TOOLBOX ON SOLAR POWERED IRRIGATION SYSTEMS (SPIS)

POWERING AGRICULTURE:

AN ENERGY GRAND CHALLENGE FOR DEVELOPMENT

# Module 1: Get Informed

The Toolbox on Solar Powered Irrigation Systems is made possible through the global initiative Powering Agriculture: An Energy Grand Challenge for Development (PAEGC). In 2012, the United States Agency for International Development (USAID), the Swedish International Development Cooperation Agency (Sida), the German Federal Ministry for Economic Cooperation and Development (BMZ), Duke Energy, and the Overseas Private Investment Cooperation (OPIC) combined resources to create the PAEGC initiative. The objective of PAEGC is to support new and sustainable approaches to accelerate the development and deployment of clean energy solutions for increasing agriculture productivity and/or value for farmers and agribusinesses in developing countries and emerging regions that lack access to reliable, affordable clean energy.

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Responsible
GIZ Project Sustainable Energy for Food – Powering Agriculture

Contact
Powering.Agriculture@giz.de

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## ABBREVIATIONS

| | |
|---|---|
| Ah | Ampere hour |
| CWR | Crop Water Requirement |
| DC/AC | Direct Current / Alternating Current |
| ET | Evapotranspiration |
| FAO | Food and Agriculture Organization of the United Nations |
| Gd | Daily Global Irradiation |
| GIZ | Gesellschaft für Internationale Zusammenarbeit |
| GIWR | Gross Irrigation Water Requirement |
| GPFI | Global Partnership for Financial Inclusion |
| HERA | GIZ Program Poverty-oriented Basic Energy Services |
| $H_T$ | Total Head |
| IEC | International Electrotechnical Commission |
| IFC | International Finance Corporation |
| IRR | Internal Rate of Return |
| IWR | Irrigation Water Requirement |
| MPPT | Maximum Power Point Tracking |
| NGO | Non-Governmental Organization |
| NIWR | Net Irrigation Water Requirement |
| NPV | Net Present Value |
| $m^2$ | square meter |
| PV | photovoltaic |
| PVP | Photovoltaic Pump |
| SAT | Side Acceptance Test |
| SPIS | Solar Powered Irrigation System |
| STC | Standard Test Conditions |
| TC | Temperature Coefficient |
| UV | Ultraviolet |
| Vd | Daily crop water requirement |
| W | Watt |
| Wp | Watt peak |

## GET INFORMED

1. An overview to solar and irrigation
2. Solar generator
3. Mounting structure
4. Controller and inverter
5. Water pump
6. Monitoring system
7. Reservoir
8. Irrigation head
9. Fertigation system
10. Irrigation system

## MODULE AIM & ORIENTATION

Due to significant advances in technology and drops in prices for solar panels, solar pumps have become an economical, technically and environmentally viable alternative to conventional pumping systems.

Nevertheless, few people are aware of the potential and risks associated with solar pumping for irrigation. Often the solar pump is not optimally integrated into the irrigation system, which results in inefficiencies. Consequently demand amongst producers is low and the reluctance of financial institutions to finance them is high.

The **GET INFORMED** module provides essential information for agricultural advisors and financial service providers to understand the operating principle of SPIS and to differentiate between the individual system components. Moreover, it starts to describe how the different configurations of the components can influence the performance of the entire system. The **GET INFORMED** module will allow agricultural and financial service providers to support potential users of SPIS with up-to-date information on the pros and cons of the technology and its individual components.

## BRIEF DESCRIPTION OF THE MODULE

Compared to conventional energy systems, the use of solar energy has some specific characteristics, which must be considered when planning a Solar Powered Irrigation System (see **DESIGN** module).

The following steps describe in detail the available configurations and individual system components of an SPIS operating under constantly varying conditions due to daily and seasonal fluctuations.

The description of the individual components of an SPIS and the relations between them are preceded by information on the basics of solar energy and irrigation. When solar energy and irrigation are combined in one production system we call this a Solar Powered Irrigation System. Typical configurations of SPIS are presented in this module and in the **DESIGN** module.

## 1. AN OVERVIEW TO SOLAR AND IRRIGATION

### THE SOLAR ALTERNATIVE

If traditional pumping technologies, such as manual or animal-powered pumps, reach their technical limits, the customary means of pumping irrigation water are diesel-, gas- or petrol-driven pumps. Such conventional pumps, however, have the double drawback of requiring a lot of maintenance as well as a regular supply of fuel and physical attendance for operation. Particularly in remote areas of developing countries, access to spare parts, maintenance structures or fuel can be limited, leading to frequent outages of several days or longer. The resulting lack of water can result in yield reduction or failure, and thus poses a great risk for the agricultural enterprise.

In non-electrified parts of the world, solar energy could help to provide access to an environmentally sound and reliable energy supply. Especially in developing countries, the perspective of grid extension and the establishment of a reliable, uninterrupted electricity supply into rural areas is still a remote prospect. Rural electrification in economically weak rural areas of Africa, Asia and Latin America will be largely based on investments into local off-grid solutions for basic consumptive household electrification, with little consideration for productive uses of energy.

**Access to electricity wherever the sun shines**

**(Source: Lennart Woltering)**

With the right knowledge on proper operation and maintenance of solar photovoltaic pumps, failures are much less likely than with conventional pumping systems.

Solar pumps for irrigation have been gaining importance since 2010. India, for example, has a large SPIS technology market. There are more than 12 million electric and 9 million diesel irrigation pump sets in operation to provide water for about 39 million hectares of irrigated land. If only 50% of these diesel pumps were replaced with solar PV pump sets, diesel consumption could be reduced in this area to about 225 billion liters per year.

But there are more advantages to the environment. A solar system that replaces a typical diesel generator unit will save about 1 kg of $CO_2$ per kilowatt hour of output. This already takes emissions during the lifecycle of the PV system into account. Moreover, PV-powered water pumping also helps to avoid the danger of soil and ground water contamination with fuels and lubricants. A diesel engine produces about 300 kg of waste oil over its lifetime. An environmentally sound disposal of this waste is not guaranteed everywhere. On the other hand, due to the unlimited supply of sun for pumping, there is a risk of over-pumping surface and groundwater resources if systems are not adequately sized and planned (see SAFEGUARD WATER module).

Old diesel pump

(Source: Andreas Hahn, 2015)

PV-experienced farm worker

(Source: Andreas Hahn, 2015)

## SPECIFICS OF SOLAR ENERGY

### Solar radiation

Solar energy has some specific characteristics that must be considered when planning a Solar Powered Irrigation System. Solar radiation captured by a solar panel is never constant due to daily and seasonal variations of solar radiation. The intensity of solar radiation on a surface is called irradiance (S). The irradiance is measured in watts per square meter [W/m²].

Solar irradiance varies over the course of the day, with maximum values of about 1,000 W/m² on a horizontal surface at sea level around noon on a clear day. The energy carried by radiation on a surface over a certain period of time is called global solar radiation (G). The global solar radiation is location-specific as it is influenced by cloud, air humidity, climate, elevation and latitude, etc. The global solar radiation on a horizontal surface is measured by a network of meteorological stations all over the world and is expressed in kilowatt hours per square meter [kWh/m²].

### Tilt angle

Most solar panels are installed with a fixed tilt angle "α" to increase the energy yield. Tilt angle is site-specific and has to be calculated. This can easily be done with the help of software tools such as the meteorological data base METEONORM, which provides climate data for almost every location in the world. A quick estimate of the right tilt angle α can be established when looking at the latitude in which the pumping system is installed.

