Food and Agriculture Organization
of the United Nations

The use of solar energy in irrigated agriculture

A sourcebook for irrigation water management with alternative energy solutions

The use of solar energy in irrigated agriculture

A sourcebook for irrigation water management with alternative energy solutions

Authors:

Maher Salman

Ahmed Abdelfattah

Waqas Ahmad

Camilla Simongini

Food and Agriculture Organization of the United Nations

Rome, 2022

Required citation: Salman, M., Abdelfattah, A., Ahmad, W., Simongini, C. 2022. *The use of solar energy in irrigated agriculture: A sourcebook for irrigation water management with alternative energy solutions.* Rome. https://doi.org/10.4060/cb8459en

ISBN 978-92-5-135699-9

Acknowledgements

This knowledge product was prepared by an FAO team led by Maher Salman, Senior Land and Water Officer & Team Leader of Irrigation and Water Resources Management Group, Land and Water Division (NSL). The team included: Ahmed Abdelfattah, Renewable Energy Specialist (NSL), Waqas Ahmad, Water Management Specialist, (NSL), and Camilla Simongini, Environmental Engineer (NSL).

The team gratefully acknowledges guidance and support received from Lifeng Li, Land and Water Division Director; and Sasha Koo-Oshima, Land and Water Deputy Director.

Acknowledgement is due to Ahmad Hamza, Chairperson of Mechanical Engineering Department Head, Assiut University; Ahmed Hegazy, Head of Water Engineering and Renewable Energies unit at Egyptian Atomic Energy Authority, Brian Norton, Head of Energy Research at IERC/Tyndall National Institute; Imran Haleem, Director Renewable Energy Projects at PakhtunKhwa Energy Development Organization; and Stefania Giusti, Programme Officer, Land and Water Division (NSL) for their feedback during the review process.

A special thanks to Rubén Martínez (NSL) for the design of the book.

Contents

Box

Figures

Tables

Abbreviations and acronyms

AC	Alternating current
DC	Direct current
EN	European Standard
FAO	Food and Agriculture Organization of the United Nations
I-V curve	Current-Voltage curve
IEC	International Electrotechnical Commission
Isc	Array short circuit current (DC)
ISO	International Organization for Standardization
LV	Low voltage
MPP	Maximum power point
MPPT	Maximum power point tracking
O&M	Operation and maintenance
PPE	Personal protective equipment
PV	Photovoltaic
Q	Discharge
STC	Standard test condition
VDC	Volts of direct current
VFD	Variable frequency drive
Vmpp	Array maximum power point voltage (DC)
Voc	Array open-circuit voltage (DC)
Wp	Peak power output

Units and symbols

°	arc degree
°C	degree Celsius
A	ampere
Ah	ampere hour
ft	foot (1 foot = 30.48 cm)
gal	gallon (1 gallon = 3.785 L)
h	hour
ha	hectare
hp	horsepower (1 horsepower = 745.7 W)
Hz	hertz
in	inch (1 inch = 2.54 cm)
J	joule
K	kelvin
k	kilo (1 000)
L	litre
lbf	pound force (1 pound force = 1.355 Nm)
m	meter
m^2	square meter
m^3	cubic meter
mg	milligram
V	volt
W	watt
Wp	watts peak
µ	micro (0.000 001)
Ω	ohm

Executive summary

In the last decade, solar energy has experienced a rapid growth, which brings both environmental and economic benefits. One of the driving forces behind this growth is that the solar industry keeps seeing innovation for both reducing the system cost and increasing the grid-integration performance. Similarly, solar-powered water pumping technologies are increasingly in demand in developing countries as they provide cost-effective solutions to increase agricultural productivity. In many countries, there is still no electricity grid extension in rural areas, and in the absence of a reliable electricity supply, farmers have to resort to diesel-based pumping irrigation systems. These systems create high operating costs, often experience service gaps, contribute to greenhouse gas emissions and to the energy import bill in countries that do not produce such fuels. Therefore, renewable energy options, particularly solar power, are a promising solution for sustainable agriculture in regions with high-solar-insolation. In principle, the operation of solar water pumping systems is limited to peak sunshine hours which has a high impact on the sustainability of water resources, i.e. groundwater aquifers and surface water.

The solar photovoltaic (PV) system generates clean energy and eliminates the risk of environmental pollution in the form of oil spills, contaminated soil and carbon dioxide emissions. In fact, the generated energy can be utilized for other valuable purposes when pumping is not required. Due to its fixed installation, the solar PV systems have low maintenance costs and requirements compared to diesel-operated pumps. Solar systems have comparatively high initial costs, but thanks to subsidies available in some countries and cost-sharing arrangements by the governments for agricultural purposes, it represents now a viable option in different contexts compared to other solutions.

Operation and maintenance of the solar PV pumping system is a technical job that requires specialized knowledge and information to keep the system in working conditions. For this purpose, this sourcebook is designed to provide information on the design, operation, inspection, troubleshooting, and maintenance of solar PV pumping systems. PV pumping systems include mouting structures, photovoltaic modules, combiner boxes, the balance of system components such as the variable frequency drive, inverter, switch boards, solar pumps, distribution boards, and associated wiring. It is assumed that the reader of this sourcebook is knowledgeable in solar system basics and has previous expericence with solar energy use in general.

Introduction

Water scarcity and the role of energy

Freshwater is unequally distributed across the globe, making some regions of the world water abundant while others receive less water than the demand thus falling into a water scarcity condition. Water scarcity has several definitions (Steduto *et al.*, 2012), which signify a gap between supply and demand. The unequal distribution of water coupled with higher demands in certain areas for domestic consumption, industrial use and food production poses a severe threat to its sustainable use.

Energy plays an essential role in the sustainable abstraction of freshwater from its storage phase and making it available for various uses (He *et al.*, 2019). Crop production and food processing are the largest consumers of freshwater resources in agriculture, and crop production requires large amounts of electrical and mechanical consumption during various cultivation stages such as seed bed preparation, irrigation and harvesting (FAO, 2000). Water and energy in the food production system are closely interlinked; any change in the demand in one stage has a flow-on effect on the other. On the other hand, urban energy demand increases at higher rates to ensure timely provision of related services.

Developing countries face severe problems related to water and energy supplies in rural and remote areas. Farmers and residents in these areas usually depend on fossil fuel to provide irrigation water and electricity. Alternative energy sources were out of consideration until fuel prices started to rise significantly in the last few decades. High initial costs of photovoltaic (PV) generators represented a limiting factor for those users to utilize such a renewable and clean energy source. Several research were carried out to increase PV systems efficiencies, decrease initial costs, and address open concerns (Hegazi *et al.*, 2010).

Within this context, the implementation of solar-powered pumping systems can increase access to sustainable and safe use of water in crop production systems (Lefore, Closas and Schmitter, 2021). Electrical energy from sunshine can be produced in most arid locations worldwide to lift freshwater and run an on-farm irrigation system. However, like any power generation system, solar energy generation is also a technical job. The operators of solar irrigation systems may need specialized knowledge, training and understanding of standard operating procedures (SOPs) to run the system effectively and safely. For this purpose, this sourcebook is designed for the operators to understand the basic types, operation, inspection, troubleshooting and repair of solar irrigation systems.

Water and energy in the food production system are closely interlinked; any change in the demand in one stage has a flow-on effect on the other.

Types of solar water pumping systems

Due to the high initial costs of PV generators, the power requirement of the system has to be minimized from the beginning (Mueller *et al.*,1998). Since the hydraulic power is the product of flow and pressure, the following targets should be sought to design a competitive solution:

- reduction of the required flow by avoidance of water losses;
- reduction of pressure loss through an optimum hydraulic system layout; and
- optimum matching of system components and strict dimensioning to achieve a real efficiency according to the crop water requirement.

There are many inherent advantages in using PV powered pumps for water delivery in irrigation systems. PV pumping offers high reliability, low maintenance, modularity, environmental acceptability, independence from central utility power, and a strong coincidence of water needs and water supply. These assets can be exploited to their full potential if an appropriate irrigation system is chosen for PV pumps and the proper hydraulic design procedures are used in the design of the system.

Two important factors that are characteristic of PV powered pumping facilities to be considered when matching the PV pump to an appropriate irrigation system, are the high cost per unit of pumped water, and the variable water output. These factors will guide the selection of an irrigation method over another (Girard, K., 1988). Thus, different types of solar systems for irrigation can be designed.

Standalone system for direct irrigation

A standalone system for direct irrigation works entirely on solar panel modules without the integration of grid or hybrid electricity (Ali *et al.*, 2018). It also avoids the use of electric and hydraulic energy storage devices such as lead-acid batteries or overhead water storage tanks. In this type of system, the required amount of irrigation water is pumped into the on-farm irrigation network to satisfy the crop water requirement.

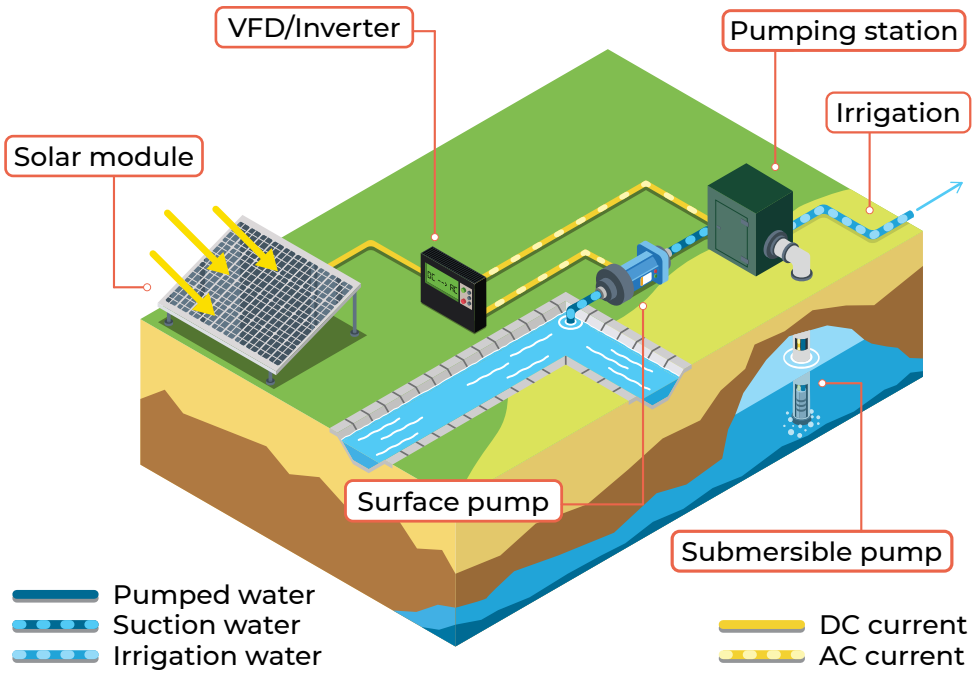


Figure 1. Standalone system for direct irrigation.

Source: authors.

To maximize its effectiveness, the peak irrigation time is synchronized with the peak sunshine hour. In this case, maximum solar energy is available to pump water into the on-farm irrigation network.

Standalone system for direct irrigation with batteries

This type of system is effective when the time of peak irrigation demand cannot be synchronized with the peak sunshine hours due to operational reasons. The system uses solar panel modules combined with lead-acid batteries to store the generated electrical energy during peak sunshine hours.

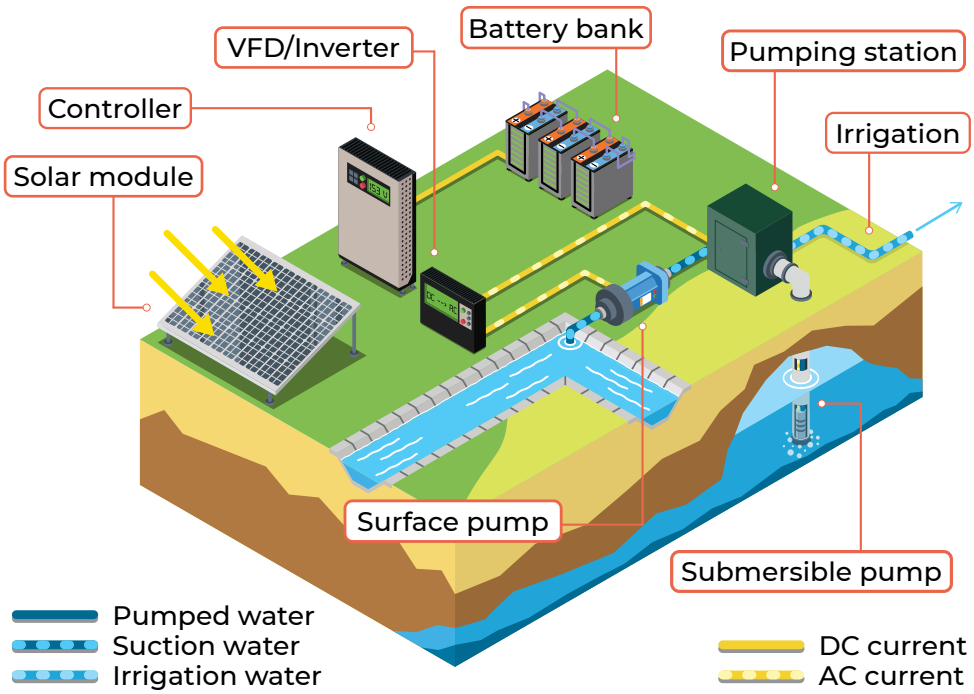


Figure 2. Standalone system for direct irrigation with batteries.

Source: authors.

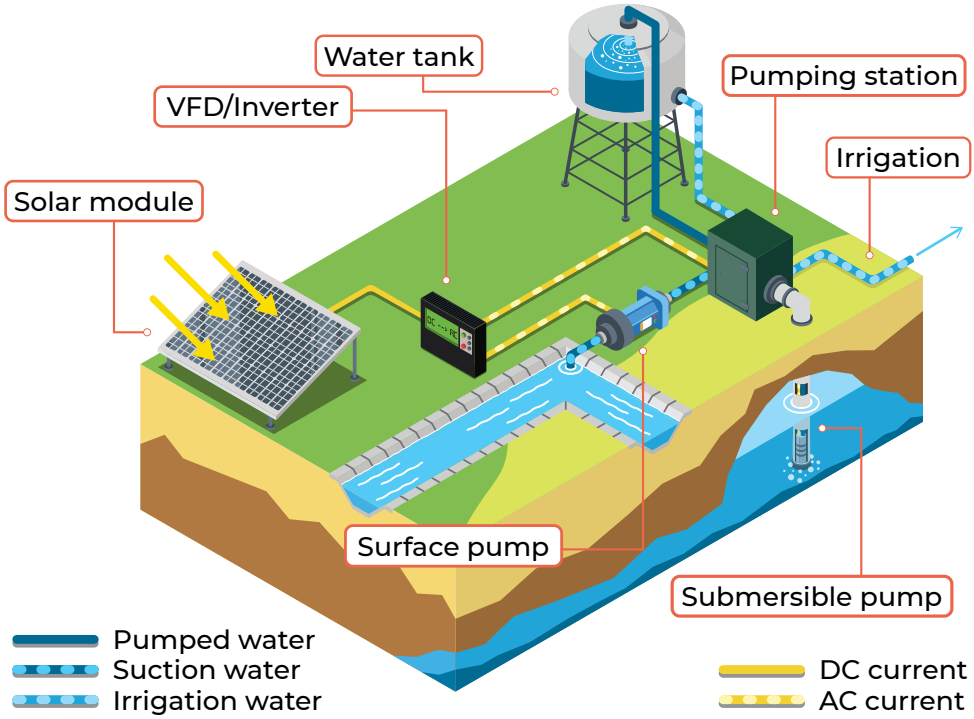
The use of controllers and batteries ensures that the energy is available to feed water into the irrigation network when the water demand is high. Energy availability in off-peak sunshine hours makes it a good option for full-day operation; however, adding a controller, batteries, and high maintenance requirement increases the overall cost of the system. It is also challenging to determine when the batteries need replacement according to site circumstances, operation schedule, and product quality.

Standalone system with overhead water storage

In this type of system, a constant irrigation demand for a longer duration of the day cannot be synchronized with the variable sunshine hours. To address this challenge, the system capacity is designed slightly oversized, and an overhead water tank is provided with the system. The pump runs smoothly during the typical daytime operation and provides more water than required for direct irrigation due to the extensive system capacity.

Figure 3. Standalone system for direct irrigation with overhead storage tank.

Source: authors.



The extra water is directed towards an overhead storage tank, where it is kept as a backup resource. The water from the tank is released to the end-users when it is demanded during the low sunshine hours. The system capacity and storage tank volume are designed to ensure enough storage volume required during the low sunshine hours. The overhead tank also provides the required pressure to feed and run the on-farm irrigation network.

Solar – diesel hybrid solutions

Solar – diesel hybrid solutions that are suitable in cases of different peaks of irrigation time and sunshine hours. This system allows the implementation of an irrigation schedule that is different from the pumping schedule. During the design phase, the hybrid system is decided based on the capacities of solar panel modules and diesel generator sets to satisfy the required irrigation profile.

Furthermore, the system parameters have to take into account the pump operating conditions at peak requirements. If solar power is unavailable and there is water demand, resources are directly supplied to the end-user from the overhead water tank. If solar power is unavailable but there is water demand, the system then switches to the diesel generator operation. The switch can be done manually or automatically, depending on system control options.

A hybrid system uses energy from renewable and non-renewable sources that produce similar results. Optimization of the two energy sources can significantly reduce carbon dioxide emissions during a year of operation.

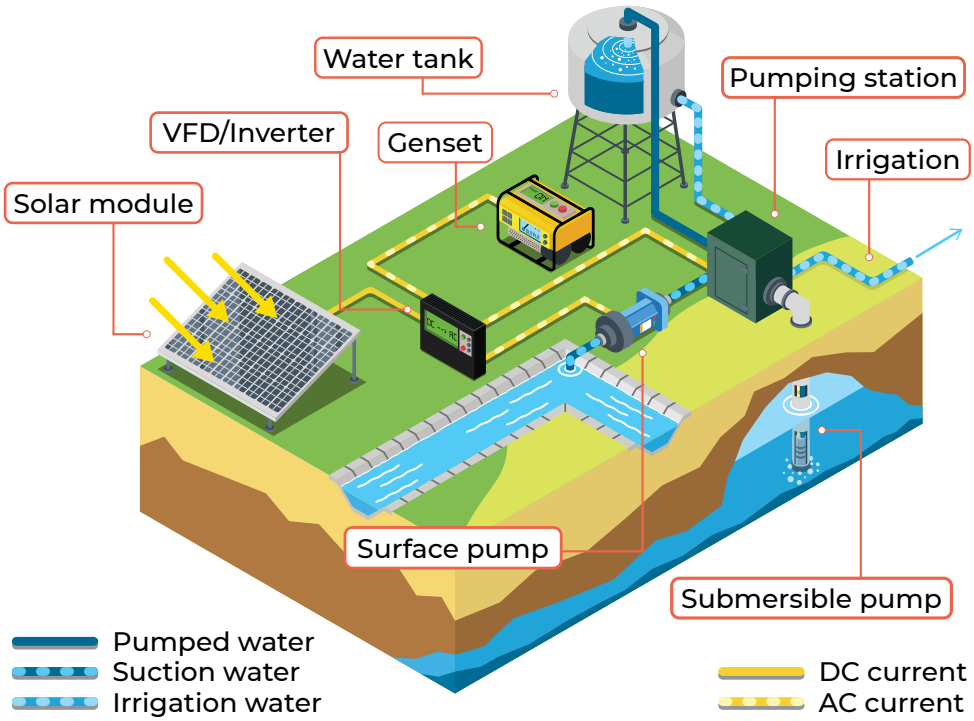


Figure 4. Solar-diesel hybrid solutions.

Source: authors.

Design of solar photovoltaic powered pumping systems

Electricity basics

Before the detailed system design, it is essential to understand the fundamental concepts related to electrical installation, such as energy, voltage, amperage, and resistance.

The capacity of doing work is called energy (Britannica, 2020). It can be solar, electrical, mechanical, chemical, potential, kinetic, thermal, nuclear, or any of the various forms. It is measured in the unit of joule (J). Voltage indicates the electrical potential, i.e. pressure, of systems that drive the electrical current, and it is measured in unit of volts (V). Amperage refers to the movement or flow of electrons, i.e. the electrical current, through a circuit; it is measured in unit of ampere (A). Resistance is the opposition offered by an electrical conductor to the flow of current. It results in an energy loss in the system. Resistance is measured in the unit of ohm (Ω). It is influenced by the length, size, and type of electrical conductor. Specifically, resistance is directly proportional to the length of the wire and inversely proportional to the cross-sectional area of the wire. The wire material also influences the energy loss; a good conductor, such as copper, has a low resistance and less energy loss. Table 1 compares the definitions and electrical concepts in equivalent terms of hydraulics for non-electrical engineers.

