Solar Pumping

For Village Water Supply Systems

TRAINING MANUAL

For techniciens, designers and managers

PRACTICA FOUNDATION

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Introduction

The elaboration of this manual is inspired by the need to support the professionalization of the departments, units, NGO's and design bureaus that are directly involved in the design of solar water systems in developing countries.
Without being exhaustive, we aim to offer with this training manual practical guidelines for the design, exploitation, management, maintenance and financial analysis of off-grid solar pumped water systems.

This manual is part of a training package offered by Practica Foundation. Together with this manual, we developed a case study that takes the participants through all design steps, calculations and considerations, as well as a series of guiding questions for each module of this manual that can serve the purpose of examination, self-examination and exercise.
The manual and training are designed for people who are already active in the water supply sector and want to upgrade their knowledge and skills on designing and implementing solar water systems. It can be provided to, and adjusted to the needs of, governmental agencies, design agencies, NGO's and water system managers. It will be a good resource for people who are charged with the elaboration or selection of design and tender documents, supervision of construction work, as well as for those in charge of operating and managing a solar pumped water system.

A second target group for this training are (teachers of) training centers who are charged with the provision of trainings to technical staff. These trainers can be trained by Practica Foundation, and equipped with training materials adjusted to the specific needs and characteristics of their country, to provide a training tailored to the needs of the water sector in their country.

Preface

Solar radiation is a perennial source of energy, available all over our planet, free of charge and entirely renewable. Photovoltaic systems, once installed, do not need any fuel input and do not emit greenhouse gases. They receive and automatically convert the solar radiation into electricity, do not contain any mobile parts and thus require very limited maintenance. Solar systems therefore have highly reduced running and maintenance costs compared to engine powered water systems.

This way, photovoltaic systems have the potential to drastically reduce the costs of water production, at the favor of the financial sustainability of water companies and service providers, as well as the water price to water users. They provide a great opportunity to respond to the needs and aspirations of people to upgrade hand pumped systems into small gravity water systems, thus improving service levels, accessibility and availability of water at affordable price.

Nevertheless, the initial investment costs of solar systems are quite high, and until recently constituted an obstacle for the application at scale. Thanks to the continuous price reduction of solar panels, this alternative has become more and more attractive, especially in areas where electric grid connections are not available.

Not in all situations, solar systems are applicable or even the best choice. As pumping hours are limited to the daily sunshine hours, a relatively high yielding water source is needed as water intake. Diesel aggregates or grid connected systems can pump 24 hours per day, thus producing a larger quantity of water at lower yielding water sources. Solar systems are less flexible, also from a financial management point of view. The relative weight of initial investment costs is high, whilst the operational costs of fuel pumped systems highly depend on their pumping hours.

Designing a water system is a process not limited to the technical and cost considerations as presented in this manual. In our view, all stakeholders including user groups (women, men, disabled people) and the (future) managers of the systems should be involved, and able to understand and influence design and management decisions according to their rights, needs and satisfaction. Technical and cost considerations are however an indispensable basis for this.

Summary of module content

Module 1 provides an introduction of the basic electric theory necessary to understand the functioning of solar systems. The concepts of voltage, current, resistance, losses, electric power and electric energy are presented, as well as the difference between direct current and alternating current.

Module 2 provides an introduction to the sun as power source. Not all energy of the sun can be captured and converted to be used for our energy needs. In order to maximize the utilization of this energy source, it is useful to understand more about sunshine and its characteristics.

Module 3 provides an explanation of the characteristics of solar cells and panels. The effects of irradiance level and temperature are presented. Attention is paid to how and where to place and locate a solar array in a water system, and what can be done against theft and vandalism. The effect of shadow is explained. As last subject, we introduce the electric losses and electric efficiency.

Module 4 is about the evaluation of water needs. Although not specific for solar systems, it is a crucial subject for the design of drinking water systems, and a basic input for all further calculations and system dimensions. We first introduce the general method and parameters for establishing the water consumption need of the target population of a community. After this, we introduce parameters for calculating the production requirements for a water system.

Module 5 treats with the borehole as water source. As the majority of small piped water supply systems make use of groundwater, this chapter describes means of access, construction aspects and quality requirements of boreholes.

Module 6 provides theory about Hydraulic Head and pump types, as next step in dimensioning the water and pump system.

Module 7 explains the dimensioning of the solar array. Although this is nowadays done by computer programs, it is important to have a good idea of how such dimensioning calculations are executed in order to avoid accepting offers from importers with inappropriate software. One also has to understand how dimensioning is done to be able to properly commission a system.

Module 8 goes into the aspects of determining the size of the storage tank, as the storage capacity requirement is related to the pumping hours and water consumption patterns.

Modules 9 treats a number of design considerations, and dilemmas are discussed, such as the choice between solar systems and grid connections; the options when the capacity of the borehole is insufficient to install a solar system. We explain why it is recommendable not to combine solar panels with different characteristics, the limitation of village size related to borehole and pump capacities, and go into pump capacity choices when pumps need replacement. Finally, we go into the quantitative effects of different combinations of design assumptions.

Module 10 presents the basic elements of financial analysis and planning that needs to take place to balance income from water consumption with the costs of water production. The unit water cost (UWC), cost elements, life cycle cost modelling and cash flow analysis are explained.

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Module 1 Introduction into Electric units and Laws

1.1 Introduction

In this module, an introduction of the basic electric theory is provided, necessary to understand the functioning of solar systems. The concepts of voltage, current, resistance, losses, electric power and electric energy will be presented, as well as the difference between direct current and alternating current.

1.2 Electric Theory, Units and Laws

1.2.1 Voltage

Electricity is invisible, and to make the concept easier to understand we could compare electricity to water. Voltage can then be compared with water pressure. Water pressure is a measure of the *force* that pushes water through a pipe. “Electrical pressure” is voltage: the force that pushes electricity through a wire. The unit of electrical pressure is the same everywhere: volts (V). A low electrical pressure of 1.5 V is the pressure provided by one dry battery cell as used in an electric torch or radio. A medium voltage of 120 V to 240 V is found at electrical power points in city homes. High voltages of more than 1,000 V are needed to move electricity over long distances, or for providing very high power.

In electricity laws, the voltage is given the letter V, whilst the *unit* of tension is the Volt. For example: V = 24 V means that the voltage is 24 Volt.

1.1.2 Current

Current can be compared with water flow. When electricity moves through a wire, it is sometimes said to flow like water. It is said to have a current rather than a flow rate. So electricity moving through a wire is called an electric current. It is measured in amperes (A). 1 A is the electric load of 1 Coulomb flowing through a wire in a time of 1 second. So an ampere is a one-coulomb-per-second flow rate. When water flow consists of molecules of water, electric current consists of electrons.

In electricity laws, current is often given the character I, whilst the *unit* of current, Ampere, is given the letter A. For example: I = 5 A means that the current is 5 Amperes.

1.2.3 Resistance, electrical losses and efficiency

Just like water flows through pipes, electricity flows through wires. The smaller the diameter of the pipe, the more energy it takes to push the water through the pipe. Also, the longer that pipeline is, the more energy it takes. As if there is a force that wants to oppose the flow. This force is called resistance (R). The larger the flow, the larger the resistance will be. The same with electricity: The thinner the electric wire, and the longer it is, the more energy it costs to transport the electricity through the wire.

The *unit* of electrical resistance is the Ohm, and has the symbol Ω. In electricity laws, resistance is given the character R. For example: R = 5 Ω means that the resistance is 5 Ohm.

The electric wire is made of metal, surrounded by plastic as isolating material. Also the type of metal is important; some metals transport electrons more easily than other metals. For most wires, *copper* is used, because copper easily transports electrons, meaning that it has low resistance.

Under a given voltage, if the resistance is high, than the current will be low. This is a linear relation, expressed in the equation V = I * R, commonly known as the law of Ohm.

Not only wires, but *all* electrical applications have resistance. Without that resistance, they would not do their work. For example, an electric bulb lamp has a filament, which heats up and glows. This way, it produces the light that we want the bulb to produce. The filament glows because it has resistance to the current. But a bulb lamp is not very efficient in its energy use: only a small proportion of the electricity is converted into light, and the rest into heat. LED lamps are much more energy efficient.

The part of the electricity that is not used for the purpose we finally want, is called the electric energy loss. The resistance of the wire causes energy loss. The (low) efficiency of the bulb lamp also causes energy loss. Electronic devices that are very useful (like inverters and maximum power point trackers about which we will present more at a later stage) also have their energy losses. Electric motors of water pumps also have electric losses: they do not convert all electric power into power at the shaft that drives the pump.

In the design of solar systems, it is important to calculate the electric losses in the system, because you need to install sufficient solar panels to compensate for the losses. By the way: also for the hydraulic losses!

1.2.4 Electric Power

Power is the ability to do work. If electricity is under high voltage (pressure), or a large volume of electricity is flowing (current), we say that there is more power. Under a given voltage, (with a certain level of resistance) a certain current will occur. The power increases when either the voltage increases, or the current increases. The symbol used for electrical power is the (often) P, whilst the *unit* is Watt (W). 1 W is the power produced by a current of 1 Ampere (A) driven by an electrical pressure of 1 Volt. The electric power produced is expressed in the equation P = V * I.

For example: P = 80 W means that the electric power is 80 Watts. If the voltage a PV system is 24 V and it operates a light that uses 2 A, the power used is 24 V × 2 A = 48 W. 1000 Watt is commonly referred to as kW.

1.2.5 Electric Energy

The energy produced depends on the power used, and on the length of time the power is applied. Multiplying the power by the time the power is used gives the amount of energy. As the electrical measure of power is the Watt, energy is measured as Watts * hours or Watt-hours (Wh). Other units are KWh (= 1000 Wh= 1000 Watts during one hour).

1.2.6 Direct current DC and alternating current AC

The electricity that we have discussed so far can be thought of as flowing directly from a source (such as a solar panel) through wires to the point of use (such as a water pump). This type of electrical power is called direct current (DC). Solar panels always produce DC electricity. Batteries too.

However, the electrical power provided by engine-driven rotating generators is Alternating Current (AC).

This type of electrical power flows in one direction for a very short time, and then reverses to flow in the other direction an equally short time before reversing again. It is like a constant vibration, or better: a wave. The electricity constantly alternates its direction of flow.

The forward and backward repetition of direction is called a *cycle* and the number of cycles that occur in 1 second is called the AC *frequency*. Frequency is measured in Hertz (Hz). Power-plant frequencies, and thus electric grid frequencies, are either 50Hz or 60Hz, meaning that the direction of flow changes 50 or 60 times per second. Generators usually produce an alternating current of 50 Hz at 1500 or 3000 rpm. The same generator would produce 60 Hz at a speed of 1800 or 3600 rpm. When such electricity is connected to an electric motor, it will start running at the same speed.

The advantage of AC power is that it allows more manipulation. It makes it easier to adjust the electricity to the characteristics we want it to have. For example, we can adjust the frequency and the voltage (transformer) in the circuit. AC motors are simpler than DC motors and AC electricity is easier to transport.

To make it easier to remember: stationary sources of electricity (batteries, solar panels, etc.) produce DC and rotating engines like generators produce AC. Because electronics have advanced considerably these last years, it is now possible to convert AC to DC and the other way around at reasonable costs.

1.3 Electric Control Boxes in a solar pumping system

1.3.1 Pump Control Unit

The pump controller is a highly specialized item and can vary significantly between manufacturers. A technical term for a pump controller is a 'linear current booster.' The purpose of the pump controller is to regulate and match the flow of DC electricity to the needs of the pump. In this manual, we only talk about AC water pumps operating on solar panels, so without batteries. The pump control unit usually contains the following components:

- MPPT
- Inverter
- Control boxes

Certain types of pumps (for example the small SQFlex pumps of Grundfos) have a control box integrated in the submerged part of the pump that is placed in the borehole. This way, they are less sensible to overheating. Other pumps are delivered with a separate control box placed above ground level.

1.3.2. Maximum Power Point Tracker (MPPT)

A pump control unit can be equipped with a Maximum Power Point Tracker. In this device, the charge controller looks at the DC output of the solar panels, changes it to high frequency AC, and figures out what is the best voltage and current to operate the pump. It takes this figure, and converts the AC current back to DC, but to a different DC voltage and current to exactly match the best voltage for pump operation.

Most modern MPPT's are around 93-97% efficient in the conversion. The power gained by a MPPT is around 10-15%, so the net effect of a MPPT is a power gain of around 10%.

Figure 1 Two different examples of MPPT's

1.3.3 Inverter

Direct current can be converted to alternating current using an *inverter*. This conversion cannot be made without the loss of some power. Almost all solar installations that drive water pumps have an inverter.

There are variable frequency inverters and fixed frequency inverters. For pumps, the variable frequency inverter is most often used. This type adjusts the output frequency of the AC current depending on the amount of sunshine received by the panels. With this frequency regulation, the pump speed is regulated, and by consequence the pumping power.

For power supply to an electric grid from a solar installation, a fixed frequency inverter is used, because the grid requires a fixed frequency (mostly of 50 Hz).

1.3.4 Control boxes

Control boxes are electronic devices with in-built feedback loops that provide an automatic response to undesired situations. There are situations in which we want the system to shut down or the pump to stop pumping immediately, in order to prevent (further) damage of the system, or in order to optimize the functioning of the system. Five of such situations are the following:

1. Lack of water in the borehole.
   Without water in the borehole, it is better to stop the pump. The pump motor is cooled because water flows around it in the borehole. Without (sufficient) water flow, the motor is at risk of overheating, and this can seriously damage the motor. It makes no sense anyhow to have the pump running when there is no water in the borehole. So a sensor is placed within the pump, which automatically sends an “emergency” signal to the control box when the water level in the borehole is too low.

2. Overheating of the electric motor of the pump.
   Overheating of the motor can have a number of reasons, one of which is lack of water in the borehole. But also other reasons can cause overheating of the motor, for example a mechanical defect in the motor itself. So a good quality motor is equipped with a sensor for overheating that sends a signal to the control box that switches off the power supply in case of overheating.

3. The water storage tank is full.
   Further pumping makes no sense. In this case, a sensor can be placed in the storage reservoir to detect this situation. This sensor will provide a signal to the control box, so that pumping will stop.

It is a design choice whether or not to use such a sensor. In some situations, it can be decided to use the overflow of the tank for additional purposes, like irrigation of a vegetable garden or watering of cattle. In such cases, no such sensor will be installed and used.

4. Over-voltage or over-current
   The system can be automatically switched off in case of too high voltage or current. For example, in case of a short-circuit in the system.

5. Inverse polarity.
   A protection of the system in case wires are wrongly connected.

Module 2 The sun as power source

2.1 Introduction

The sun provides the energy needed to sustain life on earth. In one hour, the earth receives enough energy from the sun to meet its energy needs for nearly one year.

Almost all energy used on earth comes from the sun, directly or indirectly[1]. Oil, gas and coals are substances produced by plants that have been growing in earlier times. These plants have stored the energy of the sun in them through biological processes, and later converted into carbon-holding substances. One great problem with these sources of energy is that they are finite sources of energy which are getting depleted. Oil and gas represent the energy converted by plants during millions of years and we use it in a few hundred years. Another great problem is that you have to burn them to extract their energy, and this causes the emission of greenhouse gases and the related climatic change.

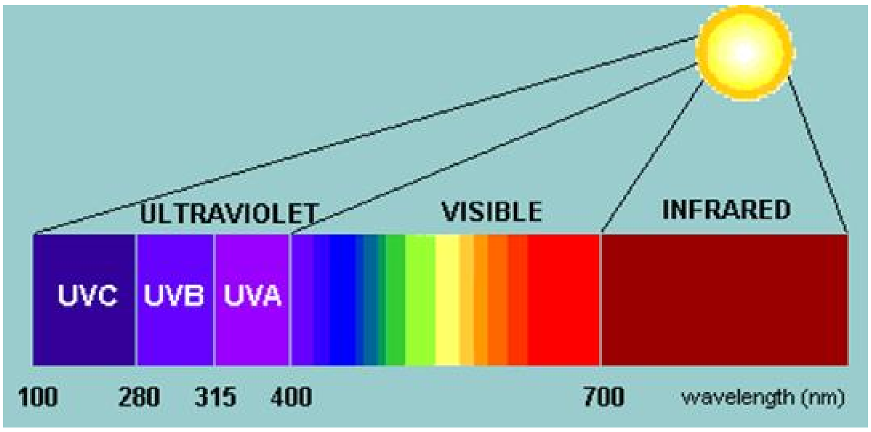
Wind is indirectly also caused by the sunshine, because differences in temperature cause low and high pressure areas to emerge, and this causes the wind to blow.

The sun itself is an infinite source of energy, not causing climatic change. And furthermore: it is free to capture! Not all energy of the sun can be captured and converted to be used for our energy needs. In order to maximize the utilization of this energy source, it is useful to understand more about sunshine and its characteristics.

2.2 Wave length and colors

The sunlight consists of waves of different wave lengths. Only a part of the energy that the sun radiates to the earth can be seen with the human eye. This part is called the "visible spectrum" and it consists of about 47% of the energy emitted. The wavelengths in the visible spectrum are 0,4 – 0,8 µm. Different colors have different wavelengths. The visible green light has a wavelength of about 0,51 µm. Grass, for example, appears green because all of the colors in the visible part of the spectrum are absorbed into the leaves of the grass, except the green light. Green is reflected, therefore grass appears green. Sunlight is seen as white light because it is a mix of all colors.

Figure 2. The solar spectrum



[1] Types of energy that do not come from the sun directly or indirectly are atomic energy, tidal energy and energy extracted from the warmth of the earth itself.

Outside this visible spectrum, the sun emits radiation with longer wave lengths, which is called infra-red, and with shorter wave length, which is called ultra-violet. The infra-red can be felt as heat.

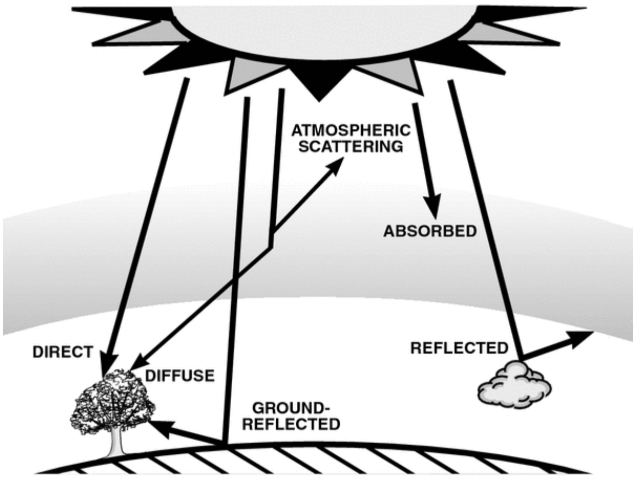
Around 44% of the sunlight is infrared. The ultra-violet is around 7% of the sunlight, and harmful to the skin and the eyes if absorbed in large quantities. That is why people use UV sunglasses and sun lotions.

