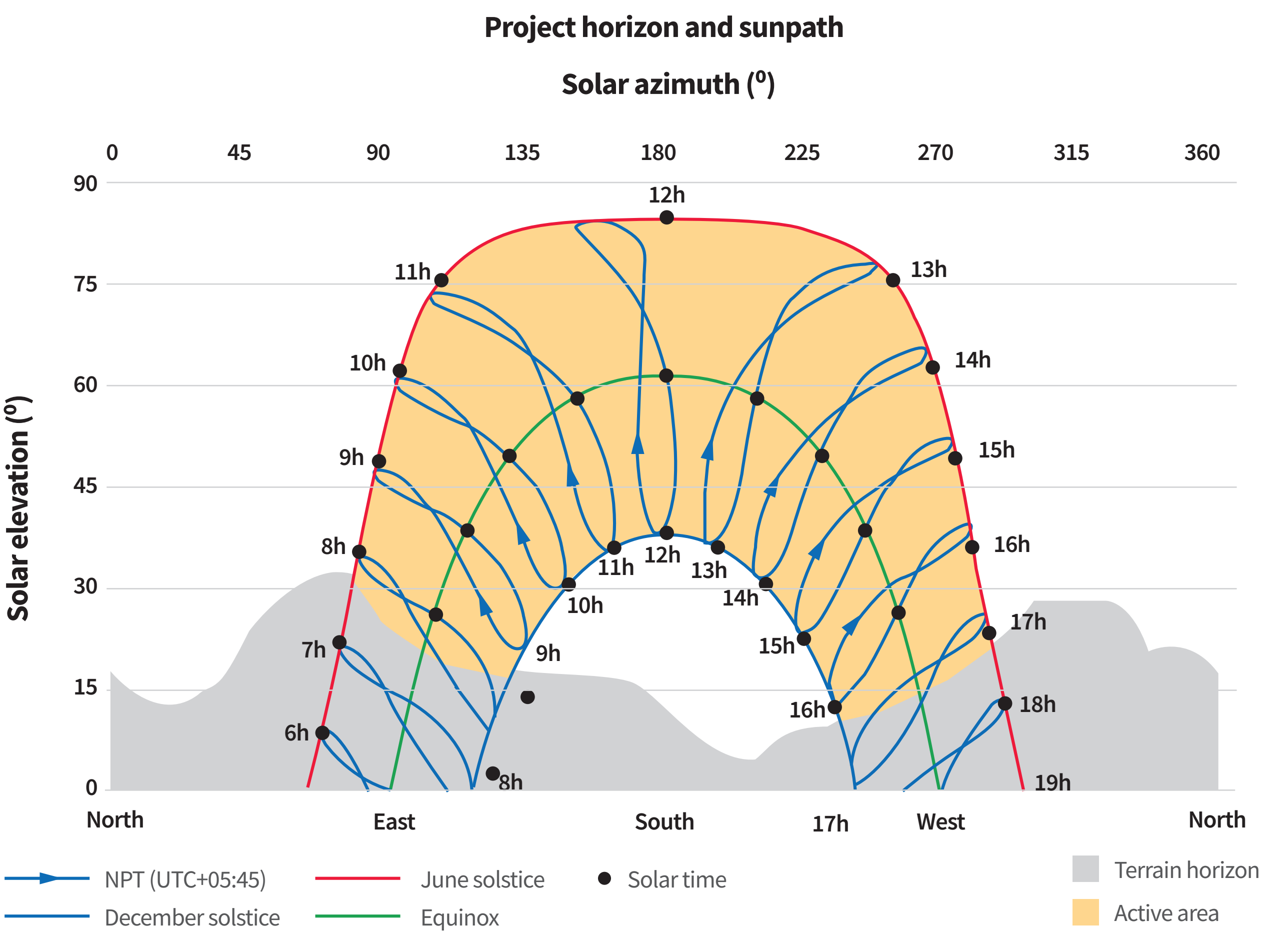
Ground distance of the transmission pipe from the pumping area to the distribution tank: 729 m

Ground distance of the distribution pipe from the distribution tank to customer locations: 1,271 m

EXISTING PUMPING MECHANISMS

There are no existing pumping mechanisms and residents have to carry water daily from a nearby natural spring. This natural spring is not suitable for pumping since its flow rate is only about 2,000 litres/hour compared to the 17,500 litres/day of demand which has to be fulfilled within an average of 3.89 hours of sunshine in a day. Therefore, water has to be pumped from the river and stored in the distribution tank of 35,000-litre capacity, i.e. for 2 days of autonomy, to account for days of low irradiance or system downtime. Then it will be filtered and distributed in the community. However, the design element in this report will only include water pumping from the river to the distribution tank.

FIGURE 39 HORIZON ANALYSIS



Source: Image obtained from Solargis

H. System design

Pump selection

Type of pump: Table 10 shows the pros and cons of using submersible and surface pumps for this design. The comparison clearly shows that a submersible pump is better for this application.

Both Model A and Model B satisfy the water requirement of delivering 4.44 m^3/hr at 147 m TDH. However, the efficiency curves of the two pumps are different. At 4.44 m^3/hr, the efficiency of Model A is approximately 56%, while that of Model B is approximately 38%. The operating efficiency of Model A is also higher than Model B's; therefore, Model A has been chosen.

TABLE 10 SELECTION OF PUMP TYPE

Submersible pump	Surface pump
Doesn't require priming, so it's easy to operate	Users have to prime the pump frequently which requires travel to the riverbank
Doesn't require additional pump housing	Requires additional housing that has to be above the flood level to protect the pump
The river-water level is not a concern if the intake is designed properly	The suction head has to be less than 6 m and the varying river-water level has to be properly assessed **Note:** The suction head capacity of pumps changes with sea-level altitude due to changes in atmospheric pressure. The higher the altitude, the lower the atmospheric pressure and hence the pump has to do more suction work, resulting in a decrease in the suction head for a given power. The reverse is true at a lower altitude where higher atmospheric pressure results in an increase of suction head for the same power.
Difficult to maintain due to accessibility	Relatively easier to maintain
Less prone to theft due to harder accessibility	More prone to theft due to easy accessibility

Next, to proceed with the pump selection, the vertical delivery height must be determined. Figure 40 shows the vertical heights in reference to the pump. Notice that a pumping level of 8 m and a tank height of 2 m have been added which are an estimation of pump-installation depth and the height of the distribution tank.

Vertical head: 141 m

Required hourly flow from pump: 17,500 ÷ 3.89 = 4,499 litres/hour = 4.5 m^3/hr

To determine the TDH, using the iterative process explained in the **Total dynamic head** section:

Initial assumed major loss: 2 m

Initial assumed minor loss: 0.71 m (0.5% of the vertical head)

Initial TDH: 143.7 m

Now, select a pump with 4.28 m^3/hr output at 143.7 m head. Two options of pump are shown in Figures 41 and 42.

The features of this pump are:

- Rated power of the pump: 3 kW
- Pump outlet: 1 1/4" (40 mm outside diameter equivalent)
- Pump outer diameter: 98 mm
- Pump length: 1,396 mm
- Maximum head: 230 m
- 400 V, 50 Hz, 3-phase AC

Now, to accurately calculate the major and minor losses from the chosen pump, the characteristics of the transmission pipe must be known:

- Pipe material: High-density polyethylene (HDPE)
- Pressure class: PN16 (maximum 160 m)

For civil design, the fittings in the transmission pipe should be known. A list of pipe fittings for this example are given in Table 11.

FIGURE 40 VERTICAL PUMPING HEIGHT

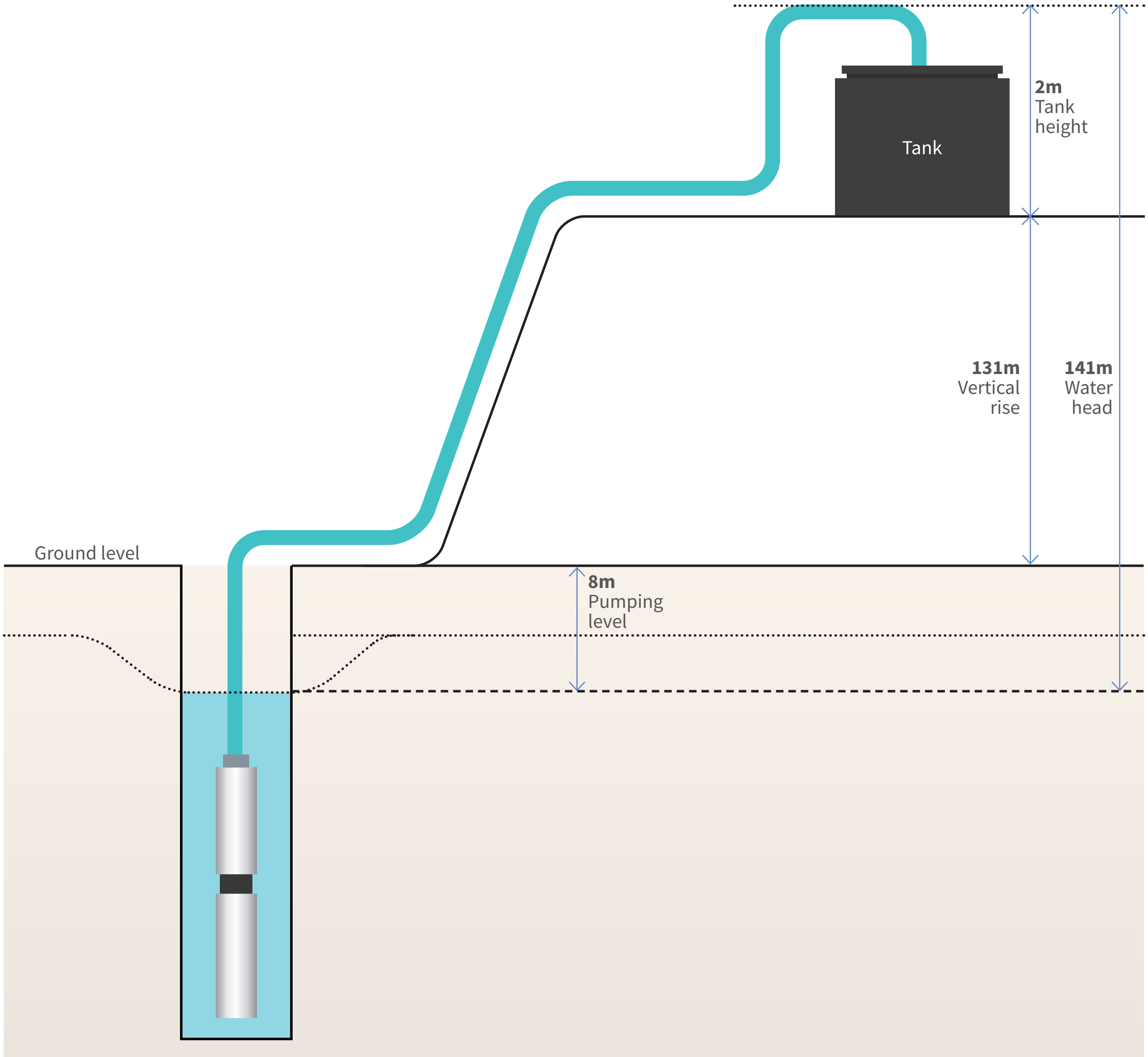


FIGURE 41 MODEL A PUMP CURVE

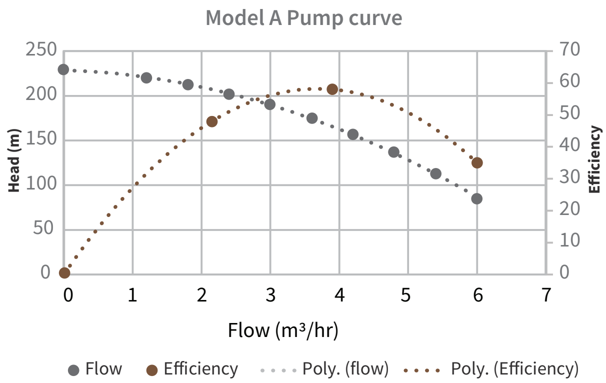


FIGURE 42 MODEL B PUMP CURVE

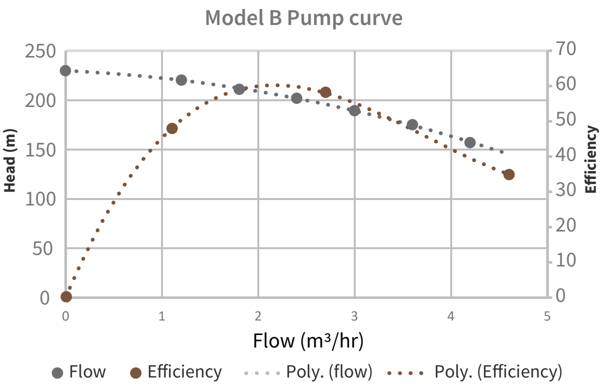


TABLE 11	MINOR LOSS COEFFICIENT DATA BASED ON THE FITTING MATERIALS PROVIDED BY CIVIL DESIGN		
Type of fitting	**Minor loss coefficient**	**No. of Fittings**	**Total minor loss Coefficient**
Union, Threaded	0.08	2	0.16
Elbow, Flanged Regular 90°	0.3	1	0.3
Elbow, Threaded Regular 45°	0.4	3	1.2
Swing Check Valve, Forward Flow	2	2	4
Water Meter	7	1	7
		Total:	**12.66**

Iteration 3: With a pipe size of 63 mm, the TDH is less than the earlier estimated TDH. Thus, the Model A pump can successfully deliver the water requirement.

The takeaways from this part of the design are:

- The Model A 3 kW submersible pump has been selected.
- The transmission pipe size is 63 mm HDPE.
- The pump will deliver 4.6 m^3/hr at 144 m TDH.

Note: The theoretical pump size (3.18 kW) from the preliminary design is close to the actual selected pump size of 3 kW. This gives further confidence to the design.

TABLE 12 LOSS CALCULATION BY THE ITERATION METHOD

	Pipe material	Nominal pipe diameter (mm)	Vertical head (m)	Major loss (m)	Minor loss (m)	TDH (m)
Iteration 1	HDPE PN16	40	141	33.66	0.60	175
Iteration 2	HDPE PN16	50	141	15.89	0.35	157
Iteration 3	HDPE PN16	63	141	2.47	0.11	144

In Table 12:

Iteration 1: The pipe size is the same as that of the pump outlet's. Here, the major loss causes the TDH to increase significantly. If the pipe size were to be restricted, then another model of the pump would have to be chosen since Model A's water output will not meet the demand at 175 m TDH. However, a cheaper option is to increase the pipe size which will then reduce the loss.

Iteration 2: Here, with an increase in pipe size, the loss is still significant and Model A cannot fulfil the water demand at 157 m TDH.

FAQ: What is PN 16 and why are pressure ratings important?