ELECTRICITY IN A WIRE	WATER IN A PIPE
Current (A): flow of electrons	Discharge (Q): flow rate of water
Voltage (V): energy potential	Pressure (Pa): energy potential
Power (W): current x voltage	Hydraulic horsepower: Q x pressure
High voltage in small diameter wire: high current (A) and high resistive losses result in heat and fires.	High pressure in small diameter pipe: high velocity and high friction losses result in blown pipes.

Table 1. Electrical definitions in equivalent terms of hydraulics for non-electrical engineers.

Source: authors.

Principles of solar energy

Photovoltaic is a method of converting solar energy into direct current (DC) electricity. It works on the principle of the photovoltaic effect (Rappaport, 1959), i.e. when a solar cell is exposed to sunlight, it absorbs a bunch of light photons (solar energy) and releases free electrons (electrical energy). Solar insolation is the total energy received from the sun in a day by a unit surface area on the earth. The unit of insolation is kilowatt-hour (kWh) per square meter per day.

The solar cell is composed of a P-type semiconductor and an N-type semiconductor. These semiconductors are joined to make a P-N junction or solar cell. Solar light hitting the cell produces two types of charged particles, the negatively charged electrons and the positively charged holes in the semiconductors. The negatively charged electrons gather around the N-type semiconductor, while positively charged holes gather around the P-type semiconductor.

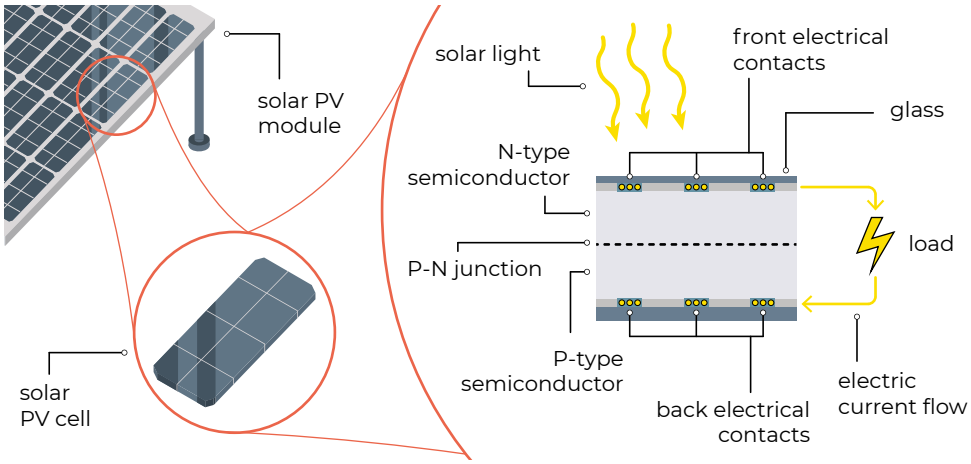


Figure 5. Diagram of the photoelectric effect within a PV cell and subsequent electron motion.

Source: authors.

Electric current flows between the two electrodes when a load, such as a light bulb, is connected across the two semiconductors. In practice, a single photovoltaic cell does not produce enough electricity to power up an electrical appliance. According to the power requirement of an appliance, multiple photovoltaic cells are electrically combined to make a solar PV module, and multiple modules are connected to form a PV array that could be sufficient to power up a water pump.

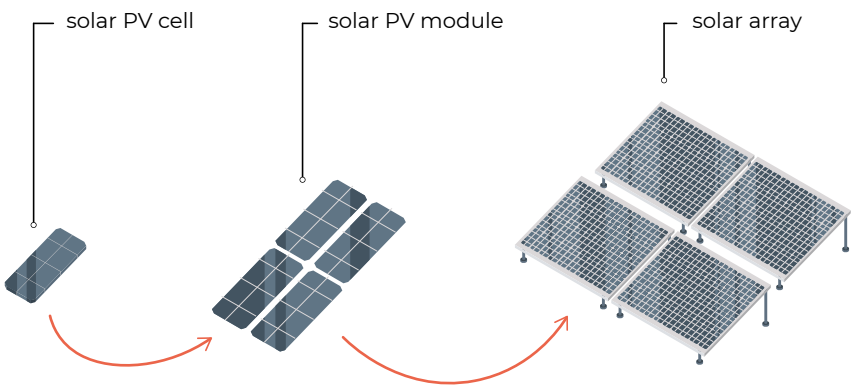


Figure 6. Solar PV cell, module and solar array.

Source: authors.

Solar water pump

A water pump is the most well-known hydraulic machine to the farmers. Pumps are used to lift the water from a deep source such as a groundwater well, low lying water storage, or an excavated canal. In old civilizations, some of the main water-lifting mechanisms were Shaduf, the Archimedes' screw, the Persian wheel and the rope and pully system (Yannopoulos *et al.*, 2015).

With the introduction of mechanical pumps, a large number of farmers across the world started to use electricity and diesel operated pumps, also in line with the objectives of the Green Revolution in the 1960-70s. Later, due to the increasing competition for energy, high cost of operation and large carbon footprint of diesel operated pumps, the solar pumps made their way into the irrigation sector.

Solar PV water pumps were first introduced for water provision in off-grid areas about 25 years ago (Shinde and Wandre, 2015). They utilize the photovoltaic effect of solar cells to produce free electricity, which is used for pumping to provide water for potable use, irrigation, and livestock. Standalone solar water pumping brings apparent benefits to rural areas and remote communities since it can operate autonomously and is generally suitable for the sustainability of boreholes due to its low extraction volumes spread over the hours of sunshine a day.

Standalone solar-powered water pumping brings apparent benefits to rural areas and remote communities.

The improvement in solar technology has helped in developing many different designs with benefits of reduced operational costs, applicability in off-grid locations, reduced carbon footprint, scalability of solar pumping systems, and its ability to be integrated with electricity from other sources to identify the optimal design capacity for a farming system.

Principle of solar water pumping

In solar water pumping systems, solar panels are used to convert sunlight into electrical energy. This electrical energy is then manipulated and used through the pump controller to run the solar pump for lifting water from the source to the desired point of utilization (Chandel, Nagaraju Naik and Chandel, 2015).

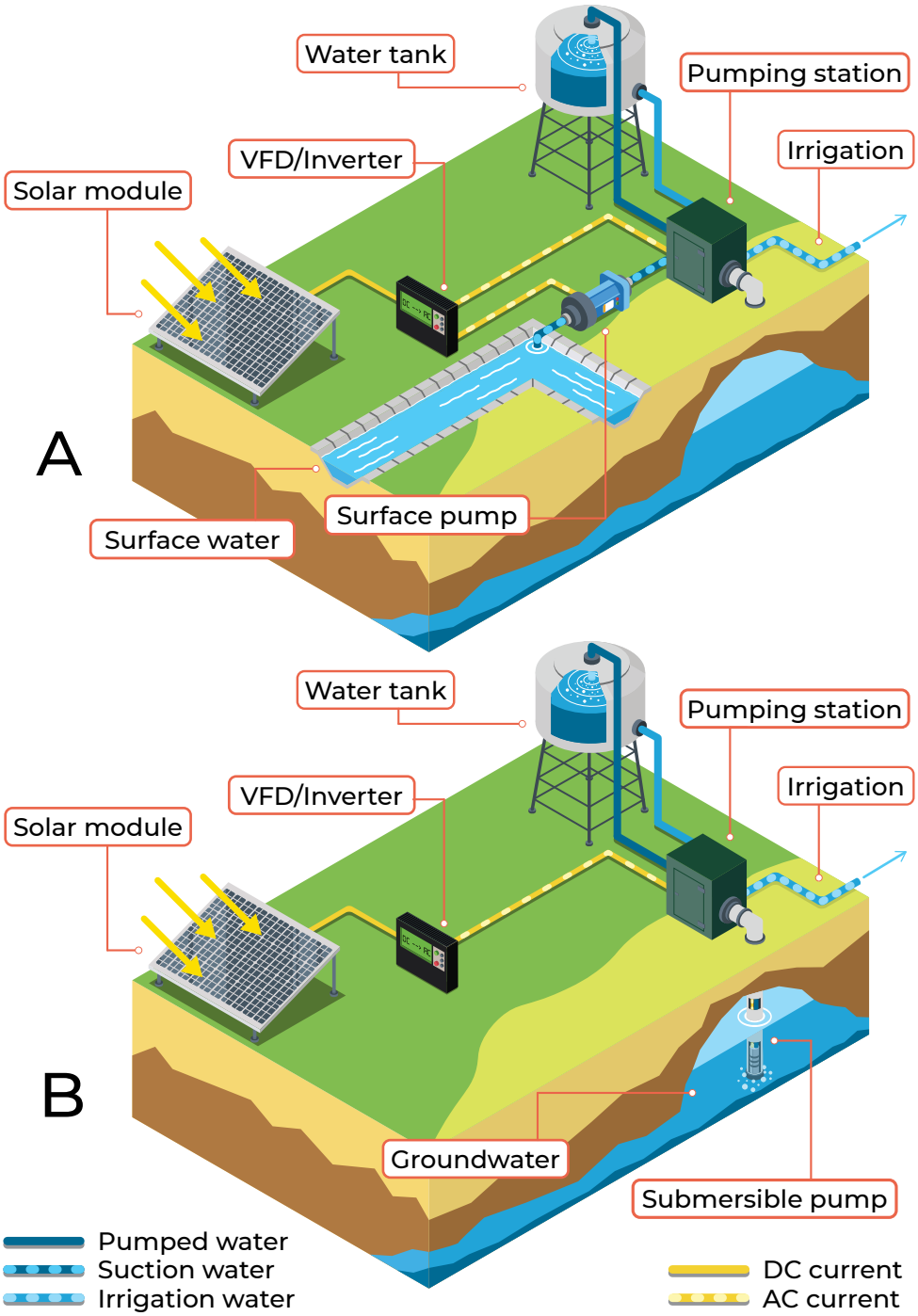
There are two types of pumps widely used in solar water pumping. The selection process depends on the depth and type of water source, the flow requirements, and the site conditions.

- Surface pumps are used to pump water from shallow wells and surface water ponds, streams and reservoirs and provide good delivery pressure, as shown in Figure 7A. They are easily accessible for repair and maintenance, but the selection is restricted by the suction head value of 4.5 to 6.5 m.
- Submersible pumps are used to pump water from deep tube wells where the suction head is greater than the permissible range, as shown in Figure 7B. Submersible pumps are positioned inside the well or attached to a floating platform to pump water from a surface reservoir.

When operated by solar energy, the role of the power control circuitry is to provide the motor-pump set with the most suitable voltage-current combination while ensuring the solar panels operate at their maximum power point.

Figure 7. Schemes illustrating solar-powered surface (A) and submersible (B) pumps for irrigation.

Source: authors.



As a result, the power control circuitry alters the motor-pump impedance to match the optimum impedance of the solar array. In the simplest form, DC electricity is produced in silicon solar cells gathered in modules and put together into arrays. This electricity is provided to a pump that can be either surface or submersible. In terms of electrical current, both DC and AC pumps can be used. In the case of AC, an inverter or pump controller is needed to convert DC to AC. The operation of the pump is controlled by a pump controller that assesses the voltage output of the panels.

During the design phase, the following characteristics of the system need to be defined:

- hybrid or standalone off-grid
- storage availability and capacity
- storage in batteries or elevated water tanks
- type of pump, submersible or surface
- type of power (AC or DC)

Quantifying the available solar energy

Before designing a solar-powered water pumping system, it is needed to quantify the available solar energy on the proposed project site. In this regard, clarification and familiarization with the following definitions of basic terms, in addition to orientation, tilt, and other considerations, is essential.

Solar irradiance

Solar irradiance is the electromagnetic radiation per unit area received instantaneously from the sun, and it is expressed in kilowatts per square meter (kW/m²) and is typically measured at the solar array's surface. Thus, solar irradiance depends on the tilt angle of the solar array, time of the day, the height of the sun above the horizon and the atmospheric condition.

Solar radiation

Solar radiation is the amount of solar energy received from the sun at a given location. This determines how much energy each solar module will generate in a day and the size of the array needed to pump a required volume of water. A site with low solar radiation levels needs a larger array than a site with high solar radiation levels. It is commonly expressed in kilowatts per square meter (kW/m²). The intensity of sunshine (i.e. solar radiation) varies based on geographic location, seasonality, time of day, project area topography and weather condition. A good analogy to describe this variation is the different conditions found on the north slope versus its south slope.

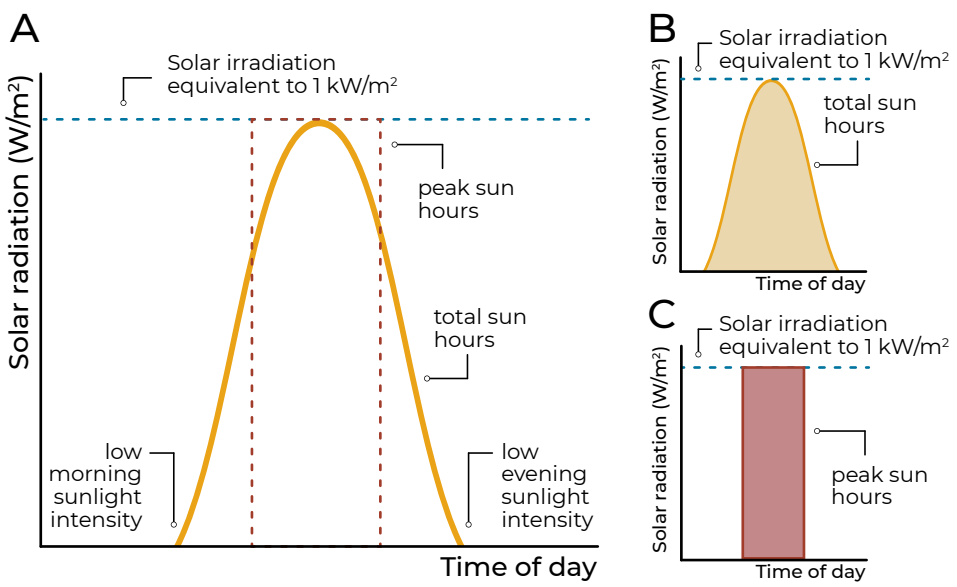


Figure 8. Daily shine profile (A), total sun hours on a horizontal surface (B) and its equivalence as peak sun hours (C). The colored area under the curve (B) and rectangle (C) are equivalent and represent solar insolation.

Source: authors.

Solar insolation

Solar insolation is the amount of solar irradiance measured over a given period of time. It is typically quantified in peak sun hours, the equivalent number of hours per day when solar irradiance averages 1 kW/m². It is important to note that although the sun may be above the horizon for 14 hours at a given location in a day, it may only generate energy equivalent to 6 peak sun hours. The project site's latitude and the PV array's proposed tilt angle affect the solar insolation.

Azimuth and zenith

Azimuth is the horizontal angle in degrees with respect to the true north. In the earth's northern hemisphere, a solar panel facing the true south has an azimuth of 0°. The azimuth angle is counted positive in a clockwise direction from the true north and vice versa in a counterclockwise direction. The zenith angle is the angle subtended by the sun disc and the horizon at the point of observation or location of the solar panel. Zenith or solar elevation is 0° at sunrise and sunset and 90° at midday.

Orientation

In order to maximize the performance of solar panels, it is essential to install them at an azimuth of 0° (facing true south). An acceptable tolerance of ±15 degrees in azimuth does not significantly affect the performance. For applications needing more solar energy in the morning than in the afternoon, a slight shift in the azimuth towards the east is practical to receive the sunshine as early as possible.

Tilt

The solar panel can get the best out of the solar radiation when its surface receives the solar rays at a perpendicular angle, allowing for a maximum solar radiation density per unit area. The sun path varies from day to day during a year, being at higher levels during the summer and lower during the winter with the horizon.

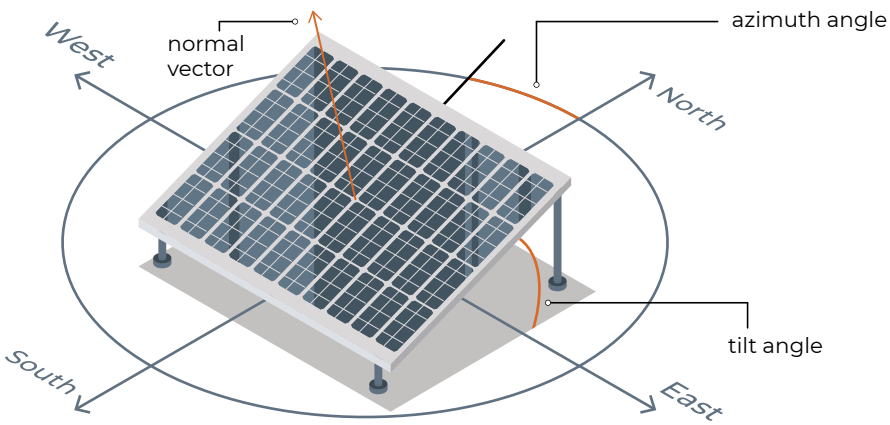


Figure 9. Orientation, positioning and tilt angle of a solar panel.

Source: authors.

The ideal solution would be changing the tilt angle on a daily basis to match the solar irradiation angle, but since this is not a practical solution, the optimum tilt angle should be decided according to the project requirement. For instance, in applications demanding maximum power production in winter, there is a tendency to go above the average tilt angle to guarantee the best performance.

Other considerations

In order to make solar PV pumping a viable solution, several considerations need to be made, especially in the case of irrigation. The following factors should be considered when designing an array to meet the electricity needs of water pumps:

- electrical characteristics such as the I-V curve and the maximum power point;
- operating conditions and the effects of solar irradiation levels and temperature;
- configuring an array, i.e connecting modules in series and parallel;
- datasheet values and ratings of a PV module;
- efficiency and power;
- composition and types of solar modules;
- solar array positioning considering the movement of the sun;
- solar array location considering shading of trees and buildings;
- solar array output, i.e system yield according to solar resource; and
- solar insolation availability, pumping time, static water level, pumping subsystem efficiency.

These considerations make PV water pumping a competitive and practical solution compared to conventional diesel or grid-tied systems.

Components of a solar-powered pumping system

A solar water pumping system essentially consists of the following main components, shown in Figure 10:

- solar modules
- pump controller
- solar pump
- battery bank
- delivery point
- water source

Solar modules

The heart of a solar PV pumping system is the solar module that receives sunlight and converts it into electrical energy. A solar module consists of individual solar cells electrically connected to increase their power output. As shown in Figure 11, solar PV modules are exposed to sunlight to produce DC electricity. They can be interconnected in series or parallel to make solar arrays, which are used to reach the desired values of voltage and current.

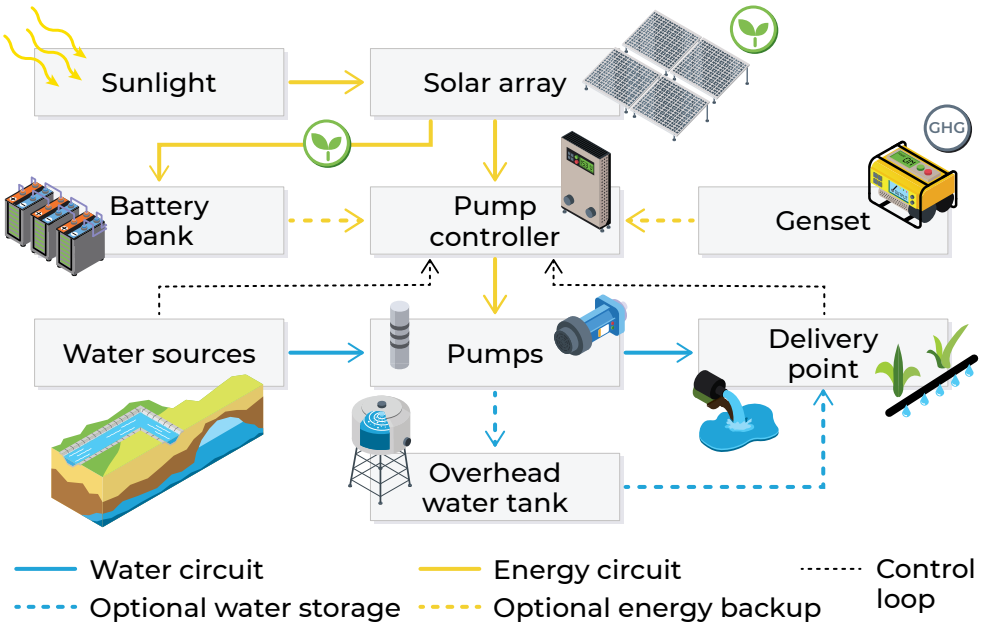


Figure 10. Components of the solar water pumping system and their interconnections.

