INTERNATIONAL SOLAR ALLIANCE

Solar Water Pumping System

Contents

Abbreviations

A.C.	Alternating Current
AWG	American Gauge Wire
BLDC	Brush-Less Direct Current Motor
BOQ	Bill of Quantities
CAPEX	Capital Expenditure
CO_2	Carbon Dioxide
D.C.	Direct Current
DG	Diesel Generator
g	Acceleration Due to Gravity, in m/s^2
GHG	Green House Gas
HP	Horsepower
kg	Kilogram
km/hr	Kilometer Per Hour
kW	Kilowatt
$kWh/m^2/day$	Kilo-watt Hour Per Square Meter Per Day
LCC	Life Cycle Cost
m	Meter
m^3/day	Cubic Meter Per Day
m^3/hr	Cubic Meter Per Hour
mm	Millimeter
mm^2	Square Millimeter
MMS	Module Mounting Structure
MPPT	Maximum Power Point Tracker
P_h	Pump Hydraulic Power, in kW
P_m	Electric power required for pump or pump capacity
PPE	Personal Protective Equipment
PV	Photovoltaic
PVC	Polyvinyl Chloride
Q	Flow Rate, m^3/hr
RMS	Remote Monitoring System
SWPS	Solar Water Pumping System
TDH	Total Dynamic Head
US	United States
UV	Ultraviolet
VFD	Variable Frequency Drive
V_{mp}	Voltage at Max Power
η_m	Motor Efficiency in Percentage
ρ	Density of Water, in kg/m3

Introduction of Solar Water Pumping Systems (SWPS)

1. Introduction of Solar Water Pumping Systems (SWPS)

Pumping water is a universal need around the world and the use of photovoltaic power is increasing for this application. A solar powered pump is a pump running on the power of the sun. A solar powered pump can be very environmentally friendly and economical in its operation. The system operates on power generated using solar photovoltaic (PV) system. The photovoltaic array converts the solar energy into electricity, which is used for running the motor pump set.

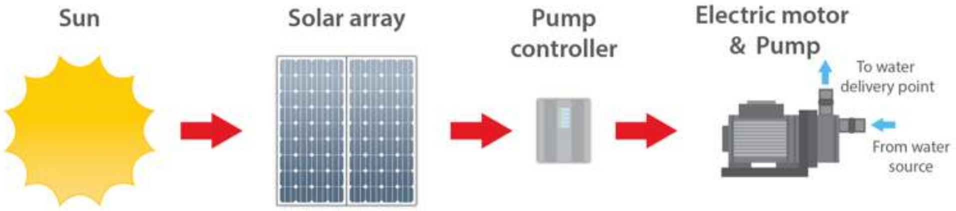


Figure 1: Typical Solar Water Pumping Systems

Picture Source: https://watermission.org/wp-content/uploads/2019/10/System-Design-Selection-and-Installation-Guidelines.pdf

1.1 Basic Function of a Water Pump

A pump is a device that uses external potential or kinetic energy to displace a fluid (typically a liquid) under suction or discharge pressure. The very basic function of a water pump is to transfer water from one location to another. Depending upon the source of water and applications the water pumping systems can be classified into various categories.

1.2 Types of Water Pumps

Based on the water pump source of power, the different type of water pumps that are predominantly used in the agriculture sector are diesel pumps, Electrical pumps and Solar pumps. They are chosen based on the budget, land size, water source, available power sources.

1.2.1 Diesel Pumps

Diesel powered water pumps are one of the most commonly used water pumping systems, especially, in rural regions with no grid supply. Basically a 4-stroke diesel engine is coupled with water pump to operate.

1.2.2 Electrical Pumps

An electric motor (A.C.) is coupled with the water pump in this type of pumping system. Such type of water pumps are generally preferred in the area facilitated with the access to the grid power.

1.2.3 Solar Pumps

A solar-powered water pumping system is like any other pumping system, except its power source is solar energy. Solar pumping technology covers the entire energy conversion process, from sunlight, to electrical energy, to mechanical energy, to stored energy. A typical solar water pumping system contains: a solar array, which converts sunlight into electricity, system controller, which controls the array and the pump; an electric motor (can be either A.C. or D.C), which drives the pump, which moves the water as per it's application.

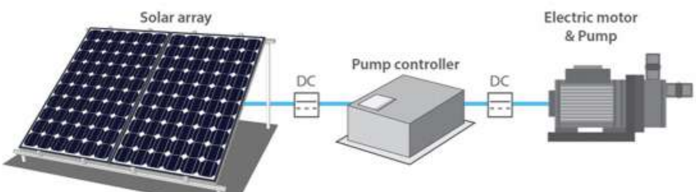


Figure 2: DC powered pump

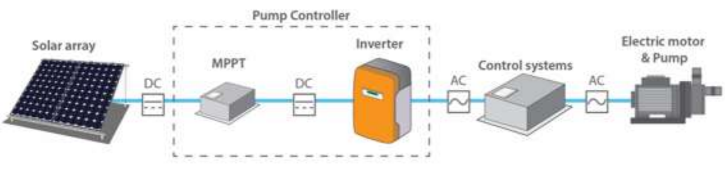


Figure 3: AC powered pump

Picture Source: https://watermission.org/wp-content/uploads/2019/10/System-Design-Selection-and-Installation-Guidelines.pdf

1.3 Application of SWPS

Due to the decentralized nature Solar water pumps are able to operate in a lot of different areas particularly in sunny areas and can provide water for various applications. Some of the key applications of the solar water pumping systems are:

1.3.1 Facilitate Irrigation Scheme

Solar water pumping systems constitute a cost-effective alternative to irrigation pump sets that run on grid electricity or diesel. The irrigation water requirements vary drastically depending on the crop. These irrigation systems may naturally suit to solar pumping, especially if more water is required during the summer season. Solar Photovoltaic (SPV) sets constitute an environment-friendly and low-maintenance possibility for pumping irrigation water.

1.3.2 Facilitate Drinking/Portable Water Supply Scheme

The drinking/portable water supply are generally consistent throughout the year, making this application suited to the solar water pumping. Water can be pumped during the daytime and get stored in the overhead tank to meet the daily needs as and when required.

1.3.3 Facilitate Domestic Water Supply

Domestic and cleaning water requirements are generally consistent throughout the year. Depending on the volume of water required, solar PV can be used in these applications together with some form of storage, such as batteries. The storage is usually required to provide power to pump the water on demand.

1.4 Categories of SWPS

1.4.1 For Borewells/Wells

Boreholes and wells are the technology measures for providing water supply during times of water shortages and drought. They are used to extract freshwater from subsurface or deeper groundwater aquifers with the help of submersible pumps

Submersible Pumps: Submersible solar pumps are typically used in areas where water is available at a greater depth and where open wells are not available. The hermitically sealed motor-pump assembly is completely immersed into the water. Solar submersible pumping system operates directly off the solar panels as power source. Submersible pumps are further classed as DC/AC depending on the type of motor.

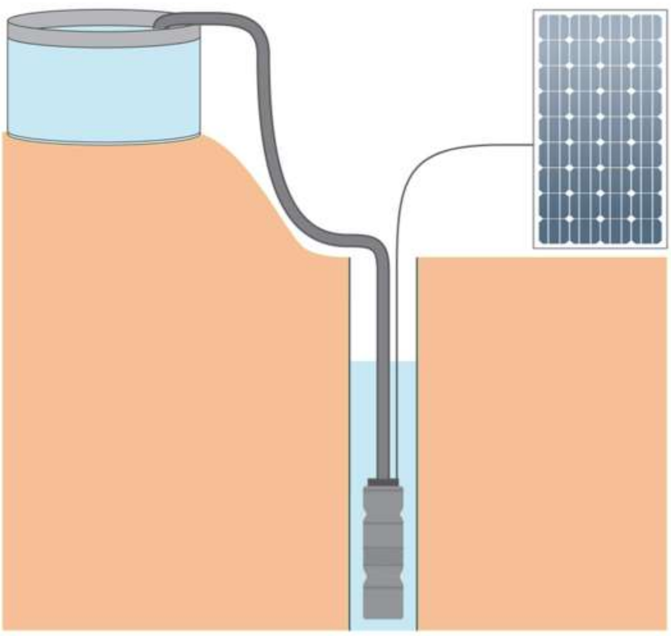


Figure 4: Borehole pump system

Picture Source: https://watermission.org/wp-content/uploads/2019/10/System-Design-Selection-and-Installation-Guidelines.pdf

1.4.2 For Open Source/Flowing Water

For open source/flowing water surface solar water pumps are installed at ground level to lift water from shallow water sources such as shallow wells, ponds, streams, storage tanks. Surface water pumps can also be used to provide pressurized water for irrigation or home water systems. These pumps are suitable for lifting and pumping water from a maximum depth of 20 meters. Submersible pumps are further classed as DC/AC depending on the type of motor.