Typical values for the tilt angle can be estimated to:

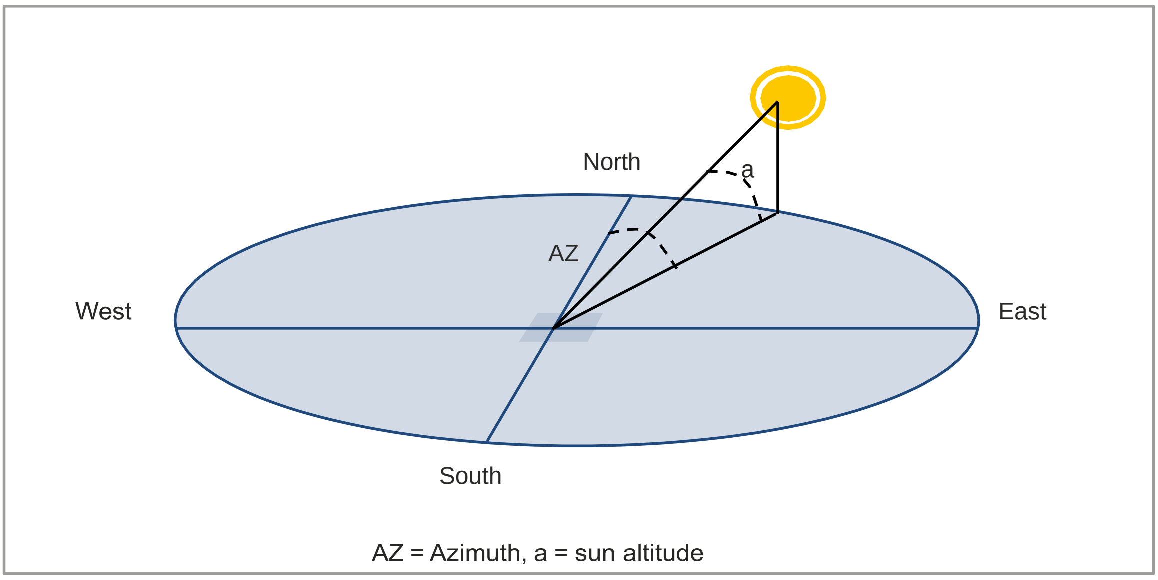
α = absolute value of geographic latitude + / - 10º

To allow rain water and accumulated dust to run off the panel surface, the tilt angle should be at least 15°, even if the system is installed close to the equator. To focus the applications in winter months, the tilt angle might be increased up to +10º, for summer months, the tilt angle might be reduced up to -10º.

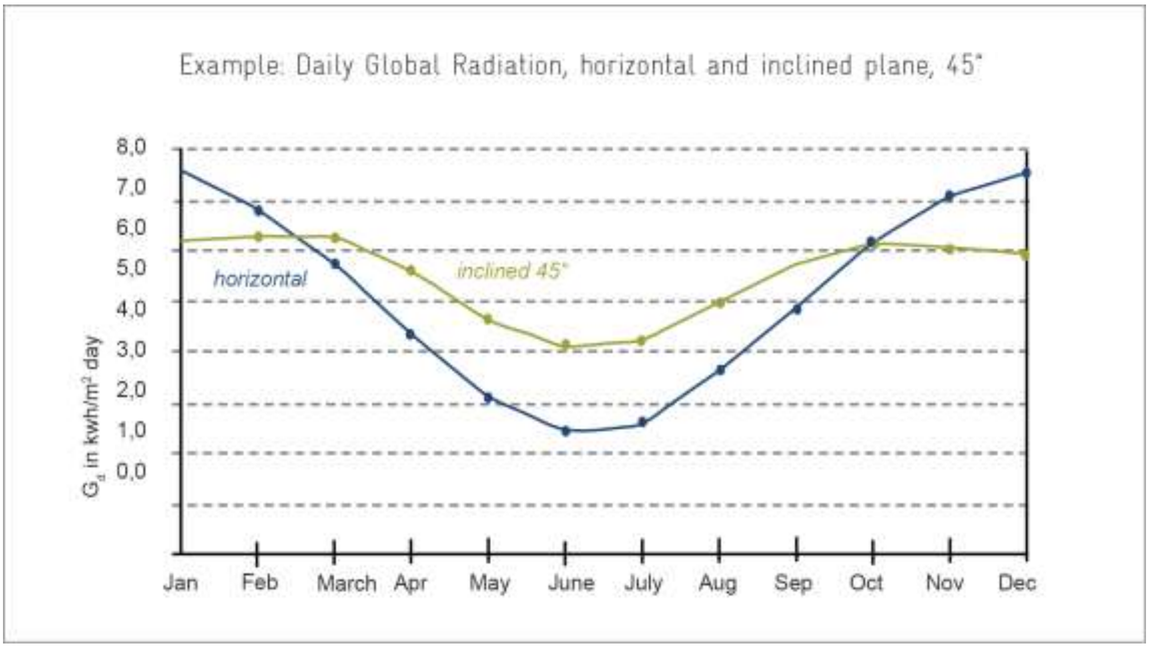
### Orientation of the solar generator

In the northern hemisphere, the panels should be facing south to maximize the energy yield, whereas in the southern hemisphere, panels should be facing north. Deviations from true north/south are possible but will result in a reduced overall energy yield.

Another method to further increase the energy yield of a solar generator is solar tracking (see Chapter 2).




**Daily movement of the sun in southern hemisphere**
**(Source: Reinhold Schmidt 2012)**




**Change of global radiation over the course of the year on a horizontal and tilted surface**

**(Source: Reinhold Schmidt, Aplicaciones de Energía Solar Fotovoltaica; Diseño, Implementación, Experiencias, June 2012)**

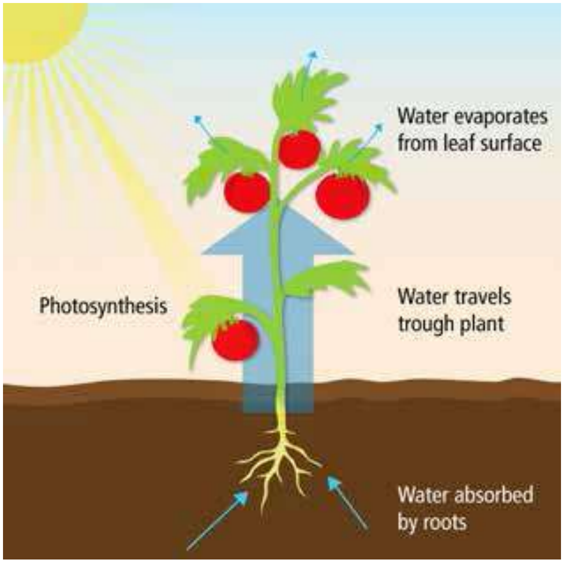
## IRRIGATION PRINCIPLES

Irrigation is the controlled application of water to respond to crop needs. Water used for irrigation may be taken from nearby lakes, reservoirs, rivers or wells (groundwater), but also from non-conventional sources such as treated wastewater, desalinated or drainage water. Irrigation water is brought to cultivated land by pipes, hoses or ditches.

Producers who irrigate are less dependent on irregular rainfall for their production. Producers can supplement rainfall with irrigation to respond to the amount of water the crop needs. Moreover, control over water improves the efficiency of other yield-improving inputs such as fertilizers and plant protection products. Consequently, the producer's ability to control the yields is enhanced. This is important for stable productivity and integration into markets.

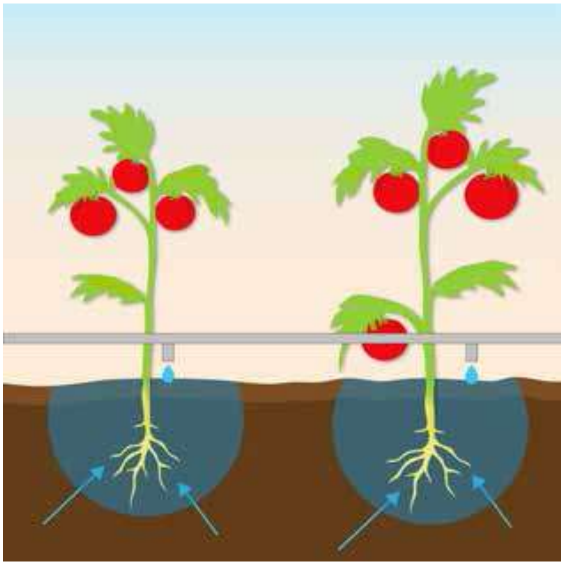
By irrigating, the soil water storage in the plant root zone is replenished. Instigated by the sun and photosynthesis, plants abstract soil moisture with their roots. This triggers a nutrient flow through the stem to the leaves, from where the water is **transpired** back to the atmosphere. Thus, only the water that is taken up through the root system contributes to plant and fruit growth.

**Important**: Most of the water that is brought to the field via irrigation should concentrate around the root zone of the plant and the volume of water irrigated should not exceed the plants' ability to absorb it.