Source: authors.

The power capacity of a PV module is measured in watts peak (Wp). PV panels are rated according to their output based on an incoming solar irradiance of 1 kW/m^2 at a specified temperature. Panel output data include peak power (Wp) in watts, voltage (V) in volts and current (A) in amperes.

When multiple panels are wired in series, the total output voltage is the sum of the individual panel output voltages; the total current stays the same. Conversely, when panels are wired in parallel, the voltage stays the same while the resultant total current is the sum of the individual panel current outputs. The total power output from a PV panel array is determined by multiplying the total output voltage by the total output current. The power output can vary by ±5 W from the rated PV panel power.

Figure 11. Solar modules in FAO´s Al-Afir irrigation project in the Nile delta, 2017.

Photo credit: FAO/Ahmed Abdelfattah.

The following terms are essential to understand the specification of solar panels:

- I_{mpp} (maximum power point current): the current produced by the solar panel when its power output is the greatest under standard test condition (STC).
- V_{mpp} (maximum power point voltage): the voltage produced by the solar panel when its power output is the greatest under STC conditions.
- I_{sc} (short circuit current): the short circuit current when the solar irradiance exceeds 1 000 W/m^2.
- V_{oc} (open circuit voltage): the open-circuit voltage or the maximum voltage that solar panel can produce at no load during the STC condition.
- Peak sun hours: the number of hours when the site receives an irradiance of 1 000 W/m^2. During these few hours, the solar panel is sized to overcome all the derate factors and operates the pump at maximum speed and a maximum frequency of 50 Hz and minimum frequency of 30 Hz. Even during sunrise and sunset, the pump works with the maximum frequency but limited current.
- Temperature coefficient: the percentage of power drop per degree rise in temperate from the STC conditions, i.e. 25 °C.
- Cell maximum voltage: the maximum number of solar cells installed in series to produce 1 000 VDC according to the International Electrotechnical Commission (IEC) and 600 VDC according to underwriter laboratories code (ULC).
- Full current intensity - voltage characteristics (I-V curves): the relationship between current and voltage developed at 25 °C for a minimum of four different levels of irradiance between 200 W/m^2 and 1 000 W/m^2.

The electricity produced by a PV module is characterized by the I-V curve, which depicts the relationship between the current (I) and the voltage (V) of the solar cell , as shown in Figure 12. For a given set of operating conditions, the PV module can be manipulated at any point along the I-V curve, i.e for every operating voltage there is a corresponding current output. PV modules are composed of PV cells electrically connected and sandwiched between a backing sheet and a glass front, with transparent glue holding it all together. Most modules have an aluminium frame that provides mechanical protection to the modules. Based on the nature of PV cells, three main types of solar modules are available commercially, namely monocrystalline, polycrystalline, and thin film.

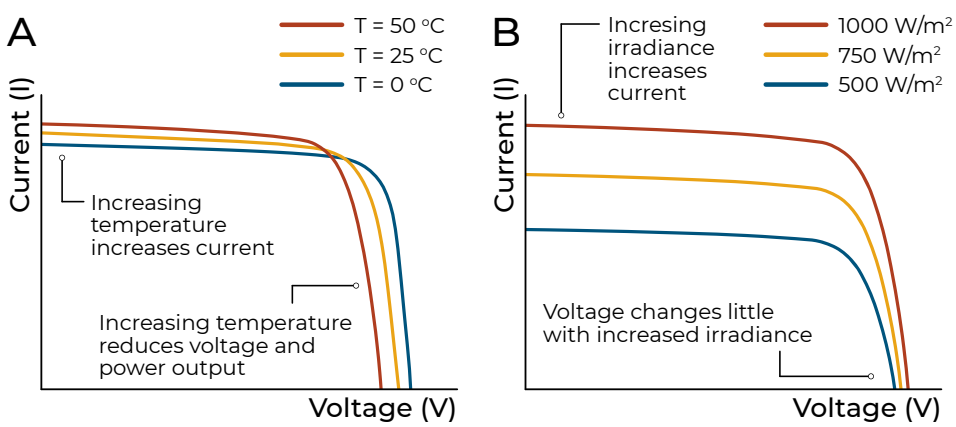


Figure 12. Temperature effect on I-V curve of a PV module.

Source: authors.

On the other hand, higher module efficiencies can be achieved by combining products that have recently appeared on the market, such as amorphous silicon deposited on a single-crystalline substrate. These high-efficiency modules may be a good choice, mainly if the area available for the installation is limited. The warranty of silicon PV modules is typically over 20 years, indicating a PV module's robustness. The modules are expected to produce 90 percent of the rated output for the first 10 years and 80 percent of the rated output up to 25 years during the warranty period.

Pump controller and inverter

The pump controller links the motor pump to the solar modules and is essential for system reliability. Pump controllers and safety devices are incorporated into PV-powered water pump systems to adjust the output frequency of PV modules and control the DC electric power input to the pump. They also play a critical role in protecting the system by turning it off when the voltage is too low or too high compared to the operating voltage range of the pump. This system controls when and for how long the pump operates. This function can be activated electronically through a programmable device or by a float switch sensing the water level on the water source side, e.g. storage tank.

The PV array control component optimizes electricity production from solar energy and matches it to the motor pump requirements. The performance of the pump controller varies according to the selected type. A PV system may incorporate a battery bank that can be charged when incoming solar energy exceeds the pumping power requirement. The battery bank can then be used to run the pump in off-peak sun hours or on an overcast day.

A more sophisticated device may incorporate a maximum power point tracker (MPPT) in addition to the functions explained previously. The MPPT converts the DC power produced by the solar array to match the voltage and current requirements of the operating solar pump. The MPPT ensures that the pump operates at its maximum performance level even on a cloudy day. Without an MPPT, the PV array would need to be oversized so that it can provide the start-up current requirement of the motor even though, once the motor has started, the pump's current requirements drop and, at that point, the array can then produce more power than is needed.

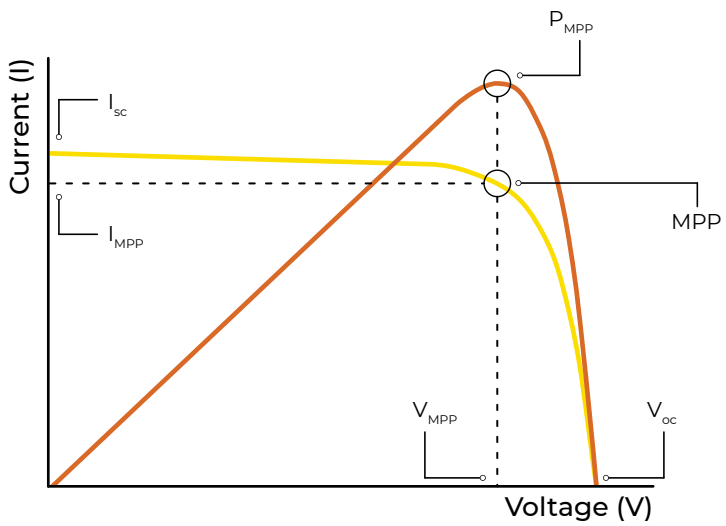


Figure 13. Maximum power point curve.

Source: authors.

An inverter is used in the system where AC power output is needed. The input rating of the inverter should never be lower than the total power requirement of appliances. The inverter must be large enough to handle the total amount of Watts needed at one time. The inverter capacity should be 25-30 percent larger than the total power requirement of the pumps.

Solar water pump

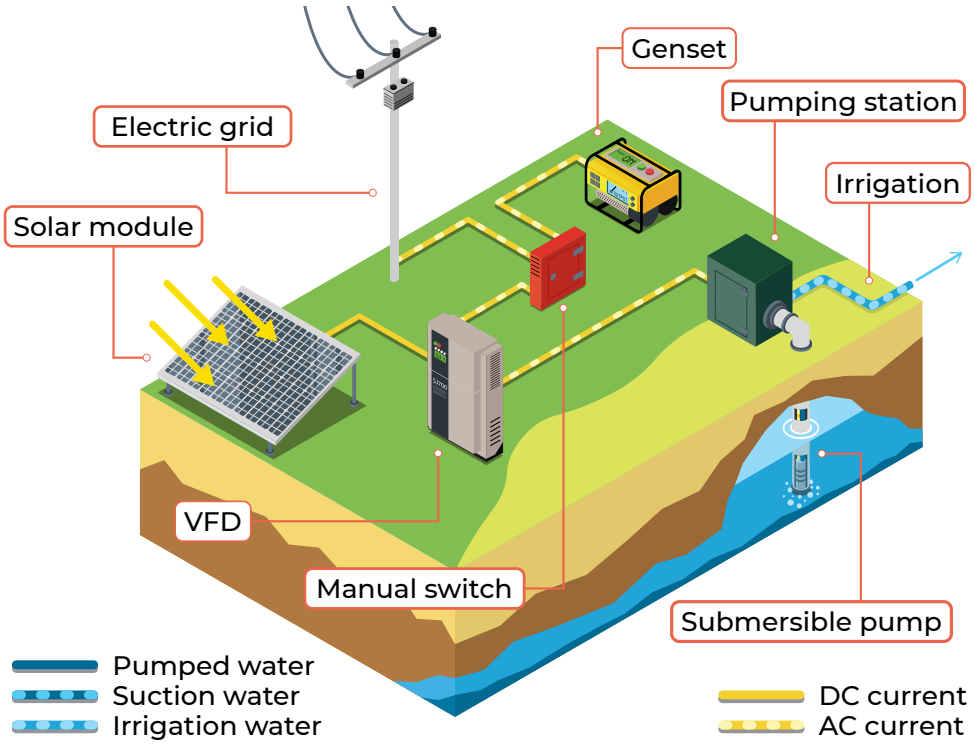


Figure 14. Diagram of solar water pumping with an SJ700 VFD Hitachi controller installed at FAO's Al Ghadeer Al Abyad project in Jordan.

Source: authors.

The solar water pump selected for a particular application must be compatible to move the required quantity of water (flow rate) from the source over the required distance and vertical lift (delivery point). The pump shall also be compatible with the power source. Depending on the water source, the pump configuration and mounting can either be submersible, surface mount or floating. Table 2 presents suitability criteria that may be used as guidelines for the selection of an appropriate pump.

The selection of the correct pump is a crucial step to achieve maximum performance. The first step before identifying the pump is to know the required flow rate and the maximum system head, including pipe losses.

Table 2. Suitability criteria of different pump types.

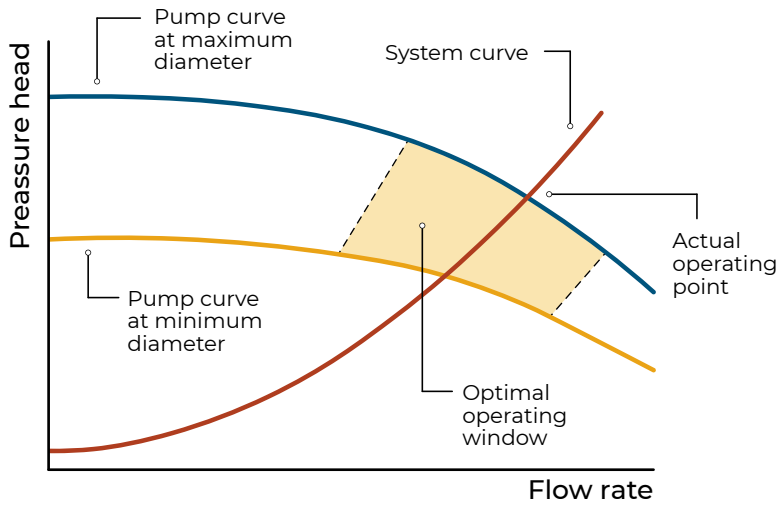
Source: authors.

PUMP TYPES		SUITABILITY CRITERIA
Pump technology	Centrifugal	Fit for applications requiring large flows and small heads. Centrifugal pumps are available for a range of flow/head combinations.
	Helical rotor	Fit for applications requiring low flows and high heads. Helical rotor pumps are available for a range of flow/head combinations.
	Diaphragm	Fit for applications where the fluid being pumped is viscous or the flow rate must be controlled within a precise range.
Pump installation	Surface	Surface pumps have a suction lift limit that must be adhered to. Surface pumps require a solid installation site close to the water source with suitable protection from the elements.
	Submersible, floating type	Floating pumps are floated on the surface of the water source so that the suction lift limit is not relevant. They require mooring to the bank and suitable protection from the elements.
	Submersible, bore type	Bore pumps are specially designed for bores, and a particular pump may only be suitable for a bore of a specific size.

The selection of the pump starts with reading the pump curve, which shows the relationship between the pump flow rate and the pressure head, as shown in Figure 15. Pump curves of different diameter impellers can be drawn on a single graph. The top left of the curve represents the shutoff head where the flow is zero and the pressure is maximum, while the bottom right of the curve shows the runout point where the flow is maximum, and the pressure is minimum. The best efficiency point of a pump lies near the middle of the curve, and the pump operates most optimally in a window of ±30 percent on both sides of the best efficiency point.

Figure 15. Superimposed generic pump curve and system curve to determine the actual operating point.

Source: authors.



The system curve is developed by plotting the system pressure under different flow rates in a specific user application and can be superimposed on the pump curve. On the system curve, the pressure head increases as the flow rate increases. The pump curve and system curve intersection indicate the actual operating point for the specific user application.

The required pump power can be computed by any of the following two methods:

- Using the chart that relates flow rate, pressure and required pump power. These charts are provided by the pump manufacturer.
- Calculating it following Equations 1-4. This method calculates water and motor horsepower from total dynamic head, flow rate, water specific gravity and pump efficiency.

$$P_{whp} = TDH \times Q \times SG / 3960$$

Equation 1

Source (all equations): Beverly, 2009.

Where: P_{whp}: water horsepower, hp
TDH: total dynamic head, ft
Q: flow rate, gal/min
SG: water specific gravity, lb/ft^3

$$P_{mhp} = P_{whp} / \eta$$

Equation 2

Where: P_{mhp}: motor horsepower, hp
P_{whp}: water horsepower, hp
η: pump efficiency, fraction

$$Ph_{kW} = (q \times \rho \times g \times h / 3\,600\,000) / \eta$$

Equation 3

Where: Ph_{kW}: hydraulic power, kW
q: water flow, m^3/h
ρ: fluid density, kg/m^3
g: acceleration of gravity, 9.81 m/s^2
h: head differential, m
η: pump efficiency, fraction

$$Ph_{hp} = (q \times \rho \times g \times h / 2\,685\,600) / \eta$$

Equation 4

Where: Ph_{hp}: hydraulic power, hp
q: water flow, m^3/h
ρ: fluid density, kg/m^3
g: acceleration of gravity, 9.81 m/s^2
h: head differential, m
η: pump efficiency, fraction

PV mounting structure

A fixed mounting structure is the most common and reliable way to support the PV arrays. It provides the optimal tilt and orientation angle to the solar array and is generally the cheapest and most sustainable option, which requires minimum maintenance.

The mounting structure holds the PV panels to their mounting posts and reduces the potential for the panels to tip or tilt. The foundation of the mounting structure must be designed according to the local building codes to carry the expected wind and ice loads. All elements of the mounting structure should be anodized aluminium, galvanized or stainless steel and need to be designed to withstand the maximum possible wind load according to the location.

The array's most significant annual power output can be obtained when the solar panels face true south in the northern hemisphere. For installations in the southern hemisphere, solar panels should be oriented true north. True south/north orientation can be helpful, but angle also plays a large part in this parameter and are tilted at an angle equal to the site latitude. However, it may be better to orient and tilt the array to generate more power at times that match the pumping regime, even if it generates less power over the year. To improve the economics of solar systems, panels should face south, as it maximizes yield gains and the employment of battery storage.

There are manual tilting and single or dual axis tracking structures to maximize the annual power output from the solar arrays. This type of mounting structure allows multiple rows of modules to be installed on the ground, a valuable feature in those regions where space constraints may limit the employment of solar-powered pumping solutions. If the water pumping requirement has a seasonal or diurnal preference, for instance, if more water is needed in summer or winter, or at the start or the end of the day, the array's orientation, and tilt should be determined to suit that preference. FAO case studies in chapter 4 elaborate on different types of array mounting structures.

Battery bank

The battery bank is an optional component in a solar water pumping system as it stores the direct current electrical energy for later uses. The battery bank is usually designed according to daily water consumption. Battery banks are measured in ampere-hour (Ah). The size of the bank may vary depending on the needs and the length of the expected power outage. For reference, battery banks for off-grid systems are usually sized for one to three cloudy days.

For systems with battery back-up, particular attention should be paid to the rated voltage of the module, i.e. the maximum power point voltage (V_{mpp}). The module voltage must be high enough to respond to the voltage of a fully charged battery. For instance, rated voltages between 16.5 V and 17.5 V are typically required for 12 V liquid lead-acid batteries. Higher voltages may be required for long wiring distances between the modules, the charge controller, and the battery bank. It is always recommended to refer to the battery manufacturer guide for the charging requirements of batteries.

Figure 17 shows the integration of PV modules and battery backup in powering the pumping unit in a 24 hours period. The PV module can simultaneously deliver power to the pump while charging the battery bank for 8 hours during a 12 hour day cycle, while the battery backup covers the remaining 4 hours of pump operation.

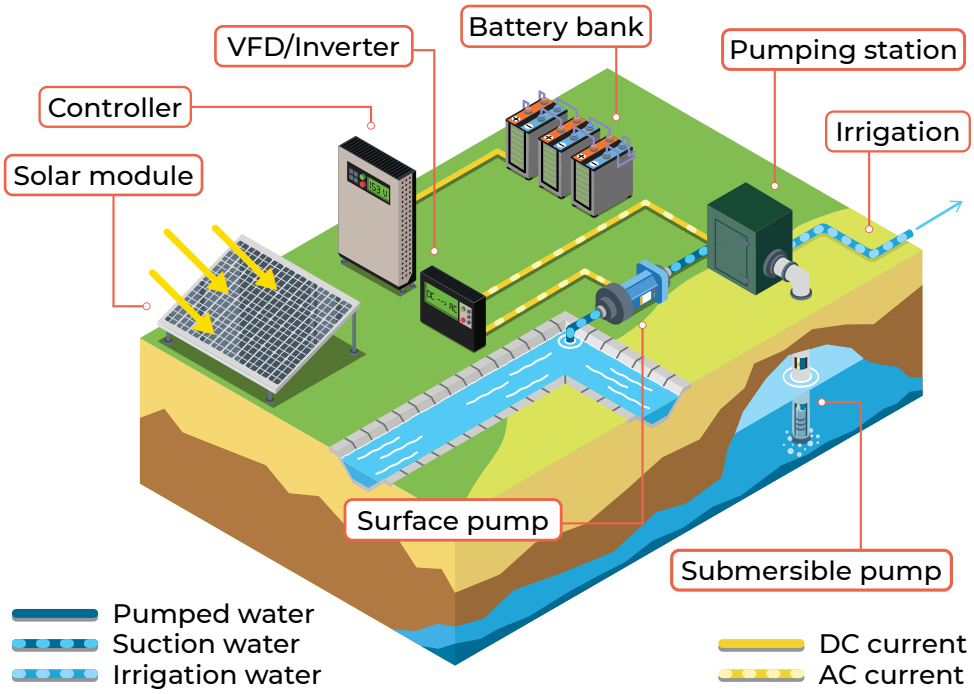


Figure 16. Concept diagram of solar pumping system with battery storage.

Source: authors.

A solar pumping system could also be operated for 12 hours during nighttime with extended battery storage, as shown in Figure 18. In this scenario, the battery bank is fully charged during the peak sun hours and the stored energy is used during the nighttime for pump operation.