Theoretically about 33% of the energy in the sunlight can be converted to electricity by a solar panel. The world record at this moment is 24% while the most common and affordable panels convert about 15% into electricity.

2.3 Solar Irradiance and Irradiation

When the sunlight enters the atmosphere of the earth, some is absorbed, some is scattered, and some part is reflected back into the atmosphere by clouds. The rest of the sun beams pass through unaffected by the conditions in the atmosphere. The part which is absorbed does not reach the surface, but raises the temperature of particles in the air. The part which is scattered turns into *diffuse radiation*, and the part which passes unaffectedly is called *direct beam radiation*.

Figure 3. Solar Radiation



The force of the sunshine is not constant during the day, even when there are no clouds. In the morning, the sun is low in the sky at the east. It steadily moves up, higher in the sky. At its highest point, called *solar noon*, the force of the sun beams is also the highest. If the sun is directly above, the zenith angle is said to be zero. And after solar noon, the sun travels further westwards[2] , gradually lowering its position until night falls.

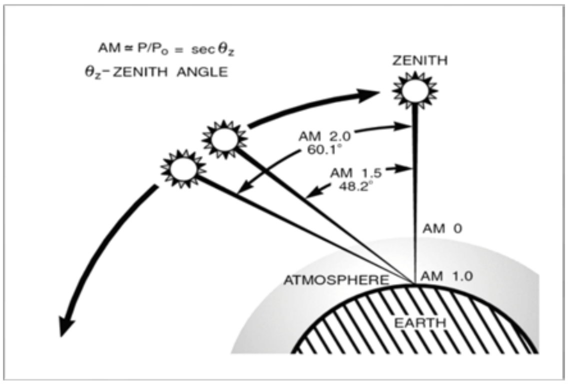
The more north or south you are from the Equator, the longer is the path that the sunbeams have to travel through the atmosphere, before reaching the surface of the earth. When the sun is at its zenith point, the distance through the atmosphere is AM = 1, which is the minimum length. When the angle is 60.1 degrees, this path becomes 2 times longer; AM = 2. When this path becomes longer, more sunlight is absorbed and scattered. This reduces the strength of the sun. This also happens in mornings and evenings during the day.

A second effect of moving more south or north, is that the *angle* under which the sun beams hit the surface becomes larger. This causes the sun beam to spread over a wider horizontal area, which also

[2] *Of course, in reality, it is not the sun that travels, but the earth that turns. We now describe how we see the sun from a place on the earth.*

reduces the strength of the sun to give warmth to the earth surface. However, you can give a solar panel a tilted position, so that it directly faces the sun.

Figure 4. Zenith angle and Air Mass (AM)



Apart from this, the position of the sun changes through the seasons. On the 21st of December, the suns position is directly above the tropic of Capricorn, 23.45 degrees south of the Equator. On the 21st of March, the sun is directly above the Equator, and on the 21st of June its position is directly above the tropic of Cancer.

With the change of seasons, what also happens is that the duration of sunshine day is longer or shorter. The more you go north or south from the Equator, the more important is this effect. In winter time in Sweden, the duration of daylight is only very short. As soon as you pass the northern Polar circle in winter time, there is no sunshine during the entire day. But in the summer time, there is sunshine the whole day and the whole night. In Benin, the number of sunshine hours per day is almost constant during the year, because Benin is situated close to the Equator.

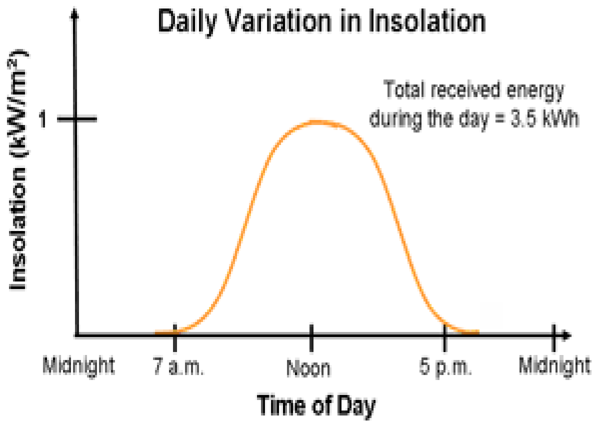
Cotounou is situated at 6,5 degrees north of the Equator. So in December, the suns' position at solar noon is at 30 degrees south, whilst on the 21st of June, the sun's position is at 17 degrees north. As we will see in module 3, the angle of the sun beam influences the amount of radiation captured by the solar panel.

Irradiance (also called insolation) is the measure of power density of sunlight at a certain moment. In other words, it is the power of the sunlight measured in Watt per m^2. When entering the atmosphere, the irradiance level is around 1367 W/m^2. After having passed the atmosphere, at sea level, the irradiance is approximately 1000 W/m^2, or 1 kW/m^2. This is a combination of direct beam and diffuse radiation. Irradiance is often given the symbol G.

At solar noon, when the sun is at its highest point, it may stand directly above us in the sky, depending on the season of the year, and depending on the latitude of your position. But in that position, at that particular moment, if there are no clouds, the irradiance of the sun is 1 kW/m^2. In (almost) all other positions, the irradiance is lower.

In the next figure, a graph is shown that indicates the curve of irradiance during a day. This graph shows the "ideal" curve at optimal sunshine conditions, on a day with no clouds or dust in the sky. During most days, the curve has a more variable shape.

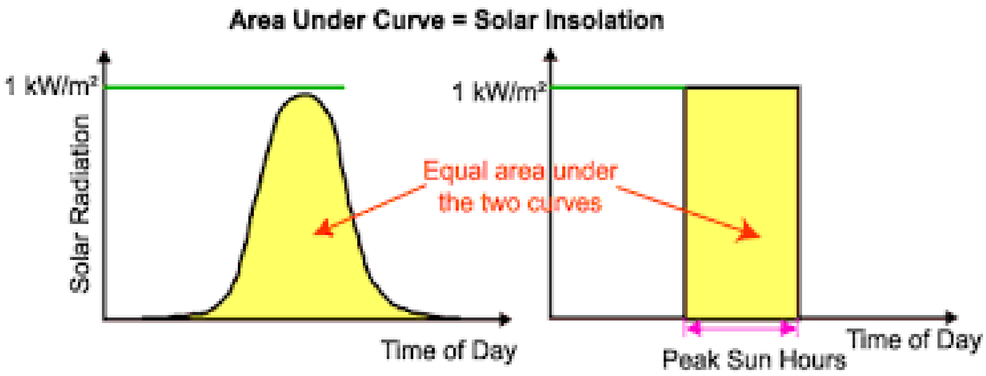
Figure 5 Ideal curve of daily irradiance



Irradiation is the total amount of energy received on the earth surface during a certain period on one square meter of horizontal surface. Normally, the time frame for measurement is one day. It is usually expressed in kWh/m^2.

Irradiation is often expressed as *peak sunshine hours.* This is the number of hours at an irradiance level of 1 kW/m^2 required to produce the energy received during one day. The next figure graphically shows how the irradiance curve is converted to peak sun hours.

Figure 6 Conversion of irradiance into Peak sun hours



2.4 Weather conditions

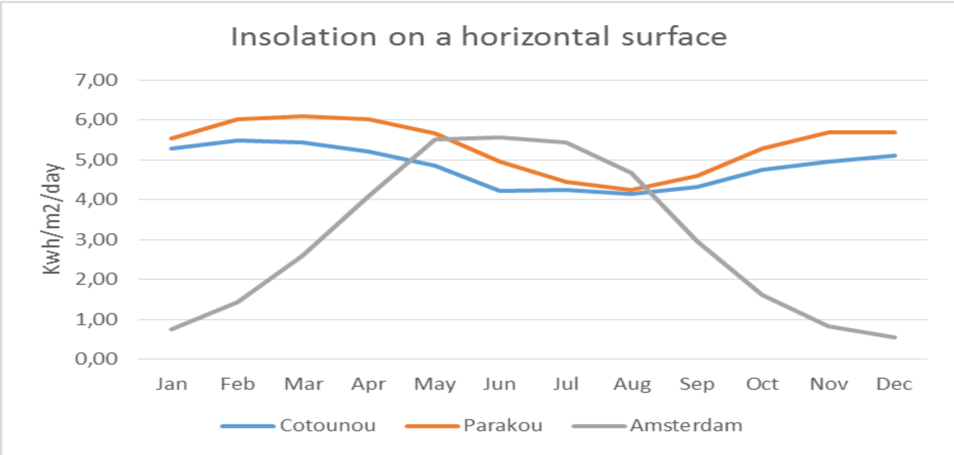
The weather conditions have a large influence on the irradiance and irradiation received on the earth surface. It may be cloudy, there may be mist or smog; there may be conditions (like harmattan) with high dust loads in the sky. Such conditions reduce the power and energy that is received.

Weather conditions generally change with the season. In rainy seasons, there is less sunshine than in dry seasons because of a more frequent and thicker cloud cover. In dry seasons, a harmattan may bring dusty skies that reduce the sunlight.

To take weather conditions into account, we can work with statistics. Meteorological stations do measurements of all meteorological parameters, including rainfall, temperature, and also sunshine and cloud cover, and irradiation figures. They produce statistics and present them in tables or graphs. Monthly and yearly and averages are usually used for calculations. For design of PV systems, the most important statistic is the average *insolation* of a location.

The *insolation figure* is the average number of peak sun hours as measured on the ground. It is measured in kWh/m2/day onto a horizontal surface. In the following graph and table, the average solar insolation figures of Cotounou, Parakou and Amsterdam are presented. (source: http://solarelectricityhandbook.com/)

Figure 7 Average daily insolation on a horizontal surface each month.



Values related to figure 7

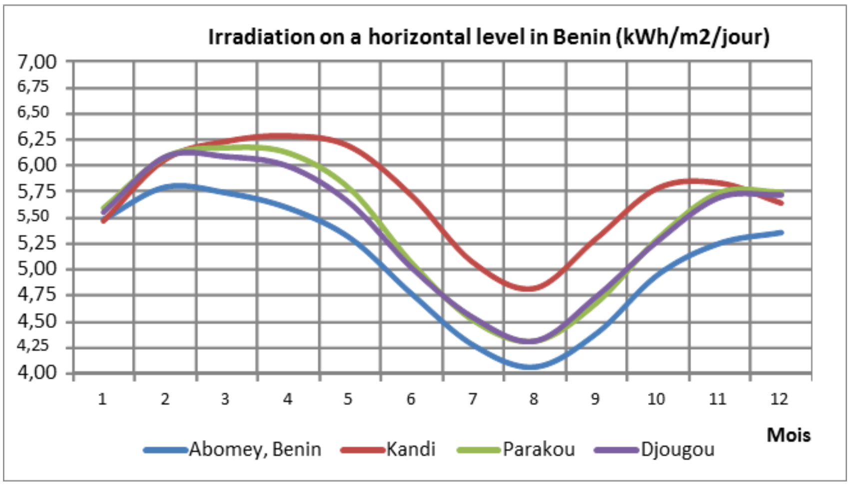
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cotounou	5.28	5.48	5.42	5.20	4.86	4.21	4.24	4.15	4.31	4.76	4.96	5.10
Parakou	5.53	6.01	6.09	6.02	5.67	4.95	4.45	4.25	4.61	5.27	5.68	5.69
Amsterdam	0.76	1.44	2.59	4.09	5.52	5.57	5.44	4.67	2.96	1.62	0.83	0.54

2.5 The critical month

The solar drinking water system should ideally produce sufficient water to meet the supply demands during the entire year. For dimensioning the system, the crux is to find the month having the most unfavorable combination of water demand and sunshine conditions.

As shown in this module, the average insolation varies between the different months of the year. In the month with the lowest insolation, the system should still produce sufficient energy to meet the power demand. In the following figure, the insolation is presented on a horizontal surface for 4 locations in Benin: Abomey, Kandi, Parakou and Djougou.

Figure 8 Average daily insolation in Abomey, Kandi, Parakou and Djougou, Bénin.



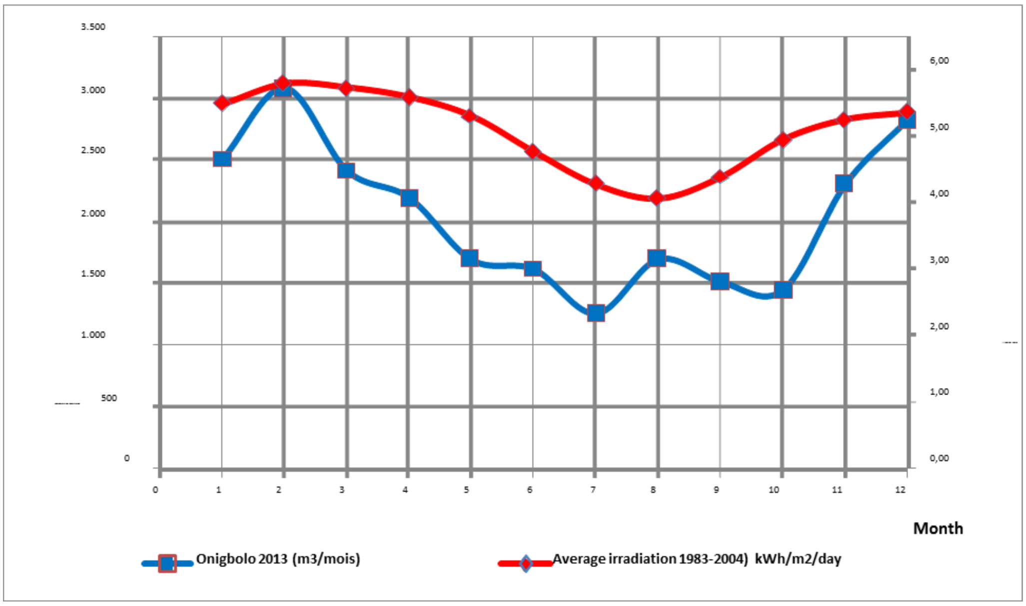
These irradiation figures have been obtained from the website of the NASA. They are monthly averages over a period of 20 years. (https://eosweb.larc.nasa.gov/sse/).

It can be concluded that the month with the least favorable sunshine conditions in Benin is August. In Abomey, the average irradiation per day drops to 4.1 kWh per m2. The further you travel north in Bénin, the higher the irradiation figures.

In many calculations about the water demand, it is assumed that the water demand is constant throughout the year. In reality however, this is not the case. Water demand may vary importantly in different months. In Benin, water supply is a paid service. When there is an opportunity, people will prefer using unpaid water from alternative sources like hand dug wells and rain water catchments for certain purposes. For this reason, piped water demand is generally lower in the rainy season. In dry seasons, some people may also use the piped water for their livestock or for washing their clothes, as alternative sources may have been dried up and further away from their household.

In the following picture, a graph is shown for a real situation as encountered in Benin in the village of Onigbolo in 2013. The blue line is the water demand line, in m3/month, of the water system. The red line represents the daily average irradiation during the months of the year. As can be seen in the graph, indeed also in Onigbolo, the lowest average irradiation is in August. However, the water demand was highest in February, and this is also the most critical month if irradiation and water demand have to be matched. Also December is a critical month, with less water consumption than in February, but also less irradiation. In August, the irradiation is at a lower level, but also the water demand is much lower.

Figure 9 Water demand and irradiation in Onigbolo, Benin.



This case is an illustration of the difference between hypothetical water need calculations as presented in Module 4 (that often assume a constant and high water consumption level), and real life consumption patterns and quantities over the year as can be encountered in communities. In a theoretical calculation, August would have been chosen as most critical month, whilst in reality, the most critical month in Onigbolo is February, during highest irradiation levels.

To demonstrate this, let us have a closer look at the graph. In February, the monthly water consumption is about 3100 m^3, which is about 110 m^3 per day. The average irradiation is 5,6 kW/m^2/day. The solar array has to be configured in such a way, that it is able to pump this amount of water with this irradiation level. The relation between consumption and irradiation is 110/5.6 = 19.6. The array has to be configured for a pumping capacity of 19.6 m^3 per kW/m^2 of sunlight power received.

In August, the monthly consumption is 1750 m^3, which is 56 m^3 per day. The average irradiation is 4.1 kW/m^2/day. The relation between consumption and irradiation is 13.6. But the array is configured to yield 19.6 m^3 per KW/m^2 received. In August, the system is able to produce (on an average day) an amount of 19.6 * 4.1, which is 80 m^3 per day. The array power used is only 70% of the maximum power it can produce. If August had been taken as design month, the array would have lacked the power to meet the demand in February by 30%.

Module 3: The solar array as power source.

3.1 Introduction

In this chapter, the solar cell, solar panel and solar array are introduced and explained with their basic characteristics. The effects of irradiance level and temperature are presented. Attention is paid to how and where to place and locate a solar array in a water system, and what can be done against theft and vandalism. The effect of shadow is explained. As last subject, we introduce the electric losses and the electric efficiency.

3.2 The solar panel

3.2.1 The Photovoltaic cell

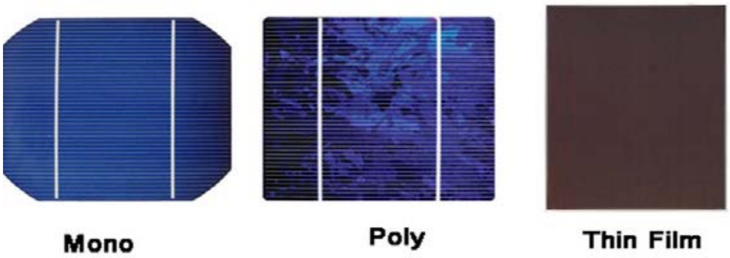
The basic element of a solar panel is the photo-voltaic cell, or PV-cell. Solar panels are built from a number of such cells. They are made of semiconducting materials that can convert sunlight directly into electricity. When sunlight strikes the cells, it dislodges and liberates electrons. An electron carries a very small electric load. When electrons start to move, they produce a direct electrical current (DC).