Photosynthesis turns the energy of sunlight into chemical energy that triggers a nutrient flow in the plant.

(Source: GFA)



In a drip irrigation system, water is delivered directly to where it is needed, the root zone.

(Source: GFA)

## WATER REQUIREMENTS

The amount of water needed by a plant is expressed as Crop Water Requirement (CWR). It depends on the climate, the crop as well as management and environmental conditions. In sunny, hot, dry and windy places the CWR is highest. The crop species, variety and growing phase determine how much water the roots need to take up to enable the plant to grow optimally. Producers can reduce the crop water requirement e.g. through mulching, changing the plant density and applying different irrigation technologies.

The CWR of a particular crop is thus very site-specific and varies day by day. It requires on-site, regional data collection e.g. with support from local extension services, to calculate the CWR (see **DESIGN** module). CWR is most often expressed in millimeters (mm), or cubic meters per hectare ($m^3$/ha). Normally crops require about 2 to 10 $m^3$ per hectare daily. Details of this assessment are described in the **DESIGN** module.

It is important to note that water is a priced commodity (water fees, pumping costs) and a scarce resource as other users compete for it (industry, energy, domestic consumption, etc.). This should be considered in financial and ecological feasibility assessments.

## IRRIGATION EFFICIENCY

When irrigating, it is important to apply the right amount of water at the right time. Too little water will lead to wilting and yield reduction. Too much water can lead to water waste, runoff and erosion as well as leaching of nutrients in the soil and salinization, ultimately leading to yield reductions. A 100% efficient irrigation system would provide an equal amount of water to all plants in the field. However, e.g. plants close to the water source tend to get more water than plants at the far end of the field. As a result, yields of the farm are compromised because some plants get too much water and some get too little water. On big farms, this can have serious consequences on operating expenses and management of water resources. The uniformity of distribution of water over the field is determined by the choice of irrigation technology. The three commonly used irrigation methods are:

- surface irrigation;
- sprinkler irrigation;
- drip irrigation.

Surface irrigation methods such as basin, furrow and border irrigation do not achieve more than 60% field application efficiency as only a limited amount of water actually reaches the root zone.

Sprinkler and drip irrigation systems rely on a network of pipes to distribute the water to the field, thereby reducing conveyance losses common for surface irrigation methods. Sprinkler systems achieve an average field application efficiency of 75%, while drip irrigation systems can go up to 95% uniformity. Drip irrigation allows a slow release of water at the plant's root zone. As a result, soil moisture conditions are good, and no water is "lost" between plants, or on the plants. Crop yields can be doubled, and significant savings can be made in water, energy and labor.

## SOLAR POWERED IRRIGATION SYSTEMS

Using solar energy for irrigation makes a lot of sense. First, irrigation is often implemented in rural areas with poor access to reliable electricity or fossil fuel supplies. Second, solar radiation is an abundant resource in many developing countries where irrigation is essential to food security and international trade. Finally, Solar Powered Irrigation Systems (SPIS) passively self-regulate because the volume of water pumped increases on clear hot days when plants need more water, and vice versa. It is important to note that a SPIS is more than just a solar pump used for irrigation. Panels, pumps and irrigation systems are designed on the basis of water availability and local crop water requirements. SPIS is a system where the different components, from pump to plant, are integrated and harmonized.

### Operating Principle

The operating principle of an SPIS is simple. A solar generator provides electricity for an electric motor pump, which delivers water either directly into an irrigation system or to an elevated reservoir. Fundamental design criteria for SPIS include minimum maintenance, maximum reliability as well as resource efficiency. A specific characteristic of SPIS is the fact that generally a battery back-up is not required. This is an advantage since batteries are maintenance-intensive, costly and require regular replacement.

### SPIS components

The individual components of a SPIS are introduced in the following sections. The table below shows that, depending on site-specific conditions and capacities of the farmer, different technology options are available. The components and alternative technologies can be combined with each other in a wide range of ways, but some configurations are better depending on the situation in the field.

**Major alternative technologies for the most important components of an SPIS**

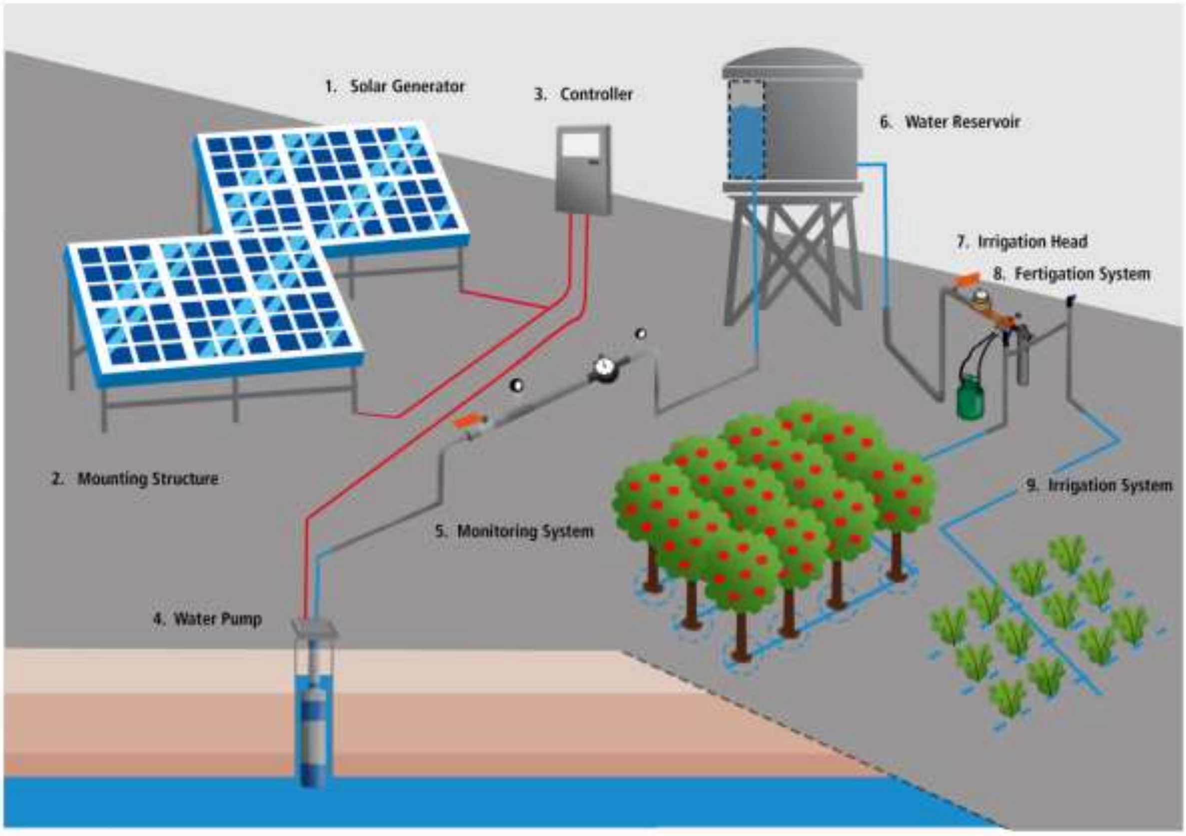
| Component | Alternative technologies | | Dependent on: |
|---|---|---|---|
| **Solar system** | fixed | tracking | costs and maintenance intensity |
| **Pump** | surface | submersible | costs and (geo-)hydrology |
| **Reservoir** | reservoir | no reservoir | costs and irrigation system |
| **Irrigation system** | surface | drip or sprinkler | costs and pumping system |

## SPIS configurations

The most common SPIS configuration is when a solar generator on a fixed mounting structure provides electricity for a submersible pump installed in a borehole. The water is then pumped to a reservoir elevated a few meters above the field. The water is stored at a constant pressure and released to a low pressure drip irrigation system where the water is filtered and mixed with fertilizer before it is slowly released to the plants. This configuration is shown in the figure below.

However, the installation of the water filter on the exit/output side of the tank can be critical/problematic, as the pressure losses in the filter can easily reach/be several meters, and then, at low tank heights, there is no water flowing any longer. Therefore it is recommendable to install the filter on the inpute side, to keep the water clean in the tank.