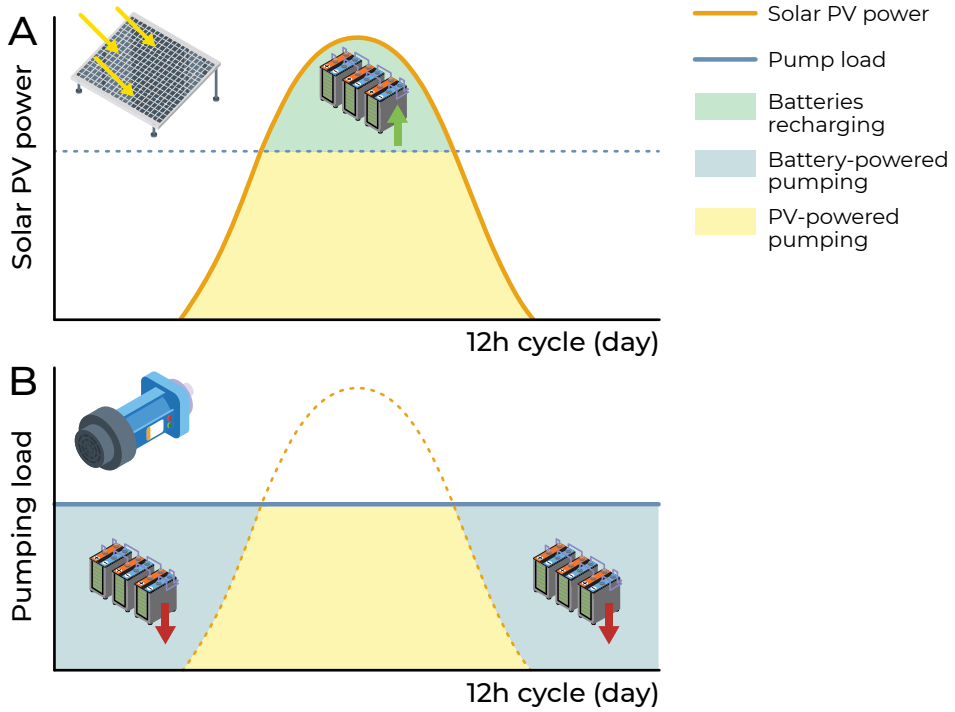


Figure 17. Integration of PV modules and battery backup in powering a pumping operation. Solar PV simultaneously powering the pumping unit and charging the battery bank (A) and 12 hours of pumping operation during daytime (B).

Source: authors.

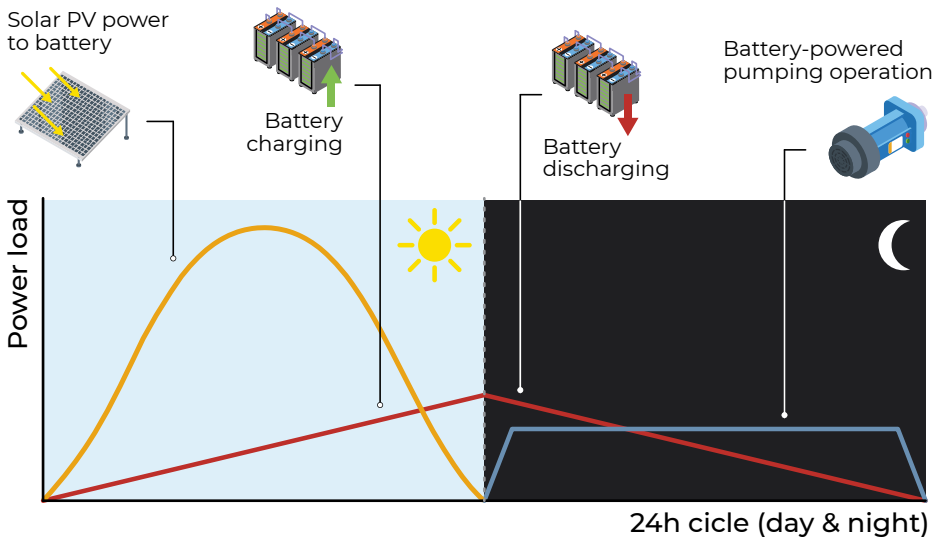


Figure 18. Day charging of battery bank for nighttime pump operations.

Source: authors.

The surplus energy stored in the batteries can be used for other nighttime loads depending on the battery bank size. Battery storage reduces the need for the solar PV system to provide any pumping redundancy as the charged batteries can supply power to the pumping system during low generated power from solar energy. Having battery storage also increases the user's control over the pumping system, but on the other hand, batteries increase the complexity and initial installation cost of the system.

Water source

Water can be pumped from several water sources, i.e. tube wells, surface reservoirs, dams, and deep canals. Depending on the water source, different arrangements for pump installation, pump type and pump horsepower need to be considered. When the total pumping head is very high, it may not be possible to pump water in one stage; therefore, multistage pumping is required. In multistage pumping, water is pumped from the source to the collection chamber of the second pumping station, and from there, it is again pumped to higher levels.

The following distances related to the source of water needs to be determined to compute head losses for selecting a pump type and pump capacity:

- depth from ground to water surface;
- distance from the water surface to the drawdown point;
- distance between the well or pumping station and storage tank; and
- elevation of overhead storage tank above the ground.

Water delivery point

Water in a solar PV water pumping system can be delivered directly to the application, e.g. a drip or sprinkler irrigation system, or delivered to a water storage facility, such as a dam or water tank. The location of the water delivery point forms the head requirement of the pump. The higher or further away from the source of the delivery point, the greater pumping power the system requires to move water from the source to its point of delivery.

A typical configuration for a solar pumping system is to install a water tank at an elevated location. The stored water can be released on demand and gravity-fed as required at the delivery point, which means there is water available even when the solar PV array produces less power than needed. If the tank is not elevated and is unable to gravity-feed water at the required pressure, the system needs additional power to move water from the tank as required.

Daily water requirements

The daily water needs for domestic and agricultural uses determine the overall daily water requirements at a project site. Monthly and seasonal variations should be considered in calculating daily water requirements, as these also affect the pumping system design.

Irrigation hours per day according to the crop type is a significant factor affecting the size of the pumping system, and it also affects the storage capacity of the overhead storage tank to ensure a sufficient and continuous supply of water to the point of delivery, taking into account the characteristics of different irrigation methods.

The location of the water delivery point forms the head requirement of the pump. The higher or further away from the source of the delivery point, the greater pumping power the system requires to move water from the source to its point of delivery, taking into account the characteristics of different irrigation methods.

General approach for designing a solar PV powered pumping system

The general approach and its steps that need to be followed in the sizing process of a new solar water pumping system are:

- Determine the monthly volume of water to be pumped and pump types based on the nature of the water source. A template for volume calculation registration is shown in Table 3.
- Determine the total water demand by studying the consumption pattern and incorporating appropriate size storage in the system.
- Determine the system head and required flow rate and select a pump based on the pump curve.
- Determine peak sunshine hours, consider pump size and study solar insolation map to size the PV generator.

Figure 19 shows the data parameters and their interconnections in the sizing process. It is encouraged to use a general project information sheet as shown in Figure 20 to compile the basic information regarding a solar powered water pumping project.

Figure 19. Data parameters and their relationship for the sizing process.

Source: authors.

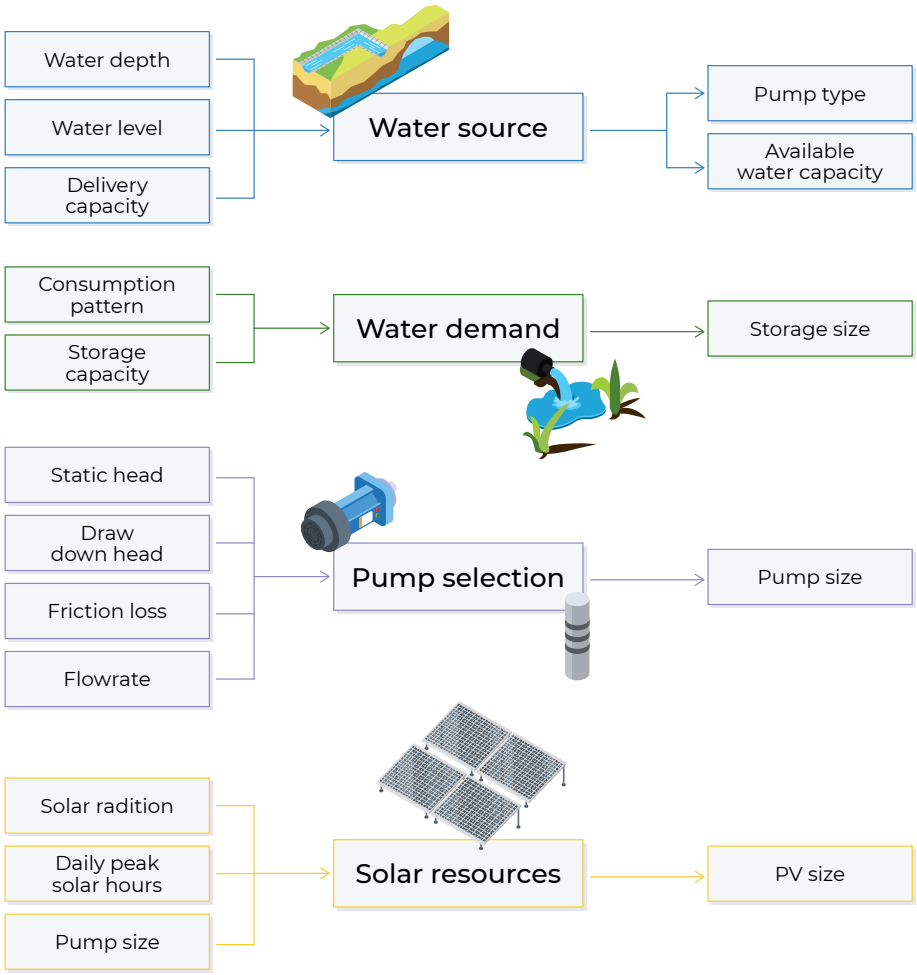


Figure 20. Project information sheet for solar PV powered pumping project.

Source: authors.

Project information sheet

Project name: _____ Country: _____

Location: _____ Latitude: _____ Longitude: _____

Water source: Bore hole diameter (in): _____

Average daily water flow rate (m^3/day): _____ Source type: ☐ River ☐ Pond

Average hourly water flow rate (m^3/h): _____ ☐ Lake

Daily irrigation period per crop type (indicate hours per each segment):

Morning (06h-12h)	Afternoon (12h-18h)	Evening (18h-00h)	Night (00h-06h)

H1 - Ground to water surface distance (m): _____

H2 - Water surface to draw down point distance (m): _____

H3 - Well surface to storage tank distance (m): _____

Irrigation network preassure (bar): _____

Pump till surface - Pipe diameter (in): _____

Pump till surface - Pipe material: _____

Pump - Power(hp): _____

Pump - Rated current (A): _____

Pump - Voltage (V): _____

Pump - Efficiency (%): _____

Motor - Efficiency (%): _____

Motor - Inrush current (A): _____

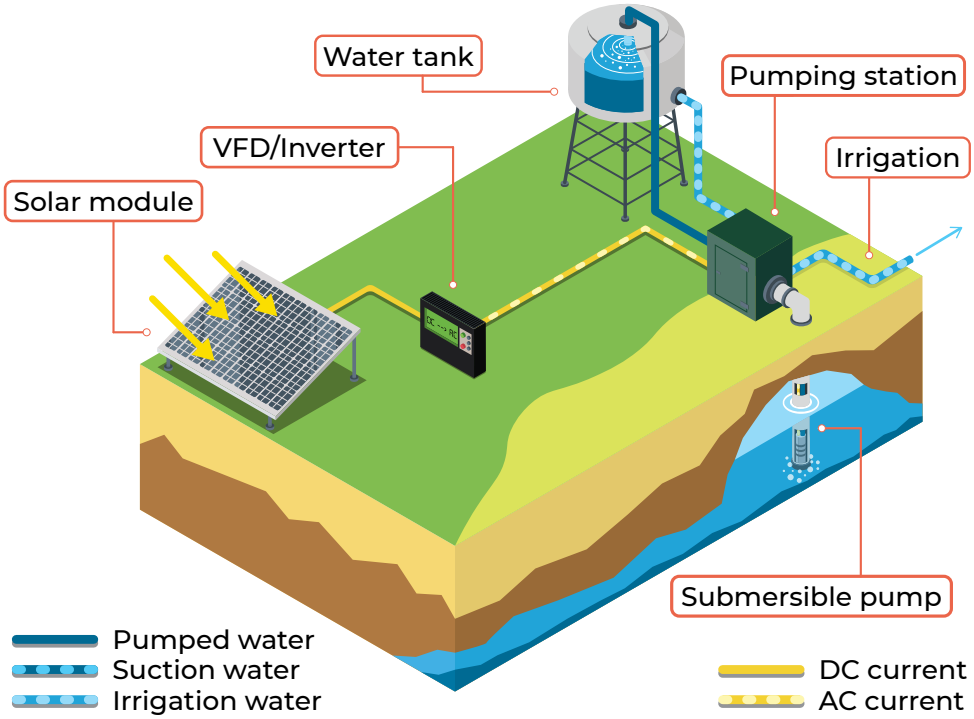


Figure 21. Scheme of a typical solar pumping system.

Source: authors.

MONTH	AVERAGE DAILY WATER REQUIREMENT (m^3)	MONTH	AVERAGE DAILY WATER REQUIREMENT (m^3)
January		July	
February		August	
March		September	
April		October	
May		November	
June		December	

Table 3. Template for average daily water requirements by month.

Source: authors.

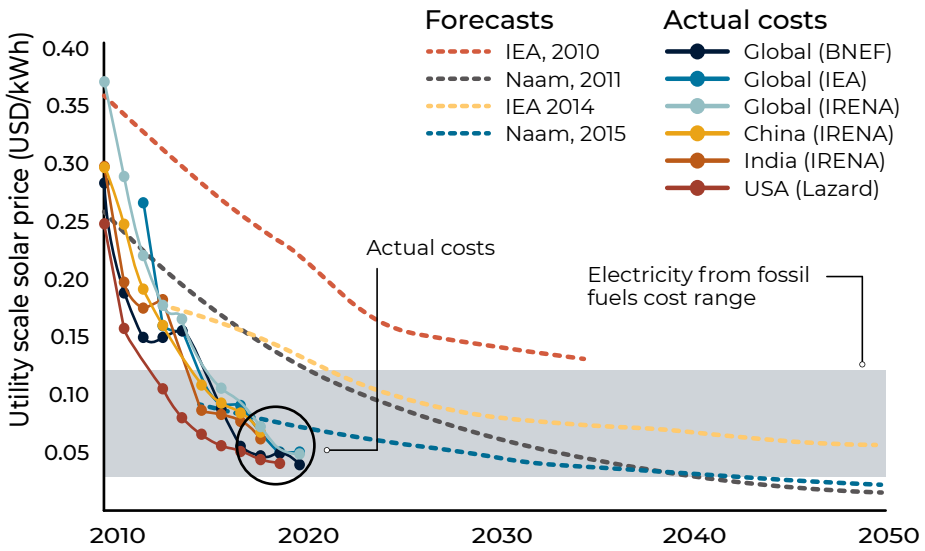
System economics

The comparative advantages of solar energy and its large-scale adoption significantly impact the price per kWh of energy supply (Liu, 2018). The actual reduction in cost per kWh has been faster during the last decade as compared to credible forecasts due to an improvement in solar technology and increased manufacturing capacity of solar systems, as shown in Figure 22.

The information and cost breakdown shown in Figure 23 are general guidelines derived from FAO's projects data in Africa and the Near East regions. It is recommended that for economic analysis and project planning of a solar water pumping system, the user should consider the volume and timing of water demand (demand hydrograph) and the availability of various components of a solar system in the local market.

Figure 22. Forecast of the price per kWh of solar energy versus the actual cost of energy supply.

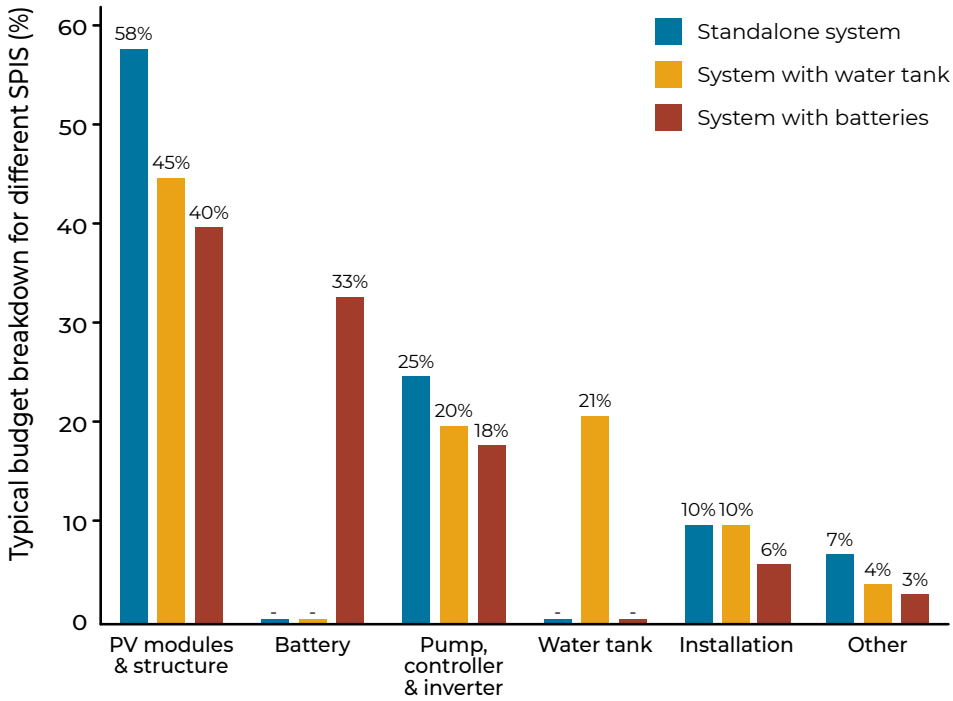
Source: adapted from Ramez Naam, 2020.



During the operation of solar water pumping systems, it is also found that around 30 percent of the PV solar systems could face several risks and flaws during the design, implementation, and operational life of the project that could lead to the loss of investment. These risks should be avoided to minimize the opportunity cost of the project operation. Figure 24 shows the breakdown of such flaws in a number of FAO's projects in Africa and the Near East regions.

Figure 23. Budgetary breakdown of FAO's solar system for irrigation in Egypt, Jordan, and Uganda with different components, analysis period 2018-19.

Source: authors.



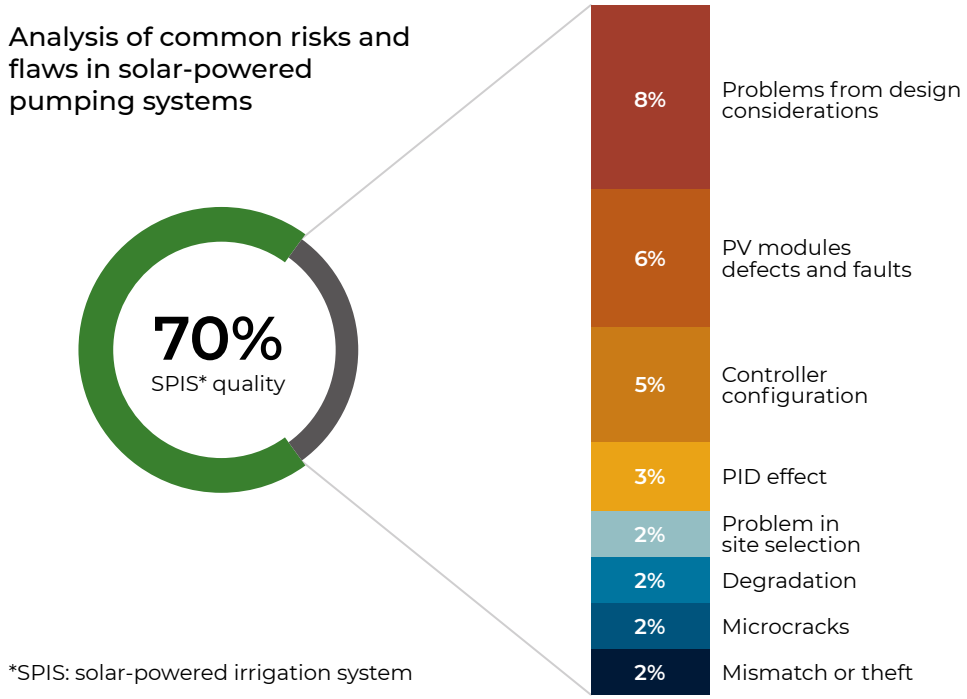


Figure 24. Analysis and characterization of risks and flaws in solar powered irrigation system, analysis period 2018-19.