Figure 10. Photovoltaic cell

The cells may be round, square or some other shape. Each cell produces about 0,5 Volt, no matter what the size is. The amount of amperes a cell can produce does depend on its size; larger cells produce more amperes. As each cell only produces about 0,5 Volt, many cells have to be connected in series to produce a high enough voltage. Usually there are from 30 to 36 of these cells on a panel intended to charge a 12 V battery.

Most commercial PV cells are made from silicon. There are three general types: monocrystalline, multi-crystalline, and amorphous or thin film cells.

Figure 11. Different cell types



Single crystal or monocrystalline cells are made using silicon wafers cut from a single, cylindrical crystal of silicon. This type of PV cell is the most efficient, with approximately 15% efficiency. This efficiency means that 15 % of the energy of the sun beam is converted into electricity. It is also one of the most expensive to produce.

Multi-crystalline or polycrystalline silicon cells are made by casting molten silicon. They crystallize into a square solid block of intergrown crystals. Multi-crystalline cells are less expensive to produce than monocrystalline ones, due to the simpler manufacturing process and lower purity requirements for the starting material. However, they are slightly less efficient, with average efficiencies of around 12%.

Amorphous silicon PV cells are made from a thin layer of non-crystalline silicon placed on a rigid or flexible substrate. They are relatively easy to manufacture and are less expensive than monocrystalline and polycrystalline PV, but are less efficient with efficiencies of around 6%. Their low cost makes them the best choice where high efficiency and space are not important.

3.2.2 Solar Panels

PV cells are combined to make solar panels, also called modules. The PV cells are grouped together, and encased in glass or clear plastic in order to protect the cells, whilst in the same time allowing the sun light to reach the cells. The glass or plastic often has an anti-reflective coating to minimize reflection of light from the panel. The panels have such a size that they yield a reasonable amount of electricity, but are still easy to handle and transport.

There are many producers of solar panels, and they produce panels of many different sizes, depending on the need of the customer and the application they are used for. The price of solar panels have dropped enormously in the last 40 years. Compared with the year 1970, the prices have gone down by as much as 90%, and it is expected that they will drop further. Because of this price reduction, solar panels have become more and more interesting as alternative energy source.

Much research and development is being carried out to increase the efficiency of the cells and panels. The most efficient PV cell currently has an efficiency of around 25%. However, this type of cell is very expensive, and for that reason cannot yet compete with the lower priced PV cells available.

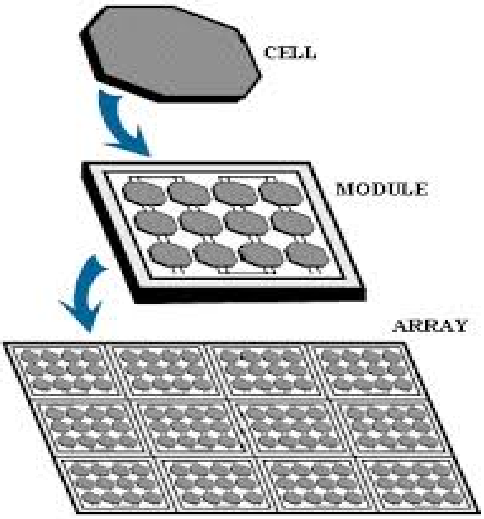
The most important characteristics of a solar panel are:

1) How much voltages it produces (in full sunshine conditions)
2) How much current it produces (in full sunshine conditions)
3) How much power and energy it produces.

3.3 Solar Arrays

Solar arrays consist of a group of solar panels, placed together in a certain configuration. The panels are grouped together in order to produce the right amount of voltage, and sufficient current and power for the purpose they serve.

Figure 12. Composition of a solar array



3.3.1 Parallel and Serial Configuration

Basically, solar panels can be connected in series, or parallel.

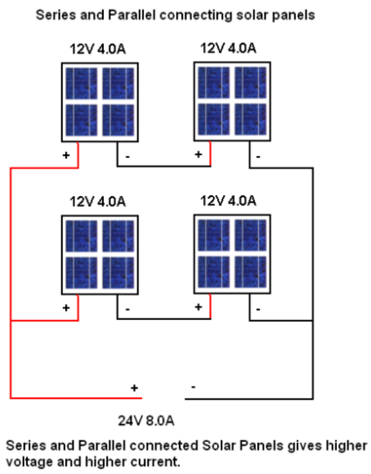
Connection in series

When electrical elements are connected end to end, they are said to be connected in series. To connect two wires in series, one end of the first wire is connected to one end of the second wire, creating a single wire as long as the two together. This is like connecting two batteries of 12 V to make 24 V. When more voltage is needed than a single panel can provide, additional panels are connected in series. If one panel provides 24 V, two panels in series will provide 24 + 24 = 48 V. For every 24 V panel connected in series, the voltage will increase by another 24 V.

The amount of current (Amperes) provided by panels in series is the same as that provided by one panel because the same electricity flows through all the panels, as they are connected in one line. As power in Watts equals Volts * Amperes, the power increases as panels are added.

Parallel connection

Figure 13 Series and parallel connections



When the voltage from a single panel is sufficient, but the amount of current needed is not enough, panels can be connected in parallel. If one panel provides 4 Ampere in bright sunlight, two panels in parallel will provide 4 + 4 = 8 Amperes. For each of these 4A panels connected in parallel, an extra 4 A will be produced in bright sunlight. As power in Watts equals Volts * Amperes, the power increases as panels are added.

Note that for both series- and parallel-connected panels, the power increases as the number of panels is increased. Two panels in parallel produce the same power as two panels in series, but the voltage and amperage are different.

3.4 Current-Voltage Diagram

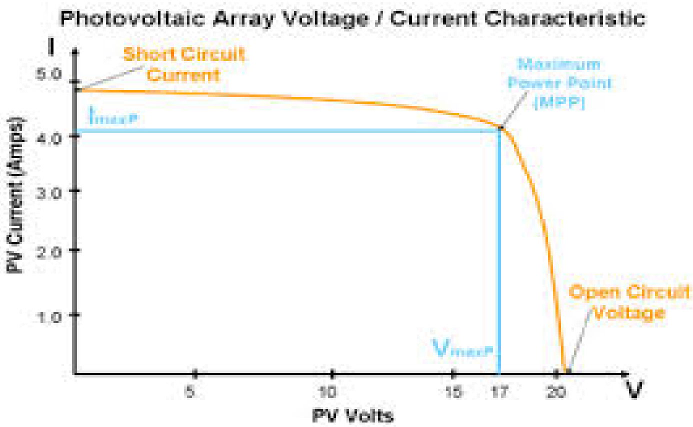
Each solar cell, and each combination of them into solar panels and solar arrays, has a current-voltage relation. This means that at a certain voltage V, they can deliver a certain current I. Now remember that the most important purpose of a solar panel or array, is that it gives us electric power. This is the multiplication of V and I. So: not only I and not only V but maximum P = V * I

The **open circuit voltage** V_{oc} is the voltage of a cell or solar panel in the situation that no electric current is flowing. In this case, the panel is not used, but it is placed in full sunshine conditions: It is the maximum voltage situation that can occur. In this situation, no power is produced, because V = Vmax, but I = zero Ampere. Vmax is important because it represents the maximum voltage a system can produce. The materials used must be able to withstand this voltage.

When the panel is connected and electricity is flowing, the voltage produced will drop. When there is no resistance in the line, the situation is called short-circuit. At this situation, the voltage will drop to virtually zero, whilst the current is at maximum (Imax). This maximum current is also indicated as I_{sh} (Current at short-circuit) or I_{cc} (French for current at "court circuit"). But the power produced in this situation is zero, because V = 0.

Maximizing the power means *optimizing* the relation between Voltage (V) and current (A). The Voltage-Current diagram is a characteristic of the cell or panel. The shape of this diagram is presented in the following figure:

Figure 14. Voltage-Current Diagramme



In this figure, the orange line represents the current voltage diagram. The relation between the voltage and the current is optimal, when the size of the square enclosed by the curve has the largest surface. In this situation, the current is ImaxP and the Voltages is VmaxP. The size of this square represents the power produced. So the optimal relation between the voltage and the current is at the Maximum Power Point (MPP), as indicated in the figure.

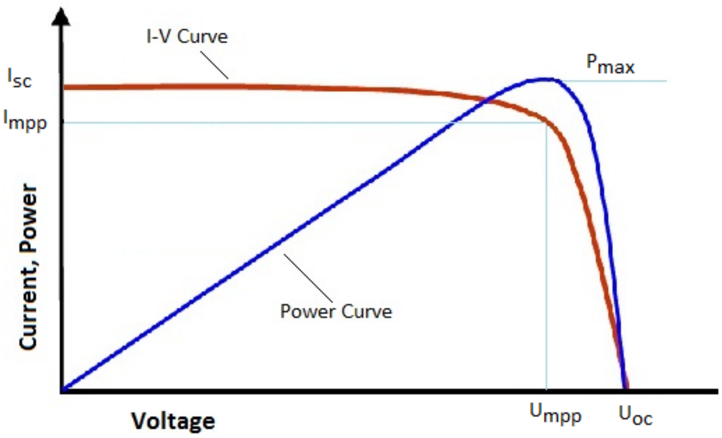
A Maximum Power Point Tracker (MPPT) is an electronic device that automatically adjusts the voltage to produce the maximum power of the solar array in place.

A very important characteristic of a solar panel is how much power it can produce in full sunshine conditions. This figure is called Peak Watt (W_p) or Watt Crête in French (W_c).

3.5 Current-Power Diagram

For a single PV cell, but also for a solar panel, one can construct a current-power diagram. On the x-axis, the voltage is displayed, and on the vertical axis, the produced power in Watts in displayed. This will typically produce a curve like the blue line in the following figure:

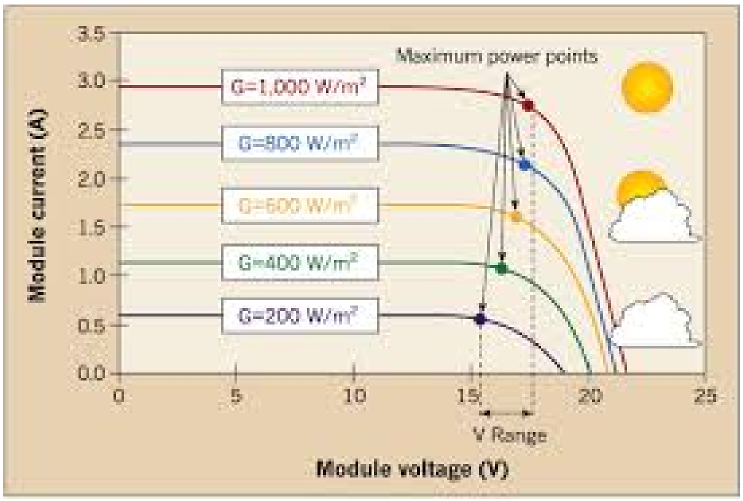
Figure 15. Current-Power Diagram



3.6 Effect of Irradiation

The current-voltage diagram presents the power output of the PV cell or panel at full sunshine conditions. The current production of the cell (or module) is almost proportional to the irradiance. This means that if the irradiance G is at 50%, then also the current production will be at 50% of the maximum production. In the next figure, this relation is shown for a solar panel of 50 Watt and 18V.

Figure 16. Relation between irradiance and PV output.



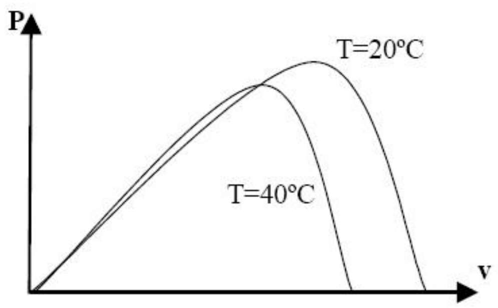
Note that also the voltage output drops at low irradiance levels, but not as much as the current. In the figure above, the voltage output of the panel is 18V at maximum irradiance, and 16V when irradiance is 200 W/m^2.

3.7 Effect of temperature

It is important to remember that when a cell is exposed to light, it will convert around 15% of the irradiance into electricity. The rest of the energy is converted into heat, resulting in a rise of temperature of the cell and panel. As a result, the cell will operate at a temperature above the ambient temperature.

The open circuit voltage (V_{OC}) of the PV cell decreases by 2,3 mV per ˚C increase in temperature, which amounts to almost 0,5%/ ˚C. This means that a rise in temperature of 10 ˚C causes the cell to be 5% less efficient.

Figure 17. Relation between Temperature and Power



In this figure, the effect of a temperature is displayed. At 40 ˚C, the module produces less voltage, and thus also the power output reduces compared to the situation of 20 ˚C.

In order to make optimal use of the panel, it is important that the panel is ventilated. If mounted on a roof, it is good to have some ventilation space between the roof and the panel. Metal roofing like corrugated iron sheets can become very hot themselves when exposed to full sunshine conditions. It is not therefore not advisable to mount solar panels on an iron roofing.

Usually, manufacturers of panels indicate the performance characteristics of the panel on a sticker on the back side of the panel. This sticker displays the performance under Standard Test Conditions (STC). The panels are tested with an irradiation of 1000 W/m^2 and a cell temperature of 25 °C. These test conditions do not represent operating conditions, because the irradiation will almost always be lower, and the cell temperature almost always higher especially in African conditions.

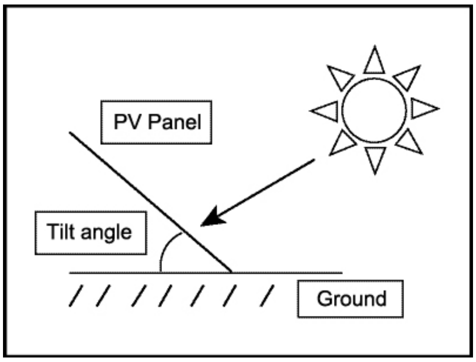
The **Nominal Operating Cell Temperature** (NOCT) is the temperature the cells will reach when operating in an ambient temperature of 20 ˚C at 800 W/m^2 (G = 0,8) and a wind speed of less than 1 m/s. The NOCT is a characteristic of the solar panel. This NOCT often around 48 °C, depending on the construction of the panel. A cell operating in an ambient temperature of 30 ˚C will have an even higher cell temperature than the NOCT value. If this rise in ambient temperature of 10 ˚C also results in a rise of cell temperature of 10 ˚C, you should reduce the expected power output by 10° C x 0,5% = 5%.

3.8 Optimal position and location of a solar panel.

3.8.1 Tilt Angle and calculations

In a horizontal position, dust and dirt will accumulate on the panel, and reduce its efficiency. The tilt angle is the angle at which the panels are placed relative to the horizontal plane.

Figure 18. Tilt angle of a PV panel.



A solar panel or array should be placed in a tilted position of at least 10 degrees. In this way, the rain washes off a part of the dirt and dust from the panel (but not all of it). And during cleaning of the panels, the water will automatically flow downward.

A panel operates most efficiently when directly facing the sun, because in that position, it catches the maximum of the irradiance available. Generally speaking, north of the Equator it is best to position them facing southward (and south of the Equator facing northward) in a tilted position. Certainly at a latitude north of the Cancer Tropical, it is obvious that a panel should be facing southward. And south of the Capricorn Tropical, facing northward.

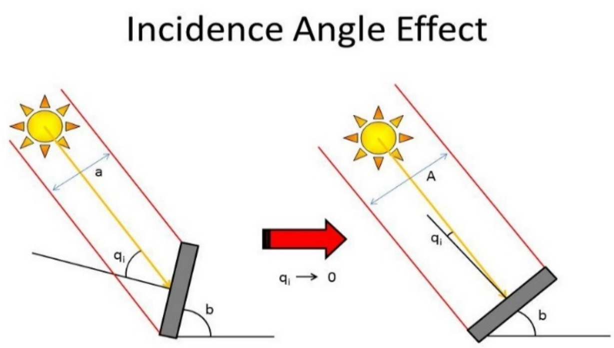
It should be remembered that there is direct beam radiation and diffuse radiation. The diffuse radiation is around 30% of radiation available. The tilt angle only influences the capture of direct beam radiation.

The optimal tilt angle depends on the latitude of your position. For general optimization of the tilt angle, it should be equal to the latitude. It is generally recommendable to optimize the tilt angle for the most critical month of the year, as explained in training module 2. For Benin, this most critical period, in practice, is in the “winter” months of December and February, when the suns’ position (relative to the earth surface) is around 23˚ south of the Equator. This means that the optimal tilt angle for this period in Benin is at (23˚ + latitude). For the south of Benin this would be 29˚ and for the north of Benin this would be 35˚, facing southwards.

At this moment, some careful consideration should be taken. We also know that the period of lowest irradiation is August. During the month of August, the suns’ position in Benin is *north*. If we position a solar panel tilted southwards with 30 degrees, what does this mean for the irradiation captured on a day in August?

This can be demonstrated with the following figure:

Figure 19. Incidence Angle effect



In this figure, the tilt angle is shown as b. The **incidence angle** q is the angle between the orientation of the panel and the orientation of the sun, which is shown in the figure as q. If q = 0, the position of the panel is optimized for maximum capture of direct beam radiation. The surface of the sun beam captured on the panel is A. On the right side of the picture, the panel is facing the sun almost directly: the incidence angle is very small, and in this way, the proportion of the direct beam sunshine captured is almost 100%.

On the left side, the incidence angle is high. The higher the incidence angle, the higher the irradiance not captured. The proportion of the direct sun beam captured is a/A, which is a function of the cosinus of q: a/A= cos q. So the loss is (1 – cos q)%. As direct beam sunshine is around 70% of total irradiance, the total loss of irradiance will be (1 - cos q) * 70%.

In an August day, with a tilt level of 30˚ southward and the sun at 18˚ north, q will be 48˚. Cos 48˚ = 0.67, so the loss is (1 -0.67) * 70% = 23%. With a tilt angle of 20%, q will be 38˚, cos q will be 0.78 so the loss will be reduced to 0.22 * 70% = 15%. This implies that reducing the tilt level from 30˚ to 20˚ results in an 8% higher efficiency in August. The same 20˚ tilt angle in December (with the sun at 30˚ south), would result in a q of 30-20= 10˚. This would result in losses of (1 – 0.98) * 70% = 1.4%.

By this calculation, we can conclude that it will be better to design with a lower tilt angle then calculated for winter optimization, in order not to lose too much power in August. A tilt angle of 15-20 degrees is optimal for the situation in Benin, with the panel facing south.