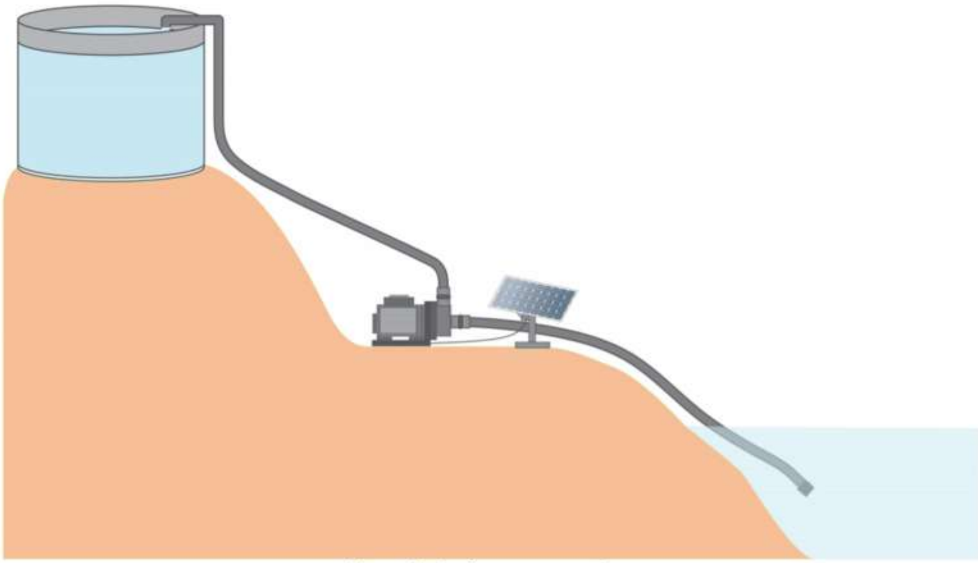


Figure 5: Surface pump system

Picture Source: https://watermission.org/wp-content/uploads/2019/10/System-Design-Selection-and-Installation-Guidelines.pdf

Features	DC Solar Pump	AC Solar Pump
Standard Capacity	1 to 5 HP	2 – 15 HP
Efficiency	It is more efficient than the AC Pump and requires less panels than the AC Motor Pump	AC Pumps are relatively less efficient for up to 5 HP and is comparable for motors of 5 HP and above
Service Life	DC pumps have longer life, but are difficult to maintain in remote areas as it requires specialized technicians	Relatively have less service life, but are easy to maintain
Price	DC Pumps are comparatively costlier	Cost of AC Pumps is low in comparison to the same capacity of DC pumps
System Configuration	The DC solar pumping system consists of solar panels, controller and the DC pump. No inverter is required, can be directly coupled with the solar panels (generating DC power)	The AC solar pumping system consists of solar panels, controller, invertor and the AC pump. Inverter is required to convert the DC supply of Solar PV panels to AC to run the AC Motor

Table 1: Comparison between DC and AC solar pump

TECHNOLOGY

2. Technology

Solar water pumps working principal is like to any other water pumping system, a power source provides the electric energy to operate the motor pump which in turn pumps water from one location to another. In case of solar water pumping system, sun is the source of electricity through solar photovoltaic panels that convert's solar radiations into electrical energy. The whole solar water pumping system includes the solar panels, support structure, cables, pipe, pump and electronics based on the system configuration and application of the solar water pump, etc.

2.1 System Configurations

The SWPS can be of various configurations based on the type of pump (AC/DC motor), and it's mode of operation. The SWPS can be broadly configured as:

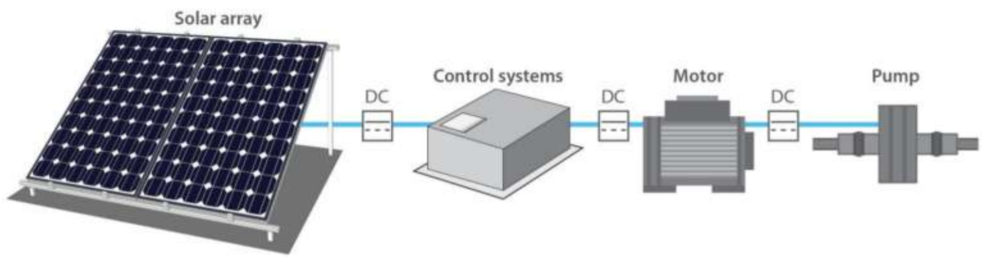
System configuration based on pump type

DC Solar Pumps: In DC solar pump configuration the direct current generated by the solar array is fed into the pump through pump controller. The pump controller consists of the Maximum Power Point Tracker (MPPT) and other system electronics to control the output of the solar array and required input to the DC pump.

AC Solar Pumps: In AC pump configuration the DC supply from the solar array is converted into AC via invertor to fed into the pump motor. Under this configuration the pump controller consists of a MPPT for solar array, inverter to convert DC to AC, variable frequency drive (VFD) to control the AC input to the pump motor and other system electronics to control the operation of the SWPS. The VFD in controller eliminates the high starting current of the induction motor and controls the frequency and voltage of the AC input to the pump motor, therefore resulting in efficient and smooth operation of the pump.

2.1.1 Standalone solar pumps

Standalone solar pumps are basically Off-grid solar pumps. The system can be configured as AC or DC solar pump as per the availability of the system components. For standalone SWPS the pumps are powered by solar energy, only, and therefore the pump can operate for a limited time period in a day. The standalone solar pumps are mostly used for agricultural purposes. Generally, DC pumps are considered for this type of configuration.

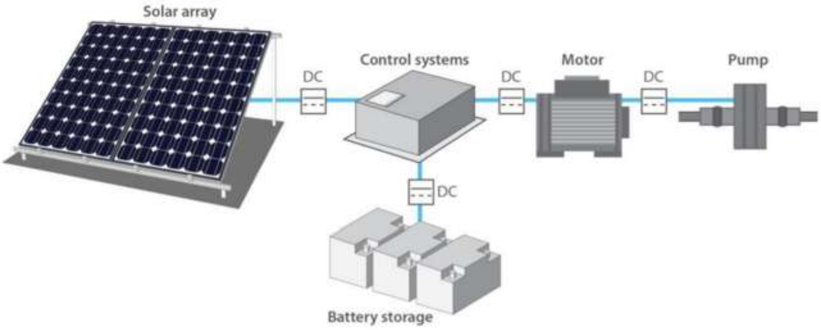


Solar pumping configuration, using just solar as the energy source

Picture Source: https://www.aginnovators.org.au/sites/default/files/Solar%20-powered%20pumping%20in%20agriculture.pdf

2.1.2 Solar pumps combined with batteries

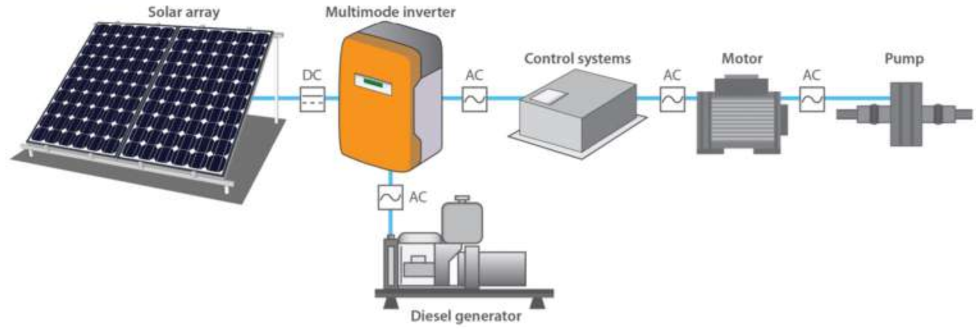
Since the solar array can generate electricity during the sun hours; therefore, backup is needed during the rainy season and during nighttime. Solar pumps with battery storage provide certain autonomy and reduces the intermittency of the SWPS. A battery bank is provided as backup source of power and the pump controller can be configured to either charge the battery bank first then supply power to the pump or charge the battery with if excess DC supply is available. The pump controller in this case is also provided with a charge controller to avoid over charging and over discharging of the battery bank.



A solar pumping configuration that uses a combination of solar and batteries as the energy source

2.1.3 Solar pumps combined with diesel generator

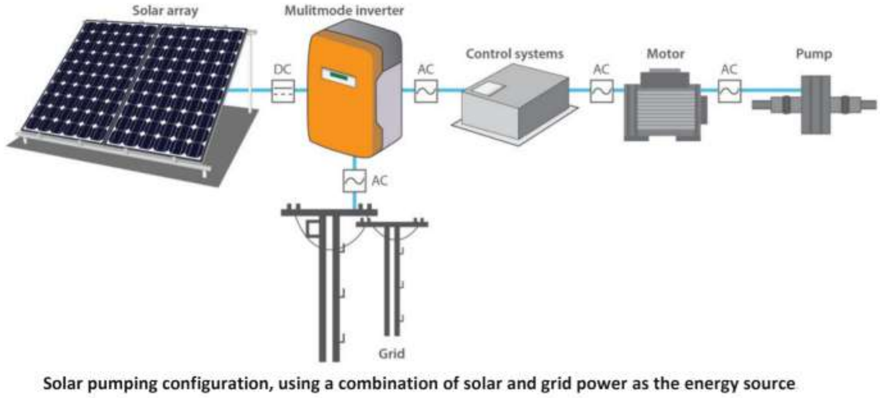
In this configuration, a diesel generator is provided as backup to operate the pump. The diesel generator is connected into the SWPS via a circuit breaker. In the absence of the sunlight the circuit is closed, and power is supplied to the pump through diesel generator. Generally, AC SWPS is used in this configuration, in case of DC SWPS the AC supply is first converted into DC via a converter provided in the pump controller.