Pipes with proper pressure rating have to be chosen. If the chosen pipe cannot hold the pressure of water, then they may burst or start leaking. HDPE pipes are manufactured in different pressure nominal (PN) ratings. For this design, PN16 has been chosen as it can handle the maximum pressure of 16 bars [66]. The equivalent water head of 16 bars is around 160 m, which is well above the TDH of this design.

While choosing any type of pipe (galvanised iron, HDPE or others), always check the pressure rating and make sure that it is greater than the water pressure of the design.

FAQ: What is IP rating?

The ingress protection (IP) rating indicates the level of sealing of enclosures to prevent the intrusion of foreign matters and moisture.

The IP number consists of two digits. The first digit indicates protection against solid objects and the second indicates protection against liquid substances. See the **Appendix** on **Ingress protection rating table** for the complete list of IP ratings.

It is important to know of the IP rating of the controller to decide whether it can be openly installed on-site or whether it needs additional protection for long-term use.

Controller selection

The controller that is selected has to support the pump. The parameters of the controller are:

- MPPT controller
- Maximum size of the array that is supported: 5 kW
- Maximum input current: 17 A
- Maximum DC input voltage: 600 V

Water output simulation

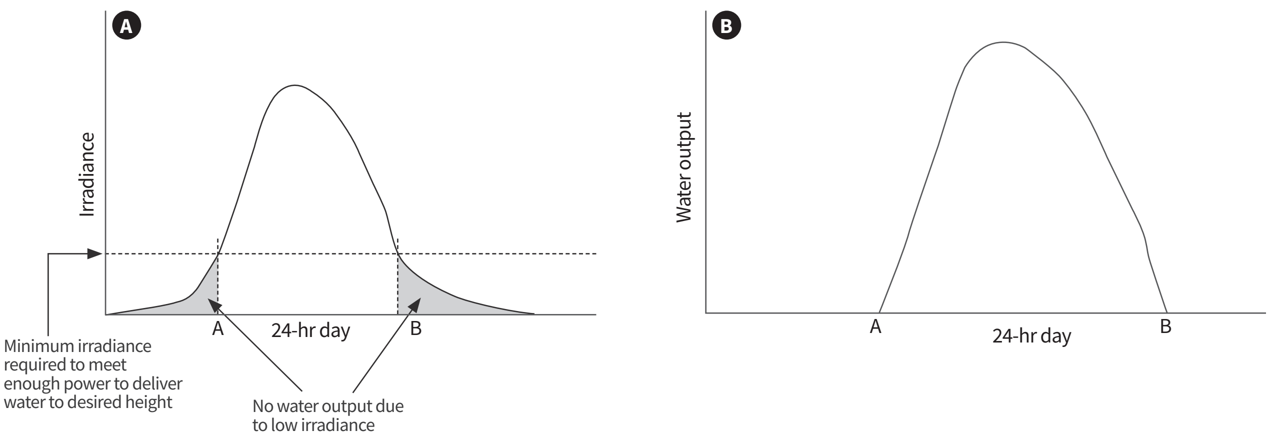
Pipes with proper pressure rating have to be chosen. It is important to mention that the water output mentioned above is based on a conservative estimate of the peak sun hours.

A more accurate method of water simulation would be to model the hourly water output for a worst-case scenario. This could be the winter solstice when the sun hours are the least. To perform this, the following information should be known:

- The minimum power required by the pump to deliver water to the desired height: This is a difficult piece of information to get. Not all solar water pump manufacturers have this data readily available. However, knowing the minimum required power will give a better estimate of water output over a day by eliminating the trickle power during early morning and evening when the minimum required power for the pump is not reached (Figure 43). The minimum power required by the pump is also related to the minimum irradiance that is required to get the water output.
- Daylight hours respective to a horizon: This can be mapped through a horizon analysis.
- Irradiance profile for worst-case scenario: This can be obtained from online resources and software. This will allow for analysis of hourly water output simulations and also for analysis of consecutive low-irradiance (non-sunny) days in a year which can be used to determine the autonomy days of the system; thus, also aiding the decision on the capacity of the storage tank.

Next, generate a table of irradiance and pump the input power after losses and water output. Eliminate rows that do not meet the minimum power to deliver water to the desired height. Now, sum up the hourly water output to get an accurate estimation of the water output over a day.

FIGURE 43 (A): IRRADIANCE CURVE FOR DAILY WATER OUTPUT SIMULATION; (B): DAILY WATER OUTPUT CURVE



- Lowest working voltage: 250 V
- Recommended MPPT voltage: 250–550 V
- Supported pump rating: Up to 4 kW
- Supported motor voltage: 380–440 V, 3-phase AC
- Output current: 16 A
- Output frequency: 50 Hz
- Efficiency of controller: 98%
- Protection grade: IP54

Panel array sizing

To size the array properly, the losses have to be properly defined. The loss factors in solar panels are:

Solar irradiance: Uncertainty of solar irradiance; this has already been considered in the global tilted irradiation (GTI) for this design

- Power loss due to cell temperature: -0.39%/°C
- DC and AC wiring: Maximum 3%
- Shading losses: Vary from 10% to 70% [42]
- Soiling losses: Estimated at 2% [43]
- Controller loss: 2% (from controller information)

Table 13 shows that the average temperature throughout the year is below the rated panel temperature of 25°C. The maximum temperature is achieved in the month of June – 31.4°C. This 6.4°C difference in temperature will result in -2.50% power loss (-0.39%/°C * 6.4 °C).

TABLE 13 AIR TEMPERATURE AT 2 M (°C) [41]

Month	Min.	Max.	Avg.
January	6	17.9	10.8
February	8	19.9	12.9
March	11.5	24.7	17
April	15	29	21.2
May	17.4	31.2	23.7
June	18.8	31.4	24.6
July	19.2	29.2	23.8
August	18.5	28.9	23.5
September	16.6	28.4	22.1
October	13.1	25.9	18.5
November	9.6	22.6	14.9
December	6.8	19.5	12
Yearly			**18.8**

Table 14 shows the theoretical calculation of the array size taking into account the losses and efficiencies.

TABLE 14 THEORETICAL CALCULATION OF ARRAY SIZE

Pump rating	**3**	**kW**
DC voltage efficiency	97%	max acceptable
AC voltage efficiency	99%	max acceptable
Shading efficiency	90%	Estimated
Soiling efficiency	98%	Estimated
Controller efficiency	98%	From controller specifications
Efficiency affected due to power loss related to cell temperature	97.5%	
Required array size	**3.71**	**kWp**

Panel selection

From the theoretical calculation and the available size of panels in the market, the parameters of the selected panel are:

- Peak power: 370 Wp
- Vmpp: 38.4 V
- Impp: 9.63 A
- Voc: 48 V
- Isc: 9.9 A
- Module efficiency: 19.1%
- Temperature coefficient of Voc: -0.28 %/°C
- Temperature coefficient of Isc: +0.057 %/°C
- Temperature coefficient of power: -0.39 %/°C
- Number of cells and type: 72 cells, monocrystalline
- Maximum system voltage: 1,000 V
- Dimensions: 1.955(l) x 0.991(b) x 0.040(d) m
- Warranty: 10 years

Array size selection: Designer discretion

During system design, the designer will have different panels to choose from, but these may be limited to the sizes of panels that are available in the market or restricted to specific preferences. In this case, let's assume that the designer is restricted to using a 370 Wp panel. Then, does the designer use 10 panels (3.7 kWp) or add another panel, making it 11 (4.07 kWp)? The decision can be made by evaluating two aspects:

1. If a lower array size is selected, will the power compromise affect the performance of the system?

In this case, the power compromise is 10 Wp (0.3% of the system size). This is a minor difference and will not affect the system performance. In addition, the estimated water output is higher than the demand.

2. If a safe array size is selected, does it complement the budget?

Selecting the 11-panel option (4.07 kWp) is a much safer option for design. The 360 Wp buffer above the theoretical array size gives room to make up for any unforeseen losses due to on-site conditions. The losses on-site may be greater than the estimated shading and soiling losses.

So, what is recommended in this case?

In this case, assuming that there is no strict budgetary constraint, it is recommended to go with 11 panels since this will allow room to make up for unforeseen losses due to on-site conditions.

The series arrangement of the panels must be compatible with the controller. Table 15 shows the arrangement of the solar panels and their compatibility with the controller parameters.

TABLE 15 ARRAY AND CONTROLLER COMPATIBILITY CHECK

	Array arrangement parameter	Controller parameter	Check
Vmpp (V)	422.4	250–550	OK
Impp (A)	9.63	Max 17	OK
Voc (V)	528	Max 800	OK
Isc (A)	9.9	Max. 17	OK
Array size (kW)	4.07	Max 5	OK

Some good design practices on the solar array and controller sizing are:

- Design the solar array input voltage close to the higher threshold of the MPPT voltage range of the controller. Given that the input voltage will vary subject to site conditions, a higher input voltage gives ample room for the SWPS to operate. For example, in the above design, there is a 172 V difference between the lower threshold of the controller MPPT voltage and the solar array voltage (422–250 V) and a 128 V difference between the higher threshold of the controller MPPT and the solar array voltage (550–422.4 V). Having the solar array voltage on the higher side allows room for 172 V of margin below the operating voltage, which will ensure that the system will operate for long hours in a day.
- It is advised to design the solar array input voltage above the pump-operating voltage where there is no boost circuit built into the controller.

Monthly simulation

Once the component selections are complete, a monthly simulation needs to be done to check the daily water output over the course of a year.

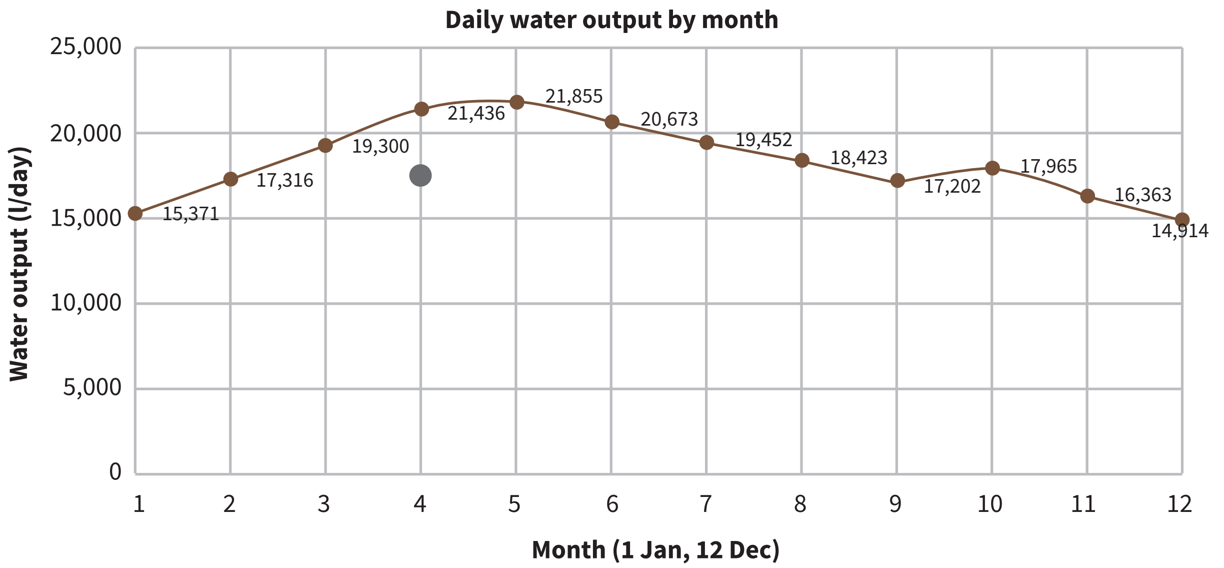
To simulate the water output of the SWPS:

- Obtain the average daily peak sun hours for a monthly projection.
- Multiply the average daily peak sun hours with the pump water output for each month and plot a graph.

The estimated daily water output over the year for the SWPS design is shown Figure 44. In the chart, it can be seen that the SWPS will have the highest output in April to June and the lowest output in December and January. This means that the SWPS will have the maximum output in the summer months (longer days) and the lowest output in the winter months (shorter days).

What is most important is to check whether the water requirement is fulfilled throughout the year. The water requirement for this design is 17,500 litres/day. The simulation below shows that the water requirement will be fulfilled for the majority of the year but will fall short in September, November, December, January, and February. The water output will decrease by 1% (in February) to 15% (in December) below the desired output. At this point, the designer has to decide whether to choose

FIGURE 44 DAILY WATER OUTPUT SIMULATIONS



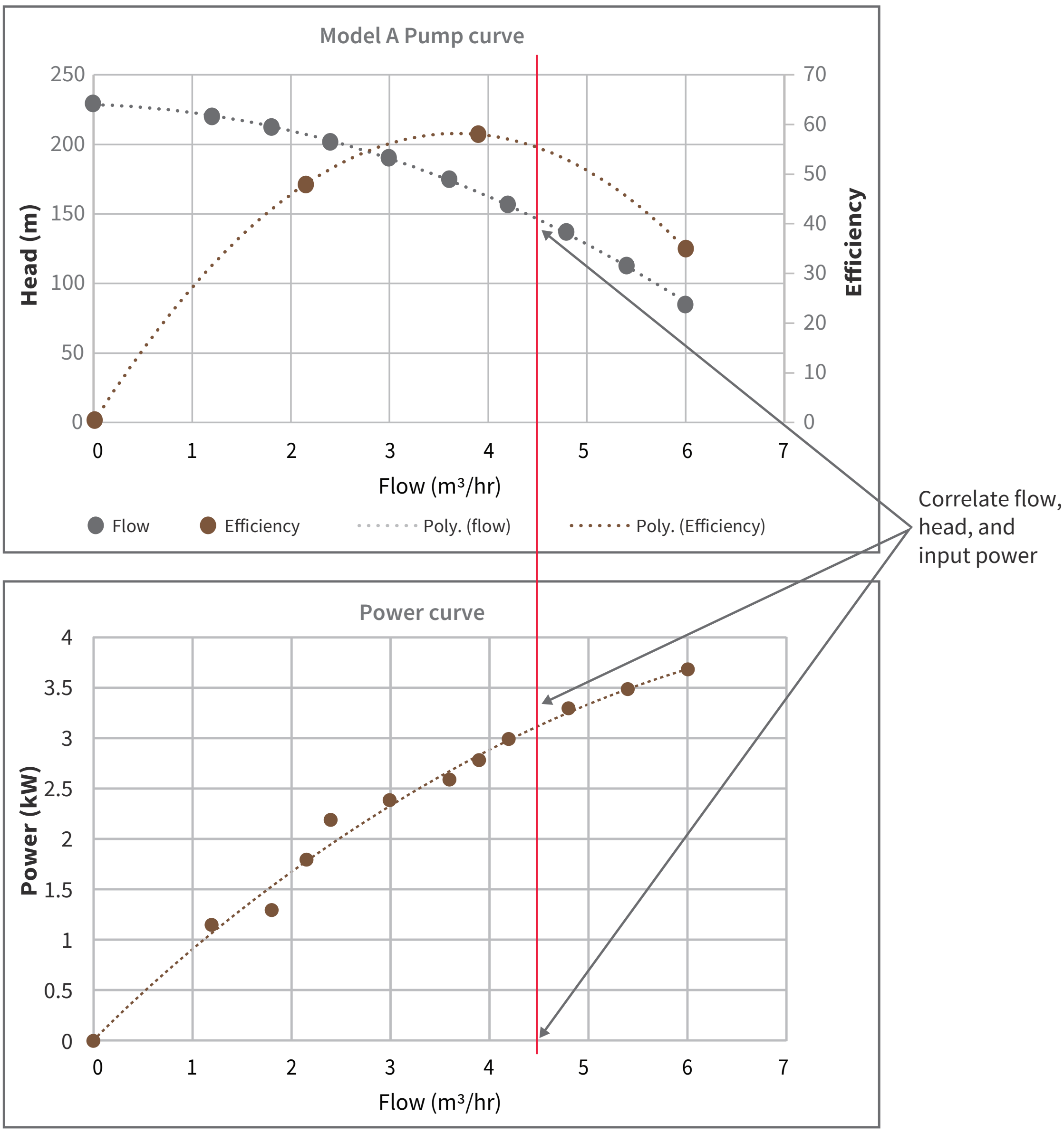
a pump with a higher output to fulfil the water requirement throughout the year or to accept the slight drop of water output for 5 months in a year. In this case, we can choose to accept the decrease in water output for 5 months as the maximum 15% decrease in December translates to a per capita water quota decrease from 70 l to 59.5 l per day – keeping in mind this is the maximum decrease. This can be acceptable in this hypothetical scenario.