This configuration would also be possible with a tracking system, but would require higher investment and more maintenance than a fixed mounting of the solar panels. The reservoir provides stable pressure and water supplies to the drip irrigation system in order to make water distribution as uniform as possible. The performance of drip irrigation decreases when the drippers get clogged by small particles in the water. Filters prevent this, but only when properly designed for the particular water quality and irrigation system, and only when regularly cleaned. Therefore, it is strongly recommended to use drip irrigation only in combination with groundwater as groundwater is generally cleaner than water from rivers or reservoirs. Furthermore, it is recommended to have a monitoring system installed between the pump and the reservoir to measure the water flow and pressure.

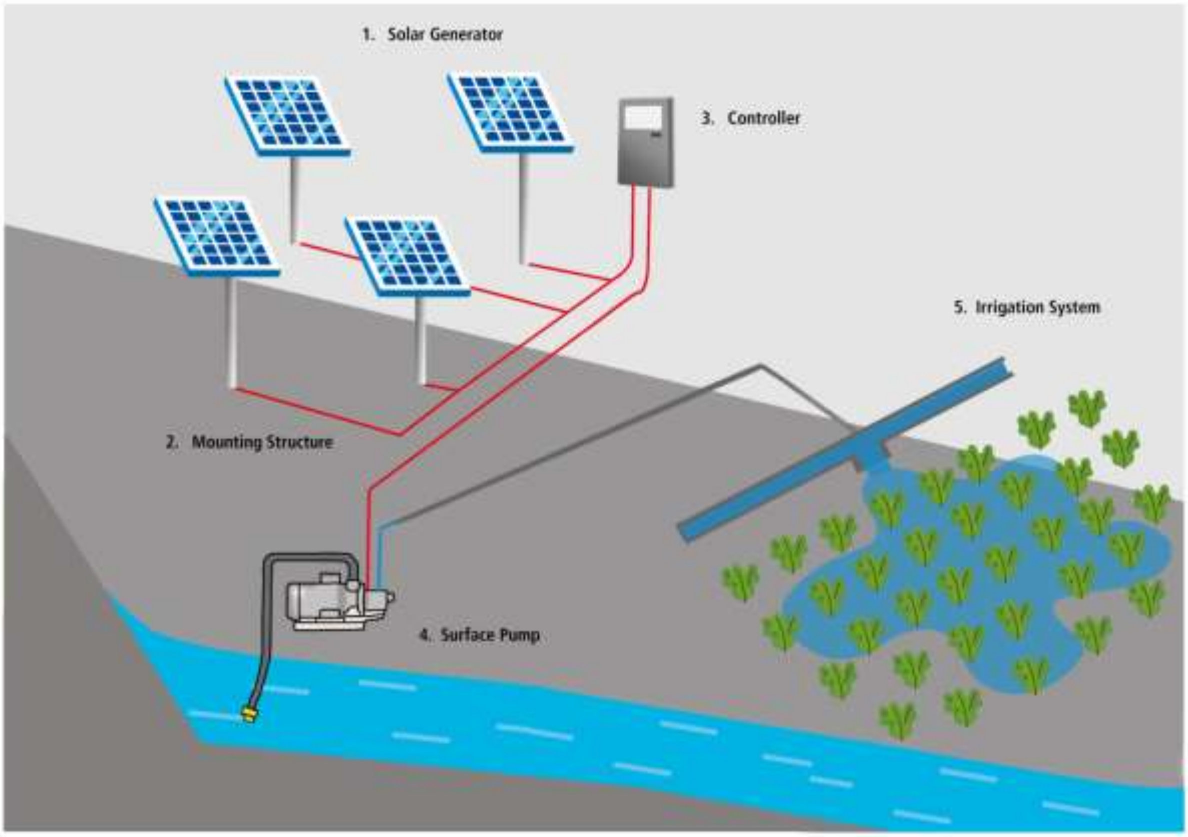



Best-practice configuration of the different components of an SPIS

(Source: GFA)

The simplest SPIS configuration is when a solar generator on a fixed mounting structure provides electricity for a surface pump installed at a reservoir or river. The water is then pumped directly to a surface irrigation system, e.g. through a network of open canals. In this configuration the pumped water does not pass through an elevated reservoir. The pressure and pump flow to the irrigation system corresponds to the actual solar irradiance, which varies over the course of the day, especially with a fixed mounted solar generator. The main advantage of this configuration is the simple installation and relatively low costs. However, the disadvantage is that the producer has little control on the distribution of water in the field over the day as there is no reservoir that regulates flow and pressure. The producer will have to use volumetric valves (see IRRIGATION HEAD) or divide his field into manageable sub-sections to control the watering of the crops as best as possible.

Another configuration to be found in the field is a **hybrid** solution, where a solar-powered pump and a diesel pump are both used for irrigation.




**Simple configuration – with a tracking system – of the different components of an SPIS**

**(Source: GFA)**

## 2. SOLAR GENERATOR

The solar generator provides the energy needed to operate the motor pump unit. It is made up of a set of solar panels that consist of individual solar cells. The individual solar cells make use of what is known as the photovoltaic effect, which converts light directly into electricity. Solar cells are made of specially prepared semiconductor materials such as crystalline silicon. When light falls onto the surface of the semiconductor, an electric field develops. This works best with the sun shining directly on the cells, but it also works with indirect solar radiation. On a cloudy day, solar panels can typically produce 10–25% of their rated capacity. By connecting a wire to the back of the solar cell, the voltage of the electric field causes an electric current to flow.

### The solar cell

To protect the cells against mechanical stress and humidity, the cell strings are embedded in a transparent bonding material (e.g. EVA), which also insulates the cells electrically. For structural stabilization and electrical insulation, they are usually placed between a plastic cover on the rear side and a glass cover on the front side. The laminate is then protected by an aluminum frame, which allows the panels to be mounted on a mounting structure.

Solar panels are usually certified by the International Electronical Commission[1] and this approval certificate has become generally accepted worldwide as one of the quality marks for solar panels. IEC standard testing, however, does not assess the durability of solar modules over a 25 year period. Standard panels typically come with a 10 year product guarantee and a linear 25 year performance warranty that guarantees at least 80% power output by the end of the 25th year.

**Note**: Solar panels are rated in peak watts (Wp) according to their output under internationally defined Standard Test Conditions (STC):

(Irradiance = 1,000 W/m², cell temperature = 25°C, air mass (AM) = 1.5)

The panels' electrical power mainly depends on the solar irradiance captured by the panel and the solar cell temperature. Solar cell temperatures increase significantly under normal operation and may easily reach 40 to 65 ºC, depending on the site-specific conditions. This leads to a lower electrical power output as compared to STC. The temperature coefficient (TC) describes the power reduction for each ºC increase in temperature, and for crystalline silicone cells it is approximately -0.5% per ºC.

A set of solar panels are connected to each other in series, parallel or a combination thereof, depending on the required electrical output (voltage, current and power). Combining solar panels in series means connecting the positive terminal of one panel to the negative terminal of the next panel. It allows you to build up the voltage to the level you need (as opposed to parallel wiring, which allows you to increase current/amperage).

[1] IEC – International Standards and Conformity Assessment for all electrical, electronic and related technologies.

## 3. MOUNTING STRUCTURE

In addition to the irradiance and cell temperature, the output of a solar panel is also dependent on the orientation and tilt angle of the panel surface. To maximize the output, a site-specific optimal orientation has to be found.

**Mounting options:**

There are basically two alternatives to mount solar panels on a metal structure:

- installation with a fixed tilt angle;
- installation on a solar tracker with varying orientation.

**The fixed installation** of solar panels on a rigid structure is the cheapest, most reliable and most common method. Metal supports that are pile-driven into the ground are generally recommended for larger systems. They make the utilization of concrete foundations redundant and save labor and material cost. However, in developing countries, simple concrete foundations are often used for smaller installations and represent an appropriate solution, provided that static requirements are met. The installation is typically oriented north or south to have a relatively good distribution of the output over the course of the day.

When the orientation of the mounting structure is variable over one or two axes, this is referred to as a **solar tracker** (see figure on the next page).