3.8.2 Solar trackers.

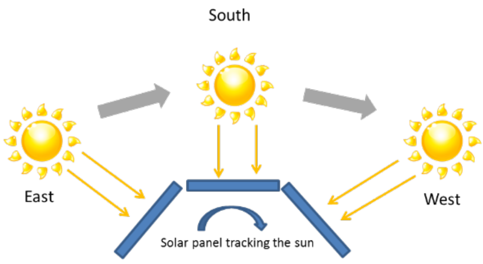
Solar trackers are devices that monitor the position of the sun, and automatically or semi-automatically adjust the direction of the solar panels towards the sun so that the productivity is increased.

Following the sun can be done on two axes: the azimuth angle axe, which means following the sun from east to west during the day, and the zenith angle axe, which means following the suns' position from north to south. The ideal tracker adjusts both axes continuously to perfectly face the sun during the day, but also during the seasons. This type of tracker is of course also the most expensive.

3.8.3 East-West Tracking

Tracking the sun from east to west during the day means continuous adjustment of the position of the panels. The sun "travels" 180˚ in around 12 daylight hours, so the speed of the sun is 15˚ each hour. With such kind of trackers, the utilization rate of the irradiance can be raised by approximately 15%.

Figure 20 East-west tracking.



3.8.4 North-South Tracking

North-South tracking means adjusting the angle of the panel according to the zenith angle: this angle is influenced by the season of the year. In Benin, at 6.5˚ latitude, the zenith angle varies between 30˚ South and 17˚ north. As such, it is not unthinkable that this kind of solar tracking could be used in Benin. The panels could be facing north in "winter" time which is the dry time of the year, and facing south during the rest of the year. Their position could be adjusted manually twice per year.

Figure 21 Simple North-South tracking

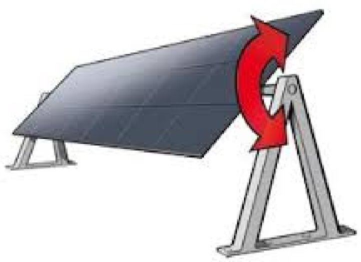
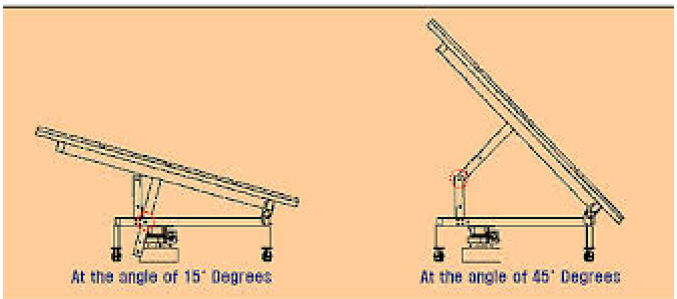


Figure 22 Manual adjustment of tilt position



3.8.5 Disadvantage of tracking systems

However, such trackers are expensive themselves. They require operation and maintenance, and have the risk of breaking down. When installing trackers, it is more difficult and costly to also take the correct precautions against theft of the panels. And with the current price levels, generally, it is most probably much cheaper, more convenient and more reliable to install some more solar panels for extra power, than to install a solar tracking system of whatever kind.

3.9 Location of the array

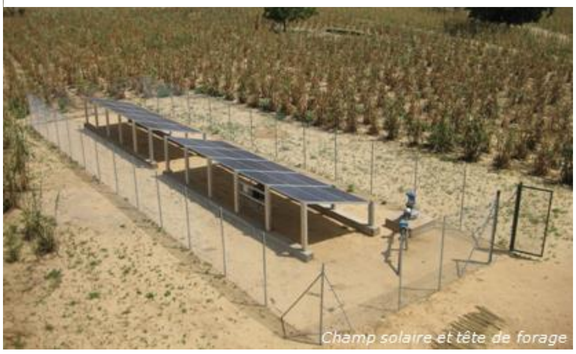
For the location of the array, two locations can be chosen: On top of the water tower or any other permanent building, or on a plot next to the borehole.

On top of the water tower can be chosen if the water tower is close to the borehole. If not, the electric wires will be too long, which will bring along high electricity losses, or high costs for thick electric wiring to avoid these losses. The advantage of placing the array on the tower is that it is a good protection against theft of the panels. Moreover, the high place of the panels will also generally be a sunny place with little shadow, and the wind will cool down the panel easily.

Figure 23. Solar panels on top of a water tower

The disadvantages are that it is more difficult and more expensive to install them. It is also more difficult to clean them when needed, add or replace panels or perform maintenance tasks on the panels. Most often, the surface of the panels will be larger than the top of the water tower, so the panels will be sticking out of the edges of the tower.

Figure 24. Solar panels on ground level plot



The other option is a plot on ground level, in the proximity of the borehole. The plot will need to be fenced, but it is anyhow necessary to fence the location of the borehole. But the fencing will need to be somewhat bigger and stronger. The advantages are that installation, maintenance, repair and cleaning are easier.

The disadvantages are that the panels more prone to theft and vandalism. Therefore, anti-theft measures and anti-vandalism measures must be taken.

3.9.1 Anti-theft and anti-vandalism measures

Theft and vandalism are serious problems for solar panels. Cases have been reported about gangs of thieves who come with trucks, angle grinders and automatic guns to take away entire arrays of solar systems. Such theft cannot be entirely prevented, but measures can be taken to make it more difficult.

But also if one panel is taken away from a solar array, serious problems can occur. Some systems require 500 V output from the solar array. If 15 panels of 33V each are connected in series, this voltage is reached. If one is stolen the voltage drops to 467V and the system may stop functioning altogether.

With the steady reduction of prices of solar panels, it can be expected that such type of robbery will become less lucrative for the thieves, and that the risk of theft will reduce.

The following anti-theft measures can be taken:

- A location of the borehole in the village, or close to the village, will enlarge the level of social control;
- Engraving the panels in a way that cannot be reversed or wiped out.
- Using strong and heavy poles.
- Using concrete anchors for the poles, so that the frames cannot be lifted.
- Use anti-theft bolts to fix the panels on their frame.

- Welding of anti-theft anchors around the panels, so that they cannot be lifted from their frame.
- Installing strong fencing and a strong lock on the access door.
- Pay a night watchman to guard the place.
- Electric lighting can be installed.

The following anti-vandalism measures can be taken:

- Educate the parents of the children and the school teachers that they should prevent children from playing with the panels, throwing stones at them, or otherwise harm them.
- Fencing of the plot.
- Locate the plot far from the playing fields of the youth, like soccer fields.

Vandalism usually affects only one or two panel in the array. One may choose to install two extra panels, so that broken panels can be disconnected and the system may continue to function when one or two panels stop functioning. This will increase the investments costs of the entire system by 2 or 3%, but it will improve the continuity of the system.

3.9.2 Safety measures

Depending on the configuration of the panel, the output voltage of the array can be very high, and dangerous to humans. Short circuit and electric shocks should be avoided, as they are hazardous for humans and can cause damage to the array. Also, lightening can strike the array: they are often mounted on iron poles that attract lightening, especially if the array is located on top of a building or water tower. The following safety measures should be taken:

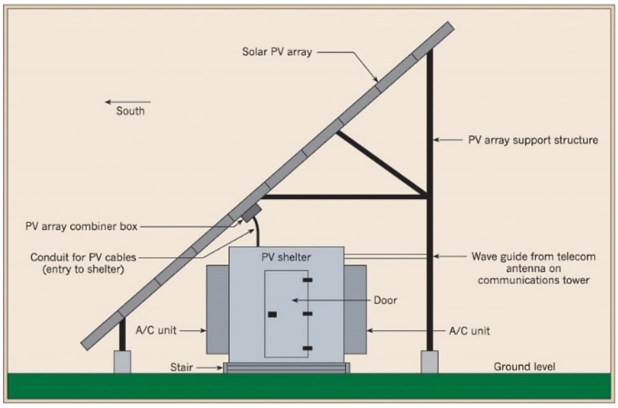
- Have the electric installation installed by a qualified electro-technician;
- Using good quality electric wires which are well isolated.
- The electric system should be earthed.
- Lightning rods should be installed at high points for diversion of lightning strikes.
- Wires should not be hanging lose, but tied with clips along the poles of the array.
- Wires should be buried well where possible.

The electric system should be protected from rain water. A cheap and convenient way to do this is to locate these elements under the solar panels, and inside plastic safety boxes that often come with the control boxes when purchased. Remember that also control boxes can heat up, and need ventilation for cooling!

Figure 25 Control boxes installed under panel

The disadvantage is that this does not provide the best protection against unqualified people. The safest option is to build the control boxes into a shelter that can be locked. The following picture shows an idea for this option:

Figure 26 Control boxes protected and locked



3.10 The enemy of the solar panel: Shadow!

Shadow on the solar panels must be avoided at all cost. The effects of shadow are often underestimated and not well understood, and sometimes not well described in manuals.

The general story about shadow is that it significantly reduces the output voltage of the solar panel. The more surface of the panel is situated on the shadow, the less is the output voltage and power of the panel. The power reduction is often said to be proportional to the percentage of the panel that is under shadow.

This statement is proven to be incorrect. The loss of energy caused by partial shading of solar modules is difficult to predict because it depends on several variables including: internal module-cell interconnections; module orientation; how modules are connected within an array and the configuration of the inverter.

Shadow, even the slightest bit, can have a disruptive effect on the functionality of the entire panel and array. Just 10% shading of a solar array can lead to a 50% decline in efficiency and even, on occasion, total system shutdown. We have seen it happen that the shadow caused by the wire of the fence around the array caused an entire array to stop functioning.

If one of the PV cells in the panel is "blocked" by shadow, it may happen that it no longer passes through any electricity. The power generated by highly illuminated cells is wasted as a heat in the poorly irradiated cells. The poorly illuminated cell may become overheated, and this can cause permanent damage to the encapsulation of the cell. Even the smallest shadow can cause such overheating and damage of a PV cell. So care should be taken to see that all the cells connected in series receive the same illumination.

How vulnerable the panel is for shadow, also depends on the quality of the panel. To prevent the whole string of cells failing when one cell underperforms, a good solar panel is equipped with "bypass diodes." These diodes reroute the current around the underperforming cells. The disadvantage is that by rerouting the current, you lose not only the potential energy from these cells, but it also lowers the entire string's voltage. But this is better than overheating and permanent damage.

The risk and amount of damage also depends on the irradiance level. Early in the morning, irradiance is not so high, so the potential damage or power loss of shadow is also less.

3.11 Electric Efficiency and Losses

Whilst calculating the power that needs to be installed, electric losses need to be taken into account. When we know the electric losses, the electric efficiency can be calculated. The electric efficiency is an important parameter that is used to calculate the array power that needs to be installed. The symbol ε is used for this parameter.

The losses that can be distinguished are the following:

Losses in the power cables.

These losses directly depend on the size and length of the power cables. In most cases, the borehole is situated in the proximity of PV system. If it is decided (for safety reasons) to mount the PV system on a water reservoir situated in the community, this distance may be longer than a few meters. In order to keep the losses in the cables low, a thicker wire should be chosen. Usually, the level of losses is around 1-3%.

Losses of the inverter and control boxes.

These losses depend on the type of inverter and control boxes installed. Information is provided by the producers. The losses can vary from around 6 to 14%.

Losses in the electric motor (motor efficiency).

In this motor, electric and electromagnetic losses occur, producing heat. Not all energy received from the system is therefore passed through as energy to the water pump. The efficiency of the pump motor is usually provided by the producer, and may vary around the 80%, meaning 20% losses. For small electric borehole pumps the electric efficiency is often even lower. (Pumps also have significant hydraulic losses. They will treated at a later stage)

Temperature losses.

The power as indicated on the panels is the power delivered at 20˚C ambient temperature, and a certain operating temperature of the panels. In reality, power production is reduced by 0.5% per ˚C. So this loss can be around 10-15%.

Dust losses.

The power as indicated on the panel is produced under conditions of a clean solar panel. In practice, often some dust is accumulated on the panel surface, reducing the output power of the solar array. These dust losses can be around 0-10%.

Aging losses

The lifetime of a solar panel is around 20 years or more. Generally, there is some reduction in the efficiency of the panel throughout the years: the vast majority of all solar panels are less than 10 years old. Of the solar panels produced today, it is not exactly known how efficient they will function after 20 years.

The majority of manufacturers offer a 25-year standard solar panel warranty, which means that power output should not be less than 80% of rated power after 25 years. Meaning that the maximum power loss can be estimated at 20%. It is often difficult to claim this guarantee after 20 years. The supplier may not exist anymore.

A summary of losses and efficiency

A summary of the minimum and maximum losses is provided in the following table:

Figure 27. Summary of electric energy losses.

Loss type	Min	Max
Power cables	1%	3%
Inverter & Control	6%	15%
Motor	15%	25%
Temp	10%	15%
Dust	0%	10%
Age of panel	0%	20%
Total	**32%**	**88%**

It should be noted that in only very rare situations, a combination of losses leads to either the minimum or maximum losses: most often, the real electric losses will be in between the value of 29% and 62%.

For design purposes, a precise calculation of the overall energy efficiency is to be preferred above a rough estimation. This can be done by multiplying the energy efficiencies of the different components. (So *not the losses* of the different components!) If this calculation is not made, electric efficiency of 45% may be assumed for new and reasonably well maintained systems. The electric efficiency ε is in that case thus 45%, or 0.45.

3.12 Optimization of electric efficiency

Losses in power cables do not have a strong influence on the electric efficiency in situations where the array is situated close to the borehole. Losses caused by the age of the panel can hardly be influenced.

The electric efficiency can be optimized through the following:

- At the design stage, the table shows the importance of careful consideration of the choice of inverter, control boxes and pump set concerning their electric efficiency.
- At installation, temperature losses can be minimized by taking care that the array installation permits good ventilation of the solar panels. It is also important that the panels can be easily reached for cleaning.
- During operation, regular and proper cleaning of the panels is shown to have an important efficiency effect.

Module 4 Evaluation of water needs

4.1 Introduction

Although this subject is not specific for the use of solar systems, we still want to pay attention to it, because it is a crucial subject for the design of drinking water systems, and a basic input for all further calculations and system dimensions.

We first introduce the general method and parameters for establishing the water consumption need of the target population of a community. After this, we introduce parameters for calculating the production requirements for the water system.

4.2 Calculating the water needs

4.2.1 Project or system horizon and lifetime of system elements

A project horizon is established to take into account the use of the system in the future, with a certain population growth. What you effectively do, is over-dimension the system so that it will still be large enough in that future. The longer the time horizon is, the higher the degree of over-dimensioning compared to the current situation.

The choice of the project horizon is essentially a choice of investment policy. The further you look into the future, the less certain are the projections made. For example, it is very difficult to foresee the habits of water use of a population in 10 years, let alone in 20 or 25 years. In order to make projections, the only thing you can work with is the knowledge and information now available, and to assume that current trends will continue in the future.

The availability of investment funds, and the way they are used, are an important factor. Generally, a shorter time horizon will bring along less investment costs for a water supply system because it brings along smaller dimensions of infrastructure. This way, more systems can be constructed with the same amount of funds. With a longer time horizon, you take better account of the future generations, but the investments costs will be higher.

The common technical lifetimes of different components of the systems are an important factor to take into account. These lifetimes can be estimated as follows:

Figure 28. Lifetime of water system elements

Component	**Lifetime in years**
Borehole	20 - 25
Pump	5 – 10
Electric converters	10-12
Solar panels	20 – 25
Water tower	20 – 25
Water tank, concrete or steel.	20 - 25
Water tank, Poly-Ethyleen	10 – 15

The choice of horizon is also a matter of financial planning and management. If you choose a horizon of 10 years, does that mean that the system will also be written off in ten years, even if most components have a much longer lifetime? Do you foresee financial reservations for the extension or replacement of the components of the system? Are these reservations included as part of the water price? If so, how do you manage these savings? If not, how does one guarantee the investments required in the future and the continuity of the water provision?

Each choice of horizon has its advantages and disadvantages. Once the water system has been constructed, there is little flexibility in its components. You could add storage capacity, but this is expensive. The highest flexibility can be found in the type of pump installed, as well as in the number of solar panels installed. The pump is the component with the shortest lifetime, which gives the opportunity to install a pump of larger capacity each 5-10 years if required (and if the capacity of the borehole allows).

4.2.2 Population and population growth factor

The design population of the project at the time of project horizon (P_n) is calculated in function of the current population P_0, the population growth factor T_C and the project in years (n), using the following formula:

$$P_n = P_o(1 + T_C)^n$$

The table underneath presents the values of the multiplication factor (P_n / P_0) for different project horizons and growth factors:

Figure 29. Values of the multiplication factor for different project horizons and growth factors

	Horizon in years n >				
Growth factor T	5	10	15	20	25
T_C = 2,0 %	1,10	1,22	1,35	1,49	1,64
T_C = 2,5%	1,13	1,28	1,45	1,64	1,85
T_C= 3,0 %	1,16	1,34	1,56	1,81	2,09

The Direction Générale de l'Eau du Benin uses a population growth factor of 2%. This growth rate is shown in the first row of the table above.

4.2.3 The service factor

The service factor (TD) is the percentage of the population served by the water system, divided by 100. This factor is established by the policies and objectives of the investment project. Thus TD is used as multiplication factor, to calculate the number of people served by the system.

The value of TD cannot surpass 1,00. This value means that the investment is aiming to reach 100% of the population. Usually, the TD value is between 0,80 and 0,95. To calculate the number of people served by the system Pser, multiply P_n with TD:

$$P_{ser} = TD * P_n = TD * [P_o(1 + T)^n]$$

4.2.4 Specific consumption.

The specific consumption Csp is the (hypothesis of the) water consumption per person per day, expressed in liters/capita/day (l/c/d) or in liters/day/capita (l/d/c). Also this water consumption level is based on the objectives and strategies of the project. It is often informed by the desired consumption level for a good hygiene level of persons and households involved, or by national or international norms and standards of acceptable water consumption levels.

The total consumption is calculated by the following formula:

$C_{tot} = P_{ser} * C_{sp}$ **(liters/day or m³/day)**

4.2.5 Growth of specific consumption.

In some cases, it is assumed that the specific consumption will increase over time. For this a specific consumption growth rate is used: T_{sp}. The specific consumption in year n can be calculated in an identical way as is done for the population growth rate.

$$C_{sp_n} = C_{sp_0}(1 + T_{sp})^n$$

The Direction Générale de l'Eau of Benin uses a growth rate of the specific consumption of 2,6%. At the same time, it recognizes that the current levels of water consumption are not yet 20 liters per day nowadays, and can better be estimated at a level of 12 l/c/d.