Solar pumping configuration that uses a combination of solar and diesel as the energy source

2.1.4 Solar pumps combined with the electricity grid

The solar pumps are interacted with the electricity grid in this type of configuration with grid electricity used as backup in the absence of the sunlight. The SWPS can also be configured to supply the excess solar supply to the grid through the grid and may result in additional revenue to the user. Generally, AC SWPS are preferred in this type of configuration.



Solar pumping configuration, using a combination of solar and grid power as the energy source

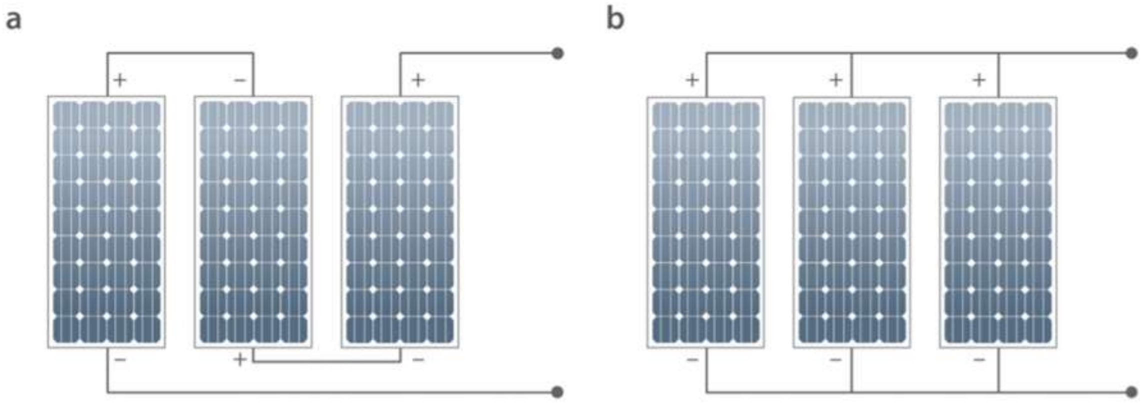
Picture Source: https://www.aginnovators.org.au/sites/default/files/Solar%20-powered%20pumping%20in%20agriculture.pdf

2.2 System components

The key components of the solar water pumping system include the solar panels, module mounting structure, system controller, electric motor, system wiring, associated piping and other backup generation sources and battery storage.

2.2.1 Solar photovoltaic modules

Solar panels are the main components used for driving the solar pump. Several solar panels connected in arrays produce DC electricity. Interconnections are made using series or parallel combinations to achieve desired voltage and power for the pump. The number of modules in series generates the required voltage suitable to supply power to the controller and the number of modules in parallel generates the required current.



a) modules connected in series; b) modules connected in parallel

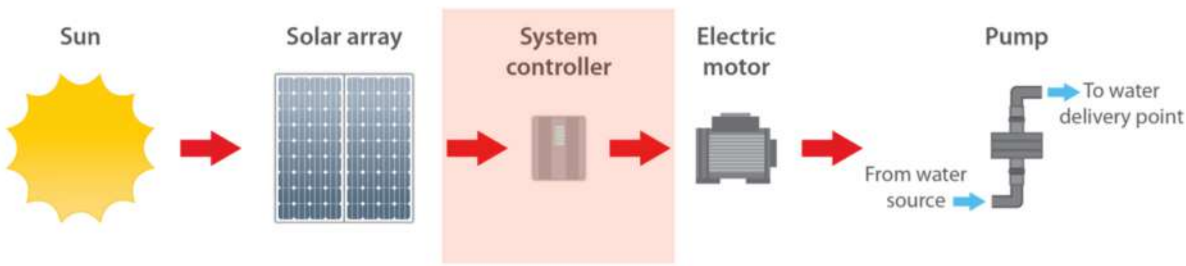
Picture Source: https://www.aginnovators.org.au/sites/default/files/Solar%20-powered%20pumping%20in%20agriculture.pdf

2.2.2 Module mounting structure

Support structure provides stability to the mounted solar panels and protects them from theft or natural calamities. To obtain maximum output of water, a manual tracking device is fixed to the support structure.

2.2.3 System controllers

The system controller is a buffer device between the pump and the solar array. The controller takes DC input from solar PV array and supply the required DC or AC power to the pump motor. The pump controller consists of a MPPT, which maximizes the Solar array DV output, in case of AC SWPS the system controller also consists VFD to operate the AC motor optimally. Further, the pump controller protects the pump from high voltage/ under voltage conditions. The controller also contains electronic monitoring system to remotely monitor, operate and record the pump performance.



The system controller as part of a solar pumping system

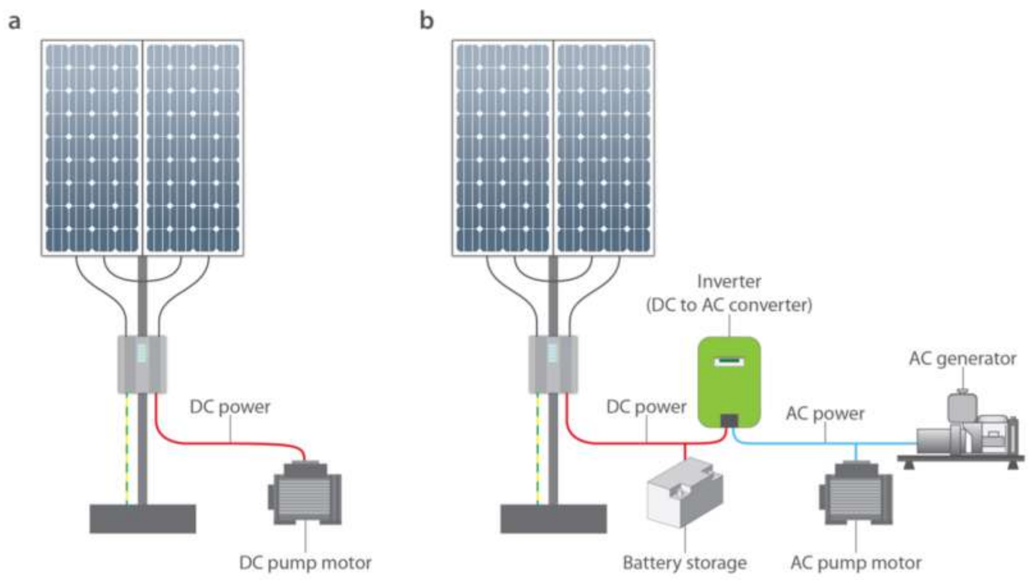
Picture Source: https://www.aginnovators.org.au/sites/default/files/Solar%20-powered%20pumping%20in%20agriculture.pdf

2.2.4 Electric motor

There are mainly two type of motors used for water pumping applications:

i. DC Motor: A Brush-Less DC (BLDC) motors are used in the water pumping applications and a DC motor-based pumping is more efficient compared to an AC motor. A pump with DC motor is more efficient and starts its operations even in the early hours of the day and operates till late evening.

ii. AC Motor: As the solar array supplies DC power, AC motors require an inverter to convert DC supply into AC. The system controller of the SWPS also requires VFD to control motor operation as per the available solar DC supply and the load on pump. Thus, increasing and optimizing the water output concurrently based on the input radiation level.



a) In this configuration, the array powers the DC pump motor via a solar controller; b) in this configuration, the array produces DC power, which is stored in batteries. The battery power is converted into AC electricity by the inverter so that the pump motor can be powered by both the array and an AC generator. In this configuration, the pump motor is an AC motor. Other configurations may make use of a grid connection to supply part of the required power.

Picture Source: https://www.aginnovators.org.au/sites/default/files/Solar%20-powered%20pumping%20in%20agriculture.pdf

2.2.5 System wiring

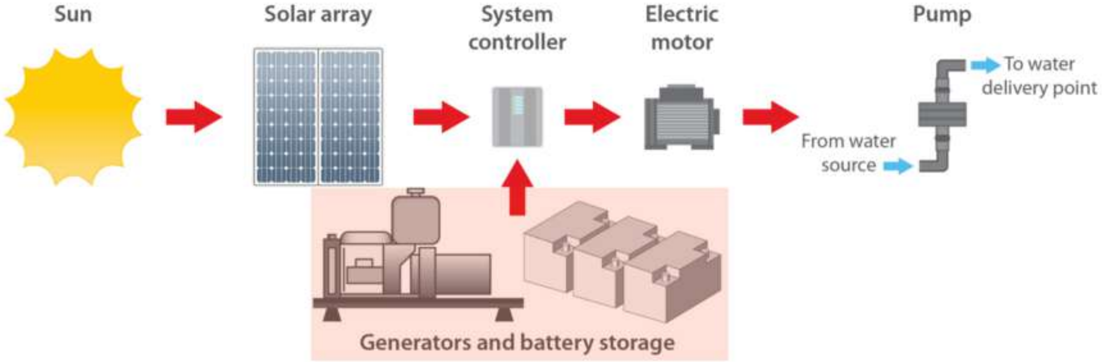
SWPS are typically provided with all wiring appropriate to the DC and AC power supply for the installation. Thus, it is very important to determine the distance between the solar array, system controller and the pump. The solar water pump manufacturer should specify the cable size in cross sectional area (mm2 for metric cables and AWG for US cables) for the needed length of wire. Under maximum load conditions, the voltage drop from the most remote module in the array to the pump controller's input shall not exceed 3% of the array's maximum power point voltage (Vmp under Standard Test Conditions). The wiring for the grounding and lighting protection must also be considered in accordance with the climatic condition.

