Solar Powered Water Systems

Design and Installation Guide

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INTRODUCTION

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A. INTRODUCTION

1. General

1.1. Scope

This document gives detailed instruction of all technical topics pertinent to the design and installation of solar powered water systems within the rural water supply context. The motivation for this document is to provide guidance that is based upon internationally recognized technical standards and to provide instruction for fulfilling those standards.

The technical basis for this guidance document is the International Electrotechnical Commission (IEC) International Standard 62253, Photovoltaic pumping systems – Design qualification and performance measurements. This document seeks to show the reader how to fulfil the requirements of these IEC standards. Additional IEC standards that are relevant to this guidance document are listed in **2.1. Water System Compliance**.

This document does not address all topics pertinent to ground water development and drilled water well (borehole) best practices, as these topics have previously been thoroughly addressed by others (UNICEF/Skat Foundation, 2016, and UNICEF/Skat Foundation, 2018).

This document assumes that the power to the pump and motor is solely provided by a solar power system. This document does not include secondary energy sources (AC grid or generator) or energy storage (battery).

1.2. Author

This guidance document is authored by Water Mission – Engineering & Innovation Department, Charleston, South Carolina, USA (watermission.org), as part of a programme cooperation agreement with UNICEF WASH Headquarters Programme Division and is the product of discussion and extensive review by UNICEF Programme Division, Supply Division, Regional Advisors, and country WASH teams.

Special thanks is extended to the following organizations for reviewing and providing valuable insight on the content of this document: Global Solar Water Initiative, IOM, Oxfam, Practica Foundation, University of Texas at Austin.

The Spanish and French translated versions of this guidance document were made possible through the generosity and support of the Global Water Center, the Global Solar Water Initiative, and the USAID Bureau for Humanitarian Assistance.

Additional materials and instruction will be forthcoming, including example Terms of Reference documents and guidance, example Bill of Quantities examples and guidance, advanced design examples, and case studies from various regions of the world. As these materials become available, they will be accessible through the similar channels where this Guide is available.

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Photo courtesy of Water Mission

1.4. Definitions

Engineer of Record: The individual, or entity (as in an engineering firm), accountable for the portion of the design for which he or she takes formal responsibility by signature, professional stamp or seal, and/or other legally recognized means. The Engineer of Record may also be referred to as the Design Engineer or the Consultant Engineer.

IEC: International Electrotechnical Commission

Incident Irradiance: The irradiance on a surface, either tilted or flat, which varies depending on the tilt angle of the surface.

Inverter: A device that converts direct current (DC) electricity into alternating current (AC) electricity. The device is also referred to as a PV Converter.

Irradiation: The sum of the incident irradiances at a given location on earth during a solar day (given in units of $kWh/m^2/day$).

NEC: National Electrical Code (United States)

NOCT: Normal Operating Cell Temperature, measured at an irradiance of 800 W/m^2 and an ambient temperature of 20°C.

Photovoltaic (PV) System: Converts irradiance (solar power) from the sun into electricity.

PV Pump Aggregate: Another way to refer to a pump and motor combination.

Solar Array (or PV Array): A configuration of solar panels arranged and wired together to output power as a single unit.

Solar Array Racking System: Structural system designed and constructed to support the solar array per the design conditions.

Solar Irradiance: The power per unit area received by the sun (the sun emits an average of 1,367 Joules per second per square meter of surface area, and of this, a maximum of approximately 1,000 Watts per meter squared (W/m^2) reaches the earth's surface).

Solar Panels: Panels that use sunlight (or light energy from the sun) to produce electricity. Solar panels are also referred to as photovoltaic modules or generators (or PV modules or generators) or a combination of those terms (such as solar PV panels or photovoltaic solar panels).