According to the standards for dimensioning water systems in Benin, the specific consumption will reach the 20 l/c/d in the year 2032. In order to calculate the water consumption, the following table is used:

Figure 30. Estimated growth of specific consumption in Benin.

Year >	**2012**	**2022**	**2032**
Specific consumption (l/c/d)	12	15	20

In order to do a more simple calculation, you can combine the population growth rate with the consumption growth rate, and calculate the total growth factor. This is done by multiplication. In the case of Benin, the total growth rate is the population growth rate plus the consumption growth rate, 2% Td + 2,6% Tc = 4,6% per year.

This way, the calculation of the consumption in a certain year can be done using the following equation:

$$C_{tot_n} = P_0 * C_0 * (1 + T_c + T_{sp})^n \qquad \text{[litres / day] or [m}^3\text{/ day]}$$

4.2.6 Other water needs

Depending on the policy of the project, it is possible that also other than domestic water needs are taken into account, like water needs for schools, mosques, churches, or health posts and clinics, or livestock needs. Often, such norms and standards are available from the Water Authorities of the country.

4.3 Calculating the water production requirements

After having calculated the water consumption needs, there are two factors that are usually taken into account to determine the production requirements: the system water losses and the days of peak water use.

4.3.1 System Efficiency

The efficiency of the system E is the percentage of water produced that is actually consumed (and paid) by the water users. Water produced but not consumed or paid is water loss. You can (roughly) distinguish two causes of losses: losses caused by leaking pipes or joints, and losses caused by illegal water connections and unpaid water bills.

You should calculate with a factor 1/E to calculate the production needs from the consumption needs. In newly constructed systems, often an efficiency of 90 – 95% is assumed.

4.3.2 Peak day factor

Not during *all* days, it can be assumed that the water consumption is average. Some days of the year have exceptionally high water demand, which can be caused by several reasons, like a community festivity, an exceptionally hot day, or because of some other reason. In some cases, a peak day factor is used as multiplication factor for dimensioning the system. If this peak day factor is used, usually a value between 1,1 and 1,4 is chosen.

It is a policy and design decision whether or not to use this peak day factor, and what value should be chosen. As we have seen, the system is already designed for the most critical month. In almost all other months, the system is already sufficiently powerful to meet peak day requirements.

The factor is used as multiplication factor between (average) water demand and required production capacity of the system.

4.3.3 Daily peak use factor

This factor needs to be mentioned as well. It is a factor used to take into account the fluctuations of water consumption during the day. Usually, there are two peak use periods during the day in a community: one in the morning between 7.00 and 9.00 am, and one in the evening between 17.00 and 19.00 pm.

This factor is used to calculate the need for water stocking, and also for calculating the dimension (pipe diameters) of the distribution network, so it does not play a role in calculating the total water production needs per day.

4.4 Data collection

One of the biggest constraints in designing drinking water systems and especially solar drinking water systems is the availability of data concerning population and water use. It is very important to have correct data of population when designing a new system and data concerning the use of water of existing systems for purposes of modifying the system, financial planning (how much money will be received), etc. Water consumption data should be collected on a daily basis and throughout the years to be able to calculate the growth of the system. In practice the recording of the production will be the easiest. For this purpose, a water meter needs to be installed on the head of the borehole.

Module 5 The borehole

5.1 Introduction

In principle all types of water sources can be used for pipes water supply such as lakes, rivers, springs and groundwater. The latter is often preferred, especially in rural areas as it is often available were people are settled. At many locations it can be found in good quantity, extracted for relatively low cost and consumed without treatment. As the majority of small piped water supply systems make use of groundwater, this chapter describes means of access, construction aspects and quality requirements.

5.2 Groundwater access

Groundwater can be accessed by wells and boreholes. Wells are made by digging and boreholes are made by drilling, either by hand or machine. The hand dug wells are large in size and allows a good volume of water stored in the well itself. They are relatively easy to construct. However, dug wells are very vulnerable to contamination caused by agricultural activities, animals, poor sanitation and refuse. Hand dug wells are not frequently used in piped water supply systems as they have the tendency to be low yielding.

Boreholes on the other hand are an essential part of a solar powered drinking water systems, and the characteristics of the borehole influence design and pump choices. If they are properly designed and maintained, drilled boreholes are less vulnerable to drought or drops in water level. They can be designed to exploit more than one aquifer, and are less vulnerable to contamination; often, borehole water requires no treatment before consumption. If properly sited, they are capable of producing large yields. Disadvantages of drilled boreholes are the high initial investments costs. They also require input of specialized expertise and expensive heavy equipment.

5.3 Borehole drilling

Drilling by machine is the fastest way of creating a borehole. Within one or two days, depending on depth, diameter and soil formations a borehole can be drilled. There is a range of drilling systems, but the explanation goes beyond this module. In principle you use a mud or water based technique with rotation for soft formations. In hard rock formations, air based hammer techniques are used.

The drilling rigs are expensive, and their operation requires a lot of maintenance, skilled labor and availability of spare parts. Because of their weight and size, they are often mounted on a truck or trailer and not all locations can be reached. It is important to have clear agreements with contractors about quality requirements, planning, risks and procurement as it is a crucial component of the piped water supply system.

Figure 31. A drilling machine

Another option is to drill by hand, reducing the price of a well by a factor 4 -10 compared to a machine-drilled borehole.

Techniques used are hand augering, jetting, percussion and sludging. Hand drilled wells are a good and low cost alternative for machine drilling in situations where the aquifer depth is limited to about 35 meters and no hard rock layers are present underground.

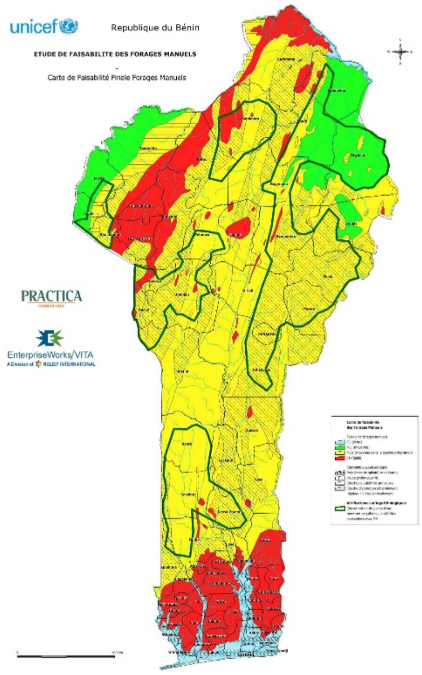
Figure 32 Hand drilling a borehole

A borehole is not just a hole in the ground. It has to be properly designed, professionally constructed and carefully drilled. Boreholes are drilled up to a depth where a good water bearing layer is found and is called an aquifer. On average, boreholes are drilled between 30 and 60 meters with a diameter of 150-250 mm, though there are many examples of deeper wells. When the final depth of drilling is reached, a filter and casing is installed. In loose soils, a casing prevents the borehole walls from collapsing. The filter is where the water from the aquifer enters the borehole so it can be pumped out. Then the borehole is being backfilled with a gravel pack, sanitary seal, space filler and top seal. At surface level an apron and drain is constructed and a pump selected that matches the user requirements or borehole characteristics.

5.4 Borehole siting

Choosing a borehole site is a critical part of the process of providing a safe and reliable supply of groundwater. It is the job of a hydro-geologist to map and assess the groundwater resources in any given area. This is accomplished through the use of maps (topographic, geological), satellite images, aerial photos, field observations (geological mapping, vegetation surveys, etc.), desk studies (literature, field reports, local knowledge etc.) and ground surveys using different measurement methods. Most common measurement methods are resistivity methods and electromagnetic methods.

Figure 33 Feasibility map for manual drilling in Benin



5.5 Drilling log

All borehole drillings should necessarily be accompanied with information that is crucial for the correct further installation of the casings and screens in the borehole, as well as for correct installation of the pump.

After the drilling operation, the following information should be at least available:

- The depth of the borehole;
- A soil formation description of the borehole;
- Borehole diameter(s)
- Depths of water strikes;
- Approximate static water level in the borehole.
- Design of the borehole (placement of filter, casing and backfill)
- The dynamic drawdown
- The water quality

All this data should appear on a borehole log sheet, and should be used while designing the borehole and system. Ideally, the borehole log sheet should be stored as part of the system documentation, and be available in case of need for repair or rehabilitation. Preferably attached to this drilling log is the pump test form and well development procedures.

5.6 Borehole installation and completion

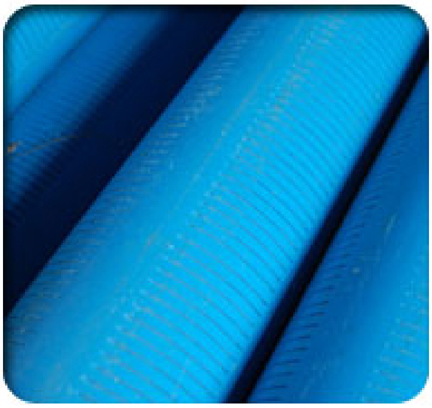
In each country there are strict regulations and standards for the materials used in borehole installation and completion.

5.6.1 Casings and screens

Casing normally extends up to the surface, with a certain amount (say 0.2 meter) standing above ground level. Lengths of casing usually come in plastic (such as UPVC). The diameter of the casing is often between 150 and 200 mm and has a wall thickness of more than 4mm.

Perforated sections are known as borehole screens or filters; they come in sizes and joints similar to casing, so can be interconnected with the casing in any combination. The choice of the size of the screen has to match with the grain size of the aquifer and the chosen gravel packing. Screen sizes range from 0,2-0,5 mm. The screens should be place at the most permeable formation of the aquifer

Figure 34. PVC screen pipes



5.6.2 Borehole development

After the drilling process, and after the installation of the permanent casing, screens, and gravel packs, drilling water and its additives will have to be cleaned out.

Borehole Development has three broad objectives:

1) Remove drilling fluid from the borehole and fine material from the aquifer
2) Optimize the flow of water from the aquifer
3) Create a filter pack out of the gravel packing

There are various methods for borehole development using submersible pumps, engine pumps and compressors. Elaboration about these methods goes beyond the objectives of this training manual.

5.6.3 Pump test

As a final step a pumping test has to be carried out to determine the maximum allowable flow rate of the borehole. This means the maximum flow that the aquifer could sustainably supply continuously without the water table going below the top of the screen. This flow rate will determine the maximum amount of water the borehole could provide to the community. This is called an aquifer test, and a high flow pump is required to do such testing. Frequently more simple continuous flow tests are conducted, e.g. if the well can sustain 700-1000 l/hr when hand pumps are installed.
The documentation of the pump test is, just like the drilling log, important documentation that should be accessible but stored safely, and made available in times of need.

5.6.4 The borehole head

The head of the borehole is connected to the riser pipe coming from the submerged pump. It connects the borehole to the pipes leading to the storage tank. Usually, some hydraulic devices are installed, like non-return valves, water meters, and water pressure meters.

The diameter of the pump head is important, because solar systems have generally a higher water flow than other systems. The diameter of the borehole head is usually determined with the Bresse equation:

$$D = 1{,}5 \times Q^{0{,}5}$$

With: D = diameter in m
Q = max water flow in m^3/s

In table form, the following diameters are used:

Q <	10,5 m^3/hr	D = 50 mm
Q <	15,0 m^3/hr	D = 60 mm
Q <	18,0 m^3/hr	D = 65 mm

Figure 35 Examples of Borehole head: design drawing and picture

5.7 Borehole characteristics

For further design of the water system, at least the following characteristics of the borehole must be available:

5.7.1 Diameter of the borehole

The diameter of the borehole is a limiting factor for the size and capacity of the pump that can be installed. The majority of the boreholes of existing community water systems have a diameter of around 125 mm, which is around 4,9 inch. This allows for pumps with a diameter of 4 inches to be installed.

Generally, pumps with larger diameters have higher efficiency rates. A pump of 5 inch will have an efficiency that is around 10% higher than a pump of 4 inch. With this 10% higher efficiency, you will have an approximate 15% reduction of the required power output of the solar array, and thus reduction in number and costs of solar panels. This means that a cost analysis needs to be done to compare the investment option of a larger borehole and 5 inch pump combined with reduction of array capacity, with the investment option of a smaller borehole with casing of 125 mm and more solar panels.

5.7.2 Dynamic drawdown at maximum water flow

The dynamic drawdown at maximum water flow is established through the pump test. While pumping, the water level in the borehole will go down from static level, because the water is being pumped out of the borehole by the pump. It will reach the dynamic level. The height difference between the static level and dynamic level is called the dynamic drawdown. It is used in the hydraulic head and power requirement calculations of the system. (See also module 6)

Because a solar pump generally has to produce the daily water needs in less pumping hours than a diesel pump, the yield (m^3/hr) of a solar pump is often higher (if the borehole permits). Therefore the drawdown may be more and the total head requirements higher.

5.8 Financial aspects

In areas where boreholes are expensive to make and yields are small, a solar pump has the major disadvantage that it function during only a relatively limited number of hours per day. A diesel pump running 20 hours per day produces much more water from the same borehole investment than a solar pump, thus increasing the investment costs per m^3 for solar systems. This implies that a solar system is not always the most economical option.

Module 6 Hydraulic Head, Pump types and choice

6.1 Introduction

After having calculated the water production requirements, the next step in dimensioning the system is calculating the Hydraulic Head. After knowing this, the most suitable pump for the system can be selected.

6.2 Calculating the Hydraulic Head

The Hydraulic Head (H) is a height dimension and expressed in meters. It consists of the static hydraulic head and the dynamic hydraulic head.

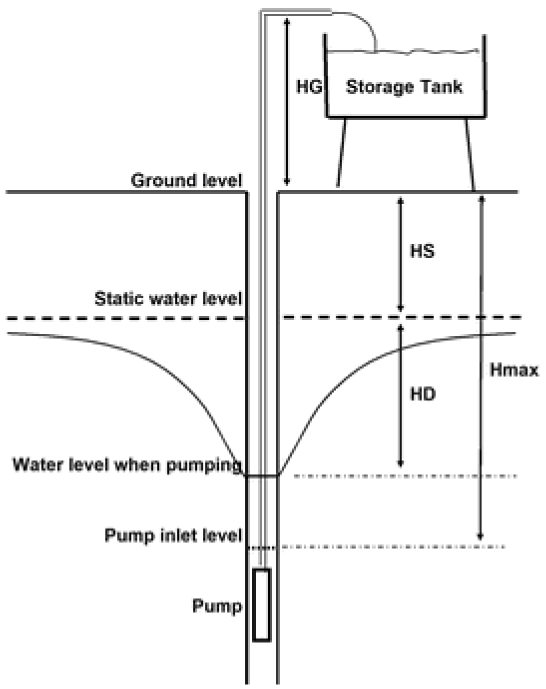
The static hydraulic head is the hydraulic head when the pump is not functioning. It is built of two elements:

1) The depth of the static groundwater level in the borehole relative to the ground level of the borehole. Indicated as HS in the picture below.
2) The height difference between the top of the water storage tank and the ground level of the borehole, indicated as HG in the picture below.

When the pump is functioning, two elements of hydraulic head must be added to calculate the total hydraulic head:

3) The dynamic drawdown: the height difference between the dynamic level and the static level in the borehole. This drawdown is a characteristic of the borehole, and should be known from pump tests. It is represented by HD in the picture below.
4) The dynamic head loss caused by water friction in the rising main, the borehole head and the pipeline to the water storage tank. This is not indicated in the picture below.

Figure 36. Hydraulic Head Components



The dynamic head loss is caused by hydraulic losses in the borehole head and pipe from the borehole head to the storage tank. The losses depend on:

1) The diameter of the pipe line to the tank. The larger this diameter, the less friction losses.
2) The length of the pipe line to the tank. The total friction is proportional to the length of the pipe.
3) The internal roughness of the type of pipe line used. A very smooth pipe has less friction than a pipe with a rougher surface. This depends on the material of which the pipe is made.
4) The water flow in the pipe line. The higher the water flow, the more friction will occur.

A hydraulic equation used to calculate the friction losses in a pipe line is the formula of Williams-Hazen, which is the following:

$$\Delta H_L = (10{,}69 * Q^{1{,}85} * L)/(k^{1{,}85} * D^{4{,}87})$$

<u>In which:</u>

J = 10,69 = the hydraulic loss per meter of pipeline
Q = the water flow in m3/s
L = the length of the pipe line in m.
K = *the Williams-Hazen coefficient for the roughness of the pipe (150 for PVC and PE pipes)*
D = diameter of the pipe line in m.

For this training, the purpose of showing this equation is only to show that such equation is used for calculating the friction losses. Most often, software like Epanet or tables are used, in which can be read what the hydraulic losses of a certain pipe length and diameter will be under a certain water flow condition.

Taking a closer look at the equation, the most important conclusion that can be read from the equation, is that the diameter D of the pipe line is a factor that highly influences the friction losses. The power factor of this is 4.87. Doubling the diameter of the pipe line results in a reduction factor of the friction (= dynamic head) of $2^{4.87} = 29.2$!

Apart from this, it is prudent to include in the calculations a certain margin, to allow for possible increase of friction head over the years, or for a decline of the groundwater level.

As will be explained later, it is important for solar systems to keep the hydraulic head, and thus also the head losses, as low as possible.

6.3 Pump types

Solar pumps are available to pump from anywhere in the range of up to 200m head and with outputs of up to 250m³/day. Solar pumping technology continues to improve. It is important to get the most efficient pump available, as the difference in cost between the poor pump and a very efficient pump is much less than the additional cost required for a larger PV panel.

There are various types of water pumps on the market, which have different working principles. The most important types are reciprocating plunger pumps, diaphragm pumps, helical rotary pumps, centrifugal pumps, deep well turbine pumps and axial flow pumps.

For installation as submersible pump in a borehole for water supply purposes, two types of pumps are important to elaborate upon a bit more: the centrifugal pump and the helical rotary pump.