2.2.6 Associated piping

Water pipe can be supplied as metal pipes, PVC pipes or polyethylene pipes. Because of its flexibility polyethylene pipe is often used with solar water pumping systems as the suction pipe for a surface pump and for the pipe within a borehole for the borehole pump. For the discharge pipe, based on the application, distance to be covered, PVC or metallic pipes can be selected.

2.2.7 Other generation and energy storage

Since sun is an intermittent source of electricity, the SWPS would be operational for a certain period of time in a day and may not be able to operate at all during the weather overcast conditions, thus depending upon the applicability the SWPS is provided with other sources of electricity generation (such as grid electricity, diesel generator, and windmill, etc.) as well as battery storage to operate the SWPS in the absence of sunlight.



Battery storage and generators as part of a solar pumping system

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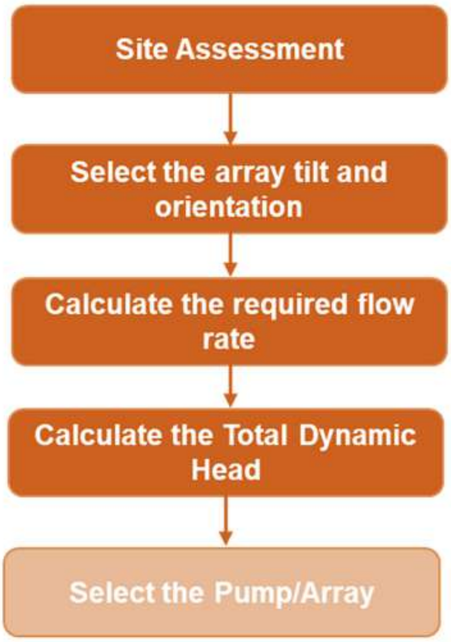
Selection of suitable SWPS

3. Selection of Suitable SWPS

There are various parameters that are required to be considered while selecting a suitable SWPS including site assessment where the pump is to be installed, solar array tilt and orientation, flow rate of water and the total dynamic head (TDH).



Steps for selecting suitable SWPS

3.1 Site Assessment

Site assessment is the first step for selecting a suitable SWPS. The key assessments that are to be considered during the site visit are to assess the daily water requirement, availability of solar energy, water resource, water delivery point and developing a system layout.

3.1.1 Daily water requirements

First, it is required to assess the need of water whether it is required for household, irrigation or cattle feeding purposes. Based on the need the daily need of water is to be determined. Generally, the daily water requirements are measured in terms of cubic meters of water per day (m3/day) or liters per hour.

3.1.2 Solar resource

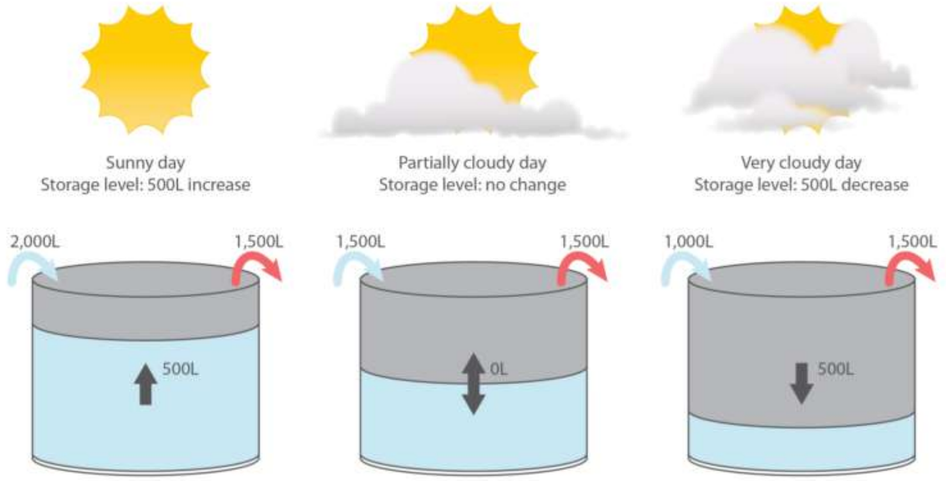
Site specific solar resource assessment is necessary to estimate the number hours that would be available to operate the SWPS. Various at site factors such as dust, temperature and shadow, etc. are also needed to be incorporated while estimating the availability of the solar resource.

3.1.3 Water resource

After determining the daily water requirement an appropriate source of water needs to be identified to meet the requirements. The water resource can be an existing well/borewell, lake, pond or flowing river. The safe yield of the water resource is needed to be noted while determining the water resource as the flow rate of pumped water cannot be greater than the safe yield.

3.1.4 Water delivery point

Water delivery point is the point where the water needed to be made available. The distance between the water resource and the delivery point need to be noted to determine the TDH in the later stage of designing of the SWPS.



The daily pumping rate of this system has been determined for an average solar day (middle). On these days, the water pumped is equal to the water used. On above-average solar days (left), more water is pumped and stored. This helps supply water on below-average solar days (right). The storage tank needs to be sized so that it can store enough water on sunny days to compensate for the water not pumped in on very cloudy days.

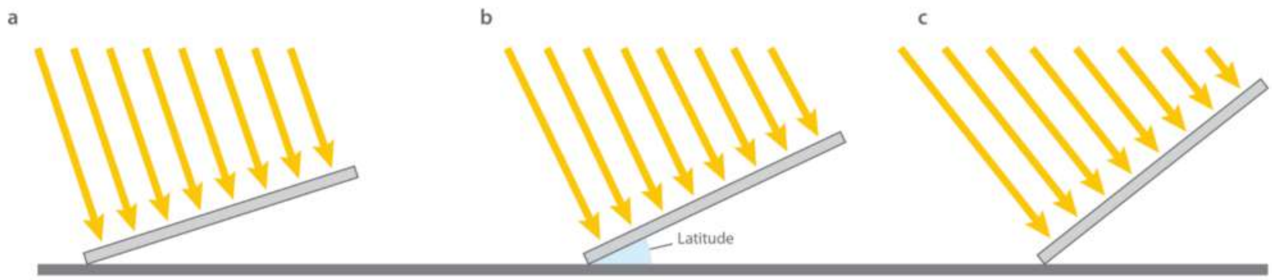
Picture Source: https://www.aginnovators.org.au/sites/default/files/Solar%20-powered%20pumping%20in%20agriculture.pdf

3.1.5 System layout: location of components

Following the determination of the water resource and water delivery point, the next step in the site assessment is to identify the locations for installing the SWPS components and developing a system layout. In general, the solar array, system controller, and pump are all installed close to each other. The purpose of pumped water determines the water delivery location.

3.2 Select the array tilt and orientation

The solar array generates the electricity effectively from the direct radiations from the sun. To be most effective, PV panels need to face incoming sunlight continuously and directly.



a) A lower tilt will give greater solar power generation in summer as then, the sun is higher in the sky; b) a tilt equal to the latitude of the site will give the greatest annual solar-power generation; c) a steeper tilt to a solar PV array will yield greater power generation in winter, when the sun is lower in the sky.

Picture Source: https://www.aginnovators.org.au/sites/default/files/Solar%20-powered%20pumping%20in%20agriculture.pdf

3.2.1 Selection of site for installation of Module Mounting Structure (MMS)

Ideally, the location chosen for MMS installation is closer to the solar pump and on leveled terrain with no shadows.

3.2.2 Tilt of the Solar Modules on MMS

The default tilt angle for a PV panel is equal to the location's latitude. Panels should be oriented towards the equator in regions with more than 10 degrees of latitude, while panels in locations with fewer than 10 degrees can be orientated east-west.

Sites with no significant variations in the annual weather conditions a fixed solar array can be considered. Whereas, if there is significant variation in the climatic conditions season specific tilt angle can be considered to maximize output from the solar array. Generally, a tilt angle of +/- 15 degrees from latitude will increase energy production for the winter or summer months, respectively.

3.2.3 Tracking Provision for MMS

The MMS tracking provision is normally given for sites with more than 10 degrees of latitude and considerable seasonal variations in the sun path. MMS can be equipped with either single or dual axis tracking. A single-axis tracking device rotates a PV panel about its vertical axis throughout the day to track the sun. A dual-axis mechanism will additionally manage the panel tilt angle (the angle of the panel relative to horizontal, where 0 degrees is horizontal and 90 degrees is vertical) to compensate for the sun's elevation in the sky throughout the year.

In general, the automatic tracking method is avoided due to its complexity and cost. However, in accordance with seasonal variations in the sun path, a manual single axis tracking mechanism with fixed tilt angles is provided for the MMS.