Solar tracking has two advantages:

- gain in additional solar radiation – the amount of solar radiation received by the solar panels increases between 25–35% (annual mean value), depending on solar tracker type and installation site.
- even distribution of solar irradiance throughout the day – the generated electricity and thus the pump's water flow is almost constant over the day. This is important in an SPIS configuration where the water is pumped directly to the field without passing through a reservoir.

Disadvantages of solar tracking:

- solar tracking is costly and substantially increases the overall system cost;
- the mechanical parts and the electrical motor of the tracking system require regular maintenance and spare parts.

This has to be kept in mind in particular for installations that are planned for remote areas or areas with limited technical services.

An interesting alternative to solar tracking can be **installations oriented in east and west directions,** which are relatively new. However, it requires more panels to get a stable output over the day. But with falling panel prices, this might be an interesting alternative for remote areas and smaller systems, as they are cheaper and require much less maintenance (as solar tracking solutions).

For both mounting options it is important to avoid galvanic corrosion when connecting metal structures. This can be done by selecting materials with similar corrosion potentials or by breaking the electrical connection by insulating the two metals from each other.

**Mounting structure and theft**

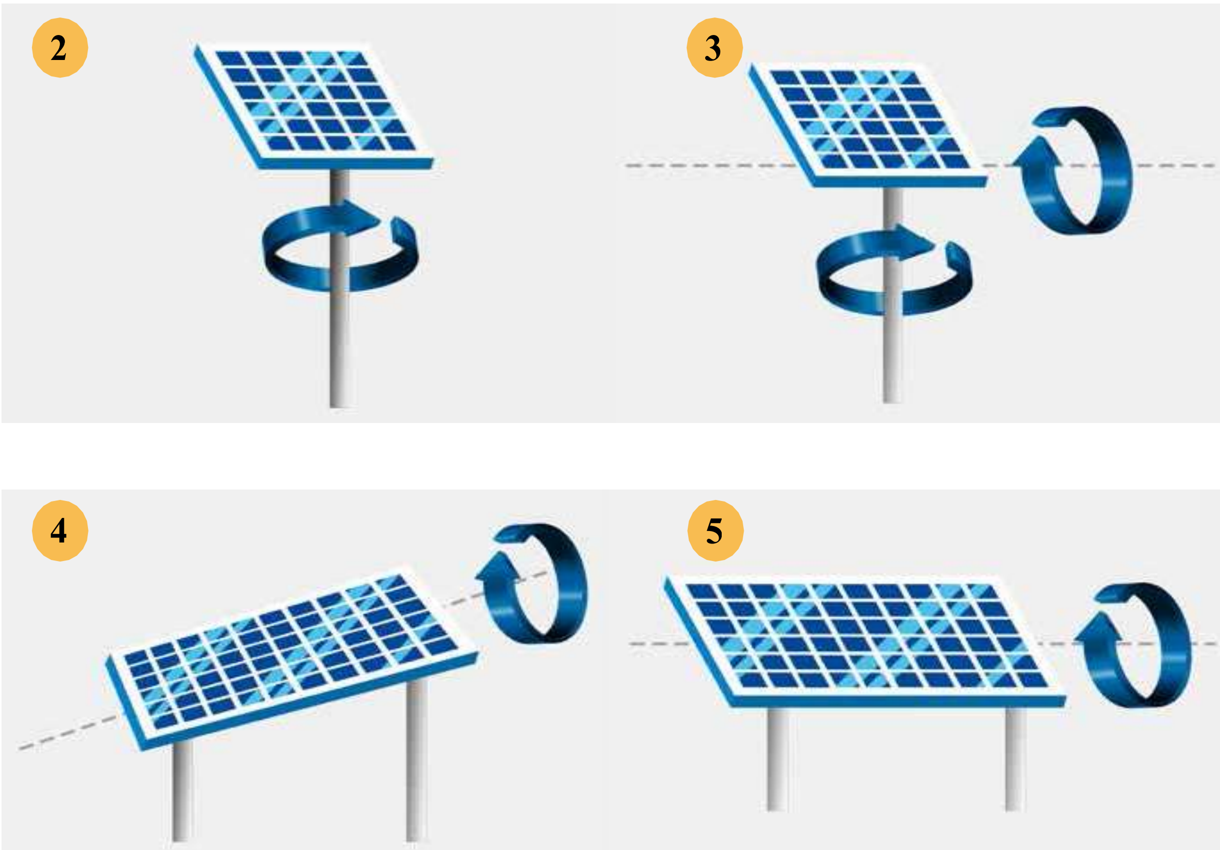
The type and the quality of the mounting structure are also a determining factor with regard to the risk of theft of the PV panels. With the increased application of photovoltaic installations for electricity generation the risk of theft is increasing. Common theft-prevention measures include:

- use of lock tie nuts;

- spraying the owner's ID with non-removable spray paint onto the back of the panels;
- integrating the solar panels into the mounting structure (non-detachable);
- placing the mounting structure out of easy reach by using elevated structures, fences or floating PV systems.


Solar systems (Source: Reinhold Schmidt, 2015):

1. fixed installation
2. one axis tracker, azimuth
3. two axis tracker azimuth and inclination
4. one axis tracker, south + north axis incline
5. horizontal one axis tracker, south/north axis.



## 4. CONTROLLER AND INVERTER

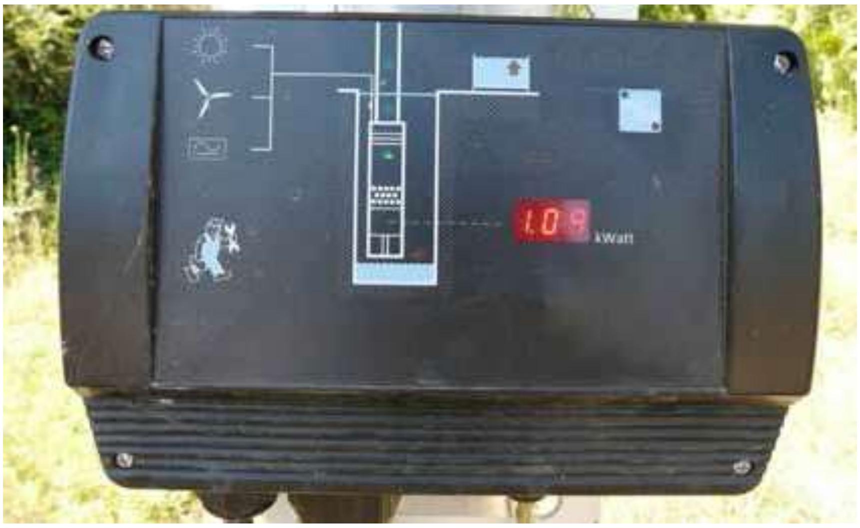
### Controller

The controller is the link between the solar generator and the motor pump and is essential for system reliability. It adjusts the fluctuation in the output frequency of the solar generator resulting from varying irradiation levels. Modern controllers incorporate highly efficient power electronics and utilize Maximum Power Point Tracking (MPPT) technology to maximize power use from the solar generator. The controller regulates the number of revolutions of the motor and protects the pump against over and under voltage, reverse polarity, overload and over-temperature.

### Inverter

Solar generators always provide DC current. Most electric motors of solar water pumps are powered by direct current (DC). Since DC motors usually have a higher efficiency than AC motors of a similar size, they tend to be preferred by solar pump manufacturers. Water-filled brushless DC motors in particular are gaining importance because they are maintenance-free and are not affected by frequent starts/stops that are typical of solar-powered systems.

Some solar pumps are still equipped with comparably cheap brushed DC motors. The main disadvantage of brushed motors is that brushes are subject to wear and tear and need to be replaced at regular intervals (approximately every two years). DC motors are mainly used for small to medium-sized irrigation schemes, while AC motors are gaining importance in applications where higher output/head combinations are required. The controller has to have an inverter if the pump is AC. Innovations in DC/AC inverter technology have led to the development of specially designed pump inverters that can drive conventional AC motors. Non-compatible inverter/motor combinations may reduce the expected lifetime of the conventional AC motor. Therefore, well matched and tested controller/motor combinations are recommended to increase system reliability.




Controller with display and LED fault indicator

(Source: Andreas Hahn, 2015)

## 5. WATER PUMP

Depending on the water source, there are two different possibilities for pump installation – submersible or surface. Surface pumps are often installed next to the water source and suck water up on one side before "pushing" it away on the other side of the pump. Surface pumps can pump water up from a maximum depth of six meters. Submersible pumps are installed under water in wells and boreholes and "push up" the water.