6.3.1 The centrifugal pump

A **centrifugal submersible pump** is the type of pump most often used in boreholes. It operates with a high speed rotating impeller in a casing that is called a stage. The impeller throws the water radially out of the casing by centrifugal force. If more pressure is required than a single stage can produce, additional stages are added (similar to adding solar panels to increase voltage output)

Figure 37. Schematic picture of single stage centrifugal pump

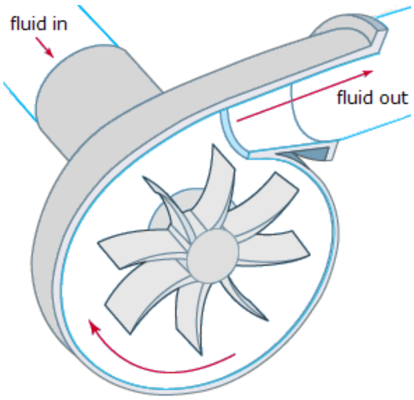
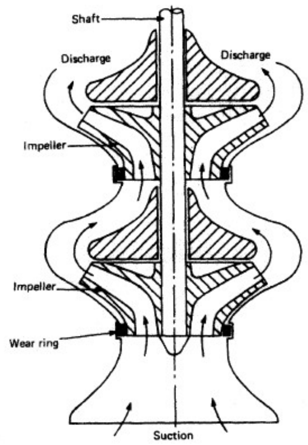


Figure 38. Multiple stage centrifugal pump **(below)**



A centrifugal pump must rotate at a certain speed before it can overcome the static lift required to pump the water into the storage tank. Before this situation, the pump can be rotating but does not yield any water. As a consequence, a centrifugal pump does not pump any water in the early morning or later in the afternoon, even when the panels receive some solar energy.

As second consequence: the higher the static lift, the shorter the pumping hours of a solar powered system with this type of submersible centrifugal pump.

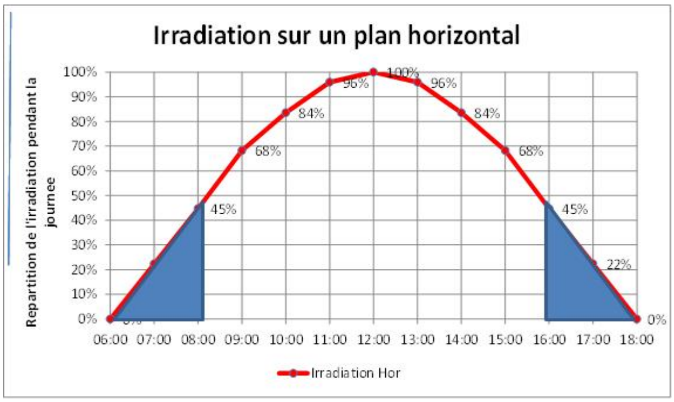
The number of pumping hours with a centrifugal pump

The graphic underneath shows the solar irradiation on a horizontally placed solar panel. On the horizontal axis, the hour of the day is plotted, from 6.00 hrs am to 18.00 hrs pm. On the vertical axis, the percentage of irradiance is plotted as compared to the maximum irradiation level at solar noon. You can see that for example at 9.00 hrs am, the solar energy received by the panel is at 68% of the maximum of the day.

For a centrifugal pump, as mentioned earlier, a certain minimum power is required before the impellers turn fast enough to overcome the Hydraulic Head required. In the early morning and late afternoon, there is a period in which there is irradiance, but not strong enough to produce water. This period is indicated in the graphic as blue surface. It can be seen that (in the case of this graphic;

field situations and pump characteristic can be different) pumping hours are restricted from around 8.00 hrs am to 16.00 hrs pm.

Figure 39. Effective pumping hours of a centrifugal pump versus sunshine hours



If the pump is designed to function at an AC frequency of 50 Hz (which is the usual pump speed of mostly around 3.000 rpm) at maximum capacity, this means that the pump only reaches its maximum capacity at noon. Before and after noon, the water flow is less than maximum.

In the table below, the water flow was calculated as a function of the irradiance and the hour of the day. In this example, a Grundfos centrifugal SP8A-30 pump was used.

Figure 40. Hourly and Daily Production of a solar pump

Hour	% of max irradiance	Flow of the SP8A-30 in m3/hr	% of total dayly water flow
06:00	0%	0	
07:00	22%	0	
08:00	45%	1,0	4,5%
09:00	68%	7,3	10,8%
10:00	84%	8,8	13,1%
11:00	96%	9,6	14,2%
12:00	100%	10,0	14,8%
13:00	96%	9,6	14,2%
14:00	84%	8,8	13,1%
15:00	68%	7,3	10,8%
16:00	45%	1,0	4,5%
17:00	22%	0	
18:00	0%	0	
Day total	730%	61,4	100%

The table shows that the **daily production of this centrifugal pump is about 6 times the maximum water flow.**

The maximum water flow is either limited by the pump maximum capacity, or by the borehole maximum capacity. Because a pump cannot produce much more than the maximum water flow of the borehole at noon, the maximum water daily production of a centrifugal pump is about 6 x the maximum water flow of the borehole.

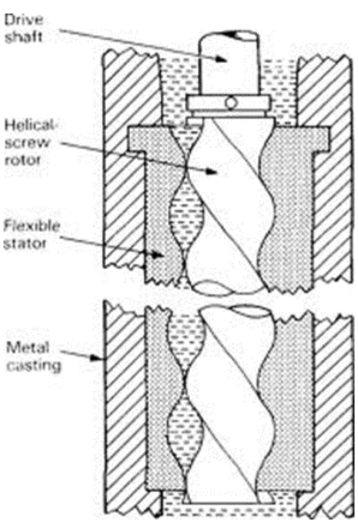
In order to maximally benefit from the borehole and the investment, you should aim at the maximum number of pumping hours per day. The more solar panels (=power) are installed, the earlier does the centrifugal pump start to produce, but this is also more costly.

6.3.2 The Helical Screw Rotary pump

An alternative type of pump also used as submersible pump in boreholes is the **Helical screw rotary pump**. These pumps have a spiral rotor, generally made of stainless steel, which rotates inside a helical stator made of flexible, wear-resistant rubber inside a metal casting. As the rotor rotates, the meshing helical surfaces force the water up by positive displacement. The water output rate is proportional to the speed of rotation, and thus can be easily varied. No valves are required for this type of pump, because the rotor and stator provide a seal against backflow.

The maximum water flow of this type of pump is around 3 m^3/hr (= 18m^3/day), which makes him suitable for the smaller water supply systems only.

Figure 41. Schematic picture of a helical screw rotor pump



6.3.3 Comparison of Centrifugal Pump and Helical Screw Rotary pump

Sensitivity for silt and fine sand

Helical pumps can operate against a wide range of pumping heads, and tolerate small amounts of silt or fine sand in the water without appreciable wear or damage. Centrifugal pumps are more sensitive to silt load, and their life time can drop considerably because of this.

Sensitivity for low irradiance levels

The advantage of helical screw rotary pumps over centrifugal pumps is that they start producing water as soon as they are turning, even if they are turning slowly due to low irradiance levels in the early morning or late afternoon. This means that the daily production of a helical rotary pump is around 7 times the maximum water flow, whilst the daily production of a centrifugal pump is around 6 times the maximum water flow. Especially in situations where the borehole maximum capacity is a limiting factor, choosing a helical rotary pump may be a better option.

Efficiency over different irradiation levels and pump rotation speeds

A particular model of centrifugal pump is only efficient in the limited range of the typical water flow and pumping head it was designed for. When operating away from its' design speed, the efficiency of centrifugal pumps drops considerably. A helical screw pump operates efficiently under a wider range of water flow and pumping head conditions: The efficiency curve of a positive displacement pump is flatter over a range of speeds.

Sensitivity to hydraulic height

Centrifugal pumps operate more efficiently under lower hydraulic heads. The efficiency of positive displacement pumps decreases with the shallowness of the borehole. This is because for helical rotary pumps, the constant fixed friction losses become a more significant part of the power it takes to lift water. Therefore it is not surprising that both Grundfos and Lorentz use centrifugal pumps for applications where the lift is less than 20 to 30m, and switch to positive displacement pumps for deeper wells.

A centrifugal pump is more suitable when flow rates are higher than approximately 25 m3 per hour.

Conclusions for pump choice

1. For hydraulic heads less than 20-30 meters, a centrifugal pump is more suitable. For deeper wells, a HR pump is more suitable.
2. When the capacity of the borehole is only just sufficient to meet the daily water demand, a HR pump is more suitable, because it has longer pumping hours under equal sunshine conditions.
3. Under very high flow rates, a centrifugal pump is more suitable.
4. HR pumps are less sensitive to sand and silt loads.

6.4 Borehole diameter and pump capacities

The diameter of the borehole determines what pump can be installed. Most of the boreholes of the community water systems in Benin have a borehole with a diameter of 125mm. The largest pumps of Grundfos that can be installed in this diameter of borehole are the following:

	Type of pump	Qmax	Hmax
o	SP8A-44 :	10 m^3/hr	150 m
o	SP14A-25 :	18 m^3/hr	70 m

These are centrifugal pumps, with a maximum of 6 pumping hours per day, so they can produce a maximum of 60 – 108 m^3 per day. Beyond the 60 m^3 per day, the max H cannot surpass 70 meters.

6.5 Borehole diameter and pump efficiencies

A borehole diameter of 125 mm permits the installation of small diameter pumps. These pumps have a lower efficiency than the pumps that can be installed in a 150 mm borehole. In such a larger borehole, you can install pumps that have a 10% higher efficiency, meaning that you need to install about 15% less capacity of the solar array.

In certain situations, a larger borehole diameter also has some positive effect on the yield of the borehole, because the surface over which the water can pass the screens is somewhat larger. It is therefore recommended to produce borehole of at least 150 mm diameter, especially in areas where the aquifers are known to be good.

6.6 Pump maintenance and lifetime

The lifetime of a pump largely depends on the number of pumping hours. A pump that is used during 2 hours per day may function twice as long as the same pump when used 4 hours per day.

Maintenance of a submerged pump is complicated, because the pump has to be taken out of the borehole casing. For this purpose the borehole head has to be removed and the pump lifted out of the borehole. Pump servicing and maintenance are expensive, because in most cases it is highly specialized work, and few people know how to correctly do this. So labor and transport costs may be very high.

Brushed motors require regular replacement of the pump brushes, approximately every one or two years, depending on the quality of the pump. It is therefore recommend to use a brushless motor.

Some manufacturers recommend that the pump be serviced every 2-3 years, in order to prolong its lifetime.

6.7 Pump selection

A water pump can be selected using pump performance curves that show the operating characteristics for the solar-powered pump. Most pump suppliers have computer programs and web-based utilities for selecting and sizing pumps for specified values of borehole diameter, available solar radiation, pump flow rate, and pumping head.

Solar-powered pumps are a dynamic and growing field that rapidly changes. The system designer may need to research the different solar-powered pumps available on the market at the time of the system development.

Module 7 Dimensioning the solar array

7.1 Introduction

Exact calculation of solar systems is very complicated. As we have seen from the previous modules the power output of the solar arrays varies during the day and throughout the year. With these power variations, also the speed of the pump varies, and therefore its yield and efficiency of both pump and motor. Furthermore, with the yield the dynamic head varies as well. And this influences the output of the pump again.

Therefore, computer programs are used for dimensioning solar systems. Such software calculates all variables and their dependency on each other. Most manufacturers of solar pumps have such software and use it to dimension the pumps and solar arrays according to operating specifications.

It is however important to have some idea of how such dimensioning calculations are executed in order to avoid accepting offers from importers with inappropriate software. One also has to understand how dimensioning is done to be able to properly commission a system.

7.2 Calculating the power requirements of the solar array

Calculating the power requirement of the solar array can be done using the following steps.

1) Calculate the hydraulic output power demand of the system
2) Factor in the pumping efficiency
3) Factor in the electric efficiency of the system

7.2.1 Calculating the hydraulic energy demand of the system

This hydraulic calculation can be done in a number of ways. In other literature, you may come across different ways of calculating, and different units used. For example, you may come across the use of Kilowatts, Kilojoules, Megajoules. The conversion may be done in different steps (calculating from days to seconds, from hours into seconds, etcetera). In this manual, we try to give you an elegant and very short way of calculating.

For a good understanding of the equations used, we first give the general formula of potential energy. Every day, the daily water production requirement (in m^3) needs to be lifted over a certain height level H, from the borehole into the storage tank, against the force of gravity. This means adding potential energy to the water mass.

The general equation for potential energy is the following:

$$\mathbf{E_{pot} = m * g * H}$$

In which:
m = the mass lifted (kg). Every m^3 of water has a mass of 1000 kg.
g = the gravity force constant = 9.81 (m/s^2)
H = the difference in height level = the hydraulic head (m)

This formula needs to be adjusted slightly to the situation. We calculate the energy per day. If Q is the daily water demand (m^3 /day), then the *mass* of Q is Q * 1000 (kg/day). So instead of m for mass, we write 1000 * Q. We also fill in the value of the gravity force constant. So the formula for the energy required per day becomes:

E/day = 1000 Q * 9.81 * H = 9810 Q * H.

7.2.2 Calculating the hydraulic power output of the array

This amount of energy E/day needs to be produced in the number of peak sunshine hours (Psh) available per day during the critical month. So we would need a power output per hour of:

P = 9810 * Q * H / Psh (J/hr) or W*s/hr.

To calculate the required power output per second, we divide this through 3600, because there are 3600 seconds in one hour. So this equals:

P = 9810 * Q * H / (Psh * 3600) (W * sec / sec) = Watts.

As 9810/3600 = 2.73, we write:

$$P_{out} = \frac{2{,}73 \ * Q * H}{Psh}$$

In which:
Q = water need in m^3/day
H = hydraulic height in m
Psh= number of peak sunshine hours per day in kW/m^2/day.
P_{out} = the hydraulic *output* power. It does not yet take into account the hydraulic efficiency of the system, nor the electric efficiency of the system.

7.2.3 Factoring in the electric and hydraulic efficiencies of the system

The total power demand P_{tot} of the system can be calculated with the following formula:

$$Ptot = \frac{P_{out}}{\eta * \ \varepsilon}$$

In which:

P_{out} = the hydraulic *output* power

η = the hydraulic efficiency of the pumping system. This is the proportion of the energy that the pump receives from the pump motor that is effectively used for the water to flow. (The rest of the energy is converted into heat). Note that other hydraulic losses (the friction losses) have been taken into account whilst calculating the Hydraulic Head.

ε = the electric efficiency (taking into account losses in motor, converter, losses through dust, losses through aging of panels, as described in module 3)

Combining all equations, we come to the equation:

$$P_{tot} = \frac{2{,}73 \ * Q * H}{Psh * \ \eta * \ \varepsilon}$$

Example

A pumping system is designed for a water production capacity of 60 m^3/day at a total pumping head of 10 meters. The pump will operate an equivalent of 6 Psh hours per day. The hourly output required is 10 m^3/hour, which is 2.78 liters per second.

The hydraulic power requirement (or demand) can be calculated to be 9.81 * 2.78 * 10 = 272 Watt.

If the hydraulic efficiency of the pump is 60%, this means that the power to be supplied to the pump should be 272/ 0.6 = 453 Watt.

If then the electric efficiency is 40%, array power to be installed is 453/0.4 = 1133 Watt.

7.3 Configuration of the PV Array

For the configuration of the PV array, we must first know the voltage used in the system, that is the voltage needed to operate the pump. This voltage must be produced by matching the voltage requirement with the number of solar panels in series, depending on the voltage output of one panel.

So if we continue with the example:

Suppose we have panels of 80 Wp, producing 15 V each. In total, we need to install (a minimum of) 1133 Watt, so we need to install 1133 / 80 panels, which is 14 panels. If we need an output of 120 V, we need to put 120 / 15 panels in series, which is 8 panels. So we will install 16 panels in total: 2 parallel series of 8 panels.

Module 8 Storage capacity

8.1 Introduction

In this module, we will go into the aspects of determining the size of the storage tank. We will not treat other aspects of the storage, like material choice for the water tower and tank reservoir, or constructional details of water tower designs.

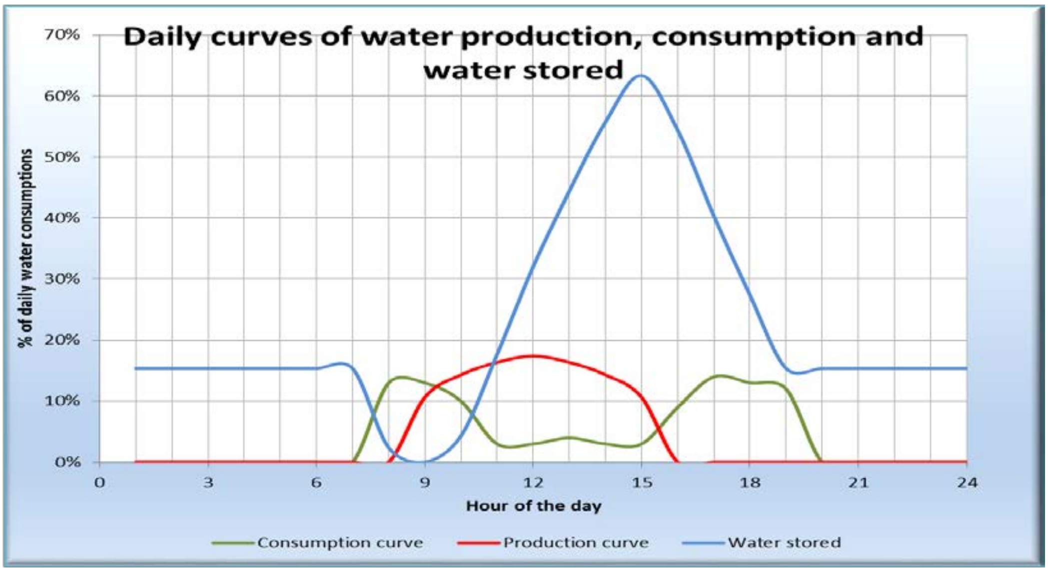
8.2 Reservoir size

Storage capacity is required to bridge the difference between the daily water production pattern and the daily water consumption pattern in the system. The most important factor influencing the size is the number of pumping hours and the time of the day the system can supply water. In water systems that receive their energy supply from generators or the electric grid, the number of pumping hours can be much higher, and they can even be adjusted to meet the water needs. The pumps can also function during the peak consumption hours of the day, resulting in a storage requirement of 20 to 25% of the daily water consumption in the last year of the project design horizon. Generally, larger systems, and systems with many household connections, have lower water use peaks than smaller systems with a relatively large number of public stand pipes. Especially with household connections, the consumption is spread more evenly over the day, because for these households water is available close by, and it is no longer a special task to collect water.

Solar pumps generally function between 9.00 pm and 16.00 pm, whilst the most important water demand peaks are before and after the pumping hours of the solar system. This means that when the system has been pumping during the day, the water storage should be sufficient to meet at least the water demand of both the evening consumption peak and the morning consumption peak of the following day. If we assume (based on experience!) that both consumption peaks together account for 60% of the daily water consumption, this means that the storage capacity should also be 60% of the daily water consumption in the last year of project horizon.