3.2.4 Civil Structure for MMS

The Civil Structure/foundation for MMS plays a pivotal role in stable operation of solar array throughout the year, especially during the adverse weather conditions. In general, depth of foundation must be uniform for all the foundation structures and the depth and type of foundation structure should be determined on the bases of worst soil conditions where maximum foundation depth is required. Foundation bolts, if applicable, must be used as per the design recommended by the Solar PV Module/MMS manufacturer. The civil structure must be able to support Solar PV modules in portrait/landscape orientation (as per the array design), absorb and transfer the mechanical loads to the ground/roof properly. Welding or complex fixing mechanism should not be permitted for the installation of MMS to the foundation. All mechanical components must be provided in accordance with the manufacturer's drawing and bill of quantities. Prior to starting work on-site, it is always recommended to refer the manufacturer's proper design and calculations report for foundations and structures.

3.3 Calculate the required flow rates

The solar water pump must be able to deliver the required volume of water on a typical day to the specified TDH. The volume of water required per day will be decided by the purpose of water use.

3.3.1 Calculate the required daily flow rate

The amount of water required each day depends on the actual application. If the water is being used within a village, household or a resort then data should be available on the amount of water required per person in the village, household or resort. If the water is required for agricultural use, then the water requirement depends on the climatic conditions at the site, the kind of soil and crop to be irrigated.

3.3.2 Estimate the required flow rate per hour and per minute

The standalone SWPS operates only during the daylight, and it’s output varies according to the time of the day. To determine the required flow rate from the SWPS, the amount of ‘sun peak hours’ can be estimated and divided into the total daily water requirement.

$$\textbf{Required Flow Rate}\ (\mathrm{m^3/hr}) = \frac{\textbf{Total Daily Water Requirement}\ (\mathrm{m^3/day})}{\textbf{Sun peak hours}\ (\mathrm{kWh/m^2/day\ or\ hr/day})}$$

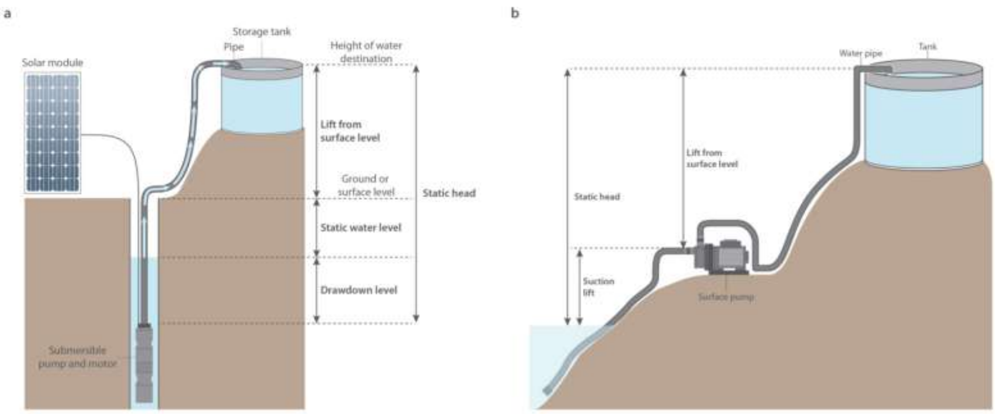
3.4 Total dynamic head

The total dynamic head (TDH) is the total water pressure required by the pump to carry water at the delivery end at the required flow rate.

3.4.1 Calculate static head

The total of the vertical distances from the water's surface to the highest point to which the water is to be delivered is known as static head. The sum of the suction head (the vertical distance between the water surface and the pump) and the discharge head (the total vertical distance between the pump and the water delivery point) are considered for estimating the static head.

$$\textbf{Static Head (m)} = \textbf{Suction Head (m)} + \textbf{Discharge Head (m)}$$



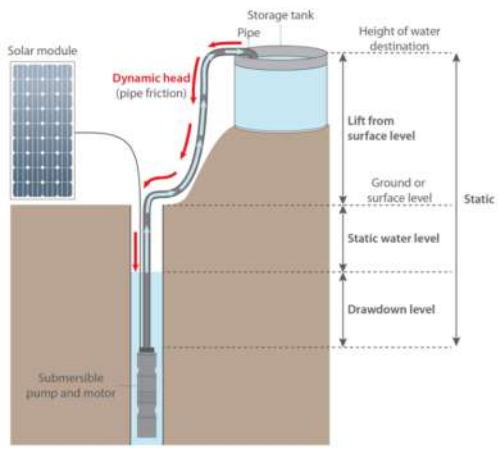
a) The static head of a submersible pump; b) the static head of a surface pump

Picture Source: https://www.aginnovators.org.au/sites/default/files/Solar%20-powered%20pumping%20in%20agriculture.pdf

3.4.2 Calculate total dynamic head

The total dynamic head (TDH) is the sum of the static head, drawdown head, pressure head and the friction head. The drawdown is the increase in the depth of water caused by the water pumping thus the term 'dynamic' is used.

$$\textbf{Total Dynamic Head (m)} = \textbf{Static Head} + \textbf{Drawdown Head} + \textbf{Friction head} + \textbf{Pressure Head}$$



The dynamic head represents the pipe friction

Picture Source: https://www.aginnovators.org.au/sites/default/files/Solar%20-powered%20pumping%20in%20agriculture.pdf

The pressure head is used to determine the minimum pressure required at the water supply end; however, in cases where the delivery end is a storage tank or an open field area, the pressure head is often overlooked. Specific irrigation techniques, such as drip irrigation and sprinkle irrigation, require the delivery end to maintain a minimum pressure.

Water is pumped from one location to another via pipes, and in order for water to move through the pipes, some inlet pressure is required to overcome the static head and friction losses (at the pipe surface). The friction head's exact value is determined by a number of parameters, including pipe material, diameter, number of bends, valves, pipe joints, and pipe size reduction, etc. For SWPS, the pipe layout is often designed so that friction head remains in the range of 1 to 10 percent of the static head.

3.4.3 Select the water pipes

Metal pipes, PVC pipes, and polyethylene pipes are all options for water pipe. Polyethylene pipe is frequently used in solar water pumping systems as the suction pipe for a surface pump and the pipe within a borehole for the borehole pump due to its flexibility. To reduce mechanical damage to the pipe, metallic pipes are utilized for the discharge pipe, and in many cases, PVC pipes are also used.

3.5 Select the pump/array

After determining the required flow rate, solar resource, TDH, and water resource, the next step is to choose the suitable type and size of pump, as well as the size of the solar array, to deliver sufficient power as per pump requirements and SWPS configurations.

3.5.1 Selection of Pumps

Submersible and surface pumps are the two most common types of solar water pumps. Both types of pumps have advantages relative to pumping water from various water sources. In all the categories of pump it should always be preferred to opt for energy efficient pump sets.

i. Submersible Pumps: The term "submersible pump" refers to a pump that is submerged in water. Submersible pumps are used in the majority of deep wells. It uses displacement to pump water. Deep well and surface water sources are both suitable for submersible pumps. These pumps are more expensive, but they last longer and are more reliable than surface pumps. Submersible pumps are intended for applications requiring a medium flow rate. The submersible pump has a built-in dry-run prevention.

ii. Surface Pumps: Surface pumps are commonly utilized in shallow wells, boreholes, lakes, rivers, and other open sources that are close to or on the surface. A suction pipe is used to extract water from the water resource, and the pump is positioned above the water level. The pumps can be used in regions where the water level is less than 7 meters below ground level. The surface pump is typically a centrifugal pump.
Depending upon the availability of SWPS components and mode of operation the choice between the AC and DC pump motor can be made.

3.5.2 Capacity of pump

To determine the capacity of the pump the hydraulic power of the pump is required to be calculated. The needed hydraulic power from the pump is:

$$\textbf{Pump Hydraulic Power, } \mathbf{P_h (kW)} = \frac{\mathbf{Q\rho g h}}{\mathbf{3600 \text{ X } 1000}}$$

Where,
Q is the required flow rate of water, in m3/hr
ρ is the density of water, in kg/m3
g is the acceleration due to gravity, in m/s2
h is the total dynamic head (TDH), in m

Once the hydraulic power of the pump is calculated the following step is to calculate the amount of electricity required to provide the requisite hydraulic power. Considering the efficiency of the electric motor (AC or AC) within the range of 60 to 75 percent the electrical power required for the pump or the pump capacity can be determined by dividing the hydraulic power with the motor efficiency:

$$\textbf{Electric power required for pump or pump capacity } (\mathbf{P_m}) = \frac{\boldsymbol{P_h}}{\boldsymbol{\eta_m}}$$

Where,
Ph is the pump hydraulic power, in kW
ηm is the motor efficiency in percentage
Before selecting the required capacity solar pump from any manufacturer, it is necessary to refer the pump chart provided by the manufacturer that provides the variation in the flow rate of the pump with respect to the TDH.

3.5.3 Capacity of Solar Array

Since the ‘peak sun hours' are already taken into account when calculating the flow rate (m3/hr), the pump capacity must be factored in along with the electrical losses in the SWPS, and the losses and uncertainty in solar generation due to dust and shadow, solar resource and temperature assessment specific to the site. In general, a factor of 1.2 to 1.4 can be used to calculate the capacity of a solar array based on the SWPS configuration.

$$\textbf{Capacity of Solar Array (kW)} = \textbf{Pump Capacity X Loss \& Uncertainity Factor}$$

Where,
Pump Capacity is in kW
Loss & Uncertainty Factor is in percentage
A typical example for sizing the SWPS is provided in Annex-1.