Submersible pumps are installed at depths ranging from 10 to 120 meters. Using control switches (such as float switches in water tanks and wells), submersible pumps can be operated in automatic mode. In contrast, surface mounted pumps usually require the attendance of an operator who regularly checks the surface pump's priming behavior. Use of primary chambers and non-return valves can prevent loss of prime.

Surface pumps have several advantages if compared to submersible ones: they are cheaper, can be easier installed and accessed for maintenance and can be used for an easy/simple fertigation at the suction/intake side.

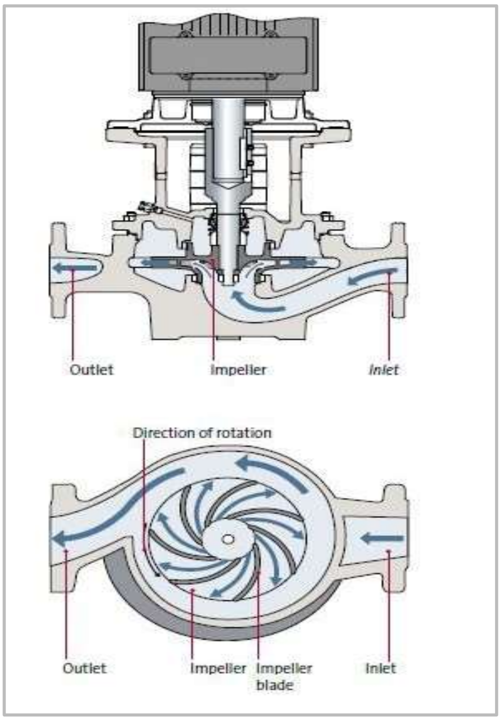
Solar water pumps are generally constructed from non-corrosive stainless steel and are designed to pump clean water without any solids and fibers. The lifetime of a submersible motor pump strongly depends on the water and installation quality. If the pump is installed in a drilled well with a proper well casing (and thus reduced sediment intrusion), submersible pumps may reach lifetimes between 7–10 years. In very poorly constructed wells and boreholes with high sediment content, the hydraulic part of the water pump may have to be replaced after 2–3 years. In order to secure a safe system operation, two safety means are necessary:

- water level sensor installed in the storage tank that switches off the pump in order to avoid overflow;
- second water level sensor installed towards the base of the well to avoid dry running of the pump.

There are two types of pumps to be typically found in today's solar pumping systems: centrifugal and helical rotor pumps.

### Centrifugal pump

A centrifugal pump creates an increase in pressure by transferring mechanical energy from the motor to the fluid through the rotating impeller. The fluid flows through the inlet to the impeller center and out along its blades. The centrifugal force increases the fluid velocity and consequently the kinetic energy is transformed to pressure. The pressure can be increased by simply adding several stages in series. Centrifugal pumps are generally utilized where pumping heads are low and water demand is high. For this reason centrifugal pumps are the preferred option for use in irrigation systems.




Centrifugal pump

(Source: Grundfos).

### Helical rotor pump

A helical rotor pump is a type of progressive cavity pump that works by the rotation of a helical rotor when sealed against a helix wall, pushing discrete sections of material through the device.

This corkscrew-like action provides a pulse-free flow, and valves are not required as the helical rotor seals the discrete sections of material. The flow rate is determined by the rotor speed and is independent of outlet pressure. Helical rotor pumps are typically found in applications with high pumping heads and low water flow rates, such as for drinking water supply.

Surface pump on a mobile structure

(Source: Lennart Woltering)

## 6. MONITORING SYSTEM

Operated by the producer on-site or on-line, the monitoring system allows readings of pressure, water flow and water level and helps to assess the performance of the system.

It is used

- to observe and track the system's operation and performance;
- to control pumping quantities to the irrigation system;
- to provide system data for the acceptance test after installation
- to avoid negative environmental impacts (e.g. ground water depletion).

Ultimately, monitoring is important to ensure that the system operates within sustainable limits for long-term productivity of the farm.

Some solar pump manufacturers have included monitoring systems in their product portfolios. Each SPIS should have a basic monitoring system comprising pressure gauges, a flow meter and a water level dipper. The water level dipper is a simple tool to check the water level in a well. Once the metal electrode reaches the water table, a light will flash and the exact value can be read from the dipper tape. Checking the water level several times over the course of the day gives an indication on the dynamic behavior of the well. The dynamic water level is an important parameter to determine the total pumping head (refer to **DESIGN** module).

Especially in cases where the water is pumped directly to the irrigation system without passing through an elevated reservoir, it is important to monitor water flow and pressure in the irrigation system as the amount of water delivered to plants may vary widely across the field. The picture below displays a monitoring system, which is composed of a water flow meter and pressure gauges on each side of the filter, which allow the monitoring of the pressure loss through the filter.

A more sophisticated monitoring system would include sensors to measure

- solar irradiance (e.g. on horizontal and inclined surface);
- rainfall, relative humidity and wind speed;
- the total pumping head.

**Monitoring system**

**(Source: Reinhold Schmidt, 2015)**

In addition, the monitoring system can be expanded with sensors in the reservoir and in the irrigation system itself.

More sophisticated (and expensive) monitoring devices may include automatic data logging. The data logger continuously records and stores all system parameters over a longer period of time. Special evaluation software allows for quick data analysis on site. In remote areas not connected to the public grid, data loggers are usually solar-powered and may even include modern communication devices (GSM) with the option of checking system performance via smart phones (also refer to the **MAINTAIN** module).

## 7. RESERVOIR

A reservoir can have several functions for an irrigation system: it can accumulate and store water pumped in over the day, it can provide pressure for the irrigation system to distribute the water to all corners of the field and, in small drip irrigation systems, it can be used to mix in soluble fertilizers. Since the output of solar pumps varies over the day as a result of irregular solar radiation, a reservoir can be useful to buffer the water amount available for irrigation.

Elevated tank

(Source: Andreas Hahn)

There are numerous ways to store water, ranging from simple open dug reservoirs, concrete and plastic tanks to expensive elevated metal tanks.

**Open reservoirs** are inexpensive and relatively easy to construct, but the big disadvantages are the high evaporation losses of water and easy accumulation of debris and sediments as well as algae growth. These effects can be significantly reduced by covering the tank, e.g. with a plastic foil. Evaporation and algae growth can be reduced when the solar panels are installed on floating mounting structures.

**Elevated water tanks:** This is the classic configuration of a Solar Powered Irrigation System. The pumped water is stored in an elevated water tank and irrigation functions by gravity. The elevated tank serves as a battery where energy is stored in the form of water. The irrigation system pressure depends on the height of the water level in the storage tank. It also allows for pre-sunrise irrigation. Ready-to-use plastic tanks are available in different sizes, easy to install and do not corrode as metal or cements reservoirs do.

In order to secure a safe system operation, a water level sensor should be installed in the water tank that switches off the pump to avoid overflow. If a submersible pump is installed in a well, a second water level sensor is required to protect the pump from dry running. Such sensors are often integrated into the motor pump by default. As water tanks usually store huge amounts of water, it is important that the foundation and support structure of the water tank meets the static requirements.

Open plastic foil-lined reservoir

(Source: Jan Sass, 2014)

## 8. IRRIGATION HEAD

The irrigation head is the part of the irrigation system where the water quantity, quality and pressure are managed. It is indispensable in irrigation systems that operate under pressure such as sprinkler and drip irrigation.

The irrigation head typically contains:

- **valves** to control the quantity of water flowing to the different sections of an irrigation system;
- **filters** to remove particles that could block drip emitters or sprinkler nozzles;
- **a fertigation system** to mix soluble fertilizer in the irrigation water;
- **pressure regulators**.

In surface irrigation systems, the irrigation head may contain valves only. The irrigation head of drip and sprinkler systems contains at least a valve and a filter.

### Valves

The irrigation system is usually divided into several sections to improve the control of the quantity and pressure of water in the field. The water flowing in each section is controlled by manual or automatic valves. Automatic valves can be volume- or time-controlled. The producer determines the required irrigation volume per section, and the automatic valve closes as soon as the target value is reached. It is recommended to use volumetric valves especially in cases where water is directly pumped to the irrigation system without passing through a reservoir. The disadvantages of automatic valves include high costs and regular replacement, and it requires electricity to operate the device.