In the figure below, we present an example of the curves of water production, consumption and storage for a water system that stores (a bit more than) 60% of the daily water demand.

Figure 42. Daily curves of water production, water consumption and water stored



In red, the production curve shows which proportion of the daily water demand is produced during what period. This curve has roughly the same shape as the daily irradiation curve. In green, the daily consumption curve is displayed. It is shown that consumption starts at around 7.00 am, and reaches a peak at 8.00 am, and then slowly drops. During the day, the water consumption is low, but a second peak starts in the afternoon and reaches its peak at 17.00 hrs, only to fall down to zero after 20.00 hrs pm. In blue, it shows the percentage of daily water consumption stored in the storage tank. In the early morning, the tank is still filled with 16% of the daily water consumption. Then, consumption starts at 7.00 am, and the tanks starts to get depleted. However, at 9.00 am the water production is so high that the tanks starts filling op again, whilst the consumption peak is over. At around 15.00 pm, the tank is full (if designed to store 60% of production capacity), but the water production has almost ended. The second water consumption peak depletes the tank content from 60% of daily water consumption to around 16%.

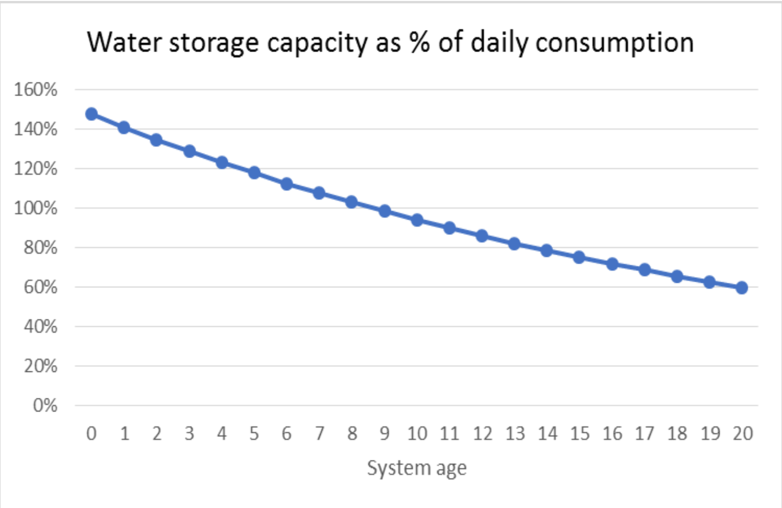
8.3 Effect of Project Horizon

We purposely mention the last year of project horizon, with the objective to point out that if the system is dimensioned for 60% water storage capacity *in the last year of project horizon*. The water storage will be more than 60% of the daily water consumption in all earlier years.

With an estimated population growth rate of 2% and an estimated growth rate of the daily water consumption of 2,6%, the overall growth rate for water consumption is estimated to be 4,6% per year. If we work with a project horizon of 20 years, this means that the system is over-dimensioned with a factor 2,46 for the first year of functioning. In the first year, the storage capacity will thus be 2.46 * 60% = 148% of daily consumption. As the years go by and consumption increases, this storage capacity will gradually reduce to 60% of daily consumption.

In the next figure, we show a graph of the actual percentage of daily water consumption stored over the project horizon, with a design horizon of 20 years.

Figure 43. Water storage capacity as % of daily consumption, with a horizon of 20 years.

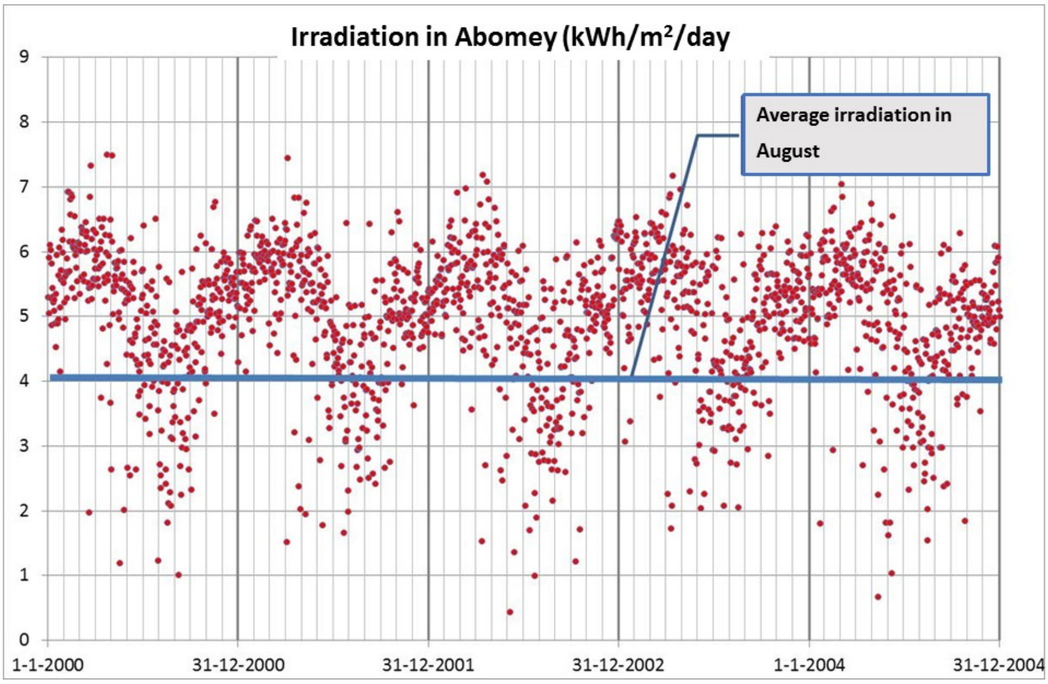


This is not only true for the storage capacity of the water system, but for the entire system, including the way the pumping capacity need and the size of the solar array were calculated.

8.4 Fluctuations in solar radiation

In the design calculation of the system, we normally calculate with the average monthly irradiation in the most critical month. This implies that in all other months, the average irradiation, power supply and daily water production will be sufficient to meet the calculated water needs of the community.

Figure 44. Yearly Fluctuations of Irradiation and August average in Abomey, Benin



Calculating with monthly averages also implies that during a number of (consecutive) days, the irradiation will be *lower* than that monthly average, especially in the most critical month. Calculation with the monthly average means that quite often, the daily water production does not meet the daily water demand.

This characteristic is unavoidable for solar water systems. Solar energy is a natural phenomenon and not a man-made energy source. The position of the sun can be calculated, but not the weather. Choosing for solar energy implies that the risk of lesser supply on some days is taken. The risk is comparable with the risks of non-availability of grid power or break down of the generator.

For the period of time in the graph above, the following can be calculated from the NASA data for solar irradiation:

Days with irradiation < 4,07 (= monthly average August):	17,3%
Days with irradiation < 3,0 (= 75% of monthly average August):	6,2%
Days with irradiation < 2,0 (= 50% of monthly average August):	1,4%
Days with irradiation < 1,0 (= 25% of monthly average August):	0,1%

These percentages depend on the weather and vary per region. A coastal region may be cloudier, mountains may enhance the formation of fog, etc. They tell us that in Abomey, during the most critical month of August, (and if the system is designed for a daily irradiation of 4 kWh/m^2/day), there is a 17.3% chance of lack of water, meaning an average of 6 days in this month.

Such days with too little water production can theoretically be overcome by installing more water storage capacity. In view of the very high costs of storage capacity, this is not an optimal solution. In the table underneath, the prices used by IGIP are shown for a water tower and storage tank of 30 m^3. The price of such a water storage is higher than the solar pumping system itself.

Figure 45. Construction costs for a water storage tower and tank, price levels august 2014, Benin.

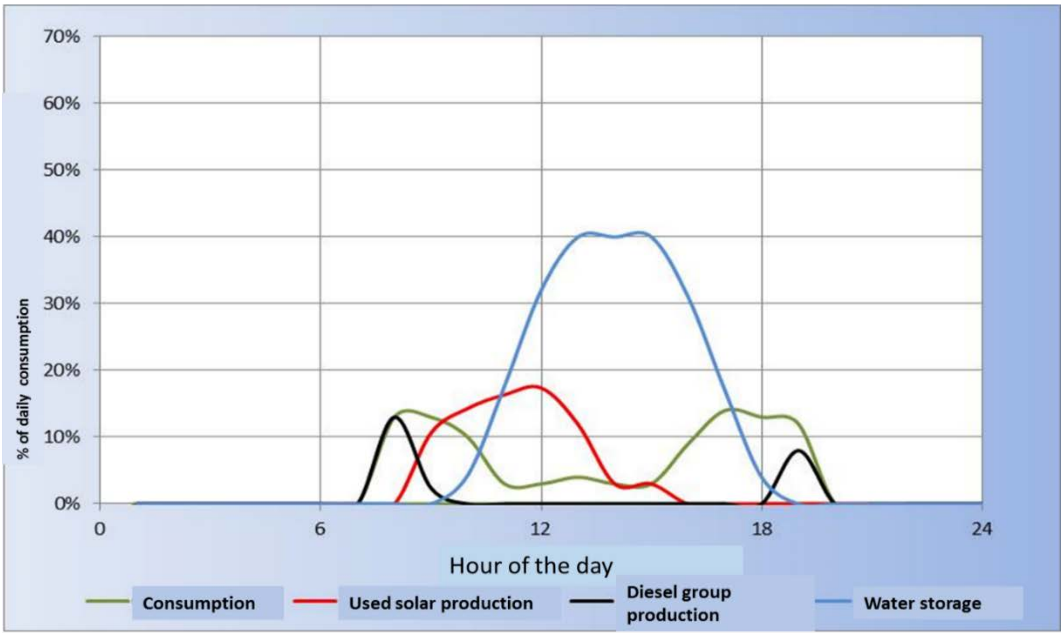
Water storage 30 m^3	**Price in CFA**
Tank at ground level	20.000.000
Tank at 6m	24.000.000
Tank at 9m	28.000.000
Tank at 12m	32.000.000
Tank at 15m	36.000.000

An economically more suitable solution would be to install extra capacity of solar panels, so that the power supply better meets demand even during very low irradiation days. Whilst matching the output voltage and power requirements with the right combination of solar panels in series and parallel, some overcapacity is already created. However, the figures above show that if the reliability in the most critical month is to be increased from 82,7 % (= 100% - 17,3%) to 98,6% (=100% - 1,4%), the double capacity of solar panels has to be installed.

An alternative option is to install a small generator set instead. This generator would only run during a limited number of days and hours during the year. It is a completely different source of energy, which makes the system as a whole much more reliable, while dramatically reducing the costs of fuel compared to a purely generator powered system.

The graph below shows a system with 40% storage (of the daily production) on the critical day at the design horizon. The other days will be more favorable. The black line shows the production of water with energy from the generator. As can be observed, the presence of the diesel generator, and thus prolongation of pumping hours into the water use peak hours, reduces de need for storage capacity.

Figure 46. Daily curves of water production, consumption and water storage combining solar production with a diesel group



8.5 Calculating the capacity of the storage tank

With reference to module 4, we take 60% of the water production need.

8.6 The height of the storage tank

As mentioned in modules 7 and 8, the height of the storage tank is part of the hydraulic height H and the hydraulic load Q * H of the system. This means that the height of the storage tank had direct implications for the power requirements and calculations of the water system.

A second reason for keeping the height of the storage tank as low as possible is the price. As can be seen in Figure 45 above, the higher the elevation of the storage tank, the more expensive it will be. On average, a 1 m increase of elevation will cost 1.33 Million CFA.

The elevation of the storage tank is required to meet the water pressure requirements of the distribution network. Minimizing the hydraulic losses in the distribution network thus also minimizes the required minimum elevation of the storage tank. Generally, this can be done through using fairly large diameters of distribution pipes, in such a way that the water velocity is close to the standard minimum velocity. An economic balance should sought between storage tank elevation and distribution pipe diameters.

8.7 Tariff structures

The storage capacity needs to be large because the incidence of consumption does not correspond with the availability of solar power. Instead of increasing the size of the storage reservoir, one could also try to change the habits of the consumers by changing the tariff structure. If the water were cheaper during the day than in the morning and the evening hours, probably more people would tap water when the sun shines and the water is produced. In that case it does not have to be stored.

Seasonwise, one could lower the tariff in rainy month of August, in order to sell more water in the rainy season. People often return to their own wells in the rainy season, but they might be tempted to buy water if it is cheaper in this period.

Module 9 Design considerations

9.1 Introduction

In this module, we discuss and evaluate a number of design considerations and dilemmas that the designer of a solar water system may encounter. We discuss the choice between solar systems and grid connections, and evaluate the options when the capacity of the borehole is insufficient to install a solar system. We explain why it is recommendable not to combine solar panels with different characteristics, the limitation of village size related to borehole and pump capacities, and go into pump capacity choices when pumps need replacement. Finally, we go into the quantitative effects of different combinations of design assumptions.

Design considerations cannot be prescriptive. It is up to the designer, in close communication with his/her clients, to make choices related to level of investment, risk levels, water price, reliability, continuity and quality of the water provision.

9.2 The choice between solar systems and grid connections

In a situation where electricity supply from the electric grid is available, this option should be chosen. Solar pumping is more expensive than a grid connection. The advantage of solar energy is that the power supply from the sun is free of charge once the system is installed. However, when an electric grid is available, the initial investment of a grid connection is much lower, and the depreciation costs an interest on borrowed money (CAPEX, see module 10) for the solar equipment are higher than the electric bills that can be expected. From the point of view of economic optimization of investment allocation, it is best to allocate solar pumping investment funds to locations where grid connections are not available, and will not become available in the next 5-10 years. It is therefore important to know the planning of grid extensions.

This is valid under normal conditions in most countries. If for example electricity is only available at night, very unreliable or very expensive, the result of the design considerations may be different.

One should keep in mind that once the investment in a solar system is done, the maintenance and running costs are very low. It is therefore important to use the installation to its maximum. One may even consider to use surplus capacity to charge mobile phones, and batteries for lighting of homes at night.

9.3 What to do if the capacity of the borehole is insufficient

In situations where the maximum yield of the borehole is not sufficient for a solar pumping system, a number of alternatives can be investigated.

9.3.1 Installation of batteries to prolong pumping hours

Storage batteries may be incorporated into the system. This can basically be done in two different ways. The first method is to completely incorporate them, meaning that the batteries are continuously integrated into the electric system, as link between the solar array and the solar pump. The second way is to separately install and charge batteries that can be used as backup power source. The panels that charge the batteries are then disconnected from the panels that directly drive the solar pump.

Occasionally, it may be decided to install light at the compound of the array. In that case, batteries will need to be installed.

In both methods, additional solar array capacity will need to be installed; not only to allow more pumping hours, but also because the electric system will have significant higher power losses. Charging and discharging batteries is a chemical process in which energy is lost. In the first method, the solar modules operating voltage is dictated by the battery bank. This voltages is much lower, and is thus reduced substantially from the Voltage levels required for directly operating the pump. The second method has as advantage that it avoids these power and voltage losses during sunshine conditions. It only uses the batteries when they are needed for extra pumping hours, which may not be the case every day.

Although many types of batteries are on the market (Ni-Cd batteries, lithium batteries), the conventional lead-acid batteries are nowadays still the most economical option. Vehicle batteries are not suitable for this purpose, because they are designed for shallow discharge only, and should not be discharged to less than 75% of their capacity. Deep discharge batteries, having lead-antimony electrodes, can be discharged to 20% of their full load, but their lifetime increases importantly when used with less discharge. Also, operating temperatures strongly affect lifetime: at a temperature of 35˚ C, the battery lifetime may be shortened with 44% of its expected lifetime at 25˚C. So it is important to keep the batteries as cool as possible; in a shaded place with good ventilation.

While batteries may seem like a good idea, they have a number of disadvantages in pumping systems.

- Higher energy losses,
- Batteries require additional maintenance and under- and overcharge protection circuitry.
- The battery charge and discharge will have to be regulated by the control unit. This adds to the cost and complexity of a given system.
- The lifetime of batteries is limited. They will have to be replaced every 1-2 years.
- Batteries are a theft risk

For these reasons, only about five percent of solar pumping systems in the world are currently equipped with a battery bank. The use of batteries should therefore be discouraged unless absolutely necessary: The added expense and complexity usually outweighs any advantages.

9.3.2 Using a PV system combined with a diesel generator.

In such a hybrid configuration, the solar array power pumping is used when possible, and the diesel generator is used for additional pumping hours in early morning and evening hours, and during cloudy days with insufficient sunshine. This way, pumping hours can be prolonged and the water supply can be guaranteed to a much larger extent. One should not forget that for example in Benin, people pay an average of CFA 600 per m^3 for their water, which is more than people pay in Europe. Continuity of supply is therefore also a factor in ensuring payment discipline by the users.

The question then is: Why should we install solar power anyhow, when we have a generator capable of doing the power delivery?

The advantage of such a hybrid system is that it prolongs the pumping hours of the system, compared to using only solar. It reduces the use of the diesel generator hours, during which fuel is required. This also reduces the maintenance costs of the diesel generator. The saved fuel and maintenance costs can under certain conditions be higher than the extra investment costs required for adding the solar power to the system. A feasibility study of such systems in Benin in 2014 has shown that this is feasible when H*Q is higher than (approximately) 2.000 m^4. With lower values, the extra investment costs would probably result in too high water production costs and thus water price levels if CAPEX would be charged to the users.

At the same time, the reliability of the system is improved, because during days of very low irradiation, the generator can be switched on as backup power source.

9.3.3 Drilling a second borehole

In this case, the boreholes need to be situated at a reasonable distance from each other, in order to avoid yield reduction of one borehole because of water extraction in the other borehole. The minimal distance depends on the soil and aquifer characteristics of the locations and should be determined by a hydro-geologist. Drilling a second borehole would imply the installation of 2 pumping systems with 2 solar arrays, extra piping, etcetera, except if the capacity of the second borehole is sufficient to meet all water needs. (The chance for this to happen is small because in the same aquifer, the yield of a second borehole is probably comparable to the first one.)

9.4 Different water source alternatives

The focus of this training is on the combination of solar powered submersible pumps in boreholes. It is implicitly assumed that in most cases, boreholes are to be preferred above other sources, because boreholes generally provide a stable yield of safe and clean water. However, if borehole capacities are insufficient, the availability of other water sources may be evaluated. Especially nearby permanent rivers and streams, the alternative of using a river intake instead of a borehole should be studied and evaluated.