Additional Requirements

4. Additional Requirements

Based on the application of the SWPS there are certain requirements that need to be considered to effectively utilize the pumped water. In case of agricultural application, the water storage tank, the irrigation techniques, and water management system need to be considered as additional requirement of the SWPS configuration.

4.1 Water Storage tank

Water storage stores the water provided by the pump unit during sunshine hours. There are numerous ways to store water, such as simple open dug reservoirs, concrete and plastic tanks to expensive and elevated metal tanks.

Generally, your storage capacity should be equal to 3 to 10 days of average water consumption, or more. This depends on your climate and your usage patterns. For domestic use in a cloudy climate, 10 days is minimal. In a sunny climate, this allows for a generous safety margin. For irrigation of deeply rooted crops or trees, 3 days' storage may be adequate because the earth itself provides storage. For irrigating a garden, 5 days may be adequate. More is always better, unless evaporation loss is excessive. A float switch is generally provided with the water storage tank to switch off the pump and to prevent water overflow/wastage.

4.2 Irrigation Technique

The choice of a particular irrigation system mainly depends on the crops to be irrigated, availability of water, irrigation water requirements and energy supply as well as the financial capacity of the farm household. Each method needs an experienced farmer to determine the quantities of water to apply and the timing of the irrigation. In the design process of a solar irrigation pump it needs to be taken into account that demand and supply of irrigation system water will vary throughout the year. The farmer can choose from three commonly used modern irrigation methods:

Surface irrigation is a technique where water is applied and distributed over the soil surface by gravity. It is the most common form of irrigation followed throughout the world. Surface irrigation is best suited to flat land slopes, and medium to fine textured soil types which promote the lateral spread of water down the furrow row or across the basin.

Sprinkler irrigation is a method of irrigation in which water is sprayed or sprinkled through the air in rain like drops. The spray and sprinkling devices can be permanently set in place, temporarily set and then moved after a given amount of water has been applied or they can be mounted on booms and pipelines that continuously travel across the land surface.

Drip irrigation systems are methods of micro irrigation wherein water is applied through emitters to the soil surface as drops or small streams. The discharge rate of the emitters is low so this irrigation method can be used on all types of soil.

4.2.1 Water Management System

Irrigation is the artificial exploitation and distribution of water at the project level with the goal of providing water to agricultural crops at the field level in dry areas or during seasons of sparse rainfall to maintain or improve crop yield. In recent years, there is decline in the groundwater level in many parts of the world. The objective of a water management system is to prevent excessive water use, reduce water pumping, reduce soil erosion, maintain or improve the quality of groundwater and downstream surface water, and increase crop output and quality.

For surface irrigation: The most simple surface irrigation water management technique is to first measure the flow of water pumped into the field using a water flow meter or volumetric measurement using a sump, and then maintain a slope towards the far end of the field. This would help to provide a suitable amount of water for agriculture needs, and the slope would facilitate the lateral flow of water across the basin.

For Sprinkler and Drip irrigation: Both sprinkler and drip irrigation techniques originally developed to optimize water usage in order to encourage optimal plant growth while also preserving the necessary levels of moisture in the soil. Sprinkler/drip irrigation systems are typically equipped with meters and sensors to adjust the volume, flow rate, and schedule of water application to match crop water requirements, water holding capacity, and soil intake. The water deficit can be monitored using soil moisture sensors, and an automatic irrigation timer can be programmed.

Operational and Maintenance Activities

5. Operational and Maintenance Activities

An Operation and Maintenance Manual, in English and the local language, should be provided with the solar PV pumping system. The Manual should have information about solar energy, photovoltaic modules, DC/AC motor pump set, tracking system, mounting structures, electronics and switches. It should also have clear instructions about mounting of PV module, DO's and DONT's and on regular maintenance and Trouble Shooting of the pumping system. Name and address of the person or Centre to be contacted in case of failure or complaint should also be provided. A warranty card for the modules and the motor pump set should also be provided to the beneficiary.

5.1 Operational Activities of SWPS

Some of the basic operation guidance are:

i. Adjusting the solar panels in line with the sun path in case single/double axis tracker is provided with the module mounting structure,
ii. The pump should be OFF when water pumping is not required,
iii. Before switching ON the pump, care should be taken to prime the suction pipe (especially for surface pumps) by putting some water in the pipe through the delivery side. The pump should never run dry
iv. If the pump is not discharging any water after turning ON and the motor is running, air may be trapped in the suction pipe through the delivery side. In this case air can be released through the air trap valve in the pump. The valve should be tightened after removing the air,
v. Inspect the water level of the water storage tank, if provided with the SWPS.

5.2 Maintenance Activities of SWSP

With technology advancement the SWPS requires very little maintenance activities that can be classified as routine and periodic activities.

5.2.1 Routine Maintenance

It is recommended that regular maintenance is carried out on the system to prevent failure of the water supply due to an unexpected system shutdown. The routine maintenance activities are similar to the daily tasks that need to perform while operating the SWPS. The following are some of the routine maintenance activities for key components of the SWPS. However, the manufacturer may require additional specific procedures which also must be carried out.

i. Clean the solar array and modules regularly
ii. Keep the unit clean and minimize the possibility of dust, cleaning to be done as required

5.2.2 Periodic Maintenance

Periodic maintenance are those set of activities that need not to be performed on daily basis but are very essential for long term operation of SWPS. The key maintenance activities for each of the SWPS includes:

5.2 Maintenance Activities of SWSP

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i. Clean the solar array and modules regularly
ii. Keep the unit clean and minimize the possibility of dust, cleaning to be done as required

SWPS Component	Inspection	Frequency	Actions to be Taken
Solar Panel Array and mounting structure	Inspect Solar Panels Array	Once a month	Check for corrosion/ oxidation and remove rust with wire brush and paint. Check panels for any hot spot
Motor and Pump	Inspection of rotary parts of the motor and pump	Once a year	The damaged parts such as bearings, sealing ring, mechanical seal must be replaced. If the pump is not in use for long time, kept it in dry and ventilated place
Wiring	Inspect the wire insulating sheath for cracks or breaks.	Once a month	If the insulation is damaged, replace the wire. Check the connections for corrosion and tightness
Water Tank	Inspection of water tank for any leakages and cleaning	Once in six months	Any leakage from the water tank needs to be rectified. Water tank must be cleaned for any algae or dirt accumulation.
Pipe distribution	Inspection for any minor leakage, damages and cleaning	Once a year	The pipe section must be repaired or replaced for any minor leakage. Any damaged valves to be replaced Periodic flushing is required (depending upon the quality of water) to avoid any blockage in the pipe.

5.3 SWPS Monitoring

5.3.1 Remote Monitoring System (RMS)

Solar pump RMS is a cost-effective monitoring solution, which allows user to monitor all data regarding Solar power generation, consumption, pump run time and fault analysis. Remote monitoring is a very tool to analyze the performance of individual SWPS and also assist in comparative analysis of multiple pumps installed in the same region.

5.3.2 On-site monitoring

Most of the performance and fault analyses can be done through RMS, at site monitoring plays an equally important role in smooth operation of the SWPS. Actions to be taken during the routine and periodic maintenance is based on site monitoring assessment. At site monitoring involves any sign of vandalism, unusual noises during pump operation, any damages to the wiring, and water leakage through pipes, etc.