Important note: While the requirement for drinking water and livestock will remain fairly constant throughout the year, the requirement for irrigation may not. The water requirements for irrigation will vary according to crop season and crop type. For example, paddy needs intensive water during plantation and this requirement decreases from that point. Therefore, if we take the average water requirement for paddy over a season, we won't be able to fulfil the higher water demand during its plantation time. In irrigation, the estimation of water requirement based on crop season and type needs to be properly assessed and the subsequent SWPS design should be able to fulfil the maximum water requirement.

Design

The SWPS design in this handbook followed a case where we dealt with pump selection based on head vs flow curve. In some cases, depending on the manufacturer, pump curves with head vs flow vs input power are given, as shown in the Figure 45. In this case, the graph will indicate the input power required for the desired water output based on which the solar array can be sized accordingly.

FIGURE 45 **CORRELATION OF FLOW, HEAD (TOP), AND INPUT POWER (BOTTOM) OF PUMP PERFORMANCE**



Panel area

INTER-ROW SPACING

In this system, the 11 panels can either be installed in one row or divided into two rows. This has to be decided in consent with the land owner on-site. For inter-row calculations, the panels will be installed in two rows.

To determine inter-row spacing, the azimuth and altitude angles are necessary for the location.

In Figure 46, the altitude of the sunrise on winter solstice (December 21) has been chosen as the worst-case scenario. This makes sure that there is no shading in the panels between 8:30 am to 3:00 pm during the winter solstice. The vertical axis shows the altitude of the sun in reference to the horizontal plane (or ground). The horizontal axis shows the azimuth angle of the sun in reference to the vertical plane (facing south).

Height of tilted panel: 1.955 m x sin(30°) = 0.98 m

Row spacing: 0.98 m div tan(19°) = 2.84 m (Figure 47 for visualisation)

Now, considering the azimuth angle:

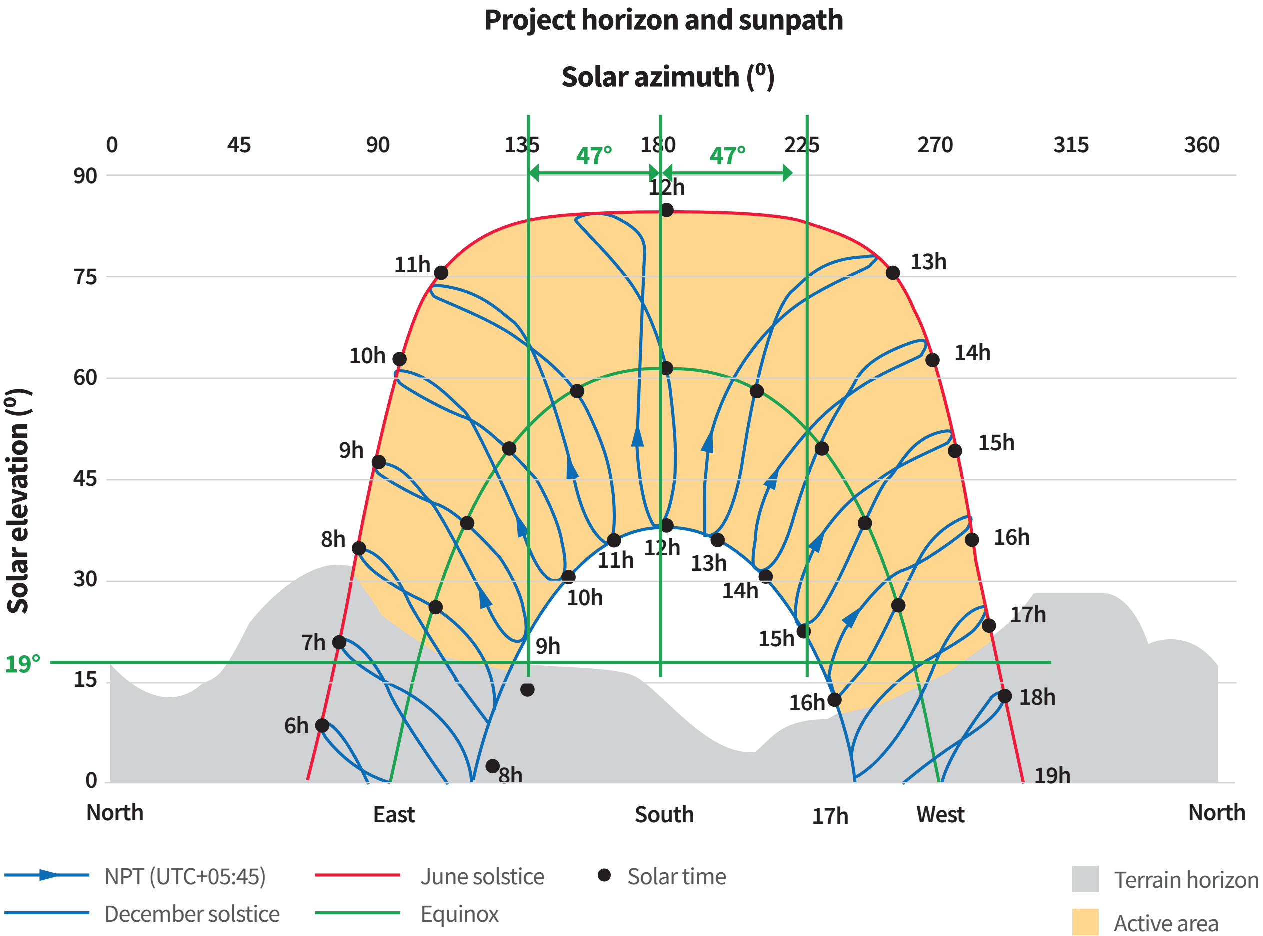
Minimum inter-row spacing: 2.84 m * cos(47°) = 1.94 m

Note: The steps shown above describe equation 2.

FAQ: Why is panel ground clearance not taken into account for inter-row spacing?

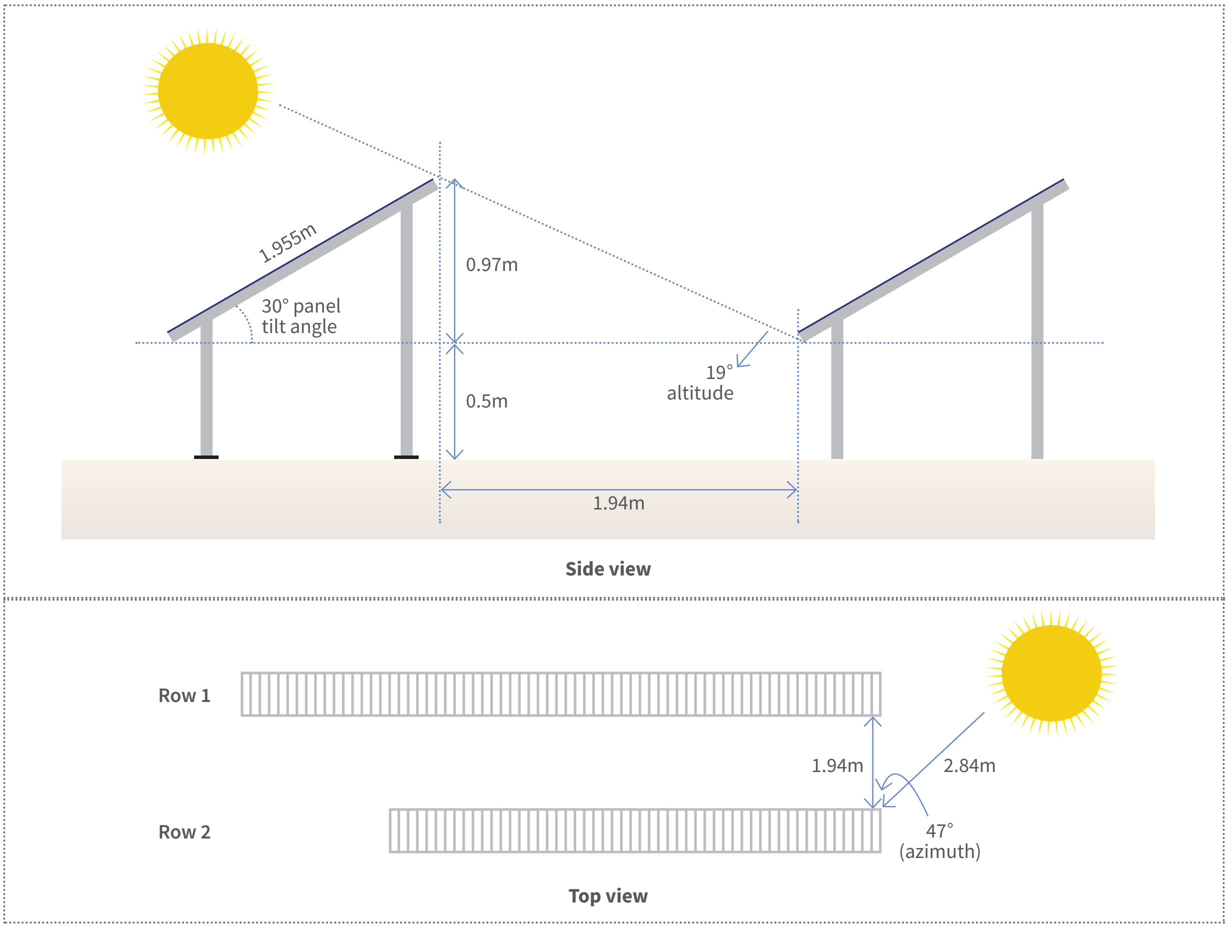
In Figure 47, it can be seen that the panel ground clearance is not taken into account for inter-row spacing calculations. The reason is obvious; this height does not include that of the solar panels and is the height of the structure only. Therefore, shading at this height will have no effect on the performance.

FIGURE 46 ALTITUDE (VERTICAL AXIS) AND AZIMUTH (HORIZONTAL AXIS) ANGLES



Source: Image obtained from Solargis

FIGURE 47 INTER-ROW SPACING DIMENSIONS (TOP); AZIMUTH CONSIDERATION (BOTTOM)



ESTIMATION OF PANEL AREA

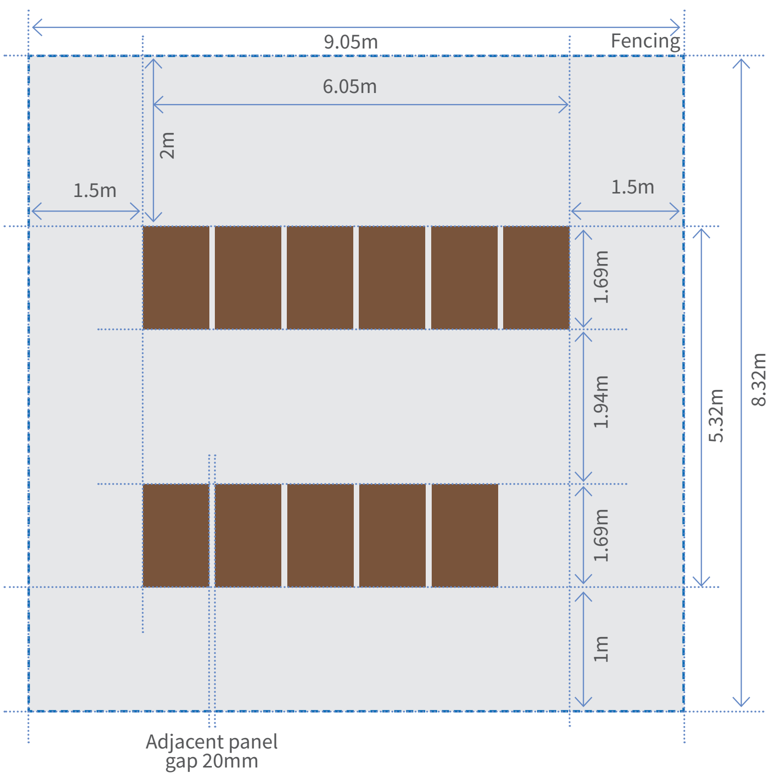
Now that the array arrangement is known, the panel area can be determined. Figure 48 shows the area required for the installation of panels in the two-row arrangement. Depending on the location, the panel area may need to be protected by a fence to stop unauthorised access and also to keep domestic animals out. A clearance of at least 1 m is given on all sides with a 2 m clearance in front of the array. This is to ease the mobliity within the panel area and to avoid shading in the panels from the fence.