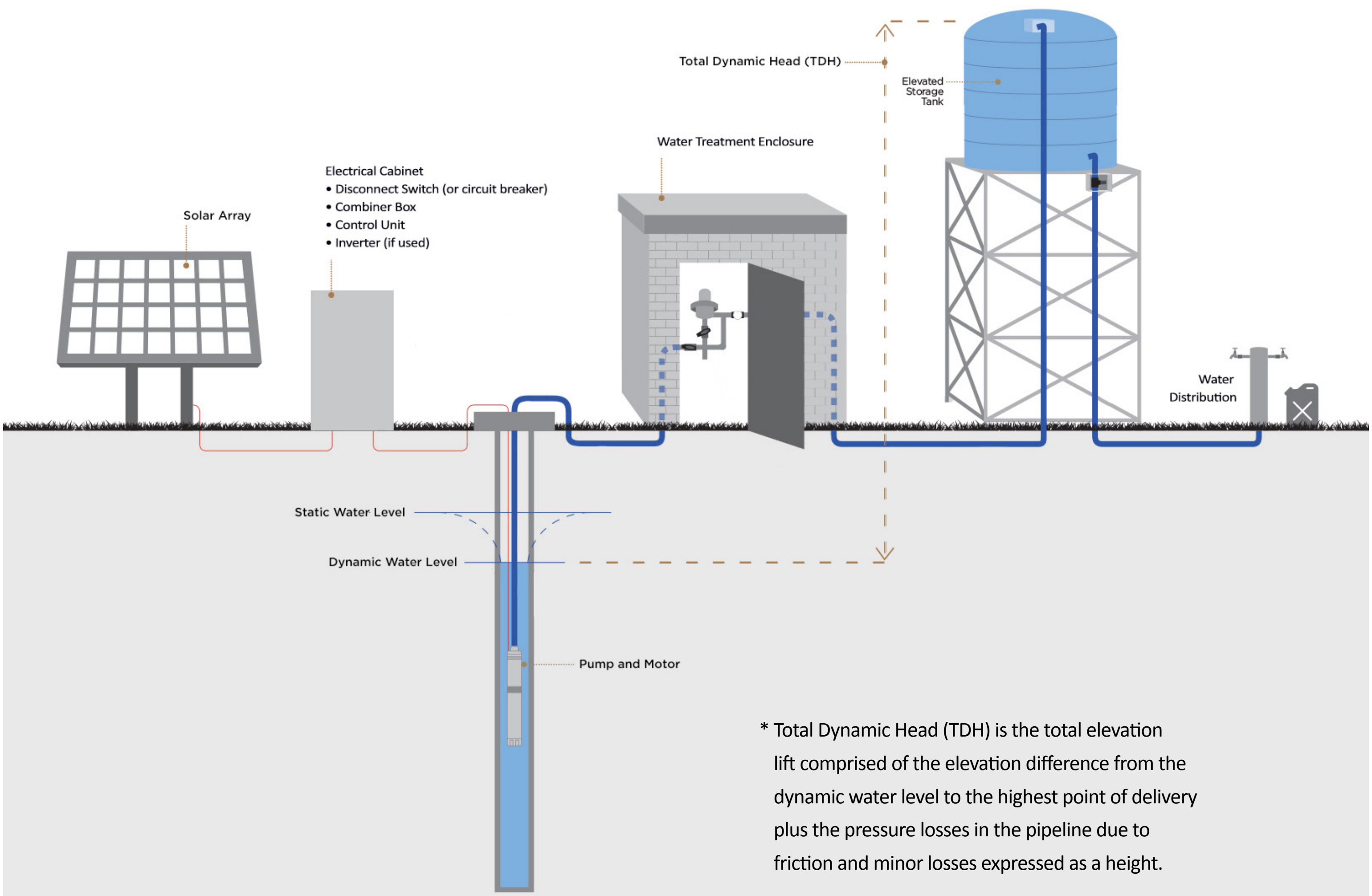
Solar Pump: This term typically refers to pumps that have a controller, motor, and pump integrated into a single unit that can accept a DC power input. However, some units referred to as "solar pumps" do not have integrated pump controls. It should also be recognised that these pumps can take any type of DC power input and not solar exclusively.

STC: Standard Test Conditions, defined as a cell temperature of 25°C, an irradiance of 1,000 W/m^2, and an air mass coefficient of 1.5 (AM1.5) (reference IEC 61215).

Tilt Angle: The incline angle of the solar panels relative to the horizontal.

TDH: Total Dynamic Head is the total elevation lift (including friction loss) required of the pump in the water supply system. The pump achieves this by applying pressure (or energy per unit volume) on the water in the system.