LIFE OF THE SWPS

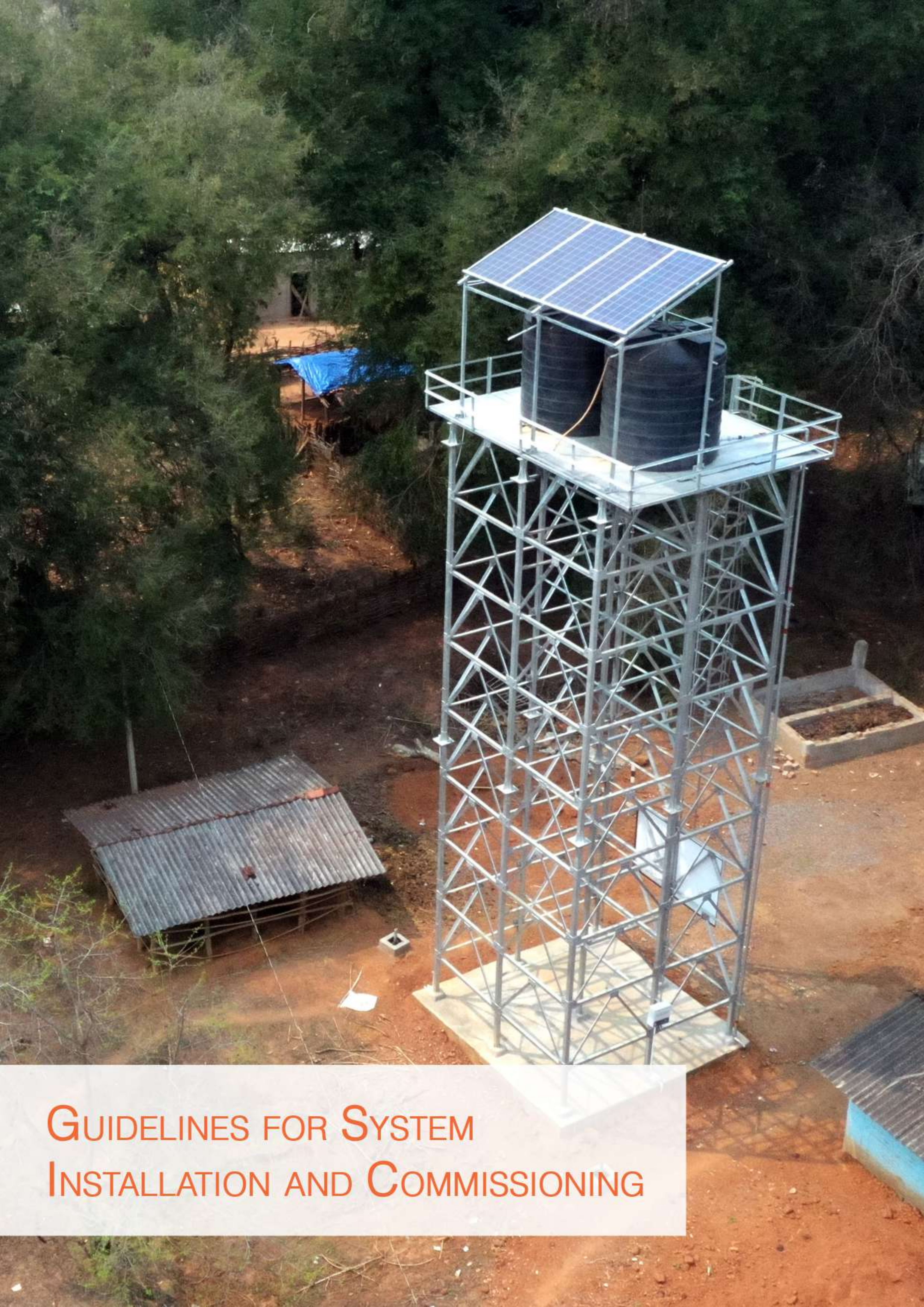
6. Life of the SWPS

SWPS comprises of various components consisting of electrical, electronic, mechanical and civil technologies and each of the components have a different lifespan. The estimated lifespan for the key components of the SWPS is as follows:

Sr. No.	SWPS Component	Lifespan
1	Solar Panel Array	25 years
2	Module Mounting Structure	25 years
4	Pump-Motor	15 to 20 years
5	Pump Controller	10 years

The solar panels that power the SWPS have a normal lifespan of 25 years and cost roughly 80 percent of the cost of the solar water pumping system. The pump controllers are projected to last for roughly 10 years. The pumps themselves have various life expectancies, depending on the motor used to power them, usually, high efficiency AC or DC motors with a life expectancy of 15-20 years are chosen for water pumps. Pumps, whether submersible or surface-mounted, typically have a lifespan of 15 to 20 years. Overall, if solar panels are the most valuable component of the SWPS and the motor-pump is the second most valuable, solar water pumping systems are meant to endure for around 20 years. However, some system components, such as the pump controller, may have to be replaced within this period.

Need of Spares: While most SWPSs operate in remote locations, an appropriate amount of spare parts is required ensure smooth operation throughout the SWPS's lifespan, particularly for small components such as wiring (wire connectors, fuses, etc.), pipe and pump fittings (flanges, valves, mechanical seals, fasteners, bearings, etc.) that are inexpensive but can impede pump operation if damaged. In the case of an extremely distant site or a significant number of SWPS to be precured as part of a project, it is recommended to have an entire pump-controller unit as a spare in an appropriate proportion. Based on the SWPS's application and site location a comprehensive list of spare parts needs to be developed on the basis of the SWPS configuration, it's application and accessibility to the site.



Guidelines for System Installation and Commissioning

7. Guidelines for System Installation and Commissioning

The installation of the solar pumping system should be performed safely and according to the equipment manufacturer's instructions. The solar PV water pump installation is highly skilled and involved task, and only knowledgeable service person is to do the installation of the SWPS. If the SWPS is being installed without a licensed pump installer, an electrician or knowledge of electrical circuits is HIGHLY recommended. Before installing the SWPS, it is suggested to make a system layout. During the layout take into consideration any potential shading of the solar electric modules, wire runs, wire size, conduit runs, trenching, controller accessibility, tank location, pump head etc.

7.1 Site safety

Site safety is one of the primary requirements while installing the SWPS. The site safety is generally categorized as non-electrical hazards and electrical hazards.

7.1.1 Non-electrical hazards

SWPS component installation: Most of the SWPS components are heavy, the technicians must wear proper personal protective equipment (PPE) such as safety helmets, gloves, specs, and shoes, etc. to protect themselves from any physical injuries.

Site cleaning: The site must be cleaned from shrubs and bushes before installing the SWPS. As most of the SWPS components are installed in open space. Always be careful of venomous insects and reptiles will installing the SWPS.

7.1.2 Electrical hazards

Electrical shocks and fire are the common accidents/injuries can occur when you are working with different electrical equipment's that means anytime when electric current flows through the human body.
Be conscious while handling the solar panels as they produce the DC electricity in sunlight and always cover the panels with opaque material/cloth while connecting in series and parallel combinations. Make sure to wear electricity resistant grade PPEs and refer to the single line circuit diagram while wiring the solar panels with the controller unit and the motor-pump. It is recommended to put caution signs of electrical hazards near the SWPS components.

7.2 Solar Array and electrical wiring installation

SWPSs are typically provided with an array mounting frame, either for pole mounting or fixed on the ground. First, determine the position where array needs to be installed. The solar PV array is to be installed carefully at a proper location to avoid shadowing of any part of the array or other obstructions throughout the day any time of the year.

7.2.1 Solar Array installation

The land surface on which the module mounted structure (MMS) is to be fixed must be leveled properly to meet the desired tilt and orientation of the solar array, as mentioned in section 3.2. Following factors must be considered while installing the Array:

i. Typically, the array frame structure is provided with the solar water pumping system. If not, the support frame may be made of chemically treated galvanized steel, or aluminum to prevent corrosion, If the supplier is sourcing the solar modules and array frame separate from the water pumping system.

ii. The array mounting frames must be wind rated (minimum 150 km/hr of wind speed) in accordance with relevant wind loading standards in the country. For those countries that have experienced Category 3 to Category 5 cyclones/typhoons then the frames shall be designed and installed in a manner that will remain intact in the wind speeds expected in a Category 5 cyclone/typhoon. The array structures shall be designed to withstand the aggressively hot and salty atmosphere of the Pacific Islands.

iii. Installation of footings, posts, screws and/or in-ground fasteners shall follow manufacturer's instructions and associated installation manuals.

iv. After installing the MMS, next step is to mount and fix the solar panels over it. Solar Panels must be tightened on the MMS with galvanized fasteners provided by the manufacturer.

7.2.2 Wiring Installation

i. **Wiring between solar array and pump controller:** Generally, SWPS include solar panels with interconnection cable/connectors set up for 'plug and play' operation. For configuring the solar panels in series and parallel combinations as required by the pump controller, it is always advisable to refer to the circuit diagram and instructions provided by the manufacturer. The solar panels interconnection and the connection between the pump controller and the solar panels must be made using the manufacturer's connectors/plugs or according to the manufacturer's recommended standards.
Wires should not be laid on the ground without a conduit, and plastic cable ties should not be utilized as the primary means of wiring support. For a longer lifespan, all exterior wiring must be protected from mechanical damage and UV rays from the sun.

ii. **Wiring between pump controller and pump:** The wiring between the pump controller and the water pump should be installed according to the manufacturer's instructions and applicable standards. If the surface pump, borehole, or well is not adjacent to the solar array/pump controller, the cable must be deployed as an aerial cable or directly in the ground in proper conduit to a depth of at least 500 mm or in metal conduit on the ground surface.
To avoid damage, the cable must be properly supported and mechanically protected. The connectors provided by the manufacturer must be used to connect to a surface water pump. The cable that connected to the submersible pump must be suitable for use in water and must only be used to support the weight of the submersible pump if it was developed and intended for that purpose. The waterproof connectors provided by the manufacturer must be used to connect to the pump motor.

7.3 Pump and piping installation

SWPS consists of surface and submersible pumps and both pumps require different installation procedures.

7.3.1 Surface pump and piping installation

The surface water pumps must be installed on a leveled foundation, such as a concrete pad. This will reduce vibrations, which would otherwise put strain on the water pipes. It is suggested that a sheet metal cover be used to shield the pump from direct sunlight.
The length of the suction pipe should be maintained to a minimum while installing it, and if using a hard pipe, keep the number of bends to a minimum and utilize sweeping bends instead of 90 degree bends wherever possible. A foot value must be provided at the end of the suction pipe to avoid draining of water when the pump is not operating. If it is unavoidable to have any part of the suction pipe below the pump level then an air release valve must be provided at the highest point of the pipe where the air can be trapped. The suction pipe should always have the same diameter as the pump's input. If it must be larger, an eccentric reduction should be utilized rather than a concentric reducer.
For discharge pipe a gate valve must be installed at the outlet of the pump and to avoid unnecessary bends in the pipe.