Total array area: 9.05 m * 8.32 m = ~75.3 m^2 – 76 m^2

The takeaways from this section are:

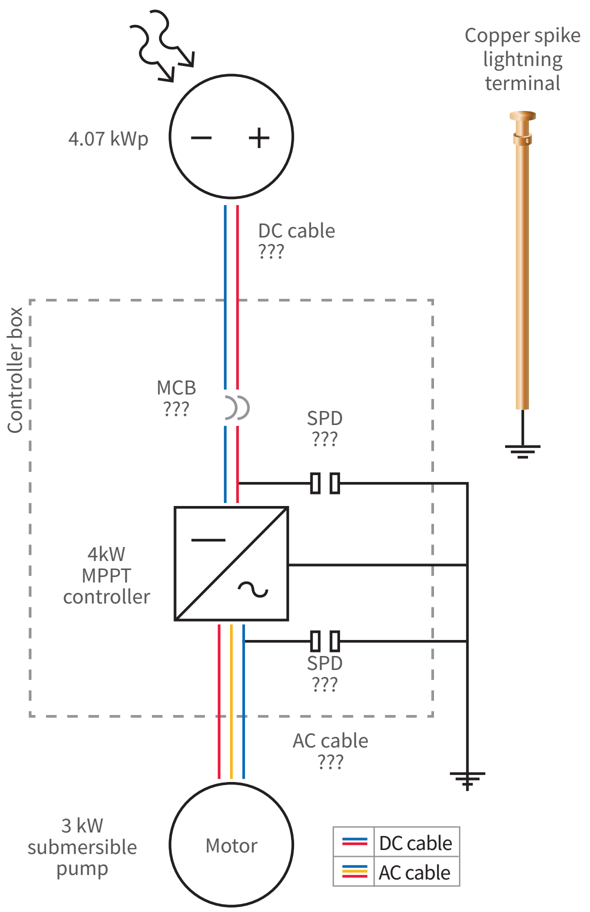
- Total array size: 4.07 kWp
- 11 units of 370 Wp panels will be connected in series
- Required panel area: 76 m^2

FIGURE 48 PANEL AREA



Before moving on to the next part of the design, it is good practice to develop a general single-line diagram (SLD) as shown in Figure 49. Notice that not all components have to be defined yet. Creating an SLD before the main components have been identified will help in systematically defining each component of the system without missing any aspect of the design.

FIGURE 49 **GENERAL SINGLE-LINE DIAGRAM**



Cables

DC CABLE

Cable from solar panel to controller

Length: <10 m from either side of the array

Voltage: 422.4 V

Current: 9.63 A

Option 1: Voltage drop in 1 core 1.5 mm^2 copper cable @ 31.4°C: 0.54%

Option 2: Voltage drop in 1 core 1.5 mm^2 aluminium cable @ 31.4°C: 0.84%

Why 1.5 mm^2 and not lower?

For the above electrical parameters, a copper cable of <0.54 mm^2 can also be chosen within the acceptable voltage drop but this is where ampacity comes into play. The maximum current of the array is 9.63 A which will require a minimum standard cable size of 1.5 mm^2 (see **Appendix on Cable ampacity and size conversion**).

Copper or aluminium?

For this system, the chosen cable size is relatively small and for a short distance of <10 m. So, the weight, dimensions, and cost will not be significant between copper and aluminium. In addition, copper cables of 1.5 mm^2 are easily available in the market compared to aluminium cables. Therefore, a copper cable will be chosen.

AC CABLE

Cable from the controller to the pump

Length: 190 m

Voltage: 400 V

Power factor at half load: 0.72 [44] (typical power factor only)

Current drawn at half load: 6.01 A

Option 1: Voltage drop with 4 core 2.5 mm^2 copper cable @ 31.4°C: 0.68%

Option 2: Voltage drop with 4 core 2.5 mm^2 aluminium cable @ 31.4°C: 1.04%

For this design, a copper cable will be chosen for its low voltage drop.

GROUND CABLE

The ground cable should be of a larger cross-section than other cables in the SWPS to allow for a lower resistance path for the current compared to other cables in the system. According to NEC (US), the grounding cable should be at least 6 AWG (American Wire Gauge), equivalent to 16 mm^2 copper solid wire. However, in practice, for systems with lower cross-section cables such as this design, 10 mm^2 copper solid wire is also used. The colour of the cable should be yellow with a green stripe. The length of the earthing cable should not exceed 7.5 metres (25 feet).

Protection devices

CIRCUIT BREAKER

Maximum DC current = 9.9 A (Isc of the panel)

Minimum rating = 9.9 * 1.56 = 15.4 A

Market-available MCB current rating: 16 A

Note: The DC MCB used will be DP 16 A rated.

SURGE PROTECTION DEVICE

As discussed earlier, for the SWPS, the common SPD used is Type II. Type II SPDs are rated based on 8/20 µs wave forms. There are SPDs available, especially for PV applications. An example of a Type II SPD rating for PV application is shown in Table 16 below.

TABLE 16 RATING OF TYPE II SPD [45] [46]

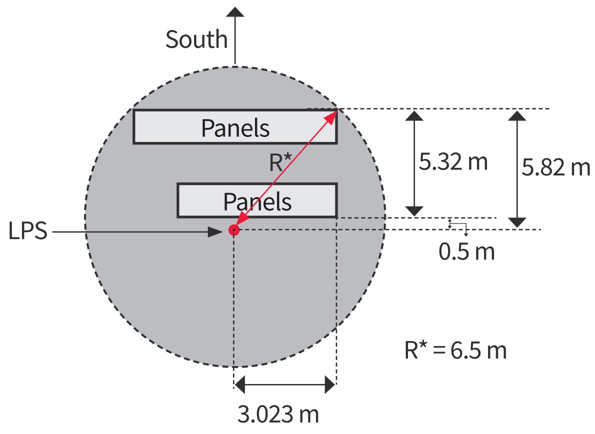
SPD Type II DC side		
Max DC voltage	600 V	The maximum PV voltage is 528 Voc
Max operating voltage	680 V	
Nominal discharge current 8/20µs wave form	20 kA	
Max discharge current 8/20 µs wave form	40 kA	
Protection level	Up to 2.5 kV	
SPD Type II AC side		
Max AC voltage	440 Vac	The pump rated voltage is 400 Vac
Max operating voltage	580 Vac	
Nominal discharge current 8/20 µs wave form	20 kA	
Max discharge current 8/20 µs wave form	40 kA	
Protection level	Up to 1.8 kV	

Lightning Protection System

The LPS is designed based on the protective angle method described earlier. In this design, the location of the LPS will be behind the second row of panels so that it does not have any shading on the panels. Based on this location, the effective lightning protection radius is calculated which is the farthest edge of the array, i.e. from the LPS to the corner of the front row of the panels, as shown in Figure 50.

Now, the height of the air terminal above the panel needs to be determined so that the protected area covers the array of solar panels.

FIGURE 50 PROTECTION RADIUS OF LPS (TOP VIEW)



Protection angle at 2 m for class II protection: 73° (see Figure 24).

By performing a few iterations as shown in Table 17, the required height of the air terminal above the panel is determined to be 2 m. The ground clearance and vertical height of the panel should be added to this height. The total required height of the LPS air terminal is ~3.47 m–3.5 m.

TABLE 17 LPS HEIGHT ITERATIONS

LPS height above panels (m)	Protection angle (degree)	Protection radius (m)
1.5	73	4.9
1.75	73	5.7
2	73	6.5

Now that all the components of the SWPS have been defined, the final SLD can be generated (Figure 52).

FIGURE 51 LPS AIR TERMINAL HEIGHT (SIDE VIEW)

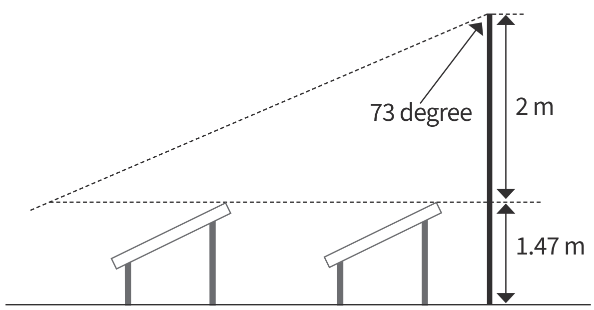
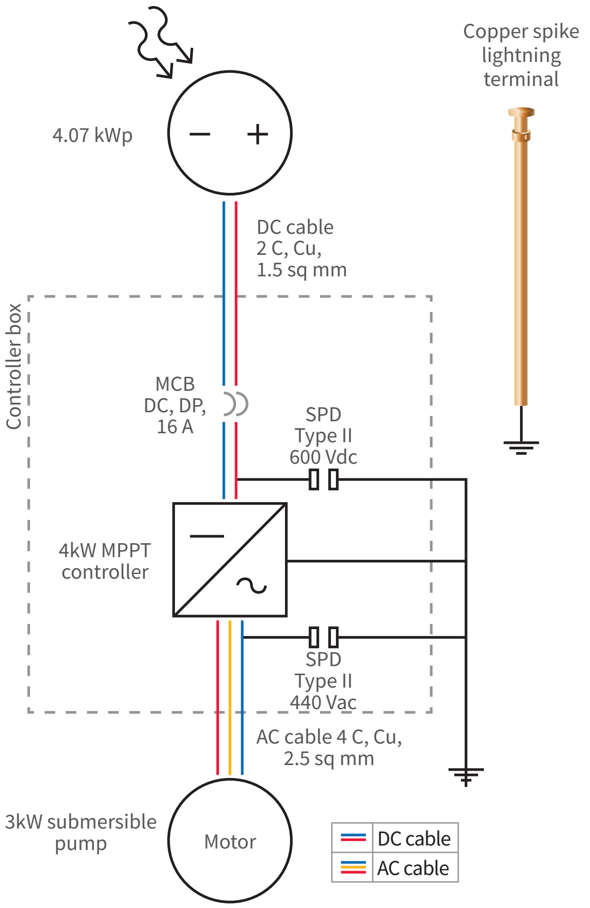


FIGURE 52 FULL SINGLE-LINE DIAGRAM



Life cycle cost

Let's now briefly evaluate the life cycle cost (LCC) of the SWPS. LCC captures the cost of the SWPS over its operating life period. This includes the cost of components, labour costs, and the expenses up to decommissioning at the end of its life. This analysis is useful to financially evaluate a project and for comparison against alternatives such as diesel pumps.

The equation for LCC analysis is [47]:

$$LCC = C_{ic} + C_{in} + C_e + C_o + C_m + C_{env} + C_d \qquad \text{Eq. 1}$$

Where,

C_{ic} is initial cost of the system (pump, solar panels, pipe, auxiliary services)

C_{in} is installation and commissioning cost (including training)

C_e is energy costs (predicted cost for system operation)

C_o is operation costs (labour cost of normal system supervision)

C_m is maintenance and repair costs (routine and predictable repairs)

C_n is downtime costs (loss of production)

C_{env} is environmental costs (contamination from pumped liquid and auxiliary equipment)

C_d is decommissioning/disposal costs (including of restoration of the local environment)

SWPS

For our design, the estimated cost of a 4,070 Wp solar array powering a 3 kW (4 HP) submersible pump system that delivers on average 17,000 litres per day at 144 m TDH over 4.32 peak sun hours was taken. (The LCC of the SWPS will later be compared to that of an equivalent diesel pump.) The input LCC of the SWPS are as follows:

- $C_{ic} + C_{in}$: USD 5,980[3] (for electromechanical components only, i.e. solar panels, controller, pump, accessories, installation, and commissioning)
- C_m
  - Annual scheduled maintenance: USD 91
  - Pump replacement cost every five years: USD 299
  - Controller replacement cost every five years: USD 237
  - Annual unforeseen maintenance: USD 120 (2% of system cost)

Here, for the community SWPS system, C_e, C_o, C_s, C_{env} and C_d have been ignored because these costs will be similar to those of diesel pumps or do not apply to the SWPS.

Diesel pumps

For direct comparison, the following cost estimates for an equivalent 4-HP diesel pump were taken:

- $C_{ic} + C_{in}$: USD 380
- C_m: USD 100 for annual maintenance
- C_e: USD 1,193 for annual diesel fuel cost

Assumptions:

- Diesel cost: USD 1.5/litre (Bhutan's average diesel price for July 2022)
- Average operation of 30 hours/month
- Average fuel consumption of 0.58 litres/hr for a 4 HP diesel pump
- Fuel transportation costs were taken as 5% of the fuel cost per month
- Maintenance cost of USD 50 every 6 months

[3] All costs for LCC calculation were based on the estimated market cost in Bhutan (for 2022) and converted into USD.

Life cycle cost analysis

For LCC analysis, the annual inflation rate of 5% was taken; a 10-year LCC graph for the SWPS and diesel pump is shown in Figures 53 and 54.

FIGURE 53 LCC GRAPH OF 4,070 WP, 4 HP SWPS

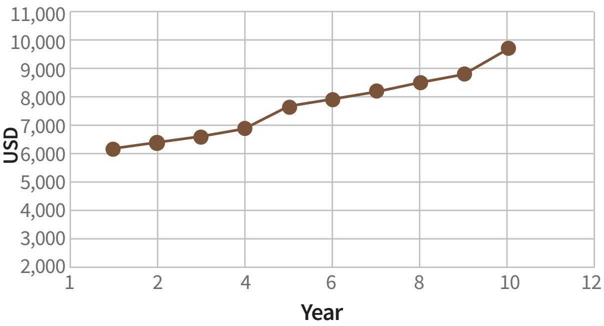
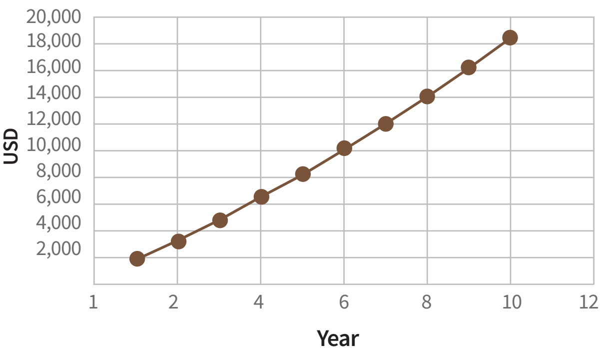


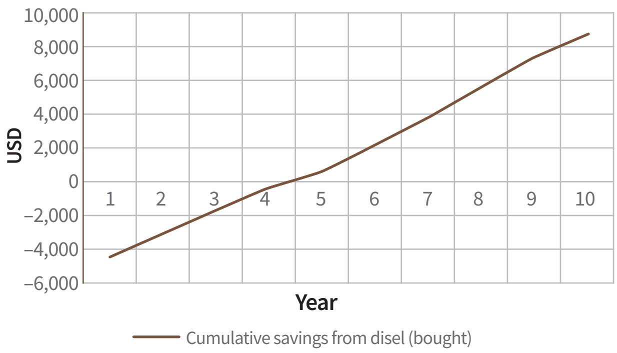
FIGURE 54 LCC GRAPH OF 4 HP DIESEL PUMP



From these LCC graphs, a direct comparison of diesel pumps with SWPS can be made. Furthermore, Figure 55 shows the payback of SWPS against an equivalent-size diesel pump. The graph shows that the break-even of SWPS is reached in four years.

The payback graph indicates that SWPS has a high initial capital investment compared to diesel pumps (hence the negative cost until 4 years) which is consistent with a study carried out by Winrock International in 2017. Even with a rapid decrease in the cost of solar panels in the last decade, affordability remains one of the major barriers to the wide-scale adaptation of SWPS; this can only be overcome by access to finance and reliable technical support [1].

FIGURE 55 PAYBACK GRAPH OF SWPS VS DIESEL PUMP



SECTION IX

Installation and maintenance

This section describes general tips on the installation of components and on best practices and basic maintenance.