Irrigation head with a disc filter and multiple valves that guide the water to different sections of the irrigation system (Source: Lennart Woltering).

### Filter

A filter is essential in any sprinkler or drip irrigation system as it reduces the occurrence of clogging of nozzles and emitters. Clogging is caused by inorganic material such as sand and clay, as well as organic material such as algae and bacteria, that accumulate and block the emitter. Depending on the quality of irrigation water (i.e. sediment, dissolved salts, etc.) filters must be cleaned multiple times per day.

Initially, a water analysis can provide information on the size and amount of particles, and from this you can identify the correct filter technology required. However, this may not be a feasible solution for all farm sites as some may not have access to test kits or laboratories. Surface water from a reservoir or river needs to be filtered much more frequently than water from a well or borehole, where the water is filtered naturally in the ground.

When choosing a filter for an SPIS it is important to realize that:

- filters must be adapted to the flow rate of the pump;
- the pressure loss through the filter should be minimized and monitored;
- maintenance should be easy and the lifetime should be long.

There are three major filter systems:

1. screen filter: a filter using a stainless steel (mesh), polypropylene, nylon or polyester screen to separate particles from the water. The pressure loss in screen filters tends to be quite high; therefore they are not recommended for use in SPIS.
2. disc filter: a disc filter element contains a stack of compressed discs with an overlapping series of grooves. Unfiltered water passes through the stack of tightly compressed discs and the water is forced to flow through the interlocking grooves of the disc rings where debris is trapped. Dirt particles are caught on a very large surface, which is the reason for the comparatively low pressure loss. For manual cleaning, the filter rings have to be taken out of the enclosure and rinsed with clean water. When using disc filters for SPIS, it is advisable to install the next larger model to reduce the characteristic pressure drop, which is proportional to the flow rate, or to install two filters working in parallel. The maintenance intervals should be short so as to significantly reduce the accumulated pressure loss. Automatic backflush systems work with considerably higher pressure and therefore do not suit the pressure minimizing concept of SPIS.
3. Granulate/sand filter: these filters have a large capacity to remove particulates from water. Water is routed through a sand-filled metal tank where the sand traps large and small particles. Eventually the dirt accumulates in the space between the sand particles, requiring a backflushing with clean water. The sand filter requires high pressures for operating and backflushing, which makes it less suitable for SPIS.

## 9. FERTIGATION SYSTEM

Fertigation is the injection of **fertilizers** into an irrigation system. It is a combination of the words “fertilizer” and “irrigation”. The fertigation system is connected to the irrigation head.

Fertigation is practiced extensively in commercial agriculture and horticulture and is mainly used to spoon-feed additional nutrients. It is usually practiced on high-value crops such as vegetables and fruit trees. Drip irrigation systems in particular are well suited to fertigation because of their operation frequency and since water application can be easily controlled by the producer. Liquid fertilizers often play hazard to clogging attributable to the frequent occurrence of a chemical reaction between the organic and inorganic matter in the irrigation water. To reduce this clogging effect, it is advisable to flush the system with pure water after using liquid fertilizer. Fertilizers delivered as a solution can be injected directly into the irrigation system, while those in a dry granular (e.g. urea) or crystalline form need to be mixed with water to form a solution. Considering the relatively low operating pressure (0.2–0.5 bar) of SPIS, the following fertigation options can be considered:

1. differential pressure tanks;
2. Venturi nozzles;
3. electric metering pumps;
4. water-powered dosing pumps.

1. **Differential pressure tanks**, often referred to as “batch tanks”, are simple injection devices where the amount of fertilizer injected slowly decreases over time, as if a bucket empties. If the chemical concentration needs to be kept relatively constant during injection, batch tanks are not appropriate.
2. **The Venturi nozzle** makes use of the “Venturi hydraulic effect”. Because of the high pressure loss of Venturi nozzles and the fact that the pressure provided by a photovoltaic water pump is not constant (this would cause a strong fluctuation in the fertilizer concentration), the Venturi nozzle is not recommended for SPIS.
3. **Electric metering/dosing pumps** are the most expensive injection devices but they provide a constant and precise injection concentration and are robust systems.
4. For off-grid applications, **water-driven dosing pumps** installed directly in the water supply line are suitable for use in SPIS. They work at comparably low system pressures and the dose will be directly proportional to the volume of water entering the dosing pump, regardless of variations in flow and pressure that may occur in the main line.

In addition, the simplest form of fertigation is to mix soluble fertilizer (e.g. urea) into the elevated reservoir of a low pressure drip irrigation system.
The challenge with fertigation is to control the concentration over time. Overdosing will harm the environment and the production cost budget.
If surface pumps are used for fertigation, it is recommended to inject the fertilizer on the intake/suction side, as it is a cheap, easy and reliable way to fertigate.
Chemigation is used as an overall term for the injection of **fertilizers**, soil amendments, and other water-soluble products into an irrigation system. In a drip irrigation system, chemigation can be used to inject chemicals to dilute debris and other materials that tend to clog the outlets or narrow bends. After a certain period of time, the treated water including the dissolved material is flushed out of each drip line. The assistance of qualified water engineers is required to develop a chemigation plan that suits the producer needs and matches the water quality situation at the farm.

## 10. IRRIGATION SYSTEM

Water is the most important input required for plant growth in agriculture production. Irrigation is the controlled application of water through man-made systems to supply water requirements of plants not satisfied by rainfall alone. Various methods can be used for irrigation (starting from simply watering plants with a pot or a bucket). The choice of a particular irrigation system mainly depends on the crops to be irrigated, the underlying water availability, irrigation water requirements and energy supply as well as the financial capacity of the farm household. Solar pumps pump up water to the farm, from where it can be collected for further distribution by hand. Alternatively, it can be pumped directly to the field through a system of canals (surface irrigation) or pipes (sprinkler and drip irrigation). In principle, solar pumps can be used for supplying water to any kind of irrigation system. The size (and cost) of the PV generator is mainly determined by the water and pressure requirements of the irrigation scheme. However, it is important to consider that SPIS are relatively expensive, requiring producers to grow high-value crops to guarantee its financial viability. In addition, water savings will have a positive influence on the investment costs of the solar pumping system and the environment.

Surface irrigation systems are not always suitable for high-value crop production and they are far from being water-efficient. However, SPIS with surface irrigation systems are widely used as they do not require the producer to adopt a new irrigation method. SPIS are seldom combined with sprinkler irrigation because sprinkler irrigation requires relatively high water pressures to operate, which demands expensive PV generators.

Water-saving irrigation technologies working at comparably low operating pressures are the preferred option in connection with PV pumping systems.

**External drip emitter**

**(Source: Andreas Hahn, 2015)**

Drip irrigation systems normally operate at high pressures of 1–10 bar. Fortunately, the technology has been adapted to cater for low pressures and a more simplified operation. These low-pressure drip irrigation systems can give 80% uniform water application even from a few meters pressure. The performance is very much dependent of the pressure, the size and shape of the field being irrigated. Solar-powered drip irrigation is the “marriage” of two systems that go very well together. Drip irrigation is ideal for high-value crop production such as vegetables and fruits, and due to its high efficiency the solar pump can be quite conservatively sized.

**Suitability of irrigation methods to PV pumping**

| Distribution method | Typical water application efficiency | Typical head | Suitability for use with PV pumps |
|---|---|---|---|
| Flood irrigation | 40–50% | 0.5 m | barely cost-efficient |
| Open canals | 50–60% | 0.5–1 m | depends on local conditions |
| Sprinkler | 70–80% | 10–20 m | No |
| Low pressure drip irrigation | 80% | 1–10 m | Yes |
| High pressure drip irrigation | 85–95 % | 10–100m | No |

## FURTHER READING, LINKS AND TOOLS

### Further reading

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Deutsche Gesellschaft für Sonnenenergie (DGS) (2008): Planning and Installing Photovoltaic Systems: A Guide for Installers, Architects and Engineers: Earthscan (Planning and Installing Series). Retrieved from https://books.google.de/books?id=fMo3jJZDkpUC&printsec=frontcover&hl=de&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false

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Woltering, L., Pasternak, D. & Ndjeunga, J. (2011): The African Market Garden: The Development of an Integrated Horticultural Production System for Smallholder Producers in West Africa. In: *Irrigation and Drainage* 60 (5), 613-621. doi: 10.1002/ird.610.