SOLAR POWERED WATER SYSTEM



* Total Dynamic Head (TDH) is the total elevation lift comprised of the elevation difference from the dynamic water level to the highest point of delivery plus the pressure losses in the pipeline due to friction and minor losses expressed as a height.

Figure 1.4 – Solar Powered Water System

BASIC STEPS TO DESIGNING A SOLAR POWERED WATER SYSTEM

There are five basic steps involved in designing a solar powered water system.

STEP 1 | Calculate the daily water demand for the project.	
Reference in Guidance Document:	2.2. Daily Project Water Demand
Question to answer:	What is the water demand that the solar powered water system will be designed to produce?
STEP 2 | Determine the yield of the water source available to the solar powered water system.	
Reference in Guidance Document:	2.3. Water Source
Question to answer:	Does the yield of the water source meet or exceed the demand calculated in Step 1?
STEP 3 | Determine the total dynamic head (TDH) of the water system at the chosen design flow.	
Reference in Guidance Document:	2.4. Water Supply System Design Layout 3.1. Design Flowrate
Question to answer:	What is the design flow and TDH that the pump will be required to meet?
STEP 4 | Select a pump and motor.	
Reference in Guidance Document:	3.2. Pump and Motor Selection (or PV Pump Aggregate Selection) 3.3. Power Required 3.4. Manufacturer Specifications
Question to answer:	What are the power requirements of the pump motor to achieve the desired pump performance?
STEP 5 | Design the PV system.	
Reference in Guidance Document:	4. PV System Design
Question to answer:	How will the solar array need to be configured to supply the power required by the pump motor?
As this Guidance Document shows, each system may have specific considerations that need to be accounted for in the system design details. However, these five steps constitute the major building blocks of each system, and no solar powered water system design is complete without them.	

DESIGN

Photo courtesy of UNICEF

B. DESIGN

2. Design Criteria

2.1. Water System Compliance

The design and construction of any water system (regardless of the system's source of power) must be performed in full compliance with all codes, standards, and regulations of those governing entities that have enforceable jurisdiction over the location at which the water system will be installed. As such, under no circumstance shall this guide be used to circumvent any such code, standard, or regulation. As this guide covers design and construction topics related to solar powered water systems, it must be noted that compliance with local governing entities will go beyond topics pertaining only to water and will, therefore, include electrical codes, standards, and regulations as well.

All international standards relating to photovoltaics apply to the design guidance of this document. IEC International Standard 62253 is the technical basis for this guide. As previously stated, this document seeks to show the reader how to fulfil the requirements of the IEC standards. In addition to IEC 62253, the following international standards from IEC also hold specific relevance:

- IEC 60364-7-712 Electrical installations of buildings – Part 7-712: Requirements for special installations of locations – Solar photovoltaic (PV) power supply systems
- IEC 60947-1 Low voltage switchgear and control gear – Part 1: General rules
- IEC 61215-1 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1: Test requirements
- IEC 61215-1-1 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1-1: Special requirements for testing of crystalline silicon photovoltaic (PV) modules IEC 61215-1-2 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1-2: Special requirements for testing of thin-film Cadmium Telluride (CdTe) based photovoltaic (PV) modules
- IEC 61215-1-3 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1-3: Special requirements for testing of thin-film amorphous silicon-based photovoltaic (PV) modules
- IEC 61215-1-4 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1-4: Special requirements for testing of thin-film Cu (In, GA) (S, Se)2 based photovoltaic (PV) modules
- IEC 61215-2 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures
- IEC 61730-1 Photovoltaic (PV) module safety qualification – Part 1: Requirements for construction
- IEC 61730-2 Photovoltaic (PV) module safety qualification – Part 2: Requirements for testing
- IEC 62109-1 Safety of power converters for use in photovoltaic power systems – Part 1: General requirements
- IEC 62109-2 Safety of power converters for use in photovoltaic power systems – Part 2: Particular requirements for inverters
- IEC 62124 Photovoltaic (PV) stand-alone systems design verification
- IEC 62548 Design requirements for photovoltaic (PV) arrays

All IEC standards are available for purchase at the International Electrotechnical Commission's website (https://www.iec.ch/).

All governing entity permitting processes must be followed according to their requirements, which may include water usage permits, land rights/acquisitions, and construction permits.