I. General overview of installation

Solar panels

The first part of the electromechanical installation process is the erection of the panel structure. During this stage, ensure the following:

- The land area where the structure is to be erected must be clear, dry, and level.
- Make sure the structure direction and angle are correct before bolting or concreting the legs of the structure.
- In the case of concrete footing, wait for the mixture to dry before installing the solar panels. Installing the panels or fastening the structure screws tight before the concrete is dry may cause the structure to misalign and become loosely gripped with the concrete.
- Optional anti-theft bolts: Anti-theft bolts can be used to hold the panels. These cannot be undone after they have been bolted; they can only be cut. This provides security to the solar panels, especially those installed in open fields.
- Recheck the direction and angle of the panels. Ensure that the structure is rigid and that there are no sags in it which may indicate mechanical stress.

Grounding pits

- The ground pit should be near the solar panel structure and where soil resistivity is low.[4] The lightning ground pit should be below the air terminal.
- Measure ground resistance after the ground electrodes have been installed and make sure it meets the required value explained in the **Grounding** section earlier. The method for measuring ground resistance is described below.
- Proper terminal connectors must be used for connecting with the ground electrodes.

MEASURING GROUND RESISTANCE

One of the basic ground resistance test methods is called the "fall-of-potential" method or the "three-terminal" test [48]. To perform this test, a ground resistance tester equipment is required. It is recommended to disconnect the ground electrode from the system before performing this test so as to obtain accurate readings.

The three terminals should be connected as shown in Figure 56. The name of the connection terminals of the tester may vary as per the manufacturer. Here, the first terminal is the ground electrode itself connected to C1. Another terminal is placed as far away from the electrode as possible – only limited by the length of the extension wire and the geography of the location – and connected to C2. The distance between these terminals is labelled D. Then the third terminal is placed between the two terminals which are connected to P2.

The tester passes a known current from the earth electrode to C2 and measures the voltage difference between the earth electrode and P2. The tester then calculates the ground resistance using Ohm's law, V=I*R. Then, terminal P2 is moved along the distance D and multiple readings of resistance are made and plotted in a graph. Terminal P2 must be placed in line between the ground electrode and C2.

The effective ground resistance is determined to be at around 62% of distance D or where the curve is relatively flat (Figure 57). This values must correlate with the required ground resistance – usually less than 10 Ω – as described in the **Grounding** section earlier.

[4] Read about the measurement of soil resistivity at: https://www.electricalengineeringtoolbox.com/2015/12/how-to-measure-soil-resistivity.html

FIGURE 56 **FALL-OF-POTENTIAL GROUND RESISTANCE TEST**

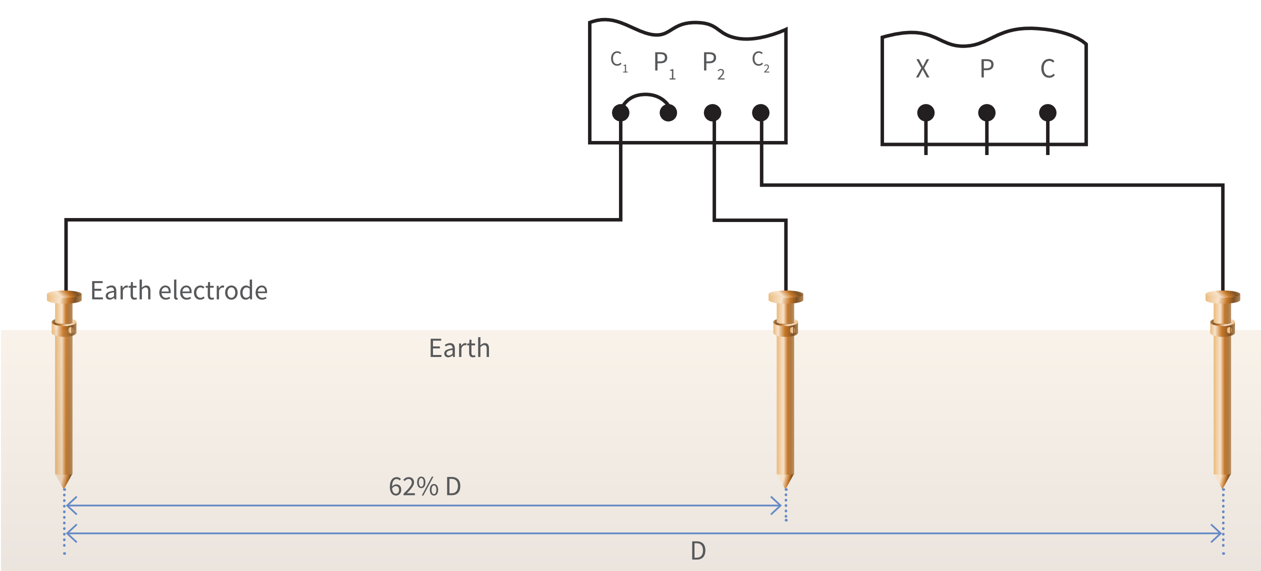
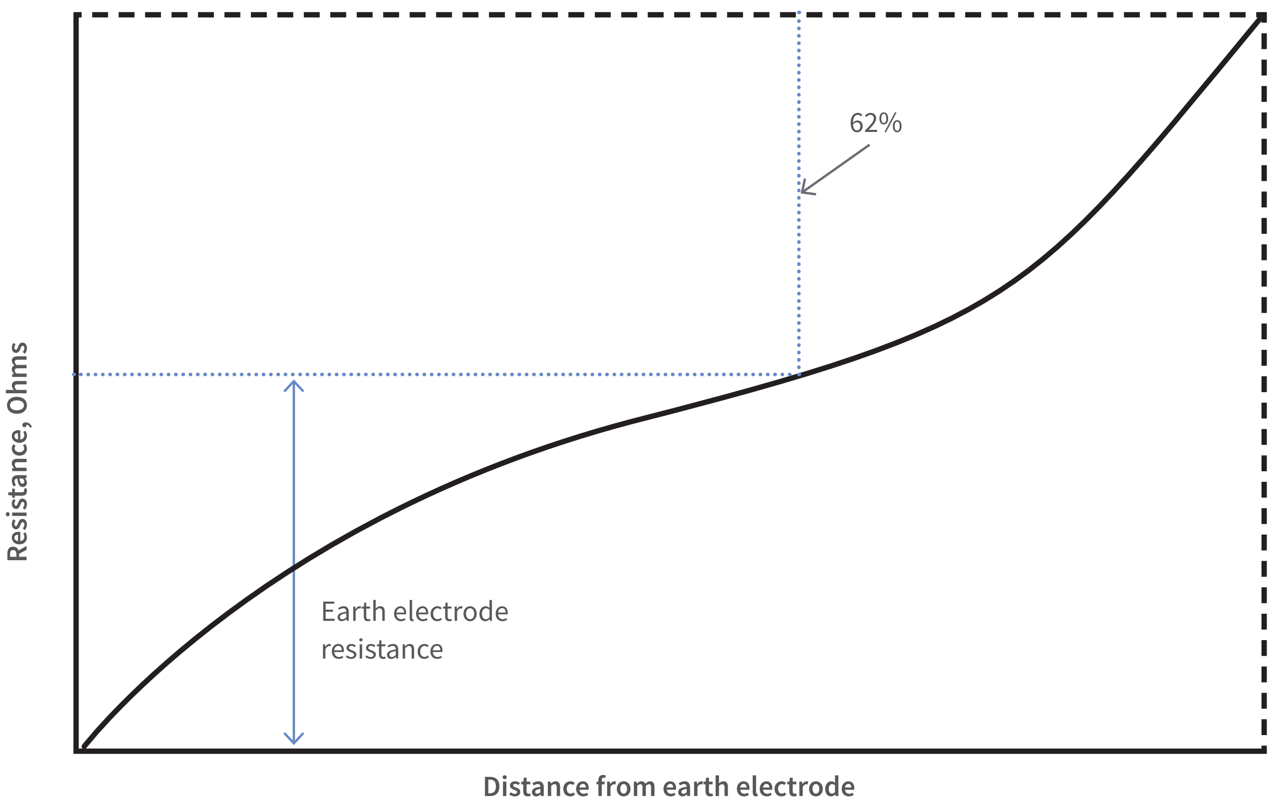


FIGURE 57 **GROUND RESISTANCE PLOT**



Source: Images obtained from Weschler Instruments [48]

Pumps

SUBMERSIBLE PUMPS

- All pipe connections must be leakproof.

Submersible pumps come with a safety hook at their top. Stay wires (safety cables made of stainless steel) must be fastened using steel grips to hold the pump under water (Figure 58). The stay wires must be properly hooked to the anchor points in the ground (Figure 59). Do not use hooks to grip the pump pipe; this may seem easy at the time of installation, but it's difficult to pull the pump out during maintenance and if the water level in the well is high (Figure 59).

FIGURE 58 **GENERAL SUBMERSIBLE PUMP CONNECTION – A**

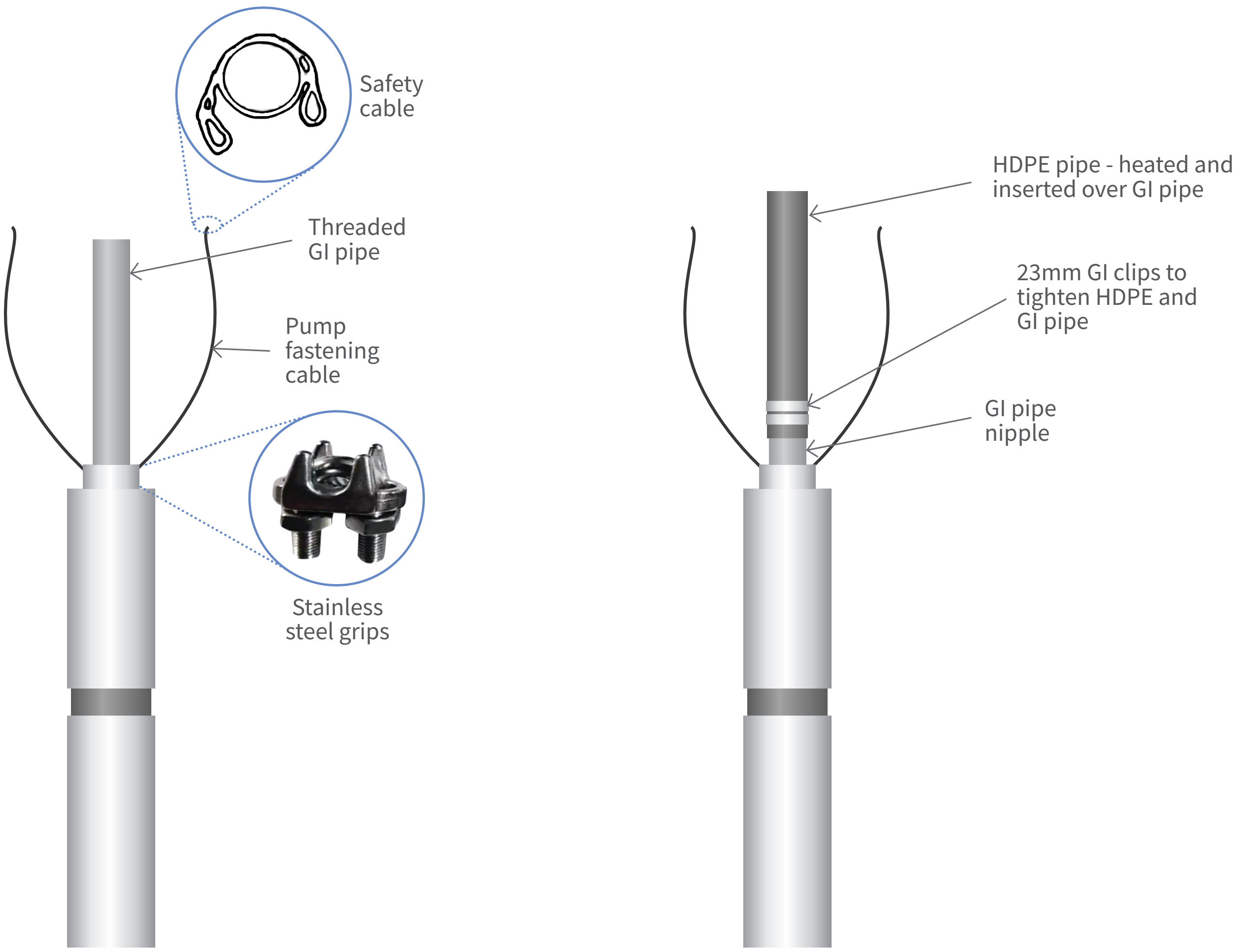
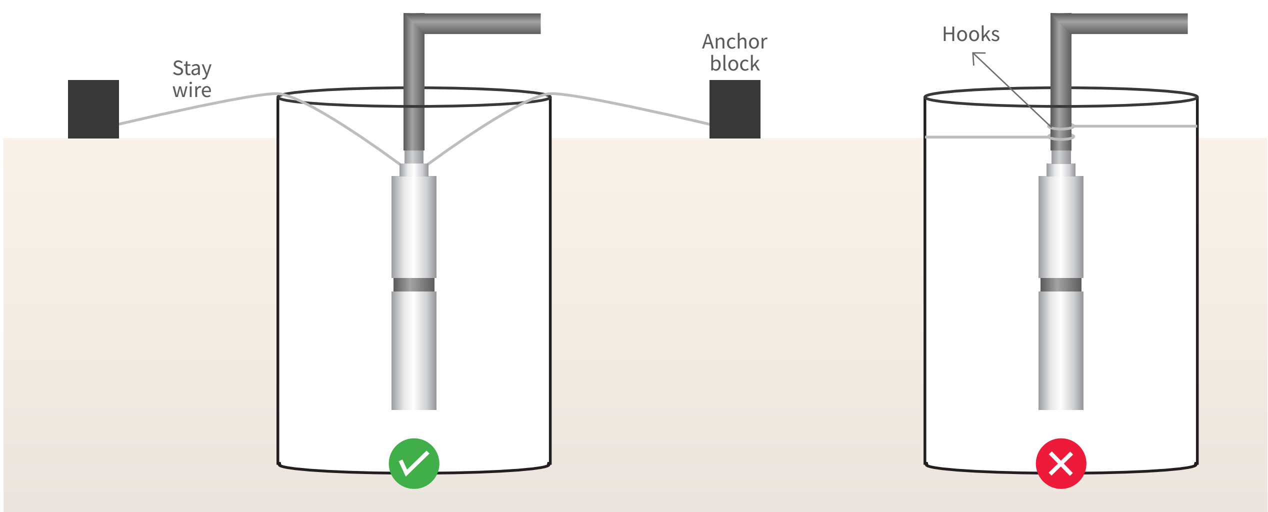


FIGURE 59 **GENERAL SUBMERSIBLE PUMP CONNECTION – B**



A union connection must be given above the pump when it is to be disconnected for repair or maintenance. The union should be placed in the pipe section above the well (not below) for ease of disconnection (Figure 60).