Parameters for evaluation would be the investment costs, operation and maintenance costs, and the capacities available to manage the system. A river intake requires a water treatment plant, and possibly two pumping systems: one near the river bank to pump the water from the river into the treatment plant, and a second near the treatment plant to pump the water from the treatment plant to the water storage tank. The design and cost calculations of such systems are beyond the scope of this training. The fact that multiple stage pumping is required at different locations, often further apart, makes such systems less suited for solar power.

9.5 Can different solar panels be combined?

When you intend to wire two panels produced by different manufacturers, the manufacturer is not the problem. The problem is in different electrical characteristics of the panels, together with different performance degradation.

When you connect a 15V panel to a 24 V panel in parallel, the overall voltage will be dragged down to 15 Volts. When a 3A panel is connected to a 3.5A panel in series, the overall current will be dragged down to 3A. Such a reduction in current will always lead to a reduction in power output and therefore loss in system performance.

Compared to voltage and current, wattage is not a significant problem. A 60W panel connected in series to a 100W panel will give a total power of 160W, provided that the two panels are of equal voltage.

So when one panel is of lower voltage, the whole bank will run at that lower voltage, or the panel with the lower voltage does not contribute anything because it cannot reach the voltage of the other panels (compare pumps in parallel). That means that when the whole bank runs at lower voltage, the maximum power point of the other panels is not reached and also the Power output (Watt) is lower. In the second case the panel with the lower voltage does not contribute at all.

It is therefore recommended to use panels of the same manufacturer and the same type. However, a very old panel of the same manufacturer and type, could have such different characteristics that it does no longer combine well with a new one.

In parallel connections, if one of the panels has a power output lower than the other panels, this will not seriously affect the power output of the other panels, provided that all panels have equal rated voltage.

However, solar panels of different manufactures also have a different performance degradation rate over the years. And because the voltage output is determined by the "weakest link" in the panels in series, the array will end up providing the voltage of its weakest link.

In conclusion, different solar panels with the same array is not recommended since either the voltage or the current might get reduced. Sometimes it cannot be avoided and one should leave the choice of the new panel to be combined with an older one to specialists.

9.6 In what size of village is it more feasible to install a solar system, compared to a diesel generator pumped system?

With the current diesel prices, in most cases it will be more feasible to install a solar system, than to install a diesel generator (if the capacity of the borehole permits the installation of a solar system). With the most usual size of boreholes in Benin (125mm), the daily consumption rate for a solar powered system cannot surpass 100-120 m^3/day (depending on the pump type and brand), because the pumping capacity of 4 inch submergible pumps is not higher than this. With boreholes of larger diameter (>150mm) 6 inch pumps can be installed, and larger volumes can be pumped if borehole capacity allows.

9.7 Is it possible to change the pump into a larger pump, and more solar panels, after the first pump is worn-out?

The lifetime of the pump largely depends on the number of pumping hours. The number of pumping hours per day (or year) can be reduced by installing the largest capacity pump that possibly fits in the borehole and does not exceed the maximum capacity of the borehole. This option might be favorable because the price difference between the smallest type pump and the "second step" pump generally is much less than the difference in capacity. In other words: with a relatively small extra investment, it can be possible to significantly increase the lifetime of the pump. Two remarks should however be made: Firstly, especially with centrifugal pumps, care should be taken that the pump operates at the H and Q it was designed for, in order not to lose pump efficiency. Secondly, for a larger capacity pump also more power needs to be installed, and possibly larger piping. A calculation is required to evaluate whether the longer lifetime of the pump outweighs these higher investments costs.

Usually, the submergible pump has a lifetime of around 5-7 years. By the time the pump needs to be replaced, the choice needs to be made to purchase the same capacity of pump, or a pump with higher capacity. At that moment, a new calculation needs to be done to evaluate what pumping capacity will be required in the next years. Water meter readings of the system will provide all historic water production and consumption levels of the system, including the consumption trends and months of peak use. The system manager as well as the community population will be able to inform about the frequency of any water shortage in the system, most likely in critical months.

If initial design assumptions have been close to correct, and the solar array size was correctly calculated, then the solar array power output will still be sufficient to continue providing the required power output. However, if water consumption is (much) higher than foreseen during the design stage, it may be decided that a larger capacity pump is required to meet the water demands. In that case, new projections and calculations need to be made in order to newly determine the required pump capacity and solar array capacity and configuration.

Technically, it is possible to choose a pump of higher capacity and expand the solar array output power, taking into account the stipulations under “Can solar panels be combined”. It should in that case be evaluated if the inverter needs replacement as well.

9.8 Overdimensioning

The design assumptions and regulations often lead to grossly over-dimensioned water systems. The following factors contribute to this:

1) The assumption that the water use will be 20 l/day/cap.

In most real life cases, in rural communities in Africa, the water consumption is much lower, and in the range of the 6-10 l/day/cap. The water price is an important factor: many people will continue to use alternative sources available, especially for non-drinking purposes like washing, house-cleaning and laundry washing: they will tend to minimize consumption from the water system in order to save cash expenses. So this assumption leads in many cases to over-dimensioning of 100% or more.

Over-expectations of water consumption will also lead to disappointing income from the water system. This can have great repercussions for the operation and maintenance, and thus for the sustainability of the system.

2) The assumption of growth of specific demand.

The basis of this assumption is often not very clear. It should be investigated and demonstrated. Is it true that people will consume more piped water every year? Has this been demonstrated in other piped systems? If the assumption is 2,6% per year, and it turns out to be a false assumption, this leads to over-dimensioning with 30% for a project horizon of 10 years, and 67% for a project horizon of 20 years.

3) The length of the project horizon.

A longer project horizon leads to overdimensioning with respect to the current situation. The longer the horizon is chosen, the greater this factor becomes. In module 4, it is demonstrated that a 10 year project horizon with a 2% population growth leads to an initial overdimension of 22%, and a 20 year project horizon to an initial overdimension of 49%. The difference is 27%.

4) Calculating with Peak use factors

The practice of calculating with peak use factors, in the range of 1,1 to 1,4, adds to the overdimensioning of the system with 10-40%. It does not take into account that the system is already over-dimensioned for most of its lifetime.

Now let us compare some combinations of design assumptions and their consequences. Five combinations of assumptions are evaluated. (1) A conservative estimate of water consumption and growth would take into account a water consumption of 10 l/day/cap and a population growth of 2%

and a project horizon of 10 years. (2) The same conservative estimate, but adding a specific consumption growth of 2,6%; (3) A water consumption of 20 l/cap/day but with moderate growth assumptions and 10 years project horizon, and no peak use factor; (4) The maximum assumptions under a 10 years' project horizon and; (5) A maximum estimate using all factors and a project horizon of 20 years, assuming a water consumption of 20l/day/cap, a growth factor of 4,6% and a peak use factor of 1,4.

Comparing the water consumption calculations for a community of 2000 people results in the following design quantities. The combination of assumptions is displayed in the different rows.

Figure 47. Table summarizing effects of Design Assumptions on Design Consumption

		Design Assumptions				
	Unit	**Conservative**	**Conservative +spec growth**	**Conservative 20 liters/cap**	**Max 10 years hor**	**Maximum in 20 years hor**
Population	hab	2.000	2000	2000	2.000	2.000
Estimated Consumption/day	l/hab/d	10	10	20	20	20
Water demand/day at 1st project year	l/day	20.000	20.000	40.000	40.000	40.000
Population growth factor	%	2,0%	2,0%	2,0%	2,0%	2,0%
Growth specific consumption	%	0,0%	2,6%	0,0%	2,6%	2,6%
Total growth factor G	%	2,0%	4,6%	2,0%	4,6%	4,6%
Project Horizon n	years	10	10	10	10	20
Mult factor project horizon	$(1+G)^n$	1,22	1,57	1,22	1,57	2,46
Calculated consumption at horizon	m3/day	24,4	31,4	48,8	62,8	98,4
Peak use factor	unit	1	1	1	1,4	1,4
Design consumption	**m3/day**	**24**	**31**	**49**	**88**	**138**

This table serves to demonstrate the enormous effect of the choice of design assumptions on the size of the designed water system. The total effect of differing assumptions can lead to a system that is 575% larger (138/24) than the minimum system that still takes into account population growth. It also demonstrates that it is prudent to limit the project design horizon 10 years.

In order to make realistic design assumptions, the following recommendations can be made:

1) A good way to estimate a realistic consumption level per day is using the consumption data from existing similar water systems in the area. These data, if recorded long enough, can also serve to estimate the total growth factor. (It will be difficult to separate between actual population growth and specific consumption growth, except when exact data are available about the population served each year)
2) System operators should keep a good administration of water consumption data and trends.
3) Use a project design horizon of 10 years.
4) Do not apply a high peak use factor.

Note should be made that doubling the design consumption does not imply doubling the investment costs: smaller systems are more expensive per m^3 than larger systems.

Module 10 Financial Analysis, Management and Planning

10.1 Introduction

Financial analysis and planning needs to take place to balance income from water consumption with the costs of water production. Financial sustainability is achieved when the income is sufficient to pay all expenditure required to operate, maintain and replace the water system. The unit water cost (UWC) reflects the cost of water. It therefore provides a measure for the cost at which water at a particular installation needs to be sold at in order to recover the costs for providing the water supply service.

In this module the basic elements of this subject will be presented.

10.2 Costing

The following types of costs are distinguished in this chapter:

10.2.1 Capital expenditure (CAPEX)

The capital expenditure consist of the initial investment costs made at the beginning of the project, together with the costs involved for financing the project.

The initial investment costs consist of the cost of all physical elements (solar array and mounting rack, fencing, control boxes, borehole elements, pumping system, borehole head, conduction pipe, water storage tank, distribution system, water meters, water treatment) of the system, the installation costs (site cleaning and preparation, drilling costs, labor costs) and the transport cost (of laborers and materials). These costs are to be paid at the start of the project (payment to the contractor) and do not change during the project. Therefore as much water as possible should be sold to keep the unit costs low.

The costs involved for financing the project are made in case the project is financed through a bank loan or other loan. They consist of the following costs:

- Depreciation (pay back of the loan to the bank)
- Interest on the borrowed capital to be paid to the bank

10.2.2 Fixed operational costs

Fixed operational costs come back every year, but depend only to a small extent on the quantity of water produced. To recover these costs, as much water as possible has to be sold.

- rent of land
- staff payment
- maintenance (to some extend),
- overhead, billing and administration
- water quality analysis, etc.

10.2.3 Variable operational costs

These costs depend on the quantity of water produced. No production → no costs. Such costs are very interesting because when sales are less the entrepreneur runs no risks as also the costs are low.

The following variable operational costs can be mentioned:

- Fuel for generators
- Electricity from the grid
- Chemicals for water treatment (chlorine)
- Costs of feed water (ground water tax, etc,)
- Cubic meter based payments to the government

Cost calculations are highly influenced by the policy choices made about how to calculate them. Often, the expenses made in the preparatory and construction phase (like mapping and selection, planning and design, contracting, supervision and control, monitoring and administration) are not included in the cost calculations, whilst these are real costs and can be important. They could be considered as part of the initial investment costs. The reason why they are not included is that community water supply is a public service, and these costs are made under general budgets paid indirectly by tax incomes and sometimes development support. In the case of private supply, the company or farmer will have to assume most of these costs as well.

If the water system is considered to be a gift from a donor agency or government, the initial investment costs are usually not included as system costs. If the system is paid from a bank loan, not only the investment costs but also the financing costs like loan interest rates must be included in the calculation. Even if the investment is a gift, it is always good to ask the question whether the money is well invested, or that it would give a higher rate of return somewhere else.

In many situations, replacement costs are not considered as costs of the system, and not taken into account in the financial planning and management. As a consequence, re-investments cannot be done. A well established and managed water supply system always has access to credit for replacement (break down, aging, theft, etc.) either from the government (replacement fund to be filled with a contribution per m^3 by the entrepreneur running the water supply) or from a bank.

10.3 Life cycle cost modelling and analysis

Life cycle cost modelling is an approach to take into account all water production costs involved, and establish a projection of the cash flows and income required.

Usually, a reference case water system is used, in which the design assumptions are clearly shown. Typical design assumptions for financial analysis are the following:

1. consumption assumptions (consumption growth parameters, daily consumption pattern)
2. production assumptions (borehole yield, irradiation patterns)
3. financial assumptions (inflation of input prices, interest rates, return on investment, project horizon, horizon of financial analysis, inflation, etc.)
4. hydraulic assumptions (static level, hydraulic losses, hydraulic drawdown, hydraulic lift)
5. life time assumptions of system elements.

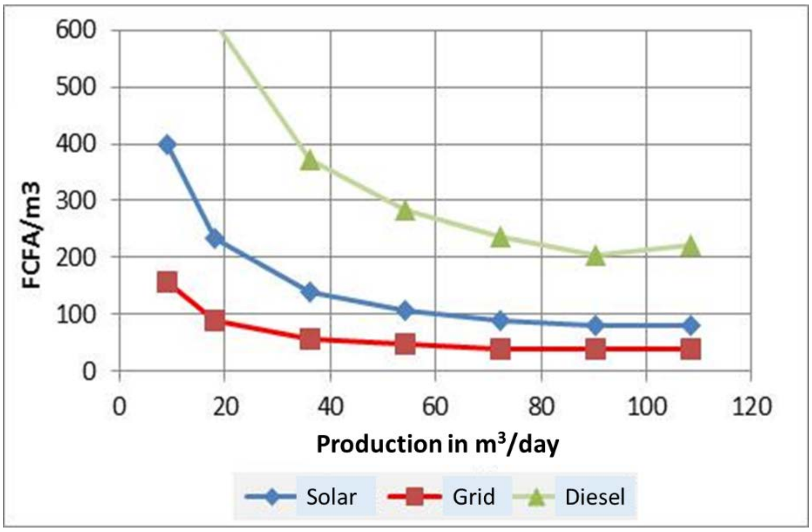
By allowing variations of some of the parameters, the cost consequences of design choices can be calculated, as well as the sensibility of design choices for variations in these parameters, so that their feasibility and risks can be evaluated. When using this methodology, design choices can be made upon the relevant information produced.

An example of such analysis is given in the following. The question was asked what the water production cost were for different system sizes, if different energy sources would be used: a comparison was made between diesel generator powered pumps, electric grid use, and solar systems, situated in Benin. In the calculations it was assumed that:

- The electricity or diesel driven water supply system existed already. The lines for diesel and electricity represent the continuation of these system without adding a solar system. Initial investment (already done) was not taken into account but all required reinvestments are included.
- The solar system (panels, converter and new pump) was to be added to the existing diesel driven system. The initial investment for the solar system was considered, as well as the replacement investments for diesel generators. As the diesel is making less hours, the reinvestment comes much later than for the purely diesel driven system.

When investment costs are not considered, solar is always cheapest because it only requires investment costs, and virtually no running costs.

Figure 48 Water production cost comparison for solar, grid and diesel generator powered systems in Benin.



(source: COWI 2014; Etude de Faisabilité « Solaire » concernant les AEV et PEA du Bénin)

Out of this graph, three conclusions can quickly be drawn:

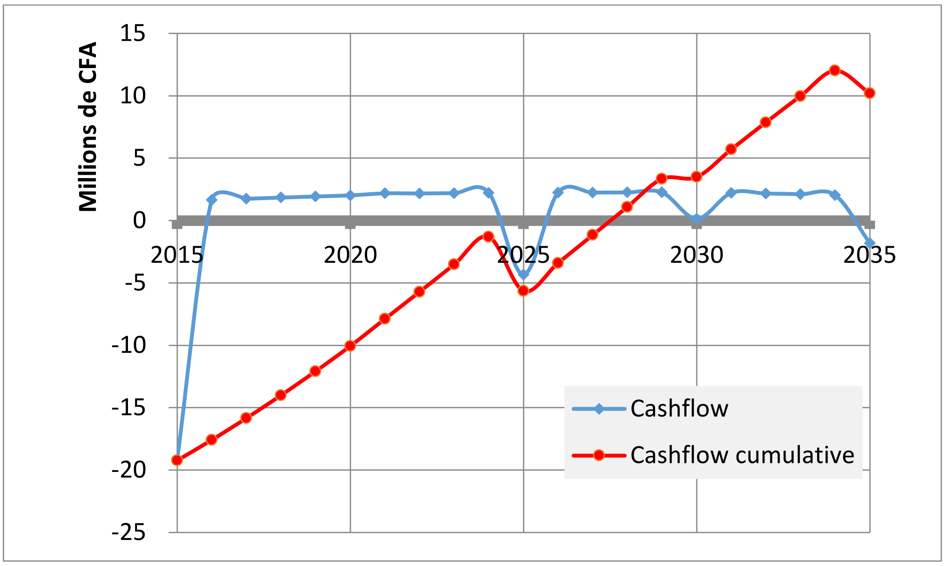
1) In general, grid powered systems are the most economic systems in terms of water production costs. With solar systems, the water production costs are approximately twice the costs of grid powered systems. The use of diesel generators results (on average!) in much higher water costs.
2) The larger the system, the lower the prices per m^3.
3) Especially in systems with a water production of less than 20 m^3/day, the water production costs are generally high.

10.4 Cash Flow Analysis

For financial planning a cash flow analysis is used. Cash flow is the sum of investments (not depreciations or interest!), the operational costs and the revenues (costs are negative).

The example underneath shows the cash flow and the cumulative cash flow of a water system over 20 years. The graph shows that in the first year we need a lot of money to pay the contractor and the consultants, in order to pay the initial investment costs. This money is either borrowed from a bank, or received from a government or donor agency. In the example, we assume a bank loan.

We start with a depth at the bank of almost 20 million CFA. The second year we start selling water and the revenues are higher than the costs. This can be seen because the blue line is above zero. We pay back some money to the bank every year, so that our depth becomes smaller; This can be seen because the red line is on the rise, but still far below zero. Just before we have paid back all our debt, in 2024, we have to change the pump and converter. So we need money again, and we ask the bank to increase the loan. Between 2027 and 2028 we have paid back all debts, including all interests, to the bank. The red line is above zero, meaning that there are savings on the bank account. In 2030 we have to change the well head, but we have saved enough money to pay for this expenditure from our own funds.



Also this cash flow analysis is based on a good number of assumptions. In this case, the projected income is sufficient to recover the investment costs, and even have savings for renewal of the system elements after lifetime depreciation. It is a good example of a financially sustainable water system.

References and Further Reading

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