Source: authors.

Comparison between solar and diesel pumping

There are apparent differences between solar and diesel-powered water pumping systems in terms of cost and reliability, as seen in Figure 25.

Solar systems have higher capital costs while diesel pumping has significantly higher operating costs over the life of the system. Diesel pumps are typically characterized by a lower initial investment but a very high O&M cost. Solar-powered systems, on the opposite, require higher initial investments but have very low O&M costs.

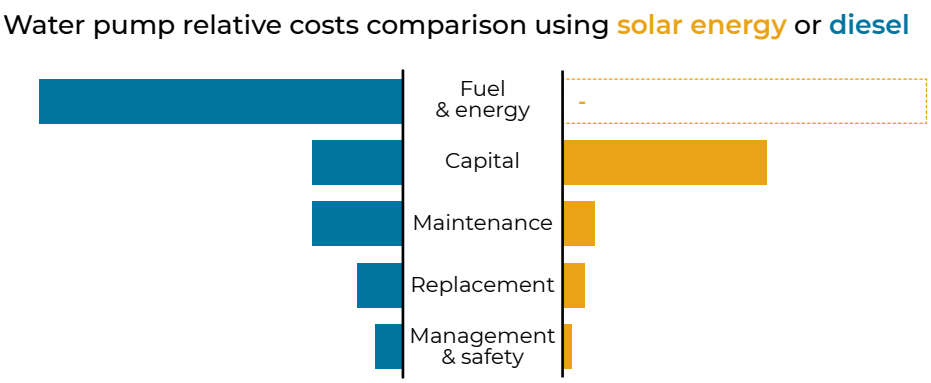


Figure 25. Comparison of costs associated with the installation, operation, and maintenance of solar and diesel-powered pumping systems.

Source: authors.

Operation and maintenance overview

An overview of the operation and maintenance (O&M) services for a solar PV powered pumping systems is provided in Figure 26, while a selection of applicable standards is shown in Figure 27. Effective operation and continued maintenance are critical measures to ensure the solar water pumping and system longevity and optimal performance.

Preventive maintenance shall be performed per the defined checklists and equipment maintenance recommendations through monthly, quarterly, half-year and yearly inspections.

All health, safety and environment requirements are to be followed during any inspection and maintenance activities at the site. Preventive maintenance shall be carried out as per the preventive maintenance schedule defined by the O&M team.

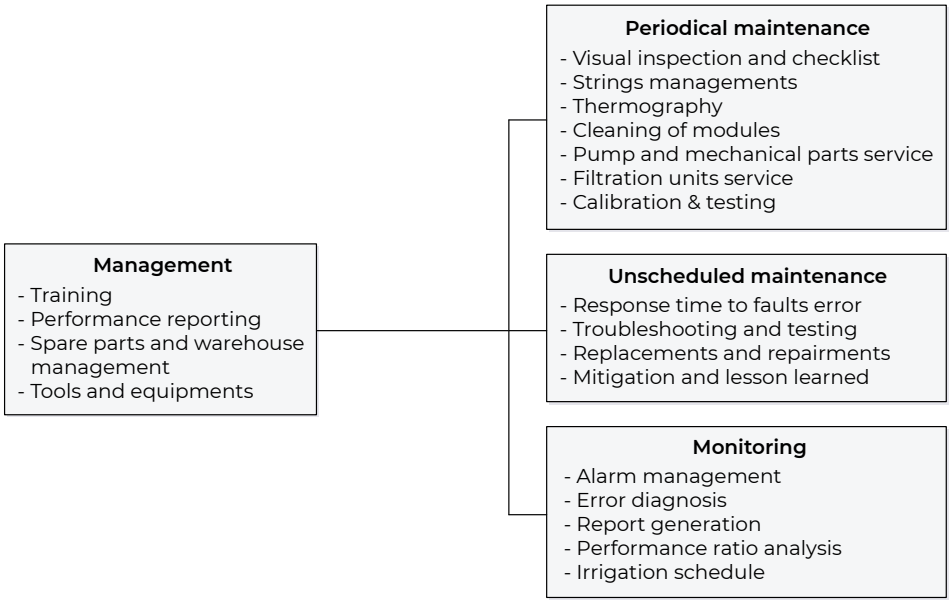


Figure 26. Operations and maintenance overview.

Source: authors.

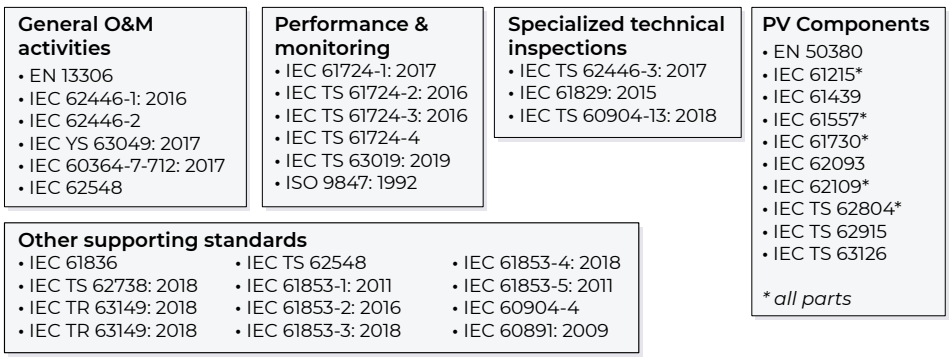


Figure 27. Overview of a selection of applicable standards for O&M (valid as of 2019).

Source: authors.

Operation of solar photovoltaic powered pumping systems

An essential part of operations is the analysis of all the information collected throughout O&M, such as response time, and how this links to the various classification of events and root cause analysis (RCA).

Another vital part of operations is the analysis of costs occurred during various interventions, categorized into materials and labour. Having such information helps to further optimize the asset by reducing production losses and the cost of O&M itself.

System operations

The O&M of the PV solar power pumping system deals with the day-to-day power generation activities, interconversion between DC/AC, identification and rectification of system faults, and electrical power transmission to run water pumps. The system's operational performance is monitored continuously to reduce downtime and produce the guaranteed output sustainably. Table 4 outlines the necessary features of an operation strategy of a PV solar power system.

Capacity building of the plant operators and maintenance crew is a vital activity.

Training and toolbox talk

Capacity building of the plant operators and maintenance crew is a fundamental activity. The solar power plant O&M manager should regularly arrange refresher courses, lectures, and toolbox talks to ensure that the project staff follows the required safety procedures during O&M. These courses and lectures should cover essential topics such as:

- dangers of DC and AC electricity;
- safe handling when cleaning PV modules;
- importance of staying warm in the winter and hydrated in the summer;
- importance of wearing Personal Protective Equipment (PPE);
- handling and lifting heavy weights;
- emergency response procedures; and
- handling fire extinguishers in case of a fire.

Everyone who enters a solar plant needs to be aware of potential dangers and training should be carried out to strengthen skills and capacities on individual tasks, taking into account faults levels and troubleshooting as shown in Figure 28. Awareness of the necessary health and safety regulations is mandatory.

Table 4. Operating strategy of a PV solar system.

Source: authors.

ACTIVITY	DESCRIPTION
System performance monitoring	The operational performance of the system devices shall be regularly monitored. Any shortfall in power generation capacity and notification of faulty devices shall be reported with an alarm. The reported notification is then sent to the operations contractor or manufacturer to initiate appropriate maintenance or action.
Monthly reporting	The system operations team shall provide monthly performance reports including: • actual electricity produced by the system; • frequency and duration of the outage; • cleaning report; • summary of preventive maintenance of each equipment with detail of executed measure; • summary of corrective maintenance of each equipment with details of the defect and executed rectification measures; • summary of emergency response; • summary of monthly weather reports; • summary of the spare parts replaced and the actual status onsite; • extraordinary events and site observations with photo evidence; • overall summary of corrective actions reported by the O&M technicians; • duration of pumps operation; • availability of water in the overhead storage tank or surface reservoir; • status and number of open valves; and • recommendations for the next reporting period. The operator shall archive the following operations data for further analysis and studies. A summary of the data is also included in the above report, indicating: • frequency and nature of faults and errors that took place; • download energy data of each VFD for the month. • records of total pumps operation duration; • records of filtration unit pressure; and • records of system outage duration and the opportunity cost of energy which was lost.
Annual reporting	Preparation of annual report detailing system performance for the full year including performance calculations, total energy yield, peak power, frequency and duration of outages, performance ratio, weather conditions, amount of pumped water, health and safety and general summary of main preventive and corrective maintenance activities.
Other reporting	Operator reports beyond the monthly and annual performance reports include the following: • records of activities performed at the site, i.e. time keeping of operators working hours, on the spot modules cleaning activities, etc. • fault analysis of PV solar system, i.e. the nature of the fault, its cause, effect and mitigation or rectification by the operator.
Disposal of all waste generated from O&M services	The operator shall keep the site clean and regularly dispose of the collected or generated waste through the O&M operations, i.e. empty cardboard boxes of equipment, wooden pallets, packing material etc. Therefore, as an option, the wastewater generated from the cleaning of modules should be collected in a tank and disposed of appropriately according to the local environmental laws.

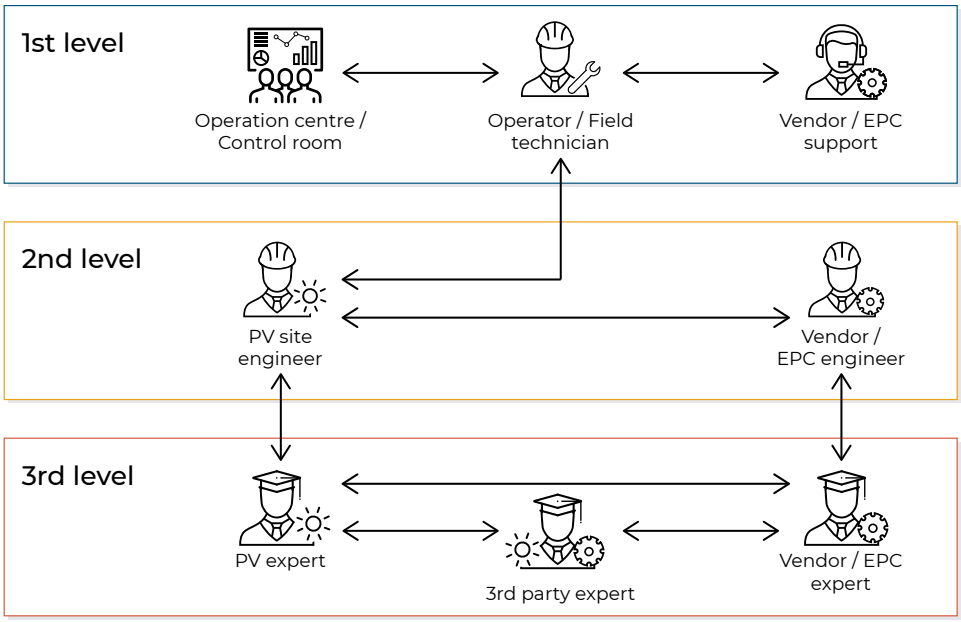


Figure 28. Support levels in fault and troubleshooting management.

Source: authors.

Cleaning arrangement

Regular cleaning of solar panel modules is performed to maintain an acceptable limit of soiling losses in a solar-powered pumping system. Specialized PV module cleaning brushes should be used for this purpose, such as rotary brushes designed to dry clean. Wet cleaning cycles should be used on a need basis – after a dust storm, a stubborn build-up of birds dropping, or whenever plant material is detected. An optimized cleaning schedule should consider different seasons and site conditions to plan a cleaning cycle.

Box 1. Standard operating procedure for the cleaning of PV panels.

The following points should be considered while planning a cleaning activity:

- Cleaning should not be performed with bare fingers or hands; touching or handling the glass surface of modules without gloves could result in skin burns, broken glass and exposed solar cells that may cause injury or electric shock.
- Only soft materials should be used for dry-cleaning the PV modules, such as soft sponges, soft brushes, microfiber cloth and hairbrushes.
- Abrasive cleaning products or chemicals should not be used to clean the PV modules.
- Soap may be used. However, it is not recommended since the PV module builds up a layer of grime.
- Pressure water cleaning should not be used.
- Cleaning broken PV modules should not be attempted as it may cause electric shock or increase micro cracks.

An ideal cleaning cycle can be developed during the first year of operation when the deposition pattern of dust in the project area is understood. However, different cleaning cycles can be considered for different zones of an extensive solar system by considering varying soiling levels.

Wet cleaning

Wet cleaning of PV modules should be planned with the agreement of project beneficiaries and end-users. The water used for the cleaning should have a pH of greater than 5.5 and less than 8.5, while the total hardness of the water should be less than 450 mg/L, subject to requirement by the module manufacturer. It is recommended to purchase a water tanker if the locally supplied water does not meet the above specifications. The water should be tested during the delivery and before refilling the water tank to determine if it can be used or rejected.

Litmus test strips and a handheld salinity meter can be used to determine the water's pH and total harness levels, and the results should be documented in the delivery log. Wet cleaning may be used less frequently or in unavoidable circumstances, as mentioned above. The module should be cleaned with a non-abrasive wet mop and wiped using a microfiber cloth to avoid scratches. If necessary, the module may be cleaned with a commercial non-corrosive glass cleaner along with a non-abrasive sponge or microfiber cloth.

Dry cleaning

Deposits such as accumulated dust on the module surfaces should be swept off with a dry brush having soft bristles. This method uses extendable telescopic handles with soft-bristled brushes at the ends, and proves very effective in eliminating dust, although time-consuming. It is recommended to use this method to reach areas that have not been cleaned properly.

Figure 29. Manual dry cleaning of solar PV.

Photo credit: © Winaico

The following steps should be followed to dry-clean the PV modules:

- slowly laying the telescopic brush on the top module to avoid hard impact;
- using hands, sliding the telescopic handle backwards with slight pressure to brush off dust; and
- moving to the next section by slowly shifting the soft brush diagonally to the next module.

Cleaning frequency

The cleaning frequency depends on the season and environmental conditions of the site. The project operation team should frequently assess the soiling levels in order to vary the cleaning schedule based on the recommended energy drop.

Cleaning should commence once the following energy loss is met (clean reference energy – dirty reference energy > 2.0 percent). On average, a cleaning of the entire site, using appropriate resources, should be planned at least 12-15 times a year.

The cleaning frequency can be adjusted to achieve the guaranteed power output. In addition, regular on the spot cleaning with the help of manually operated telescopic mops is foreseen. This method ensures that no hard dust, bird droppings, or stubborn stains develop on the PV modules and maintains modules clean in order to avoid any hot spots or efficiency drops in the system's performance.

Figure 30. Training session on the cleaning of PV modules for the beneficiaries of FAO's Al-Afir project, El- Behiera Governorate, Egypt, 2017.

Photo credit: FAO/Ahmed Abdelfattah

Cleaning of facilities

It is recommended that the cleaning crew cleans the system control building and water filtration house at least once a week, including the lighting system, to keep a clean environment. Table 5 provides information on the cleaning cycle of different parts of the system facility.

Table 5. Cleaning cycle of system facilities.

Source: authors.

FREQUENCY	ACTIVITY DESCRIPTION
Pump controller - Inverter - VFD room inspections	
Monthly	**VFD 1.** Visually confirm that all indoor ceiling lights are operational inside the rooms.
	VFD 2. Inspect and verify that doors open and close properly, the door locks are functioning, and the doors are properly sealed.
	VFD 3. Walk around the room and inspect for any signs of building leakage, fix by waterproofing plaster and paint.
	VFD 4. Check that all conduit covers are in place and properly sealed.
	VFD 5. Check that labels and tags are in place, check for signs of label peeling.
	VFD 6. Check VFD room and clean with brush and vacuum out excess dust.
	VFD 7. Check exterior lighting are operational and clean if necessary.
Quarterly	**VFD 8.** Visually inspect the dust levels on the floor inside the room and clean using vacuum and/or damp cloth if necessary. Avoid liquids from entering the inverter.
	VFD 9. Check rodent and pest control facility and change if required.
Annually	**VFD 10.** Check gutters around roof top to ensure there is no blockage.
Filtration house and steel duct	
Weekly	**FH 1.** Check pressure gauge for all filtration units.
	FH 2. Visually inspect the dust levels on the floor inside the room and signs of no water leak.
Monthly	**FH 3.** Visually confirm that all indoor ceiling lights are operational inside the building.
	FH 4. Check that emergency lighting and emergency exit signs are operational.
	FH 5. Inspect and verify that doors open and close properly the door locks are functioning, and the doors are properly sealed.
	FH 6. Walk around the room and inspect for any signs of building leakage, fix by waterproofing plaster and paint.
	FH 7. Verify that all steel ducts are appropriately sealed and all pipes and conduits are concealed.
	FH 8. Check that all conduit covers are in place and sealed tight.
Quarterly	**FH 9.** Check rodent and pest control facility and change if required
	FH 10. Check the main valves and drainage line
Annually	**FH 11.** Check gutters around roof top to ensure no blockage.

Maintenance of a solar photovoltaic powered pumping system

In order to perform systematics maintenance, a plan on location showing how components and systems must be tested is required. In case of reparation or replacement of any component of the system, ensure it complies with the applicable regulation.

General maintenance procedure

PV solar systems are characterized as "low maintenance" due to the lack of moving parts. However, regular inspection and maintenance guarantee optimum performance. Regular maintenance activities and inspections enable a pre-warning before something can go wrong or might help to find the cause after a failure or malfunction.

The maintenance of the PV solar system can be distinguished between preventive and corrective maintenance. All warning and safety notices posted on the system components must be observed for most issues, including any unscheduled drop-in system performance.

The maintenance philosophy of solar PV is to safely maintain all critical plant equipment and components to increase the overall reliability of the solar power pumping plant. All maintenance activities will be conducted according to IEC 62446, which defines the information and documentation requirements for testing, documentation and maintenance for photovoltaic systems. The annual plan includes regularly scheduled visual, mechanical, and electrical maintenance activities.

Much of the electrical maintenance should be performed during the off hours of the plant to

Box 2. Standard operating procedure when high voltage is present in the system.

Warning! Dangerous voltage or condition may exist.

Levels of voltage may always be present regardless of when the PV panels are exposed to sunlight, and the inverters are connected to the AC. Maintenance of PV system should only be performed by authorized personnel who is knowledgeable on the hazards present in the system.

These rules of working with electrical equipment must always be observed:

- Disconnect from the power supply.
- Prevent reconnection (lock-off).
- Check for the absence of voltage.
- Earth and short circuit (if appropriate).
- Protect from adjacent live parts.

minimize interference with the PV power and water production. Maintenance cycles will be arranged in such a way as to impact as little generation as possible per maintenance cycle.

Lockout procedure

Lockout is an electrical isolation procedure adopted before starting maintenance of an electrical network. The lockout device physically breaks the connection between the energy source and the electrical equipment. It could be a mechanical disconnect switch or circuit breaker. When the lockout is activated, it locks the system in a safe mode. Only qualified personnel using appropriate personal protective equipment (PPE) must perform the isolation work. It is recommended to refer to the user manual of the equipment for specific information or further instructions.

Tagout procedure

Tagout is a labelling process that is always used with the lockout. This process involves attaching information tags or flags to the system under lockout. The tag should have the following minimum information:

- purpose of the lockout, i.e. repair, maintenance or upgrade of specific equipment;
- date, time, and duration of a lockout; and
- name and contact details of the authorized person who requested the lockout.

It must be ensured that the authorized person who applied the lock is the only permitted individual to remove it. This is to ensure that the system cannot be started without the permission of the authorized person to avoid damaged system and personnel injury. The lockout tagout procedure should be applied for all work, maintenance, commissioning, testing of machines and equipment capable of unexpected start-up or release of stored energy.

Notification to concerned parties

All concerned parties that may be affected by the maintenance work shall be notified through appropriate communication channels. Notification must include the purpose of the work, duration of lockout, the area affected by the lockout, instructions on not to remove or bypass locks/tags/lockout devices, and not to attempt to start the machinery or equipment.

Remove lockout

On completion of maintenance activity, all maintenance tools, material, and spare parts should be moved away from the equipment on which the maintenance has been done. The employees performing the maintenance and those affected by the lockout should be notified and the lockout should be removed within the specified time by the authorized personnel.