### Links

European Commission, Joint Research Centre (2012): Photovoltaic Geographical Information System (PVGIS). Geographical Assessment of Solar Resource and Performance of Photovoltaic Technology. Retrieved from http://re.jrc.ec.europa.eu/pvgis.

Irrigation Association (2017): Irrigation Glossary. Retrieved on http://www.irrigation.org/IAGlossary.

Meteonorm: Meteonorm Software. Irradiation data for every place on Earth. Retrieved on http://www.meteonorm.com/en/.

NASA (2016): Surface meteorology and Solar Energy. With the collaboration of Atmospheric Science Data Centre. Retrieved on http://eosweb.larc.nasa.gov/sse.

Some mounting / tracking system manufacturers provide product-specific design tools, which can usually be found on the relevant manufacturer's website.

### SPIS tools

No tools for this module.

## TECHNICAL GLOSSARY

| | |
|---|---|
| Aquifer | Underground geological formation(s), containing usable amounts of groundwater that can supply wells or springs for domestic, industrial, and irrigation uses. |
| Chemigation | The process of applying chemicals (fertilizers, insecticides, herbicides, etc...) to crops or soil through an irrigation system with the water. |
| Conveyance loss | Loss of water from a channel or pipe during transport, including losses due to seepage, leakage, evaporation, and other losses. |
| Crop coefficient | Ratio of the actual crop evapotranspiration to its potential (or reference) evapotranspiration. It is different for each crop and changes over time with the crop's growth stage. |
| Crop Water Requirement (CWR) | The amount of water needed by a plant. It depends on the climate, the crop as well as management and environmental conditions. It is the same as crop evapotranspiration. |
| Current (I) | Current is the electrical flow when voltage is present across a conductor, or the rate at which charge is flowing, expressed in amperes [A]. |
| Deep percolation | Movement of water downward through the soil profile below the root zone. This water is lost to the plants and eventually ends up in the groundwater. [mm] |
| Drawdown | Lowering of level of water in a well due to pumping. |
| Drip irrigation | Water is applied to the soil surface at very low flow rates (drops or small streams) through emitters. Also known as trickle or micro-irrigation. |
| Emitter | Small micro-irrigation dispensing device designed to dissipate pressure and discharge a small uniform flow or trickle of water at a constant discharge which does not vary significantly because of minor differences in pressure head. Also called a "dripper" or "trickler". |
| Evaporation | Loss of water as vapor from the surface of the soil or wet leaves. [mm] |
| Evapotranspiration (ET) | Combined water lost from evaporation and transpiration. The crop ET (ETc) can be estimated by calculating the reference ET for a particular reference crop (ETo for clipped grass) from weather data and multiplying this by a crop coefficient. The ETc, or water lost, equals the CWR, or water needed by plant. [mm] |
| GIWR | The Gross Irrigation Water Requirement (GIWR) is used to express the quantity of water that is required in the irrigation system. [mm] |
| Fertigation | Application of fertilizers through the irrigation system. A form of chemigation. |

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|---|---|
| Financial viability | The ability to generate sufficient income to meet operating expenditure, financing needs and, ideally, to allow profit generation. It is usually assessed using the Net Present Value (NPV) and Internal Rate of Return (IRR) approaches together with estimating the sensitivity of the cost and revenue elements (See Module **INVEST**). |
| Friction loss | The loss of pressure due to flow of water in pipe. It depends on the pipe size (inside diameter), flow rate, and length of pipe. It is determined by consulting a friction loss chart available in an engineering reference book or from a pipe supplier. [m] |
| Global solar radiation (G) | The energy carried by radiation on a surface over a certain period of time. The global solar radiation is locations specific as it is influenced by clouds, air humidity, climate, elevation and latitude, etc. The global solar radiation on a horizontal surface is measured by a network of meteorological stations all over the world and is expressed in kilowatt hours per square meter [$kWh/m^2$]. |
| Gravity flow | The use of gravity to produce pressure and water flow, for example when a storage tank is elevated above the point of use, so that water will flow with no further pumping required. |
| Head | Value of atmospheric pressure at a specific location and condition. [m]:<br>Head, total (dynamic) Sum of static, pressure, friction and velocity head that a pump works against while pumping at a specific flow rate. [m];<br>Head loss Energy loss in fluid flow. [m] |
| Infiltration | The act of water entering the soil profile. |
| Insolation | The rate at which solar energy reaches a unit area at the earth measures in Watts per square meter [$W/m^2$]. Also called solar irradiance. |
| Irradiation | The integration or summation of insolation (equals solar irradiance) over a time period expressed in Joules per square meter (J/m2) or watt-hours per square meter [$Wh/m^2$]. |
| Irrigation | Irrigation is the controlled application of water to respond to crop needs. |
| Irrigation efficiency | Proportion of the irrigation water that is beneficially used to the irrigation water that is applied. [%] |
| Irrigation head | Control unit to regulate water quantity, quality and pressure in an irrigation system using different types of valves, pressure regulators, filters and possibly a chemigation system. |
| Lateral | Pipe(s) that go from the control valves to the sprinklers or drip emitter tubes. |
| Latitude | Latitude specifies the north–south position of a point on the Earth's surface. It is an angle which ranges from 0° at the Equator to 90° (North or South) at the poles. Lines of constant latitude, or parallels, run east–west as circles parallel to the |

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|---|---|
| | equator. Latitude is used together with longitude to specify the precise location of features on the surface of the Earth. |
| Leaching | Moving soluble materials down through the soil profile with the water. |
| Maximum Power Point Tracking (MPPT) | An important feature in many control boxes to draw the right amount of current in order to maintain a high voltage and achieve maximum system efficiency. |
| Net Irrigation Water Requirements (NIWR) | The sum of the individual crop water requirements (CWR) for each plant for a given period of time. The NIWR determines how much water should reach the crop to satisfy its demand for water in the soil. [mm] |
| Power (P) | Power is the rate at which energy is transferred by an electrical circuit expressed in watts. Power depends on the amount of current and voltage in the system. Power equals current multiplied by voltage (P=I x V). [W] |
| Photosynthesis | Photosynthesis is a process used by plants and other organisms to convert light energy into chemical energy that can later be released to fuel the organisms' activities (energy transformation). |
| Pressure | The measurement of force within a system. This is the force that moves water through pipes, sprinklers and emitters. Static pressure is measured when no water is flowing and dynamic pressure is measured when water is flowing. Pressure and flow are affected by each other. [bars, psi, kPa] |
| Priming | The process of hand-filling the suction pipe and intake of a surface pump. Priming is generally necessary when a pump must be located above the water source. |
| Pump | Converts mechanical energy into hydraulic energy (pressure and/or flow).<br>Submersible pump: a motor/pump combination designed to be placed entirely below the water surface.<br>Surface pump: pump that is not submersible and placed not higher than about 7 meters above the surface of the water. |
| Root Zone | The depth or volume of soil from which plants effectively extract water from. [m] |
| Salinity (Saline) | Salinity refers to the amount of salts dissolved in soil water. |
| Solar panel efficiency | Solar panel efficiency is the ratio of light shining on the panel, versus the amount of electricity produced. It is expressed as a percentage. Most systems are around 16% efficient, meaning 16% of the light energy is converted into electricity. |
| Suction lift | Vertical distance from the surface of the water to the pump. This distance is limited by physics to around 7 meters and should be minimized for best results. This applies only to surface pumps. |

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| Surface irrigation | Irrigation method where the soil surface is used to transport the water via gravity flow from the source to the plants. Common surface irrigation methods are:<br>Furrow irrigation – water is applied to row crops in small ditches or channels between the rows made by tillage implements;<br>Basin irrigation – water is applied to a completely level area surrounded by dikes, and<br>Flood irrigation – water is applied to the soil surface without flow controls, such as furrows or borders. |
| Transpiration | Water taken up by the plant's roots and transpired out of the leaves. [mm] |
| Voltage (U or V) | Voltage is the electric potential between two points, or the difference in charge between two points, expressed in Volts [V]. |