7.3.2 Submersible pump and piping installation

The submersible pump must be located at least one meter above the bottom of the borehole/well and very well below the 'drawdown level' to avoid any dry run operation of the pump. A stainless-steel cable should be connected to the pump and fastened to the top end of the borehole/well to support the weight of the pump and to reduce the strain on the discharge pipe. It is recommended to provide a water level sensing system with the pump and a non-return valve in the discharge pipe near the pump.

7.4 System commissioning

Commissioning of a SWPS is basically operating the SWPS for the first time after installation of the component. While operating the system it is recommended to check that the water is being pumped and the flow rate is achieved as per the voltage and pump specifications.

System Economics

8. System Economics

8.1 Introduction to life cycle cost

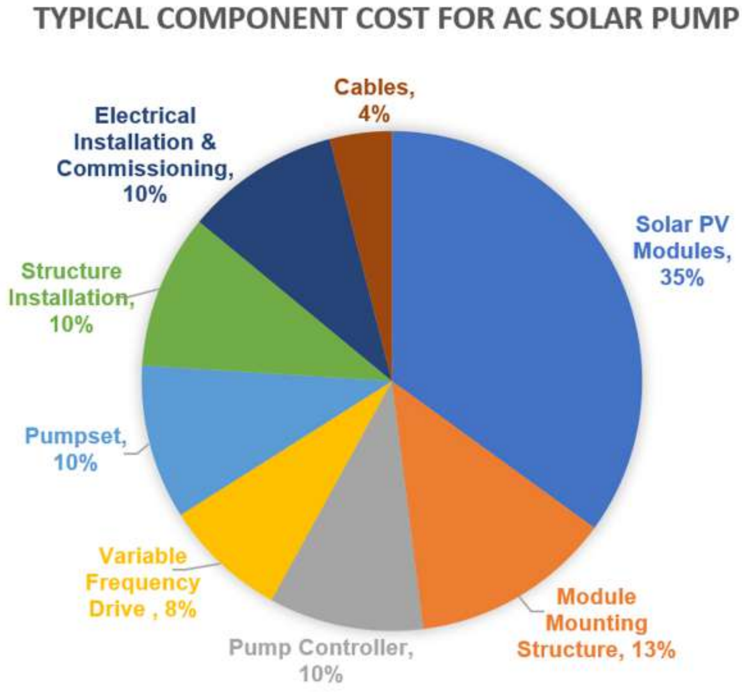
When considering the investment cost of a new system, the life cycle cost (LCC) is an important factor to consider. The LCC is the total of all costs incurred by a system over its lifespan, including both recurring and non-recurring costs. Because of the high initial investment costs of renewable energy projects, LCC is especially significant. Traditional fossil-fuel-based choices may appear to be less expensive at first glance due to lower startup expenses; nevertheless, operational costs can add up quickly during the project's lifetime. Initial costs, installation and commissioning costs, energy expenses, operating costs, maintenance and repair costs, downtime costs, environmental costs, and other costs are often included in an LCC analysis. A typical LCC comparative analysis is provided for both solar and diesel water pumping system is provided in Annex-2.

8.2 Pumping cost breakdown

The pumping cost of SWPS is broadly categorized as capital costs and operating cost, where

8.2.1 Capital costs

Initial costs, including capital expenditures (CAPEX) and installation/commissioning are referred to as capital costs. Most of these entails purchasing solar pump system equipment, such as PV panels, pumps, control systems, pipes and fittings, wiring, etc. Initial costs also include design engineering, system installation, commissioning testing and inspection.



8.2.2 Operating & Maintenance costs

Operation and Maintenance costs are labor, replacement and energy costs related to a pumping system's operation and maintenance. They can vary widely depending on the system's complexity and duty. For example, a hazardous duty pump may require daily checks for emissions and operational performance, whereas an automated nonhazardous system may only require limited supervision. Security and managerial costs are also included here.

8.3 Comparison between solar and diesel pumping

The only technology difference between the solar and diesel pumping is the source of power. In solar and diesel pumping, solar PV panel and diesel generator (DG) is used to generate the requisite power to pump the water. The key comparison parameters between the solar and diesel pumping are as follows:

Parameters	Solar Pumping	Diesel Pumping
Capital Cost	Solar PV panels have a high capital cost, and they account for the majority of the capital costs.	Very low capital cost in comparison with solar pumping.
Operation Cost	It has a low operating cost because no moving part is involved in power generation.	High operational cost due to regular monitoring of the diesel generator GHG emission, fuel consumption and proper functioning of diesel engine.
Fuel Cost	Nil. Solar Pumping utilizes the solar energy to operate that if freely available across the globe.	Vert high. Fuel cost is the most prominent expenditure in diesel pumping during it's operation.
Maintenance Cost (pump and associated piping maintenance cost is common for both pumping system)	Maintenance cost of Solar pumping is low. Under normal operating conditions, solar PV panels and pump controller require only dusting and cleaning as part of regular maintenance. Regular/periodical check of the cable connections and its continuity assures trouble operation.	Diesel pumping has high cost of maintenance. It is required to maintain the lubrication oil level, cleaning of oil filters, replacing seals, bearings and coupling wear. These components need to be checked as part of preventive maintenance on monthly, bi-annually and yearly basis for smooth operating of the diesel generator.
Replacement cost	The solar part of the pumping system is broadly classified as the solar PV panels and controlling unit. PV panels with a 25-year projected life do not need to be replaced, but the controlling unit, which has a 10-year expected life, may need to be replaced once throughout the SWPS' lifetime.	Diesel generator have a life expectancy of 10 years only and the whole generator might be required to replace at least once in the whole lifespan of the diesel water pumping system.
Environment Benefits	Solar pumping has no negative effects on the environment. If carbon tax credits or carbon trading are available in the country, the end user may also benefit.	The use of diesel pumps has a significant negative influence on the environment. When 1 liter of diesel fuel is used, approximately 2.7 kg of CO_2 is released into the atmosphere. Due to lubrication oil or fuel spillage, it may potentially contaminate the water supply.

In general, if more than 1,000 hours of pumping operation are required per year, the LCC of a solar pumping is substantially lower than that of a diesel pumping system.

ANNEXURES

9. Annexures

Annex -1: Typical example of SWPS system sizing

A. Required information for sizing the Solar Water Pumping System (SWPS)

Assume the daily required water discharge for the selected site is of 30,000 liters (30 m3/day) for a total dynamic head of 70 meters with a daily average solar irradiation of 4.5 kWh/m2/day. This data would be required to select a SWPS that will provide the requisite volume of water per day.

B. Considerations:

- Efficiency of Pump-motor unit: 60 %
- Losses and uncertainty factor for inverter and solar array: 1.4

C. SWPS sizing[1]:

- Water pumping requirement for SWPS = $\frac{30}{4.5}$ = **6.7 m³/day**
- Pump hydraulic power required = $\frac{6.7 \times 1000 \times 9.81 \times 75}{3600 \times 1000}$ = **1.4 kW**
- Electric power to generate required pump hydraulic power = $\frac{1.4}{60\%}$ = **2.3 kW**
- **Required size of pump =** $\frac{\mathbf{2.3}}{\mathbf{0.746}}$ **= 3 HP**
- **Required size of solar array to operate the pump =** 2.3×1.4 **= 3.2 kW**

[1] Refer to section 3: Selection of suitable SWPS for formula and units

Annex-2: Solar and Diesel Pump Life Cycle Cost Comparison

A typical life cycle cost analysis is provided for 3 HP and 5 HP for both solar and diesel water pumping system. The cost of water pipe is not considered in this study as it will be common for both pumping systems.

Life Cycle Cost[2]					
Sr. No.	**Components**	**Solar Water Pumping System**		**Diesel Water Pumping System**	
		3HP	**5HP**	**3HP**	**5HP**
A	**System life (equivalent to pump life, in years)**	**20**	**20**	**20**	**20**
B	**Capital Cost of pumping system**	**9,761**	**11,301**	**857**	**1,000**
C	**Maintenance Cost[3]**	**1,952**	**2,260**	**171**	**200**
D	**Replacement Cost**				
	Controller unit of Solar water pumping system[4] (life of 10 - 12 years)	1,464	1,695	-	-
	Replacement of Diesel generator[5] (every 7 years)	-	-	686	800
	Total Replacement cost, in USD	**1,464**	**1,695**	**686**	**800**
E	**Fuel**				
	Annual hours of operation (for 200 days/year @ 5 hours per day)			1000	1000
	Annual Fuel Consumption[6], (in litres)			658	1097
	Fuel Cost[7], in USD	**0**	**0**	**15,271**	**25,452**
F	**Salvage cost[8], ((D+B)*20%) *in USD***	**2,245**	**2,599**	**309**	**360**
G	**Life Cycle Cost (B+C+D+E-F), *in USD***	**10,932**	**12,657**	**16,677**	**27,092**
H	**Annual expenditure for the pumping, (G/A), *in USD***	**547**	**633**	**834**	**1,355**

[2] All costs are in USD, 1 USD = 70 INR
[3] Considering maintenance cost for Solar @ 1% and Diesel @ 5% of capital cost
[4] One-time replacement in 20 years of pumping system life and costing around 15% of the capital cost
[5] Two-time replacement in 20 years of pumping system life and costing around 40% of the capital cost
[6] Considering 1 liter of diesel generate 3.4 kWh of electricity
[7] Price of diesel at 1.16 USD/litre
[8] Salvage cost equivalent to 20% of capital cost