Energize equipment

With the removal of locks, the repaired equipment should be reenergized from the energy sources, and the machinery should be started when the system is fully energized and stable.

Isolation procedure (lockout) of different equipment

The following warning signs should be observed before approaching any part of the system.

Box 3. Standard display of caution and warning signs.

CAUTION: it is crucial that all warning notices posted on the system components are observed and understood, e.g. the risk of lethal shock from touching electrical components.

WARNING: a solar PV system is an electric power generation system and, as a result, contains current-carrying components which can injure or even kill. Even electric current produced in an environmentally friendly manner can be dangerous.

Isolation procedure of PV string

A set of solar panels or modules are connected by strings in a combiner box to consolidate the generated power. The technician performing the isolation of PV strings must be aware of the electric shock hazard, and he/she must be responsible for ensuring a safe working environment by considering the precautions shown in Box 4.

The technician must consider the presence of electric voltage in the strings even if they are disconnected, or fuses are opened.

Box 4. Precautions for isolating PV strings.

Warning! Dangerous voltage or condition may exist.

Most common hazards:

- Accidental head injury
- Electrical shock or static charge

Safety tools and equipment:

- Arc proof long sleeve
- Clamp meter and multi-meter
- Electrical gloves
- Hard hat
- Nonconductive footwear
- Visor

Safety notes:

- Wear appropriate PPE

The following general procedure for disconnecting the strings should be followed:

- Open the on-load disconnect switch inside the affected combiner box.
- Confirm there is no DC current on the open fuses by placing a clamp meter on the cable attached to them. If the current is zero, proceed to the next step.
- Open all or the respective positive fuse holders in the combiner box.
- Open all or the respective negative fuse holders in the combiner box.
- Lock and tag the on-load disconnect switch at the combiner box.
- Confirm current is zero with a clamp meter on the DC cable of the string to be opened.
- Open the string section where the maintenance is going to be performed on both edges.

Isolation procedure of combiner box

The combiner box is a specialized compartment with an Ingress Protection (IP) coded enclosure to protect its components from weather and ultraviolet radiation. The combiner boxes are installed at the end of every second row of solar modules and are attached to the mounting structure.

Combiner boxes are used to combine the output of several PV modules to consolidate the power generated by them. The consolidated output from the combiner box is then connected to the inverter for manipulation and distribution.

The technician performing the combiner box maintenance must ensure a safe working environment by considering the precautions shown in Box 5.

Box 5. Precautions for isolating combiner box.

Warning! Dangerous voltage or condition may exist.

Most common hazards:

- Accidental head injury
- Electrical shock or static charge
- Hazardous voltage
- Multiple power sources

Safety tools and equipment:

- Arc proof long sleeve
- Clamp meter and multi-meter
- Electrical gloves
- Hard hat
- Nonconductive footwear

Safety notes:

- Wear appropriate PPE

The following general procedure should be followed to perform maintenance of the combiner box.

- Open the on-load disconnect switch inside the combiner box.
- Confirm there is no DC current on the open fuses by placing a clamp meter on the cable attached to them. If the current is zero, proceed to the next step.
- Open all the positive fuse holders in the combiner box.
- Open all the negative fuse holders in the combiner box.
- Open all the string connectors to isolate the combiner box from the solar field and avoid hazardous voltage inside the combiner box.
- Lock and tag the on-load disconnect switch at the combiner box.
- Open the on-load disconnect switch for the rest of the combiner boxes that feed the inverter and lock these on-load disconnect switches.
- Switch off the affected inverter and open the switches on both sides of the inverter, AC and DC, and then wait 10 minutes for the discharge of the remaining currents of the equipment.
- Confirm there is no DC current on the open fuses by placing a clamp meter on the cable attached to them. If the current is zero, proceed to the next step.
- Extract VFD fuses (carefully with a fuse puller) corresponding to the circuit from the affected combiner box.
- Check that there is no presence of voltage in the work area before starting the works.

Isolation of variable frequency drive (VFD)

A VFD is an electrical device used to control the revolution per minute (RPM) of AC motors by changing the frequency of the electrical current supplied to the motor. They are also used to ramp up the motors under heavy loads for a smooth start-up, thus avoiding excessive motor straining.

The technician performing the isolation of VFD must be aware of the electric shock hazard, and he/she must be responsible for ensuring a safe working environment by considering the precautions shown in Box 6.

However, to carry out any maintenance task on the unit involving access to the inside, it is necessary to disconnect the unit and isolate any source of voltage. The following procedures should be followed to disconnect voltage sources safely:

- Turn off the VFD from the integrated control panel. All power modules must be disconnected to cut off the supply of AC power.
- If the unit has an AC disconnection control outside the DC/AC supply module, switch it off and lock it using a consignment lock. Open the thermomagnetic circuit breaker. A sign reading “Do not touch. Personnel at work” should be posted.
- Disconnect the voltage at the central inverter AC supply located in the DC/AC supply module. This action needs to be carried out using an element external to the unit. If it is not possible to disconnect the main AC supply from outside of the unit, bear in mind that the AC connection plates to be live and work must be carried out using the appropriate PPE (dielectric gloves suitable for the working voltage, face shield, safety boots, work clothes, recommended fireproof clothes, etc.).

- Press the emergency stop button. This action causes the motorized DC isolating switch to open. Check that the DC isolating switch changes to the "Off" position after two seconds. If the isolating switch has not moved automatically to the "Off" position, operate it manually.

Box 6. Precautions for isolating variable frequency drives.

Warning! Dangerous voltage or condition may exist.

Most common hazards:

- Accidental head injury
- Electrical shock or static charge
- Hazardous voltage
- Multiple power sources

Safety tools and equipment:

- Arc proof long sleeve
- Clamp meter and multi-meter
- Electrical gloves
- Face shield
- Fireproof clothes
- Hard hat
- Nonconductive footwear
- Visor

Safety notes:

- Wear appropriate PPE

Preventive maintenance

Preventive maintenance of the solar system is a maintenance strategy that prevents the occurrence of an equipment failure. It is carried out regularly to inspect the system components even if there is no indication of a failure. This strategy reduces the probability of failure of system components and ensures high performance of the system. The preventive maintenance schedule for different components is predefined at regular intervals to ensure reliability.

Schedule of activities

The following tables summarize recommended preventive maintenance activities and frequency for the different components of a solar powered pumping system.

FREQUENCY	MAINTENANCE ACTIVITY
Monthly	Checking the control panel lights and indicators.
	Visual inspection of signals of fuses.
Quarterly	Checking for proper fastening, impacts, breaks or deformations.
	Visual inspection of terminals, panels*, and conductors.
Semi-annually	Grounding condition checking.
	Visual checking for loose connections.
	Location of switches and circuit breakers with deficiencies.
	Checking the condition of the surge arresters.
	Circuit-breaker trip checking.
	Checking the condition of the thermal magnet circuit-breakers.
	Checking for proper sealing.
	Visual inspection of the enclosure.
Annually	General cleaning.
	Retightening of the screws.
	Insulation measurement of bus bars (i.e. metallic strips inside switch box for power distribution) with respect to grounding.
	Checking for possible heating using thermography and correction of hot spots.
	Checking the door and lock.
	Checking the plates and identifying elements in the switch box.
	Thermographic analysis of DC switchboxes.
	Electrical voltage checking of DC switchboxes.

* Panels to be checked for apparent visual damage, whenever the opportunity arises.

Table 6. Recommended inspection and maintenance frequency of DC switch boxes.

Source: authors.

FREQUENCY	MAINTENANCE ACTIVITY
As needed	Low voltage cables: measurement of grounding resistance where abnormal behaviour is detected.
Annually	Low voltage cables: verifying sealing of buried cables tubes.
	Low voltage cables: checking the condition of pipelines.
	Low voltage cables: checking cable holders and clamps conditions.
	Low voltage cables: visual inspection of insulation and covering.

Table 7. Recommended inspection and maintenance frequency of low voltage installation.

Source: authors.

Table 8. Recommended inspection and maintenance frequency of inverter, controller, VFD.

Source: authors.

FREQUENCY	MAINTENANCE ACTIVITY
As needed	Changing charger controller and batteries if applicable.
Monthly	Verifying the absence of alarms in the control equipment.
	General inspection of the equipment.
	Checking the condition of cables and terminals.
Quarterly	Checking the correct ventilation of the equipment.
	Changing filters.
Semi-annually	Checking the proper tightening of screws, works, and cables.
	Visual checking of connections.
Annually	Checking the proper anchoring of equipment.
	Checking the lack of humidity inside the VFD enclosure.
	Checking the grounding of the VFD.
	Checking the environmental condition.
	Thermography: detecting and correcting hot spots.

Table 9. Recommended inspection and maintenance frequency of PV modules.

Source: authors.

FREQUENCY	MAINTENANCE ACTIVITY
Monthly (or if energy drop is bigger than 2%)	PV module cleaning.
Monthly	Visual inspection.
Annually	Visual checking of stability, rigidity and fixing of the PV modules.
	Thermography as a video feed to detect any hotspots.

Table 10. Recommended inspection and maintenance frequency of VFD enclosure.

Source: authors.

FREQUENCY	MAINTENANCE ACTIVITY
Monthly	Ventilation: general state supervision.
	Ventilation: absence of unwanted noise checking.
Quarterly	Checking fastening, possible impacts, breaks or deformations.
	Grounding condition check.
Semi-annually	Thermographic analysis and correction of hot spots.
	Circuit-breaker trip checking.
	Inspection of the condition of the thermal magnetic circuit-breakers.
	Off/grid: checking the inverter statistics and event logs on the display.
	Inspecting batteries & battery charger for proper charge.
	Ventilation: checking status of anchoring and vibration.
	Ventilation: exterior cleaning of equipment and components.
	Visually checking for possible loose connections.
	Checking the correct state of voltage dischargers.
Annually	Insulation measurement of busbars (i.e. metallic strips inside switch box for power distribution) with respect to grounding.
	Checking the door and lock.
	Re-tightening the panel protection device screws.
	Artificial ventilation – pressure switch and thermostat control checking and adjusting.
	Checking the voltages of the switchboard.

Table 11. Recommended inspection and maintenance frequency of solar pump and related components.

Source: authors.

FREQUENCY	MAINTENANCE ACTIVITY
As needed	Freeing the electrical power and sensor cables of cuts or frays and ensuring that the strain relief mechanism correctly supports them.
	Checking unusual noise, vibration, and temperature.
	Checking leaks in pump or piping system.
	Mechanical sealing to avoid leakage.
	Ensuring that drain lines are working properly.
	Cooling water flow in both the bearing housings.
Quarterly (or every 2 000 operation hours)	Checking coupling alignment and integrity (maintain records).
	Changing anti-friction bearing oil (maintain records).
Quarterly	Grounding condition checking.
Semi-annually (or every 4 000 operation hours)	Flushing of cooling water lines and strainers, whether carried out or not, to ensure proper flow of cooling water.
Semi-annually	Visually checking for possible loose connections.
	Checking exterior surfaces for dents, corrosion, or abrasion.
	Inspecting condition of mechanical seals.
	Checking motor-pump current at shutoff and open position of the discharge valve.
	Ensuring optimum liquid level to avoid dry run wherever auto cut or in cut is not provided.
	Checking that the electrical installation and controls meet all local safety regulations and match the motor requirements, including fuse or circuit breaker and motor overload protection.
Annually	Condition of coupling, coupling bolts, nuts, spring washers and their conformity to uniform size. Changing grease in half coupling in case of gear type.
	Avoiding rotating pumps in hot service unless they are gradually heated up to a temperature close to that of the working fluid.

Corrective maintenance

Corrective maintenance of the solar system includes rectifying and resolving faults, anomalies, and malfunctioning of any component by wear and/or defects arising during the system's regular operation. Corrective maintenance minimizes the negative effect of the faults on the availability of power.

If the monitoring system indicates an alarm or onsite staff detects an anomaly, the operator should do everything possible and technically reasonable to correct the malfunction and replace or repair the defective component or part onsite. Upon receiving an error message, clearing the error, fault and/or defect should be attempted remotely. If an error, fault and/or defect at the facility cannot be cleared remotely, best judgment and technical knowledge to implement a solution should be used.

Table 12. Recommended response time for different maintenance events and scenarios.

Source: authors.

PRIORITY LEVEL	MAINTENANCE ISSUE	RESPONSE TIME
Absolute priority	Events that involve safety risks for people.	• Less than 1 hour
Critical priority	Critical incidents could be any of the following: • Contractor's ability to monitor the facility is compromised. • Events that affect the integrity of the system.	• Less than 1 hour if solar irradiance is >100 W/m^2 • Less than 2 hours if solar irradiance is <100 W/m^2
High priority	High priority incidents could be any issue that: • Cause an outage of at least one entire inverter unit. • A connectivity or SCADA* failure that impacts the contractor's ability to monitor the facility. • Events that cause an outage of 5% nominal power of the facility.	• Less than 2 hours if solar irradiance is >100 W/m^2 • Less than 3 hours if solar irradiance is between 10 W/m^2 and 100 W/m^2
Low priority	Low priority incidents could be: • Any other issues that cause outages of any element of the facility other than critical incidents or high priority incidents	• Less than 6 hours if solar irradiance is >100 W/m^2 • Less than 8 hours if solar irradiance is between 10 W/m^2 and 100 W/m^2

* SCADA: supervisory control and data acquisition.

The solution, either temporary or permanent, should fix the error, fault and/or defect in the shortest time possible in order to maintain at least the guaranteed annual availability of the facility.

As part of the corrective maintenance, the availability of all necessary tools, components, and materials should be ensured. The components should be consistent with the standard operating conditions of the system. An inventory must be maintained for the available spare parts, special tools, materials, and their location. The contractor is responsible for unscheduled corrective maintenance and repair of the facility. Moreover, any fault error or defect that may include damage to the facility and disruptions of its performance should be resolved as soon as possible.

Repair activities can only be performed by trained personnel only after the approval of the solar plant manager. Any equipment must be maintained according to its manufacturer operations manual. The following sections describe the general repairing procedure of main components of the solar system. For all other repairs, the user manuals of the equipment must be consulted.

Module replacement

The warnings in Box 7 must be considered before replacing a PV solar module. The following general procedure should be followed to replace damaged solar PV modules:

- Switch off the string following the string isolation procedure.
- Measure the current on DC cables connected to the module to confirm that the circuit is open.
- If no current exists, unplug the DC cables.
- If a current exists, cover the panels or wait until the nighttime to perform the maintenance.
- Drill the rivets to loosen the module.
- Disconnect the positive and negative cable leads of the damaged module.
- Remove the damaged module and install the replacement module.
- Reverse steps 6 through 1 using M5 screws to replace the drilled rivets.
- Check if the string is working normally.

Box 7. Precautions for replacing PV modules.

Warning! Dangerous voltage or condition may exist.

Most common hazards:

- Accidental head injury
- Hazardous voltage

Safety tools and equipment:

- Cellphone for emergency contact
- Clamp meter and multi-meter
- Electrical gloves
- Face shield
- Fireproof clothes
- Hard hat
- Nonconductive footwear
- Visor

Safety notes:

- Wear appropriate PPE.
- High level of voltage may be present under certain conditions. Extreme caution should be exercised during all maintenance activities.
- A minimum of two qualified personnel equipped with non-conducting hard hats and appropriate safety attire for electrical work shall be required to perform these procedures.
- Emergency contact numbers must be present along with a functioning cell phone.

DC cable repair

Figure 31. Damaged DC cable connector.

Photo credit: FAO/Ahmed Abdelfattah.

The warnings in Box 8 must be considered before replacing DC cables as described below.

Visual inspection of the photovoltaic module array, including the DC cabling and DC connectors in the cable tray, should be done every month for any signs of damage or burns as shown in Figure 31. Occasionally, there could be signs of burn marks on a solar cable or DC connector for reasons such as a nick in the cable, resulting in wear of the insulation layer from heat and thermal expansion or improper crimping of a connector. If any burn signs are noticed, a precaution should be taken to avoid contacting the burned cable or connector without wearing safety boots, and 1 500 V rated electrical gloves.

The burned cable or connector should be repaired or replaced with a new one depending on the extent of the damage caused. If there is any piercing of the connector, then a new connector is needed. To install a new connector, it is required to remove the solar drops and seal the openings with the connector seals. If there is damage to the solar drops connected to the piercing connecter, the cable should be removed and replaced.

Box 8. Precautions for repairing DC cables.

Warning! Dangerous voltage or condition may exist.

Most common hazards:

- Accidental hand injury
- Electric shock hazard
- Hazardous voltage

Safety tools and equipment:

- Cable cutter rated for 1 500 V operation
- Cable striping tool rated for 1 500 V operation
- DC current clamp meter
- Electric tape
- Electrical gloves rated for 1 500 V operation and safety boots
- MC4 crimping tool and lock tight tool
- Nonconductive footwear

Safety notes:

- Wear appropriate PPE.
- Be aware of electric shock hazard, as DC conductors are energized during hours of sunlight. DC voltage is always present when solar modules are exposed to sunlight.

The following procedure should be followed for the repair of DC cables:

- Wear safety gloves and shoes, and DO NOT remove safety gear at any point.
- Go to the combiner box for the corresponding burned cable and use the isolation procedure to disconnect the string.
- Lock-out, tag-out the combiner box.
- DO NOT attempt to fix the cable or connector if there are sparks or any signs of arcing.
- Cut one end of the cable using a cable cutter with no burn marks, then isolate the end of the cable using electric tape.
- Cut the second end of the cable using a cable cutter with no burn marks, then isolate the end of the cable using electric tape.
- Strip off the insulation of the first cable end using a cable stripper.
- Crimp-on the connector to the first end and using a proper tool to torque the connector
- Repeat the above steps for the second cable end.
- Connect the new DC connector ends until you hear a click, and the connectors snap in place.
- Return to the combiner box and flip back the DC disconnect to the ON position.
- Measure the current in the repaired string using a DC clamp meter to ensure proper operation.
- Remove lock-out, tag-out from the combiner box.

Combiner box fuse replacement

The warnings in Box 9 must be considered before replacing combiner box fuses.

The fuse holders can carry up to 1 fuse in each combiner box. Positive and negative DC output cables are connected between the combiner box and the fuse cabinets in the VFD. Each combiner box homerun cables constitute a DC branch circuit feeding the VFD fuse cabinet.

The combiner box includes a string monitoring system that continuously monitors the power from single strings or groups of strings as well as the voltage of the photovoltaic system. Defects, which lead to reduced output, can be detected immediately, allowing rapid repairs or adjustments to be made to the system. Although these boxes do not need inspection other than possible retightening of the attachment mounting screws, it is recommended that the combiner boxes are visually checked on a monthly basis for any signs of burned fuses, defective surge protectors and damage on the enclosures.

If an inconsistent measurement to the expected value arises after testing the branch circuit currents at the inverter fuse cabinet, the technician must individually test the load current at each string in the combiner boxes using a clamp meter to verify strings and fuse integrity. Provided that the sun is constant during this measurement, the voltage should be the same for each of the 24 source circuits.

Box 9. Precautions for replacing combiner box fuse.

Warning! Dangerous voltage or condition may exist.

Most common hazards:

- Accidental head injury
- Electric shock hazard
- Hazardous voltage
- Multiple power sources

Safety tools and equipment:

- Arc proof long sleeve electrical gloves
- Calibrated 1 500 V-rated digital multi-meter
- Clamp meter and multi-meter
- Hard hat
- Nonconductive footwear
- Standard technician tool kit comprised of basic hand tools

Safety notes:

- Wear appropriate PPE.
- Be aware of electric shock hazard, as DC conductors are energized during hours of sunlight. DC voltage is always present when solar modules are exposed to sunlight.

Tightening of the cables inside the fuse holder is recommended every year.

- Check the combiner boxes for well-tightened lids and glands and ensure the attachment points to the mounting structure are not loose.
- Perform a visual check on all interconnections and solar cables for punctures, loose connections, rubbing on sharp edges and cable ties.
- Check the window of the surge arrestors: if green, the indicator functions correctly; if red, remove and replace the surge arrestor.

Below are the procedures that describe the steps necessary to perform a controlled shutdown of array combiner boxes. Always wearing electrical safety gloves and other protective attire when replacing fuses is needed. Before replacing a fuse that is burned, check the modules' string wiring to ensure the correct operation is needed. To replace a burned fuse:

- Measure the current on the string which is connected to the burned fuse.
- Turn the DC Disconnect switch to the OFF position.
- Open the touch-safe fuse holder in the combiner box.
- Check the label of the fuse.
- Pull out the burned fuse.
- Insert a new fuse making sure it is of the same type rated.
- Close the touch-safe fuse holder.
- Turn the DC disconnect switch to the ON position.
- Measure the current on the string.