- All electrical connections near the water source must be properly insulated by waterproof tapes.

SURFACE PUMPS

Surface pumps must be housed properly to protect them from excessive rain and dirt (Figure 61). Excessive rain can cause the water to seep inside the motor coil and burn the motor; it can also corrode the pump body.

- Ventilation provision must be given to the pump housing to prevent pump overheating.
- The pump housing should be big enough to allow for comfortable plumbing workmanship.
- If pressure gauges and unions are to be installed near the pump inlet or outlet, make sure these are located inside the pump housing.
- The pump housing and pump should be at an elevated height to prevent it from flood water.

FIGURE 60 GENERAL SUBMERSIBLE PUMP CONNECTION – C

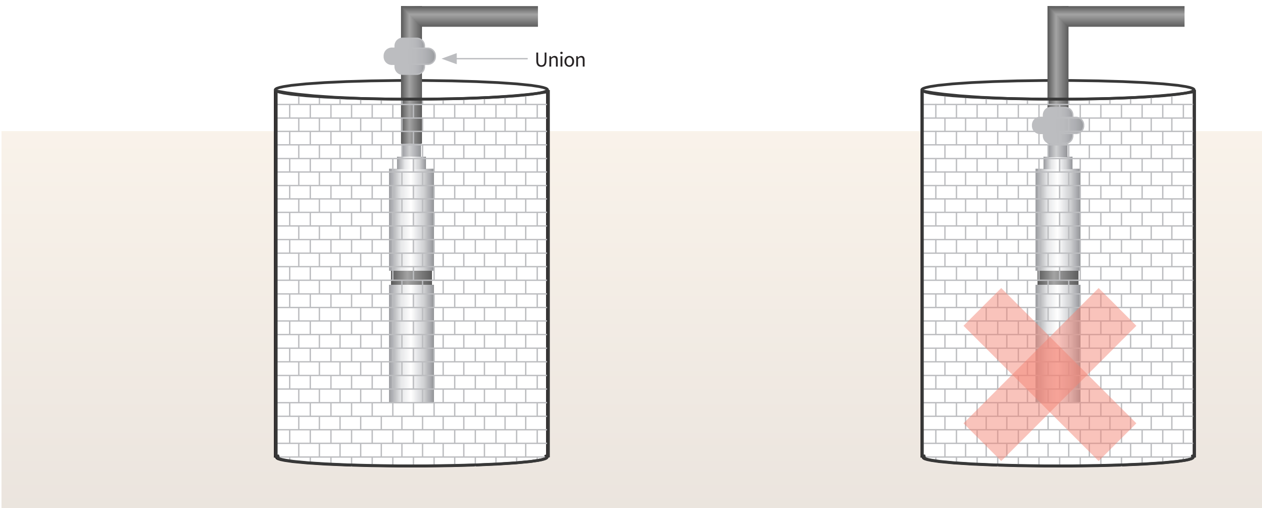
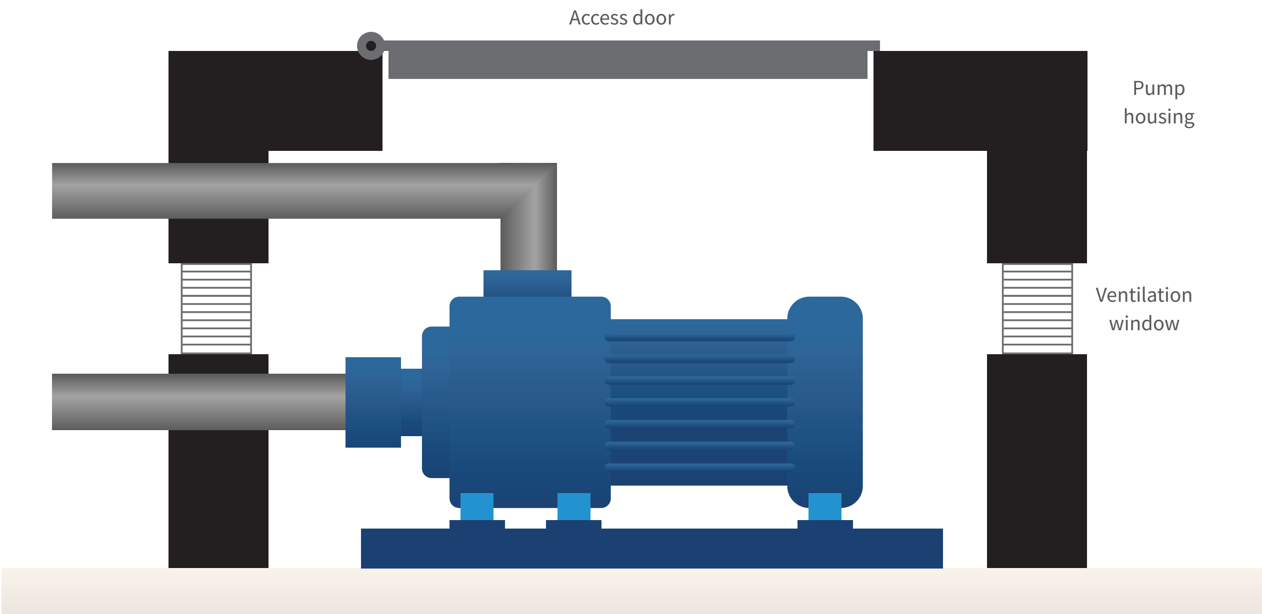


FIGURE 61 SURFACE PUMP HOUSING



FLOAT SWITCH

A float switch is important to protect a pump from a dry run. A dry run can damage pump parts due to overheating and vibration. A float switch is a simple contact switch that acts as an input to the controller and stops the pump from running dry when the water level is low. For submersible pumps, the float switch should be installed above the pump but below the water. For surface pumps, the float switch should be installed below the water level on the suction side. There are two types of float switch connections as described below:

- NO (Normally Open) contact: In this case, two contacts inside the float switch is not connected during normal operation, i.e. when the water level is adequate. It can be visualised as a LOW signal going to the controller which understands it as a normal operation. When the water level decreases, the contacts touch each other and a HIGH signal is generated and the controller stops the pump.
- NC (Normally Closed) contact: In this case, two contacts inside the float switch are connected during normal operation, i.e. when the water level is adequate. It can be visualised as a HIGH signal going to the controller which understands it as a normal operation. When the water level decreases, the contacts separate from each other and the LOW signal sensed by the controller stops the pump.

It is recommended to connect the NC float switch because any damage to the wire will be detected when the signal becomes LOW and the pump stops working. If a NO float switch is used, then any damage to the wire will not be easily detected since the normal signal will always remain LOW.

Always refer to the manufacturer manual for appropriate connection and the setting of the float switch contact in the controller. The float switch cable must be inside a conduit. Float switches run on low voltage and current, so avoid laying float switches alongside power cables since this can induce electrical noise in the float switch cable which increases over long distances. This may cause unintended operation of the float switch or even damage the input terminals of the controller.

The float switch locations for submersible and surface pump systems are shown in the Figure 62.

Controller box

- The controller should be properly housed inside a box to protect it from rain and dirt unless the controller is IP68 rated (see Annex for details of protection ratings).
- All the components, including the wire inside the controller box, must be labelled appropriately.
- For cooling of the electronic components inside the controller box (mainly the controller), proper ventilation and a cooling system are required to dissipate heat so as to prevent overheating of the components (Figure 63).
- All the wires need to have a setting for inlet or outlet from the controller box through appropriately sized cable glands.

FIGURE 62 **FLOAT SWITCH LOCATIONS IN SUBMERSIBLE AND SURFACE PUMP SYSTEMS**

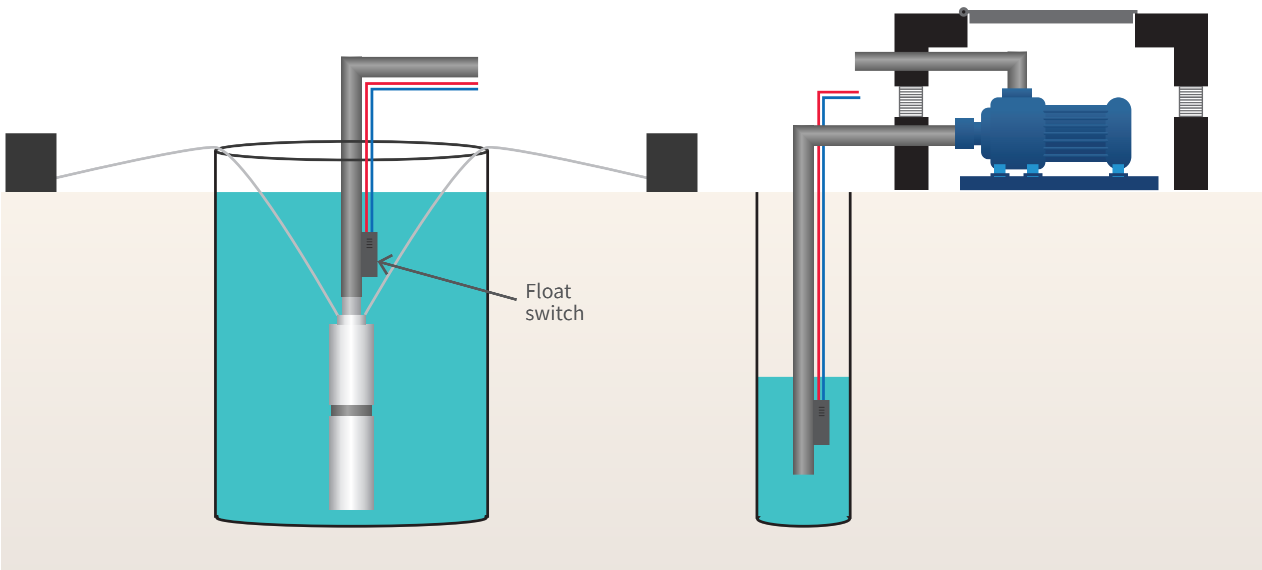
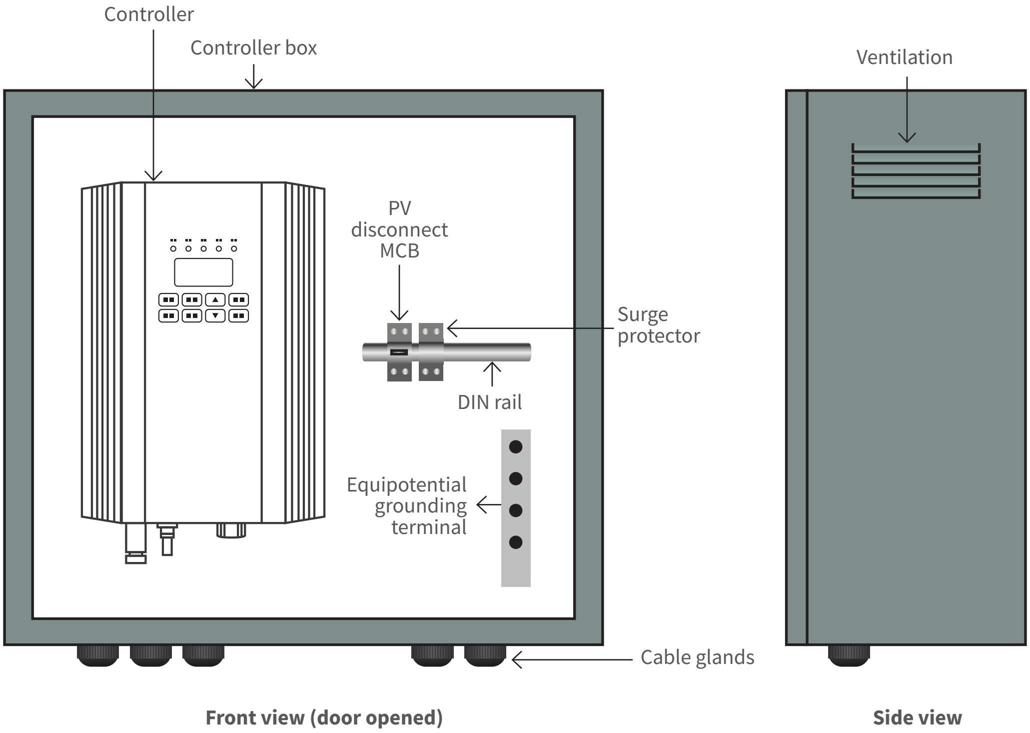


FIGURE 63 CONTROLLER BOX



Pipe layout and access points

- While laying the transmission pipes, access points should be given in intervals so as to aid in operation and maintenance. Access points are small chambers along the pipe path where the pipes are connected, and can be accessed by opening a cover which allows the technician to check the connections and test the water flow at different intervals (see Figure 64).

Let's say an issue arises in the future when the pump is running, but no water output is observed in the storage tank. A possible reason for this could be pipe blockage. To check for this blockage somewhere in the middle of the transmission line, access points are needed where the pipes can be disconnected and checked for water output up to that point. The number of access points depends on the transmission length. Providing too many access points will have cost implications, so the distance between the access points needs to be reasonably identified; this also depends on the terrain. Also note that the pipe fittings used at the access points will introduce additional losses to the system which need to be accounted for during the design stage; they also have to be connected properly to ensure no leakages.

For the example design, the transmission length is 729 m. So, 14 access points at an interval of every 50 m are reasonable.

The same applies to distribution pipes. Not having pipe access points will cause loss of time and money during operation and maintenance.

The pipe burial depth should consider the nature of activity on the land; for example, the movement of vehicles above the pipes and digging activities in farmlands. However, pipes must be buried at least 0.76 m (2.5 feet) below the surface [49]. Inadequate burial depth poses a high risk of damage due to digging activities and the pressure caused by vehicular movement on the surface.

Cables and conduits

- **Cables behind solar panels:** Neatly fasten the cables behind the solar panels using cable ties.
- **Cables inside a controller:** Cables inside the controller should either follow trunking or be properly fastened with cable ties, along with labels, to avoid confusion in wiring for later maintenance.
- **Buried cables:** All exposed cables must have an appropriate conduit and be buried at an appropriate depth (Figure 65).
- **If there is a need for a cable joint,** the cables need to be properly insulated using waterproof tape.