Discussion

The use of solar energy for pumping was introduced in 1970s but the recent increase in commercial manufacturing of solar systems, technical improvements in the design and reduced costs of solar power equipment have provided an opportunity for medium and large farmers of arid and semi-arid regions to adopt this technology for pumping water to irrigate agricultural lands and increase crop production.

The use of solar energy for pumping water reduces the greenhouse gas emissions by 95 to 97 percent as compared to the pumps operating on diesel fuel. Switching from conventional to solar pumping is a clean alternative to reduce the significant carbon footprint of irrigated agriculture. At the same time, the operation and maintenance cost of solar power pumping systems is very low, and the users get clean energy at lower price per kilowatt-hour as compared to grid power.

Switching from conventional to solar pumping is a clean alternative which oppose the development of large carbon footprint in irrigated agriculture

Since most of the arid regions have abundant sunshine hours per day, it increases the reliability of irrigation water, reduces unnecessary water stress, and ensures pumping in off-grid and remote locations. In spite of these benefits, the implementation of solar pumping system still has certain challenges. The initial investment for the installation of a solar pumping system for small scale farming is challenging due to the non-affordability by individual farmers, or to the costly loans from financial institutions for solar systems and its long payback periods. As a result, small farmers would often need government subsidies and micro loans to adopt the technology.

Although solar pumping system can only be operated for a limited time during the sunshine hours to lift water, it is still necessary to ensure sustainability of water resources. With groundwater, clear pumping regulations should be enforced to keep discharge and recharge within the sustainable boundaries, ensure environmental flows and avoid undesirable environmental conditions such as saltwater intrusion, salinization, land subsidence and groundwater level depletion.

Water resources shall be sustained by control pumping through effective water monitoring systems, water allocation to end users, and through participatory approaches involving Water Users Associations. Increasing water use efficiency and water productivity through higher efficiency irrigation systems is another viable solution to address over extraction of water. Financial incentives to farmers should also be incorporated into the solar water pumping models to help sustain water resources such as net electricity metering which would encourage the farmers to sell part of their generated energy to electricity grids at an attractive price instead of using it for pumping water.

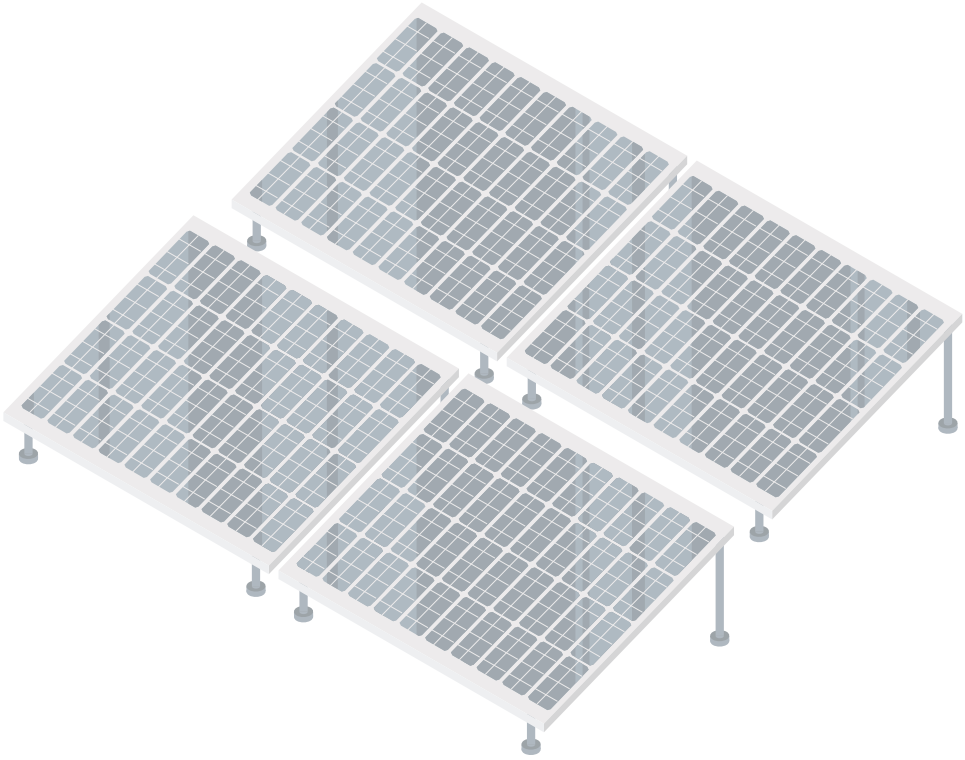
Increasing water use efficiency and water productivity through higher efficiency irrigation systems is another viable solution to address over extraction of water

Another challenge with the use of solar system for pumping water in agriculture is its end-of-life impacts. Solar panels, and cables are largely composed of glass, crystalline silicon, iron, aluminium and copper. Trace amounts of cadmium, lead and toxic resins are used in the manufacturing of solar panels to improve their electrical efficiency and durability. With an average working life of 20 to 25 years, large number of solar panels scrap or waste is expected to be ejected into the environment. It is hazardous to dump the used solar panels, electrical and electronic control equipment and cables in landfills and waste disposal sites as the toxic and trace elements from them could leach to groundwater and the environment.

It is imperative that all countries should establish and enforce clear guidelines on the disposal and end-of-life sustainable waste management of solar water pumping systems

Used and damaged solar panels, inverters, controllers and cables should always be recycled at specialized facilities to extract the maximum practical benefits from products while generating the minimum amount of waste. Large parts of solar systems such as glass, aluminium and copper are easy to be extracted and recycled through well-known processes; however, recycling and extraction of trace and heavy metals from the hazardous waste (commonly referred to as e-waste and battery waste) is more challenging. Specialized methods have been developed and under practice in the USA, Germany, France, and Malaysia which guarantee up to 90 percent of electronic material extraction during the recycling of solar panels, inverters and controllers which is crucial in mitigating their end-of-life impacts. So far, the European Union has taken concrete steps in holding the manufacturers of solar systems responsible for their recycling with the cost of recycling being built into the selling price of solar systems, this is an effective way to minimize the impacts on the environment with a marginal increase in the selling price.

It is imperative that all countries should establish and enforce clear guidelines on the disposal and end-of-life sustainable waste management of solar water pumping systems. Manufacturers, moreover, should be persuaded to play a facilitating role by developing and using effective recycling methods of their solar systems, especially for solar panels hazardous waste, both at the end of a solar project's lifespan and in case of any damage events for solar components.



References

Ali, W., Farooq, H., Rehman, A.U., Awais, Q., Jamil, M. & Noman, A. 2018. Design considerations of standalone solar photovoltaic systems. Paper presented at "2018 International Conference on Computing, Electronic and Electrical Engineering (ICE Cube)", 12-13 November 2018, Quetta. https://doi.org/10.1109/ICECUBE.2018.8610970

Beverly, R.P. 2009. Pump selection and troubleshooting field guide. Denver, Colorado. American Water Works Association.

Britannica. 2020. Energy. In: *Britannica - Matter and energy [online]*. Cited November 2021. https://www.britannica.com/science/energy

Chandel, S.S., Nagaraju Naik, M. & Chandel, R. 2015. Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. *Renewable and Sustainable Energy Reviews*, 49: 1084–1099. https://doi.org/10.1016/j.rser.2015.04.083

FAO. 2000. *The energy and agriculture nexus. Environment and Natural Resources Working Paper No. 4.* Rome, FAO. (also available at http://www.fao.org/3/x8054e/x8054e00.htm#P-1_0).

Girard, K. 1988. Photovoltaic drip irrigation. Paper presented at the "1998 Annual meeting, American Solar Energy", 14-17 June 1998, Albuquerque, American Solar Energy Society, Inc.

He, X., Feng, K., Li, X., Craft, A.B., Wada, Y., Burek, P., Wood, E.F. & Sheffield, J. 2019. Solar and wind energy enhances drought resilience and groundwater sustainability. *Nature Communications*, 10(1): 4893. https://doi. org/10.1038/s41467-019-12810-5

Hegazi, A., Awady, M. N., Hegazi, M. M., & Elgindy, R. W. 2010. Performance evaluation of locally assembled solar powered irrigation pump. *Misr Journal of Agricultural Engineering,* 27(1), 141-150.

Lefore, N., Closas, A. & Schmitter, P. 2021. Solar for all: A framework to deliver inclusive and environmentally sustainable solar irrigation for smallholder griculture. Energy Policy, 154: 112313. https://doi.org/10.1016/j.enpol.2021.112313

Liu, Z. 2018. What is the future of solar energy? Economic and policy barriers. *Energy Sources, Part B: Economics, Planning, and Policy,* 13(3): 169–172. https://doi.org/10.1080/15567249.2017.1416704

Mueller, J., Algohary, S., Hegazi, A., & Koeller, K. 1998. *Solar power drip Irrigation for orchards in remote areas.* In 13th International Congress on Agricultural Engineering, Rabat (Morocco) (Vol. 4, pp. 279-287).

Ramez Naam. 2020. Solar's future is insanely cheap. In: *Ramez Naam [online]*. Cited November 2021. https://rameznaam.com/2020/05/14/solars-future-is-insanely-cheap-2020/

Rappaport, P. 1959. The photovoltaic effect and its utilization. *Solar Energy,* 3(4): 8–18. https://doi.org/10.1016/0038-092X(59)90002-7

Salman, M., Bunclark, L., AbuKhalaf, M., Borgia, C., Guarnieri, L., Hoffmann, O., Sambalino, F., van Steenbergen, F. & Lebdi, F. 2016. *Strengthening agricultural water efficiency and productivity on the African and global level: Status, performance and scope assessment of water harvesting in Uganda, Burkina Faso and Morocco.* Rome, FAO. 59 pp. (also available at www.fao.org/3/i5976e/i5976e.pdf).

Salman, M., Casarotto, C., Bucciarelli, M. & Losacco, M. 2018. *An assessment of policies, institutions and regulations for water harvesting, solar energy, and groundwater in Jordan: A review and gap analysis.* Rome, FAO. 67pp. (also available at www.fao.org/3/I8601EN/i8601en.pdf).

Shinde, V. & Wandre, S. 2015. Solar photovoltaic water pumping system for irrigation: A review. *African Journal of Agricultural Research*, 10(22): 2267–2273. https://doi.org/10.5897/AJAR2015.9879

Steduto, P., Faurès, J.-M., Hoogeveen, J., Winpenny, J.T. & Burke, J.J., eds. 2012. *Coping with water scarcity: an action framework for agriculture and food security.* FAO water reports 38. Rome, FAO. 78 pp. (also avaiable at www.fao.org/3/i3015e/i3015e.pdf).

Yannopoulos, S., Lyberatos, G., Theodossiou, N., Li, W., Valipour, M., Tamburrino, A. & Angelakis, A. 2015. Evolution of Water Lifting Devices (Pumps) over the Centuries Worldwide. *Water*, 7(12): 5031–5060. https://doi. org/10.3390/w7095031

Glossary

Applicable standards	The national and international standards and codes with which the works shall comply and include (but are not limited) to standards and codes set out in the Industry Standards and Codes section.
Array	Describe the entire PV system or a portion of it, representative of all equipment necessary to facilitate PV power generation and delivery of electricity including but not limited to modules, mounting structure/ racking, combiner boxes and wiring.
Cell maximum voltage	It represents the maximum number of solar cells installed in series to produce 1 000 V_{DC} according to IEC and 600 V_{DC} according to UL code.
DC switch boxes	DC Switch Box includes IP-54 enclosure, overvoltage protection, and overcurrent protection (as required).
Earthing	An electrical safety concept that prevents people from being electrocuted by providing a low resistance path along which electricity can flow harmlessly to the ground if there is a fault.
Electric current	Stream of charged particles, such as electrons or ions, moving through an electrical conductor. It is measured as the net rate of flow of electric charge through a surface or into a control volume. The International System (SI) unit of electric current is the ampere (A).
Electric current, alternating (AC)	An electric current that reverses its direction at regularly recurring intervals.
Electric current, direct (DC)	An electric current that flows in one direction only and is substantially constant in value.
Electric potential (voltage)	Amount of work needed to move a unit of electric charge from a reference point the specific point in an electric field. Although the concept of electric potential is useful in understanding electrical phenomena, only differences in potential energy are measurable. If an electric field is defined as the force per unit charge, then by analogy an electric potential can be thought of as the potential energy per unit charge. The International System (SI) unit of voltage is the volt (V).

Electric power	Rate, per unit of time, at which electrical energy is transferred by an electric circuit. The International System (SI) unit of electric power is the watt (W).
Electric resistance	A measure of an object's opposition to the flow of electric current. It presents some conceptual parallels with mechanical friction. The International System (SI) unit of electric resistance is the ohm (Ω).
Electrical energy	Energy derived as a result of movement of electrically charged particles. Used loosely, it refers to energy that has been converted from electric potential. Generally, the term refers to the amount of power generated over a period of time. The internationally accepted non-SI unit of electrical energy is typically measured in kilowatt-hour (kWh).
Flow rate	The volume of water provided per second, minute, hour or day.
Irradiance	Amount of solar radiation received by a surface per unit area. The International System (SI) unit of irradiance is the watt per square meter (W/m^2).
Low voltage (LV)	In electrical engineering, it is a relative term that varies depending on the country and specific regulations and codes. In this publication, it is used to refer to less than 1 500 V_{DC}.
Maximum power point tracker (MPPT)	A technique used commonly with photovoltaic solar systems to maximize power extraction, producing the maximum power possible at any given time under all conditions.
Maximum power point current (I_{mpp})	The current produced by the solar panel when its power output is the greatest under standard test conditions.
Maximum power point voltage (V_{mpp})	The voltage produced by the solar panel when its power output is the greatest under standard test conditions.
Open circuit voltage (V_{oc})	The open-circuit voltage or the maximum voltage that solar panel can produce at no load during the standard test conditions.
Operating spare parts	The spare parts, special tools, consumables, and other things required for the operation and maintenance of the plant, including the initial stock.
Overcurrent protection	A device that disconnects the system in the event of excessive levels of current.

Peak sun hours	Period during the day in which the intensity of solar insolation reaches an average of 1 000 W/m^2. In other words, it refers to the solar insulation which a particular location would receive if the sun was shining at its maximum value for a certain number of hours. Since the peak solar radiation is 1 kW/m^2, the number of peak hours is numerically identical to the average daily solar insolation.
Root cause analysis (RCA)	In science and engineering, root cause analysis is a method of problem solving used for identifying the root causes of faults or problems.
Short circuit current (Isc)	The short circuit current when the solar irradiance exceeds 1 000 W/m^2.
Solar altitude	The angle between the sun and the horizon, defined between 0° and 90°.
Solar azimuth	The angle between the north and the point on the compass at which the sun is positioned on a horizontal plane. The azimuth angle varies as the sun moves from east to west across the sky throughout the day. In general, azimuth is measured clockwise from 0° (true north) to 359°.
Solar radiation	Amount of power received from the sun per unit area over a specified period of time. Although the International System (SI) unit for solar radiation is the watt per square meter per second (W/m^2/s), it is commonly expressed in kilowatt per square meter per year (kW/m^2/year) or in megajoules per square meter per day (MJ/m^2/day).
Standard test conditions (STC)	Test conditions defined by international standards, such as IEC 61215, IEC 61646 and UL 1703, under which the nominal power of PV devices is measured and referred to in the technical documentation or datasheets. In this publication, it refers to a light irradiance of 1 000 W/m^2, where the cell temperature is 25 °C and airmass is 1.5.
Temperature coefficient	The percentage of power drop per degree rise in temperate from the standard test conditions.
Variable-frequency drive (VFD)	A variable-frequency drive or adjustable-frequency drive, variable-voltage/variable-frequency drive, variable speed drive, AC drive, micro drive or inverter drive is a type of motor drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage.

Annex - Case studies

Case 1. Solar-powered irrigation in the Nile Delta

The prospects of solar energy for irrigation in Egypt

With less than 700 m^3 of resources annually available per capita, the water sector in Egypt faces several challenges. In addition, the agricultural sector is dealing with more energy crises, as increasing electricity demand from urban areas results in frequent shortages and blackouts. This results in the disruption of the irrigation schedules required to meet the crop water needs, with decline of crop yields. Furthermore, the increasing cost of pumping is further burdening the sector.

Therefore, a low-cost alternative energy source is required to ensure farmers have a reliable system to pump and irrigate. Green solar technology can reduce the delta's agricultural vulnerability to energy supply, shocks and shortages, and water scarcity concerns. The implementation of solar energy provides reliable pumping capabilities at the farm level, reinforces efforts for optimal irrigation-water resource management, and strengthens the nexus of food-water energy.

Phase I – Al-Afir

The solar-powered irrigation project in the Nile Delta of Egypt was part of the Country Program Framework agreed upon between FAO and the Egyptian government. The project objective was to provide a more sustainable source of energy for irrigation purposes, reduce the negative impact on the environment, and the pollution from diesel spills/greenhouse gas emissions, while partially contributing to the reduction of water losses caused by evaporation a through an innovative solution that placed solar panels over irrigation canals. The project also advised the Government of Egypt to review their incentive schemes to favour "green subsidies" over those for fossil fuels.

Box A1. Project focus: solar-powered irrigation in the Nile delta

Water efficiency

Water efficiency represents the ratio between effective water use and actual water withdrawal to achieve water saving.

Solar energy

Most intense solar radiation coincides with the irrigation period, and is the simplest way to set up a solar-powered pumping system as "standalone system for direct irrigation".

Figure A1. Al-Afir project, Egypt, (a) Project installation, (b) project located in the Nile delta, (c) simulation of PV modules installation, 2019.

Photo credit: FAO/Ahmed Abdelfattah.

Source: authors

Design Concept

Al-Afir solar water pumping system is a solar PV-based pumping system that combines a high-performance pump VFD controller with a high-efficiency 3-phase AC motor-driven pump designed to work in a wide variety of operating conditions. The system maximizes harvested energy to deliver the required amount of water throughout the year. Power for operating the pump is provided by high-efficiency solar PV modules mounted on a rugged structure. The PV modules provide DC voltage that is fed to the controller.

The pump VFD converts DC power produced by the installed solar panels to AC power required by the pump. A microprocessor continuously monitors available energy levels and adjusts pump speed, matching the energy required to the energy available. This enables the system to operate under varying solar insolation levels and provide water throughout the day and through different seasons. The controller also utilizes a high-efficiency MPPT algorithm to maximize power harvested from solar PV modules.

Four 10 hp solar pumps powered by 14.4 kW solar panels are installed at the site. PV modules are mounted on a steel structure and placed over a buried piped canal, benefitting from unused land space, thus responding to the precious value of land in the Delta of the Nile in Egypt to be occupied by the solar modules and its mounting structure. The pumping systems are designed around high efficiency 300 Wp modules to minimize further the area needed by modules and its mounting structure and to maximize power output.

A high-efficiency 3-phase AC motor-driven pump, specifically selected based on each installation's head and flow requirements, uses power from the controller to deliver water from the source. The controller includes a switch to operate the system, a transfer switch to control the system status and provide the best operation performance to users, and protection mechanisms to ensure the easy and safe operation of the system.

Project installation

Al-Afir solar-powered pumping system consists of 4 pump rooms at a single location. However, to demonstrate the applicability of solar irrigation on the site, one solar pump

of 10 hp is installed in each pumping room. Each pump has a capacity of 160 m^3/h with 16 m head. According to all the Derate Factors, the solar pumps operate over an extended period of day, i.e. between 5–8 h/day, and the pump operates at maximum speed with a maximum frequency of 50 Hz and minimum frequency of 30 Hz.

Box A2. Specifications of project installation (Al-Afir)

Installed capacity

Pumps: 4 (14.4 kWp each)

Total capacity: 57.6 kWp

Installed modules

Type: pollycrystalline

Modules: 48 (4 pumps each)

Total modules: 192

Strings

Configuration: 3 x 16

3 V x 8-20° fixed

Mounting

Double-post steel mounting structure covering the tertiary canal (*mesqa*).

Mounting structure design

The mounting structure is designed to withstand adverse weather conditions and high winds while providing long operating life. It uses ground screw technology to enable easy and quick installation and is designed to withstand the load of modules and wind gusts of up to 130 km per hour. Wind load assumptions are customized based on the region of application to ensure optimal cost-benefit.