FIGURE 64 PIPE ACCESS POINTS

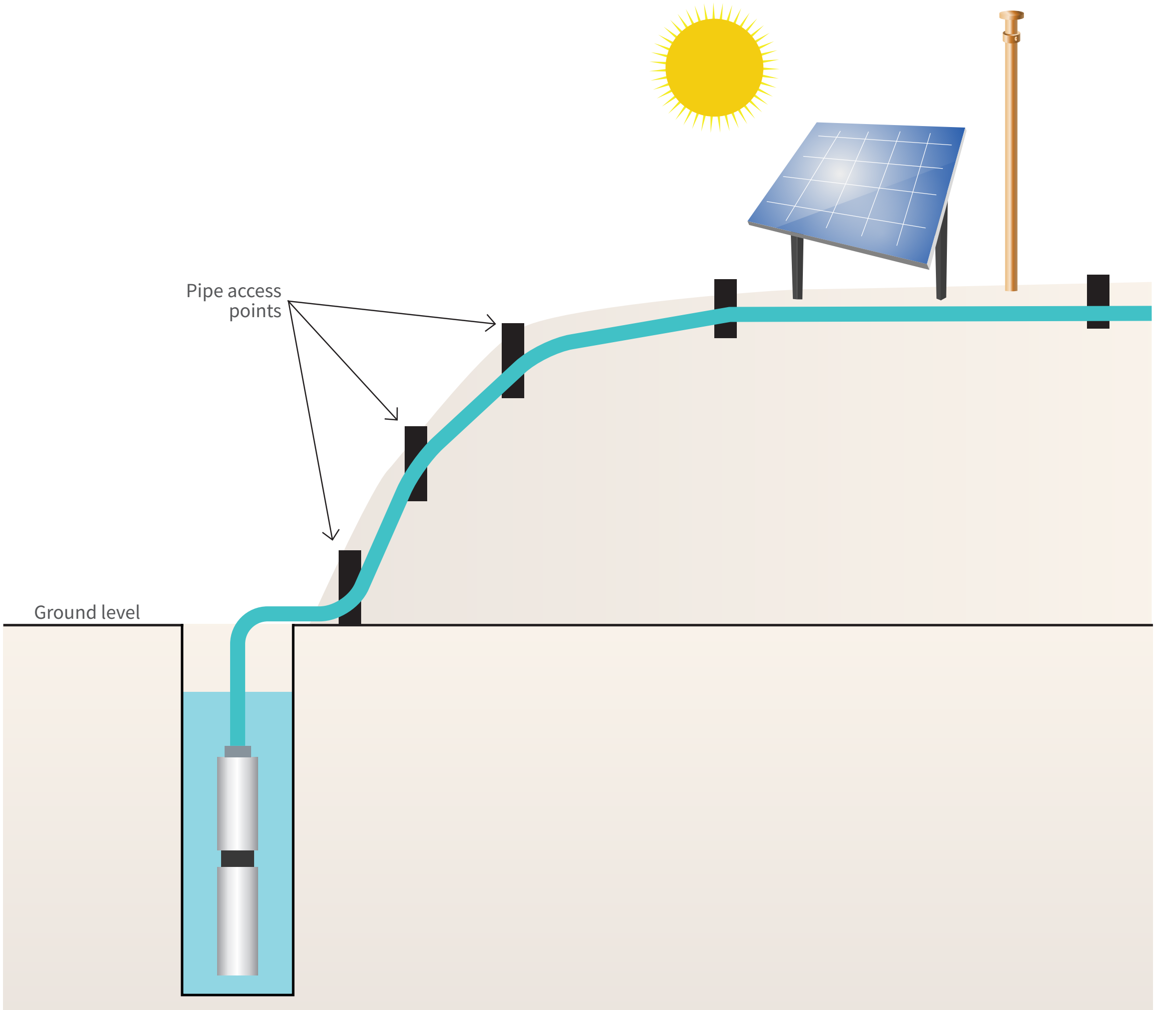
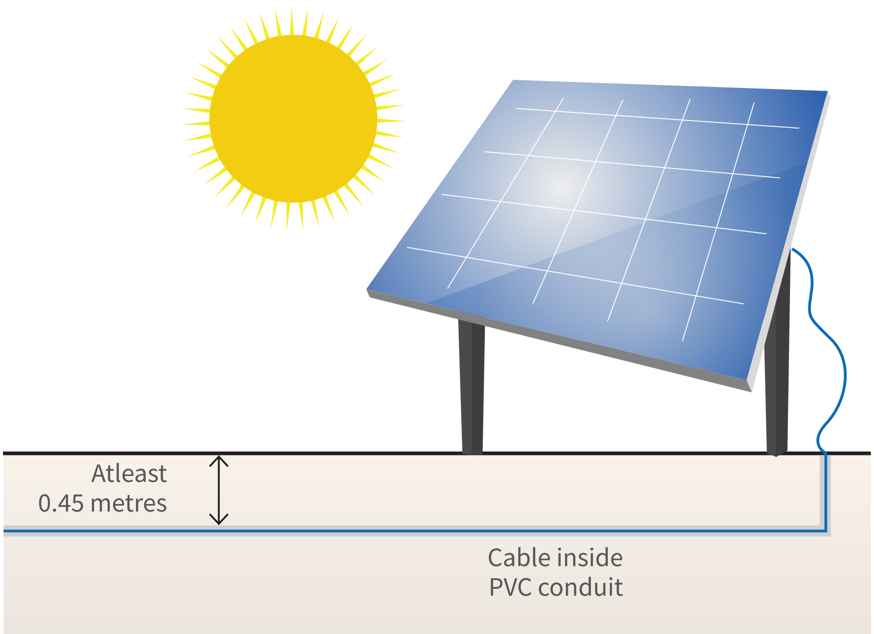


FIGURE 65 PVC CABLE-CONDUIT BURIAL DEPTH



The minimum burial depth of cables, according to California Electrical Code Table 300.5, is:

PVC conduit (non-metallic conduit): 0.45 m [50]

Metallic conduit: 0.15 m [50]

However, a cable in any conduit, including PVC, that is buried at these depths is still in danger of being damaged by the digging carried out by construction equipment.

Tools

Table 18 lists some of the tools that are relevant to SWPS installation.

TABLE 18 GENERAL TOOLS FOR SWPS

SN	Tool	Purpose
1	Compass	To verify the direction of the solar array
2	Inclinometer	To verify the tilt angle of the solar array
3	Mobile apps for sun path	To analyse near shading on the site
4	Handheld pyranometer	To measure real-time irradiance
5	Clamp meter (AC and DC enabled)	To measure voltage and current and to verify continuity checks on the various components of the SWPS
6	Earth tester	To measure the earth resistance of the grounding
7	Waterproof tapes	To secure waterproof connections of electrical cables in water-prone areas.
7	Plumbing tools	General plumbing tools required to complete all plumbing fittings
8	Pliers, spanners, electrical tapes, etc.	General tools required to erect a system

Note: This table is non-exhaustive and other tools may be required based on the selection of system components and site conditions.

J. Monitoring system performance

Remote monitoring systems

Remote monitoring systems are helpful to remotely monitor the operation of the SWPS from anywhere. This is particularly useful for the SWPS in rural environments. For project developers and operators, remote monitoring systems can feed crucial information such as on water output (discharge), input and output power, as well as on other system parameters. In addition, GPS information can help locate multiple SWPS on a map. This information can be useful in the operation and maintenance of the system and can also enable engineers to improvise in future SWPS designs. Remote monitoring systems can also remotely turn on and off the SWPS if required. This is beneficial as a control mechanism for financed projects with monthly or annual payments.

Most solar water pump manufacturers also have remote monitoring hardware for their products. The hardware may require a separate power supply or can be powered by the SWPS itself. The communication medium can be through wireless GPRS, WIFI, or wired communications depending on the type of hardware. Some even have Bluetooth for on-site monitoring. The remote monitoring hardware is connected to the controller and relays information from the controller to the cloud. Then a dedicated web interface or software allows the users to view system information and interact with the SWPS remotely.

There are also third-party remote monitoring systems that are compatible with several manufacturers; however, the communication protocol and data extraction algorithm between the controller and the remote monitoring hardware must be confirmed before purchase. It is advised to consult the third-party manufacturer regarding the compatibility of their product with the specific controller.

Pressure gauge

The pressure generated at the mouth of the pump outlet relates to the actual head of pump delivery.

1 bar = 10.197 m [51]

Installing a pressure gauge at the pump outlet gives the actual vertical head of water delivery which can help engineers confirm the actual installation conditions compared to the designed parameters. This will further help in the evaluation of actual and expected water output.

Pressure gauges are relatively cheap (~USD 5 to 10), so they are recommended for every installation.

Note: The head loss of the pressure gauge must be taken into account during the design stage.

Water flow meter

Water flow meters at the delivery point confirm the actual water output of the system and this is a crucial measurement. There are two methods to measure water flow:

Analogue flow meter: Analogue flow meters can be expensive depending on the pipe size and material (~USD 110 or more).

Water flow monitoring via controller: Water output is related to the operating frequency of the pump. The lower its operating frequency, the lesser the water output. A reasonably accurate estimate (<5%) of water output can be made by remote water-monitoring systems connected to the controller; however, the relation between the pump-operating frequency and the water output should be manually calibrated during installation for a given water-source level. Seasonal changes in the water-source level or changes in the vertical head will affect the accuracy of the water flow measurement. This option can be significantly cheaper than analogue flow meters.

Note: The head loss of the analogue flow meter must be taken into account during the design stage.

K. Best practices

Gravel the panel area

In applications where the land below the solar panels is not used for small vegetation, it is advised to cover the area with gravel to prevent water puddles and unwanted plant growth (Figure 66).

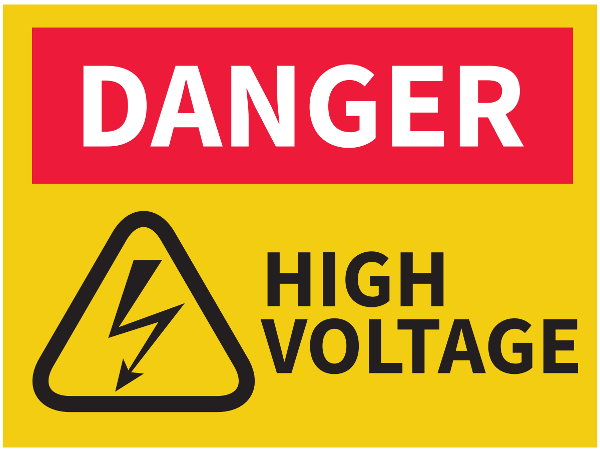
FIGURE 66 GRAVEL IN PANEL AREA

Source: Image obtained from SolarCraft [52]

Danger sign

SWPS are usually installed near a water source, so the cables to the pump may have to run through wet areas. Poorly insulated cables and exposed cables in areas where there is moisture and the possibility of human activity pose a safety risk. Therefore, all cables must be properly insulated and terminated to avoid harm. Additionally, a danger sign must be placed on the system perimeter to warn against high voltage (Figure 67).

FIGURE 67 DANGER NOTICE



L. Basic maintenance tips for users

The non-technical users of SWPS must be aware of the dos and don'ts of the system.

Dos

- **Clean the solar panels:** Use a soft, damp cloth to clean the solar panels at least once a week. If the panels are installed in a dusty environment, clean them more frequently.
- **Keep the controller box dry and clean:** Make sure the insides of the controller box are clean and dry. Since the controller box may be installed in the middle of a field, check for any insect nests that may have developed in hidden corners.
- **Inspect wire breakage:** Visually inspect for any breakage in the wires. If there is any, consult with a qualified technician for repair.

Don'ts

- **Avoid cleaning the panels during daytime:** It is advised to clean the panels in the morning or evening. Cleaning the panels during daytime may result in pump stoppage during cleaning due to shading.
- **Keep the panels shade free:** This is especially applicable to those panels installed in a field; in such instances, over time, bushes or plants may grow around the panels, causing shading. Make sure the area around the panels does not shade the panels at any time of the day.
- **Do not use water to clean any other part of the SWPS except solar panels:** The other components that house electrical systems should not be cleaned with water or wet cloth. Always use a dry cloth to clean these components and when the system is off.
- **Do not connect or disconnect any wires of the system without consulting a qualified technician:** The DC and AC wires in solar water pumping systems carry high voltages that can prove fatal if mishandled. Always contact qualified technicians to repair or dismantle the system.
- **Inspect the water source:** Always inspect the water source for any debris or potential risk to the pump. It is extremely important that the water pumped is clean and the pump is well protected and secure.
- **Inspect the output pipe:** In some irrigation systems spanning over large field areas, it is observed that farmers block the output pipe of the pump after use and forget to unblock it in the next operation only to observe no water output. Do not block the output pipe since this will result in pump overloading during operation, causing it to heat up which decreases its life.
- **Do not pull submersible pumps out of installation without consultation:** Submersible pumps are securely hooked and electric cables are carefully sealed and fastened to them. Pulling the submersible pumps out of installation without consultation with qualified technicians can result in damage to the pumps and the electric cables.

SECTION X

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Appendices

M. Preliminary SWPS electromechanical site survey template

Note to surveyor:

This survey form focuses on the key information required for the electromechanical system design of SWPS.

General information	
Date	
Name of the surveyor	
Organisation	
Name of the client	
Phone/mobile number of the client	
Name of the field contact person	
Phone/mobile number of the field contact person	
Name of the client organisation *(cooperative, company, etc.)*	
Location information	
Full address of project location	
Type of SWPS ownership	☐ Individual ☐ Group
If a group, how many beneficiaries?	
Application of SWPS	☐ Irrigation ❒ Drinking water ☐ Livestock care ☐ Others Others: …………………………….. ……………………………..

Irrigation information – In brief

Size of land to be irrigated	
No. of parcels of the land	
Is the entire land privately owned?	☐ Yes ☐ No Describe road type: …………………………... …………………………..
Type of crops	
Daily water requirement *(if known; otherwise, calculate it by the irrigation requirement)*	
Drinking water information – In brief	
Total number of beneficiaries	
Per capita daily water consumption	
Livestock care – In brief	
Types of livestock	Type 1: ………………………………………….. Type 2: ………………………………………….. Type 3: …………………………………………..
Total number of livestock	Type 1: ………………………………………….. Type 2: ………………………………………….. Type 3: …………………………………………..
Daily water consumption	Type 1: ………………………………………….. Type 2: ………………………………………….. Type 3: …………………………………………..
Water information	
Total water requirement per day for SWPS design *(if known; otherwise, calculate it by secondary means)*	
Type of water source	☐ Borewell ☐ Open well ☐ Canal ☐ River ☐ Pond ☐ Others: ………………………………... ....
GPS location of water source	Latitude: ………………………….. Longitude: …………………………..
If borewell, what is its diameter (in inches)?	
If borewell, what is its current water-level depth (in metres)?	
If borewell, what is its depth (in metres)?	

Describe the quality of water *(clear/murky/sandy, etc.)*	
The existing water-pumping mechanism	
What is currently used to harness water? *(diesel pump/electric pump/hand pump, etc.)*	
If a diesel or an electric pump is used, what is the size of the pump (HP or kW)?	
Solar panel location	
Land-ownership type *(private, public, etc.)*	
Is there unobstructed area for panel installation?	☐ Yes ☐ No
GPS location of solar array	Latitude: …………………………. Longitude: ………………………….
Controller	
Location of controller	☐ Outside (in solar array structure) ☐ Outside (any other location) ☐ Inside (nearby building) ☐ Describe controller location: ………………………………………………………………………………………………
Distance measurements	
Estimated ground distance from controller to solar array (metres)	
Estimated ground distance of transmission pipe from pumping area to the distribution tank (metres)	
Estimated ground distance of distribution pipe from distribution tank to customer location (metres)	
What method was used for the above distance measurement?	☐ Using measuring tape ☐ Via Google Earth (less accurate) ☐ Others: …………………………………………………………………………… ……………………………………………………………………
Grid connection	
Estimated distance of grid availability from the project location (metres)	
Estimated timeline when grid will be available in the project location	
Additional information	
Remarks (any other relevant information)	……………………………………………………………………………………… ……………………………………………………………………………………… ……………………………………………………………………………………… ………………………………………………………………………………………

N. Detailed SWPS electromechanical site survey template

Note to surveyor: This survey form focuses on the key information required for the electromechanical system design of SWPS.