The Ministry of Water Resources and Irrigation (MWRI) in Egypt emphasizes the maximum utilization of non-arable land for installing solar PV modules. This policy has been enforced and considered in the design of the mounting structure. To this end, FAO came up with an innovative and cost-effective solution to utilize the space over a buried piped irrigation canal for mounting the PV modules. This design is emerging as one of the leading PV mounting structures in Egypt.

Figure A2. Framework for mounting structure at Al-Afir project, Egypt 2019.

Photo credit: FAO/Ahmed Abdelfattah.

Phase II – Al-Sourya

Design Concept

This SWP system is designed to meet the requirement of water users in the Nile Delta region of Egypt. To demonstrate the applicability of solar irrigation on this site, two pump rooms are constructed along a lined stretch of the *mesqa* in Al-Sourya. The canal location provides an adequate space to install the solar PV modules on both sides and across the irrigation canal. One solar pump of 10 hp is installed in each pumping room. Each pump has a capacity of 160 m^3/h with 16 m head.

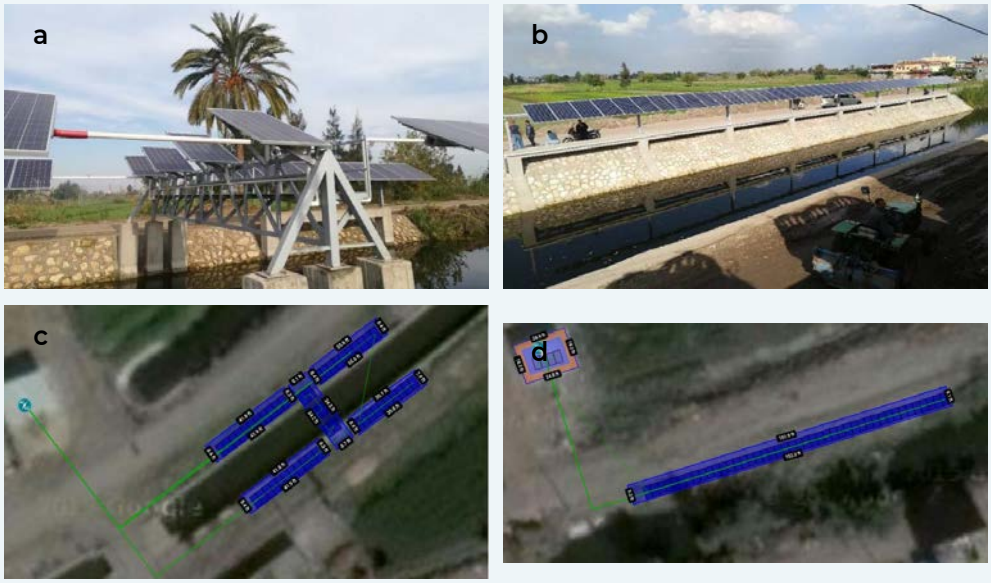


Figure A3. Al-Sourya project, Egypt, (a, b) Project installation, (c, d) simulation of PV modules installation, 2019.

Photo credit: FAO/Ahmed Abdelfattah.

Source: authors.

Project installation

The specifications for the Al-Sourya project are summarized in Box A3.

Project outcome

The project is considered a quantum leap for modern irrigation in Egypt with a solar energy-driven irrigation system as an integral part of the design of the system, and the following results:

- Curb water shortage and provide an environmentally friendly energy source for pumping.
- Provide alternative energy sources for diesel and grid electricity.
- Relieve the burden on the national electricity grid.
- Reduce the carbon footprint of irrigation water.
- Proven suitability of solar PV technology for the region.
- Provide a sustainable energy source for other uses when not irrigating.
- Help in mitigating global warming.

Box A3. Specifications of project installation (Al-Sourya, Egypt)

Installed capacity
Pumps: 2 (14.4 kWp each)
Total capacity: 28.8 kWp

Installed modules
Type: pollycrystalline
Modules: 48 (4 pumps each)
Total modules: 192

Strings
Configuration: 3 x 16
1 V x 11-20° fixed &
1 V x 48-20° fixed for
the two pumps

Mounting
Single-post steel mounting structure covering the tertiary canal (*mesqa*).

The project engaged farmers in all the process of implementation and provided trainings to both farmers and the technical staff of the MWRI. 310 farmer families showed great satisfaction with the new solar-powered surface irrigation water lifting stations. They believe these plants would contribute to electricity savings of up to 75 percent and would facilitate access to irrigation water without the hassle of searching for diesel which was a prerequisite of operating irrigation machines and pumps.

PUMPING STATIONS	IRRIGATED AREA	
	Hectares	Feddan
Al Afir Pump room 1	23.52	56
Al Afir Pump room 2	31.92	76
Al Afir Pump room 3	30.24	72
Al Afir Pump room 4	17.22	41
Al Sourya 5	25.20	60
Al Sourya 6	25.20	60
TOTAL IRRIGATED AREA	153.30	365

Table A1. Irrigated area serviced by the Al-Afir and Al-Sourya project.

Source: authors.

Case 2. Combining water harvesting, conjunctive use of groundwater and solar powered water lifting for irrigation in Jordan

The three-pronged approach

The agriculture sector accounts for 59 percent of water use in Jordan, and its water scarcity is projected to become severe in the future. The increase in water demand is expected to reduce the per capita availability if the water supply from renewable sources is not maintained.

Box A4. Project focus: conjunctive water use in Jordan

Water harvesting

Water harvesting provides an alternative water source when the existing supplies are insufficient to meet the growing water demand. Amongst others, the following methods exist for water harvesting:

- Collecting rainwater in the root zone for direct consumption by crops.
- Storing the concentrated rainfall runoff in reservoirs for intended productive use in the future.
- Harvested rainwater is stored in recharge basins and then it is allowed to slowly percolate to recharge groundwater aquifer.

Conjunctive use of surface and groundwater

An optimal combination of surface and groundwater resources to minimize the undesirable physical, environmental, and economic effects of individual solutions to balance the water demand and supply.

Solar energy

The utilization of solar energy during the intense solar radiation periods to operate solar water pumping system for supplying irrigation water to crops.

At present, total water use exceeds renewable supply, with the balance being met only through reclaimed wastewater and an unsustainable high rate of groundwater abstraction. Jordan is likely to face severe water shortages that require a comprehensive approach to manage both water supply and demand.

The importance of the agricultural sector to food security and rural employment requires the improvement of agricultural water management. This could be further achieved by adopting practical approaches to augment the water resources and combine them with sustainable energy sources. To address these challenges, and within the context of the Water-Energy-Food nexus, FAO has piloted a three-pronged, community-based approach, combining water harvesting, conjunctive use of groundwater, and solar power for lifting irrigation water to produce food and sustainably generate income.

Project installation

The specifications for the Al-Ghadeer Al Abyad project are summarized in Box A5.

Design concept

A mathematical model is developed to acquire an optimal PV system by considering water demand and irradiance and including natural processes, i.e. climate, hydrology, reservoir capacity, submersible pumping system, irrigation, cropping pattern, and power supply. The dynamic calculation is used to achieve optimal size for peak water requirements. Each part of the system operates under specific conditions to give expected results. The system consists of MPPT-based observations for improving efficiency. The outlet valves

Box A5. Specifications of project installation (Al-Ghadeer Al Abyad, Jordan)

Two submersible pumps are installed to supply irrigation water to the northern and southern zones with a head of 60m each.

	Area I	Area II
Area supplied (ha)	17	15.7
Installed capacity		
Pump peak power (kWp)	67.32	33.66
Flow rate (m^3/h)	130	65
Installed modules		
Type	polycrystalline	polycrystalline
Number	204	102
Strings		
Configuration	12 x 17	6 x 17
	1 V x 51-10° fixed	

Mounting

Single-post steel mounting ground structure

Water harvesting capacity

200 000 m^3

Cropping pattern

Peas, carrots, cabbage, lettuce, spinach, cauliflower, thyme.

Location

32.3970° N, 36.2108°E

are regulated to control the flow rate of water from the dam to the irrigation fields and optimize water use in each irrigated area.

The system is designed for a maximum water discharge of 1 200 m^3/day, and the pumps are directly connected to a solar pump inverter which starts operating in the morning when the solar output is higher than the minimum power required to start the pump.

The dynamic model of the system was designed based on optimization results. The PV arrays power the submersible pumps, which support farmer associations in the dry years by providing optimal water supply from the dam and tube wells. A submersible pump is very flexible regarding its energy supply and performance and it is designed for intermittent and continuous operation. The system can be combined and adapted to any need according to on-site conditions with a good sustainable operation.

The pumps move variable volumes of water ranging from 65 to 130 m^3/h with 60 m of total dynamic head over an extended period of the day, i.e. 5-8 h/day. After considering all the derate factors (which include inverter losses, soiling, shading profile, cell mismatch, panel age, thermal coefficient), the pumps operate at a maximum speed with a maximum frequency of 50 Hz and minimum frequency of 30 Hz. At sunrise and sunset, the pumps work with the maximum frequency, considering peak hours of 5.4-5.6 h/day.

Figure A4. Simulation of single post installation of solar PV modules (a), implementation of single post installation of solar PV modules (b) and conjunctive use of water for irrigation using drip irrigation system (c) in Al-Ghadeer Al Abyad project, Jordan 2019.

Source: authors.

Photo credit: FAO/Ahmed Abdelfattah.

Irrigation systems require constant water supply with daily operation times of up to 10 h/day; where solar operation hours lay between 6–8 h/day. To compensate for this gap, solar pumps are integrated into a solar irrigation system designed for specific local needs which addresses the challenge to harmonize the non-constant solar energy and the constant irrigation requirements. This method requires VFD, which enables the solar pumps to operate over a wide range of voltage and available current, whereas conventional AC-powered pumps require a stable voltage and frequency to operate.

Critical factors

The input and feedback of the technical working group was an integral component of the roadmap development since the three-pronged approach considered many factors related to the capacity of the water reservoir, water volume required per day, available solar insulation, pumping time, static water level, drawdown level, discharge, pipe friction losses, and pumping subsystem efficiency.

Several methods could be used to comply with the variable irrigation requirement throughout the year with peak demand during March–October. In order to optimize the performance and efficiency of the PV system, the tilt angle was fixed at 10°. This angle was selected through a simulated performance of the PV panels. Soiling had adequate impacts on the performance of PV modules. The height of PV modules in desert areas was based on the dust deposition velocity and the relationship between deposited dust density and PV module power performance.

Figure A5. Layout of irrigation zones in the project (a) and solar powered pumps (b).

Source: Google Earth 2020, edited by authors.

The optimum height of PV modules was selected as 1.4 m. However, to address the shading profile, the spacing between the modules was chosen as 1.2 times the height of the module from the ground. The delivery lines of submersible pumps were mounted on the dam wall using a wall rail fixation system for easy maintenance accessibility. With the adjustment of tilt angle and height of PV modules, the system could harvest the maximum solar irradiance to supply maximum delivery during the peak month of April.

Mounting structure

The PV mounting structure and the framework play a vital role in setting up sustainable solar energy system. The mounting structure of the project was manufactured using hot dip-galvanized material for longer life and high mechanical strength to withstand wind speeds of up to 33 m/sec. The mounting structure is installed on vertical driven single posts.

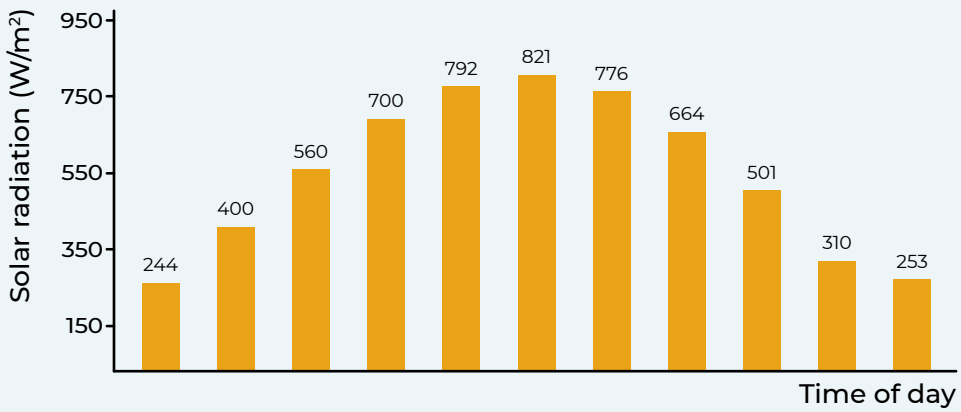


Figure A6. Maximum solar irradiance at the optimum tilt angle.

Source: authors.

Filtration system

The system used pressure line filters of 1-5 µm opening to avoid valves contamination and ensure adequate quality water to the end users. Solar energy is used to overcome system head losses and provide the required operating pressure at the field level drip irrigation system.

Figure A7. Water filtration system at Al Ghadeer Al Abyad project, Jordan.

Photo credit: FAO/Ahmed Abdelfattah.

Operating instructions

The system operating instruction were recommended according to the water requirement, number of valves and available irradiance. The control valves have an inherent flow characteristic that defines the relationship with time. Table A2 shows the optimum number of valves that could be opened during any hour, so that the maximum volume of 1 068.25 m^3 could be pumped at the end of the day.

Project deliverables

The project provided a pathway to accelerate the availability and affordability of solar water pumps used in off-grid areas. It helped exploring access to a viable alternative to the thermal and grid electricity currently used to power water pumps, hence contributing to reduce energy crisis and fuel cost. Introducing sustainable sources of energy, i.e. solar power, has also improved crop yields and increased the economic output of agriculture.

Capacity and awareness building of beneficiaries around the benefits and application of the solar system and its daily O&M was addressed through farmers' participation in all project implementation stages and a dedicated special training programme.

Case 3. Strengthening agricultural water efficiency and productivity on the African level

Combined pilot elements of the water harvesting

Agriculture dominates the Ugandan economy and society, contributing 44 percent of the national output and employing 80 percent labour force. It also contributes to over 70 percent of Uganda's export earnings and provides the bulk of the raw materials for most local industries. Like several African countries, Uganda needs the main steaming of water resources management to sustain its production potential and maintain food security.

The efficient use of solar PV technology in agriculture water management has proven applicability. In this project, "Strengthening agricultural water efficiency and productivity on the African level", FAO foresaw the importance of multiple benefits of improving water productivity and efficiency, living standards, and increasing revenue generation in an existing production system.

In the Kinoni area of Mubende district, Uganda, the pilot project focused on soil and water conservation, enhancement of water harvesting for high value crop irrigation and livestock use, integrated water management, and solar water pumping.

Box A6. Project focus: strengthening agricultural water efficiency and productivity in Uganda

Water harvesting

Water harvesting provides an alternative water source when the existing supplies are insufficient to meet the growing water demand. Amongst others, the following methods exist for water harvesting:

- Collecting rainwater in the root zone for direct consumption by crops.
- Storing the concentrated rainfall runoff in reservoirs for intended productive use in the future.
- Harvested rainwater is stored in recharge basins and then it is allowed to slowly percolate to recharge groundwater aquifer.

Conjunctive use of surface and groundwater

An optimal combination of surface and groundwater resources to minimize the undesirable physical, environmental, and economic effects of individual solution to balance the water demand and supply.

Solar energy

The utilization of solar energy during the intense solar radiation periods to operate solar water pumping system for supplying irrigation water to crops.

Project installation

The specifications for Mubende project site are summarized in Box A7.

Box A7. Specifications of project installation (Kinoni, Uganda)

Installed capacity
Total capacity: 28.8 kWp

Installed modules
Type: polycrystalline

Location
Kinoni, Mubende district, Uganda

Application
Solar water pumping, diesel hybrid

Surface reservoir
10 000 m^3

Cattle through
Three

Water tank
Elevated, polyethylene, 2 x 10 m^3

Cropping pattern
Maize: First season March–July and second season August–January
Coffee: Flowering stage January and harvesting next year January
Banana: First season March–June and second season September–December

Design concept

Strategically, the project site is selected with through broad consultations and participation of beneficiary farmers. It aims to work closely with communities, conduct demonstrations and capacity building of farmers, extension workers, and technicians. It also ensures that the actions undertaken are responsive to the needs, are supported by the local authorities and are aligned with the government policies.

The project focuses on:

- sustainable local agricultural development;
- establishment of supplemental irrigation and improvement of agricultural water management; and
- increase farming income of vulnerable rural livelihoods, especially women.

On the technical side, the project design aims to enhance power generation capacity by considering several factors since the PV powered pumping system is based on switched-mode operations. An optimal PV system is developed using dynamic calculations for this pilot site by considering solar irradiance, water demand, hydrology, pump type and irrigation method.

The project design also considers the following technical aspects:

- The system is designed for maximum water discharge of 24 m^3/day.
- Each part of the system is tested separately under specific conditions to verify its performance.

- The flow of water to irrigation fields is regulated by outlet valves to optimize the pumping rate from the dam to each irrigated area.
- The system uses the max power point tracking (MPPT) algorithm for improving efficiency.
- The pump is directly connected to a solar pump inverter which starts operation in the morning when the solar output is higher than the minimum power required to start the pump.
- The submersible pump is very flexible regarding its energy requirement and performance and designed for intermittent and continuous operation.
- The system can be combined and adapted to any need according to on-site conditions with a good sustainable operation.

Project operation

The technical working group's input and feedback is an integral component of the roadmap development since water harvesting pilot approach considers many factors related to water source capacity, water volume required per day, solar insulation availability, pumping time, static water level, drawdown level, discharge head, pipe size friction, pumping subsystem efficiency.

The reservoir has an inlet, sedimentation basin and overflow. The inlet and spillway channels are lined with stones. Water supply mode is gravity-fed from the adjacent hill slopes, which is diverted to the excavated valley by diversion bunds. The water harvesting reservoir of Kinoni is situated in a depression, far from the area of water utilization. Pumping is required to supply water to the demand area, but grid electricity is not available due to its remote location. Overhead water tanks were installed close to the community to address the difficulties in accessing water for domestic use, livestock watering, and small-scale supplementary irrigation. Water from the reservoir is pumped into the overhead tanks using solar pumps.

Figure A8. Project highlights. Community based small scale solar water pupming station (a), control room and elevated water tanks (b), rainwater harvesting pond (c) and multiple uses of water harvesting (d).

Photo credit: FAO/Ahmed Abdelfattah.

In the project, the management rules of the reservoir were discussed with the community and end-users in a participatory way, according to the following agreement:

- Priority to the satisfaction of domestic use and livestock watering demand.
- The reservoir has an inlet, sedimentation basin and overflow. The inlet and spillway channels are lined with hard core stones.
- Water supply mode flows from the adjacent hill slopes and is diverted to the excavated valley reservoir by diversion bunds.
- Tanks are installed close to the community to address the actual difficulties of water access and use, allow and easy the domestic use and livestock watering, and close to the small-scale cropping area for supplementary irrigation.
- Intensification of irrigated crops at small scale level (family) and farm level.
- Plastic tank with top removal cover
- It is a 5.5 m above ground level metal tower (designed to withstand 45 m/s wind loads).

Figure A9. Project area overview. Suitable area for pilot plots and possible layout, where plot between 1 and 2 belongs to a farmer's group (a). Valley tank highlighted at the bottom of the slope, as viewed from the selected area for the pilot (b).

Photo credit: FAO/Ahmed Abdelfattah.

Source: authors.

Deliverables

The project provided a pathway to accelerate the availability and affordability of solar water pumps used in off-grid areas. In addition, it provided water for multiple uses, i.e. irrigation, livestock and domestic purposes from the macro-catchment system. Moreover, it helped increase crop productivity through water harvesting in the root zone and improved agronomic practices and farmers' living conditions with the help of the development of the local farming societies. Field demonstrations and capacity building training for the beneficiary farmers were conducted, and study visits were organized within the framework of the project.

Figure A10. Project stakeholders meeting.

Photo credit: FAO/Ahmed Abdelfattah.

In the last decade, solar energy has experienced a rapid growth, which brings both environmental and economic benefits. Solar-powered water pumping technologies are increasingly in demand in developing countries as they provide cost-effective solutions to increase agricultural productivity. Renewable energy options, particularly solar power, are a promising solution for sustainable agriculture in regions with high-solar-insolation.

FAO works to promote coherent approaches to sustainable land and water management. FAO's work in land and water is relevant to several dimensions of sustainable development, such as the governance and management of food production systems, the provision of essential ecosystem services, food security, human health, biodiversity conservation and the mitigation of, and adaptation to, climate change.

www.fao.org

ISBN 978-92-5-135699-9

9 789251 356999

CB8459EN/1/02.22