- Please take as many photographs and videos of the project location specific to the sections in the survey below (for example, of solar array location, inverter location, water source, surrounding areas, community, and irrigated land)

General information	
Date	
Name of the surveyor	
Organisation	
Name of the client	
Phone/mobile number of the client	
Name of the field contact person	
Phone/mobile number of the field contact person	
Name of the client organisation *(cooperative, company, etc.)*	
Location information	
Full address of project location	
Is there vehicular access to the solar array location?	☐ Yes ☐ No Describe road type: …………………………………………………………… ……………………………………………………
Is there vehicular access to the water source?	☐ Yes ☐ No Describe road type: …………………………………………………………… ……………………………………………………
Type of SWPS ownership	☐ Individual ☐ Group
If a group, how many beneficiaries?	
Application of SWPS	☐ Irrigation ☐ Drinking water ☐ Livestock care ☐ Others Others: …………………………………………………………………… ……………………………………………………………………………

Irrigation information – In brief

Size of land to be irrigated	
No. of parcels of the land	
Is the entire land privately owned?	☐ Yes ☐ No Describe ownership: …………………………………………………… ……………………………………………………
Type of crops	
No. of cultivation seasons	
What is the cash crop?	
No. of months of water requirement per annum	
Daily water requirement *(if known; otherwise, calculate it by the irrigation requirement)*	
Drinking water information – In brief	
Total number of beneficiaries	
Per capita daily water consumption	

Livestock care – In brief

Types of livestock	Type 1: …………………………………… Type 2: …………………………………… Type 3: ……………………………………
Total number of livestock	Type 1: …………………………………… Type 2: …………………………………… Type 3: ……………………………………
Daily water consumption	Type 1: …………………………………… Type 2: …………………………………… Type 3: ……………………………………

Water information

Total water requirement per day for SWPS design *(if known; otherwise, calculate it by secondary means)*	
Type of water source	☐ Borewell ☐ Open well ☐ Canal ☐ River ☐ Pond ☐ Others: …………………………………………………… ……………………………………………………
GPS location of water source	Latitude: …………………………… Longitude: ……………………………
If borewell, what is its diameter (in inches)?	

If borewell, what is its current water-level depth (in metres)?	
If borewell, what is its depth (metres)?	
Describe the quality of water *(clear/murky/sandy, etc.)*	
If borewell or open well, determine the recharge rate	Cross-section of well: ……………..m^2

Reading	Time	Water depth from datum (m)
1		
2		
3		
4		

Recharge rate: ……………..

If river or canal, determine the recharge rate *(various methods such as the salt dilution method can be used)*	Method of measurement: ……………..……………. Recharge rate: ………...…..
The existing water-pumping mechanism	
What is currently used to harness water? *(diesel pump/electric pump/hand pump, etc.)*	
If a diesel or electric pump is used, what is the size of the pump (HP or kW)?	
What is the usage duration (in hours) of the pump per day?	
How many days per week is the pump used?	
What is the cost (per litre) of diesel in the location?	
Solar panel location	
Land-ownership type *(private, public, etc.)*	
Is the owner concerned willing to allocate the land for solar array installation?	☐ Yes ☐ No Any concerns? ………………………….. …………………………..
GPS location of solar array	Latitude: ………………………. Longitude: ……………………….
Area available for panel installation (sq. m)	
Topography type	☐ Flat ☐ Slope ☐ Uneven
If the land is sloped, what is the direction and degree of the slope?	The direction of slope: …...............................….. Slope degrees: ……..
Are there any nearby obstacles that may cause shading in the panels? Describe. *(trees, buildings, electric poles, etc.)*	

Sketch the panel location

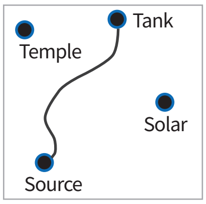
▲
South

Controller	
Location of controller	☐ Outside (in solar array structure) ☐ Outside (any other location) ☐ Inside (nearby building) ☐ Describe controller location: ………………………………..…………
Distance measurements	
Ground distance from the controller to the solar array (metres)	
Ground distance of the transmission pipe from the pumping area to the distribution tank (metres)	
Ground distance of the distribution pipe from the distribution tank to customer location (metres)	
GPS location of distribution tank output	Latitude: …………………………. Longitude: ………………………….
GPS location of distribution pipe output	Latitude: …………………………. Longitude: ………………………….
What method was used for the above distance measurement?	☐ Using measuring tape ☐ Via Google Earth (less accurate) ☐ Others: ……………………………... ……………………...…………………………..

Sketch the water-transmission path line from the water source to the distribution tank. Mark the water source, distribution tank, solar array location, and any other landmarks.

South

For example



Sketch the water-distribution path line from the distribution tank to the irrigation land. Mark the distribution tank, solar array location, and any other landmarks.

South

Grid connection

Estimated distance of grid availability from the project location (metres)	
Estimated timeline when grid will be available in the project location	

Additional information

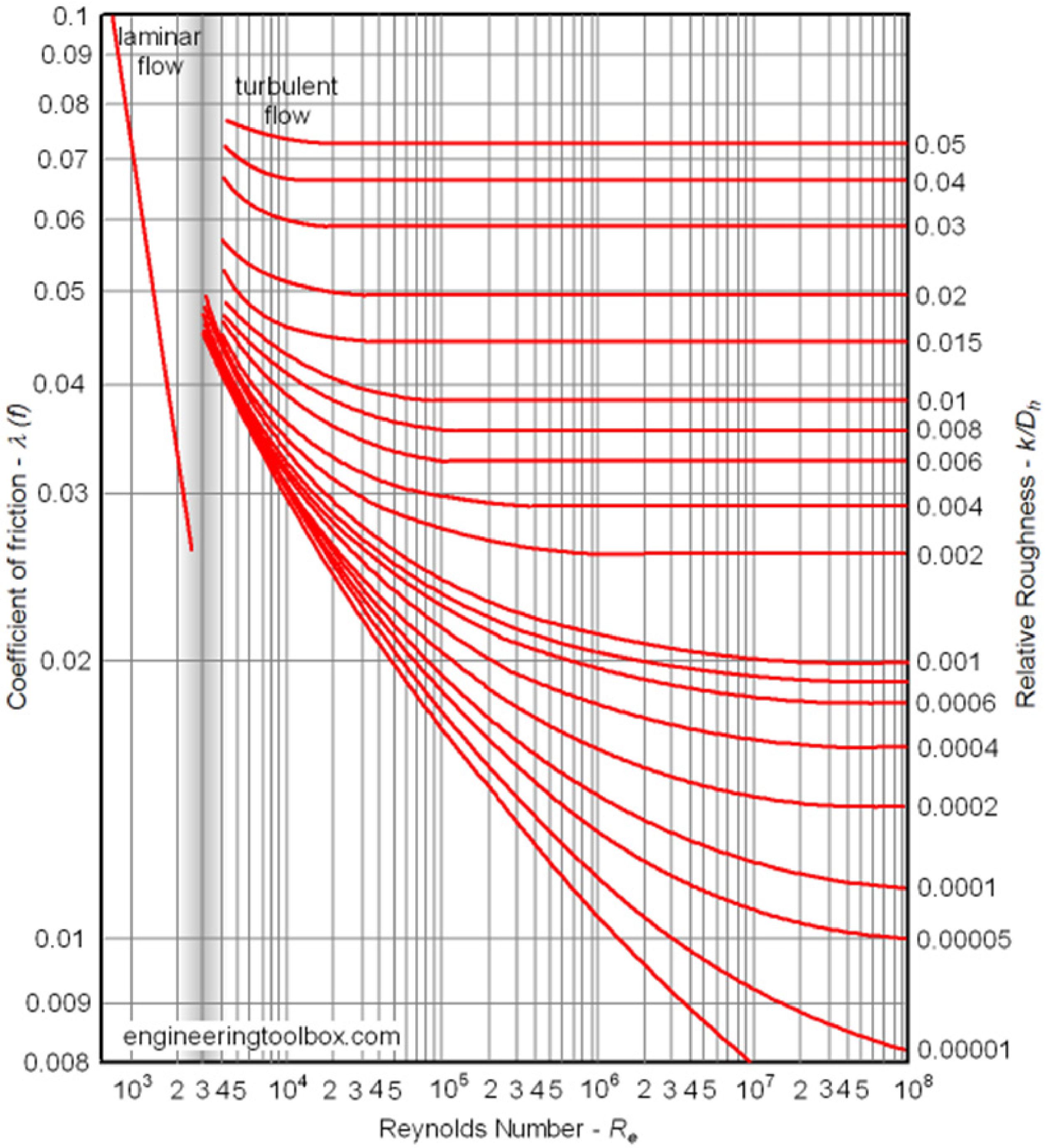
Remarks (any other relevant information)	

Supporting documents required: Land permit for solar array erection

O. Moody diagram

For reference, a Moody diagram is given below [72].

FIGURE 68 **MOODY DIAGRAM**



P. Minor loss coefficients

TABLE 19 **MINOR LOSS COEFFICIENTS [53]**

Type of Component or Fitting	Minor Loss Coefficient
Tee, Flanged, Dividing Line Flow	0.2
Tee, Threaded, Dividing Line Flow	0.9
Tee, Flanged, Dividing Branched Flow	1.0
Tee, Threaded, Dividing Branch Flow	2.0
Union, Threaded	0.08
Elbow, Flanged Regular 90°	0.3
Elbow, Threaded Regular 90°	1.5
Elbow, Threaded Regular 45°	0.4
Elbow, Flanged Long Radius 90°	0.2
Elbow, Threaded Long Radius 90°	0.7
Elbow, Flanged Long Radius 45°	0.2
Return Bend, Flanged 180°	0.2
Return Bend, Threaded 180°	1.5
Globe Valve, Fully Open	10
Angle Valve, Fully Open	2
Gate Valve, Fully Open	0.15
Gate Valve, ¼ Closed	0.26
Gate Valve, ½ Closed	2.1
Gate Valve, ¾ Closed	17
Swing Check Valve, Forward Flow	2
Ball Valve, Fully Open	0.05
Ball Valve, ⅓ Closed	5.5
Ball Valve, ⅔ Closed	200
Diaphragm Valve, Open	2.3
Diaphragm Valve, Half Open	4.3
Diaphragm Valve, ¼ Open	21
Water Meter	7

Q. Ingress protection rating table

Ingress protection (IP) rating has two digits.

The first number signifies protection against solid substances, while the second number stands for protection against liquid materials. The following tables show what each of the digits mean:

TABLE 20 **IP RATING, FIRST DIGIT [54]**

Level	Object size protected against	Effective against
0	Not protected	No protection against contact and ingress of objects
1	>50 mm	Any large surface of the body, such as the back of the hand, but no protection against deliberate contact with a body part
2	>12.5 mm	Fingers or similar objects
3	>2.5 mm	Tools, thick wires, etc.
4	>1 mm	Most wires, screws, etc.
5	Dust protected	Ingress of dust is not entirely prevented, but it must not enter in sufficient quantity to interfere with the satisfactory operation of the equipment; complete protection against contact
6	Dust tight	No ingress of dust; complete protection against contact

TABLE 21 **IP RATING, SECOND DIGIT [54]**

Level	Object size protected against	Effective against
0	Not protected	–
1	Dripping water	Dripping water (vertically falling drops) shall have no harmful effect
2	Dripping water when tilted up to 15°	Vertically dripping water shall have no harmful effect when the enclosure is tilted at an angle of up to 15° from its normal position
3	Spraying water	Water falling as a spray at any angle of up to 60° from the vertical shall have no harmful effect
4	Splashing water	Water splashing against the enclosure from any direction shall have no harmful effect
5	Water jets	Water projected by a nozzle (6.3 mm) against the enclosure from any direction shall have no harmful effect
6	Powerful water jets	Water projected in powerful jets (12.5-mm nozzle) against the enclosure from any direction shall have no harmful effect
7	Immersion up to 1 m	Ingress of water in harmful quantity shall not be possible when the enclosure is immersed in water under the defined conditions of pressure and time (up to 1 m of submersion)
8	Immersion beyond 1 m	The equipment is suitable for continuous immersion in water under conditions which shall be specified by the manufacturer. Normally, this will mean that the equipment is hermetically sealed. However, with certain types of equipment, it can mean that water can enter but only in such a manner that it produces no harmful effect.

R. Cable ampacity and size conversion

The following table is based on UL486E of the National Electrical Code, ANSI/NFPA 70-1999. The table describes the assigned maximum ampere rating versus the wire size for copper and aluminium conductors. The values are for not more than three conductors in a raceway or a cable.

TABLE 22 COPPER AND ALUMINIUM CABLE AMPACITY

AWG or kcmil	mm²	Ampacity [A] (Copper at 75°C)	Ampacity [A] (Aluminium at 75°C)
30	0.05	0.5	-
28	0.1	0.8	-
26	0.1	1	-
24	0.2	2	-
22	0.3	3	-
23	0.5	5.0	-
20			
18	0.8	7.0	-
16	1.3	10.0	-
14	2.1	15	-
12	3	20	15
10	5.3	30.0	25.0
8	8.4	50.0	40.0
6	13.3	65.0	50.0
4	21d	89.0	65.0
3	26.6	100.0	75.0
2	33.6	115.0	90.0
1	42.4	130	100
1/0	53.5	150.0	120.0
2/0	67.4	175.0	135.0
3/0	85.0	200.0	155.0
4/0	107.0	230.0	180.0
250	127.0	2959.0	205.0
300	152.0	285.0	230.0
390	177.0	310.0	250.0
400	203.0	335.0	270.0
500	253.0	380.0	310.0
600	304.0	420.0	340.0
700	300.0	460.0	375.0
750	380	475	3895
800	405.0	490.0	395.0
900	456.0	520.0	425.0
1000	507.0	545.0	445.0
1250	633.0	590.0	485.0
1500	760.0	625.0	520.0
1750	887.0	650.0	545.0
2000	1010.0	665.0	560.0

The following table shows the equivalent AWG size of some standard mm^2 cables based on IEC 998-1.

TABLE 23 **CONVERSION TABLE OF STANDARD CABLE SIZES [55]**

mm^2	AWG
0.5	20
0.75	18
1	17
1.5	16
2.5	14
4	12
6	10
10	8
16	6
25	4
35	2

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