Also, it is strongly advised that the designer and installers of the solar powered water system engage local community leaders. Without participation in the planning and execution of a project of this nature by community leaders, the project faces many sources of potential failure. Sources of failure could include usage of land, usage of water, desired water delivery methods, planned daily operation of the water system, planned fulfilment of routine maintenance requirements, and all related financial arrangements.

Daily Project Water Demand

The objective is to determine a daily project water demand stated in volume per unit of time, which then informs the design demand (see 2.2.6 Design Demand). The design demand provides the basis for the rest of the solar powered water system design.

Photo courtesy of Water Mission

2.2. Daily Project Water Demand

(reference IEC 62253 – 6.2 Customer data, d. Water demand)

The fundamental basis for the design of any mechanised pumping system is the water demand of the eventual users of the water system. Determining how much water a community needs is a complicated process but an essential step in the design. The basic components of calculating water demand include:

- calculating the total population and the daily water consumption of the individuals,
- determining any other water usages that will be provided by the proposed water system, and
- assessing any existing system water losses.

A general equation to calculate the demand is as follows:

Daily Project Water Demand = Individual Daily Water Usage × Service Area Population+Other Daily Water Uses (institutions,livestock,commercial,industrial,recreational,etc.)+System Water Losses per Day

Though this equation appears an easy calculation, the determination of each component of the equation is complex. Many factors influence the water usage of a community. This section addresses each component used to determine the demand. ***The objective is to determine a daily project water demand stated in volume per unit of time, which then informs the design demand (see 2.2.6. Design Demand). The design demand provides the basis for the rest of the solar powered water system design.*** The example on pages 22 to 25 (and Appendix b) demonstrate the use of this equation.

Before moving on, it should also be noted that section 6.2.d) of IEC 62253 says that the water demand is the "required daily water supply under defined worst condition." It goes on to list irradiance, date, and water head (or TDH) as the items that influence the worst condition. The implication of a "worst condition" is discussed more throughout this guide as each of these topics are discussed. At present, it is important to note that the worst conditions for each project and the implications thereof must be determined by the project designers. Additionally, the project designers must have the consensus of all involved parties on the project before setting a design demand and finalising the project design.

2.2.1. Service Area Population

The first step in calculating the water demand of the proposed water system is to determine the daily water usage per person in the service area of the system. To do this, the total population that will be served by the water project must first be assessed. This calculation should include the populations of both community households and local institutions.

Population figures for a given community may be acquired from the local governing authority if population statistics are kept by that authority. However, it is best to verify the figures by some means. Since the population will affect the water demand calculation and, subsequently, the design of the solar powered water system, the population figure used in the design must have a high degree of accuracy. Additionally, appropriate population growth factors should be applied to the assessed population in order to consider potential future usage of the system (see **2.2.4.3. Anticipated Future Demand**).

It should also be recognised that there are rural communities where the population shifts through different seasons of the year. This may be due to the local institutions (e.g., boarding schools), the occupations of individuals (e.g., pastoralists, travelling workers), or other reasons. A yearly shift in the population will affect the daily project water demand and may contribute to the worst condition scenario for the project.

2.2.1 1. Population Types – Households

The number of households and the average number of people per household are typically determined during the assessment phase of the project. As previously stated, this information may also be available from the local governing authority or community leaders. Regardless, the number of households and the average number of people per household can be gained (or verified) by the project designer. The easiest verification method is first to count the number of households while walking or driving through the community and to ask community members how many members reside in each household. Additionally, the number of households can be corroborated using an aerial image of the community from Google Earth.

The approximate population based on households in the community can be estimated using the following equation:

$$\textit{Approximate Population} = \textit{Number of Households} \times \textit{Average Number of Persons per Household}$$

If the project goals require a more exact household population figure, then a formal house-to-house survey can be taken. This will entail more time and investment but will also have a higher degree of accuracy.

2.2.2. Other Daily Water Uses

Other water uses by the service area must be considered prior to the design of the water system. Other uses typically include:

- Usage by institutions such as schools, clinics, and religious centres
- Usage by livestock and crop irrigation
- Usage by commercial and industrial activities
- Any recreational usage

Further comments on institutions are given below. Then all uses listed are presented in **2.2.3. Area of Service Water Usage.**

Institutions

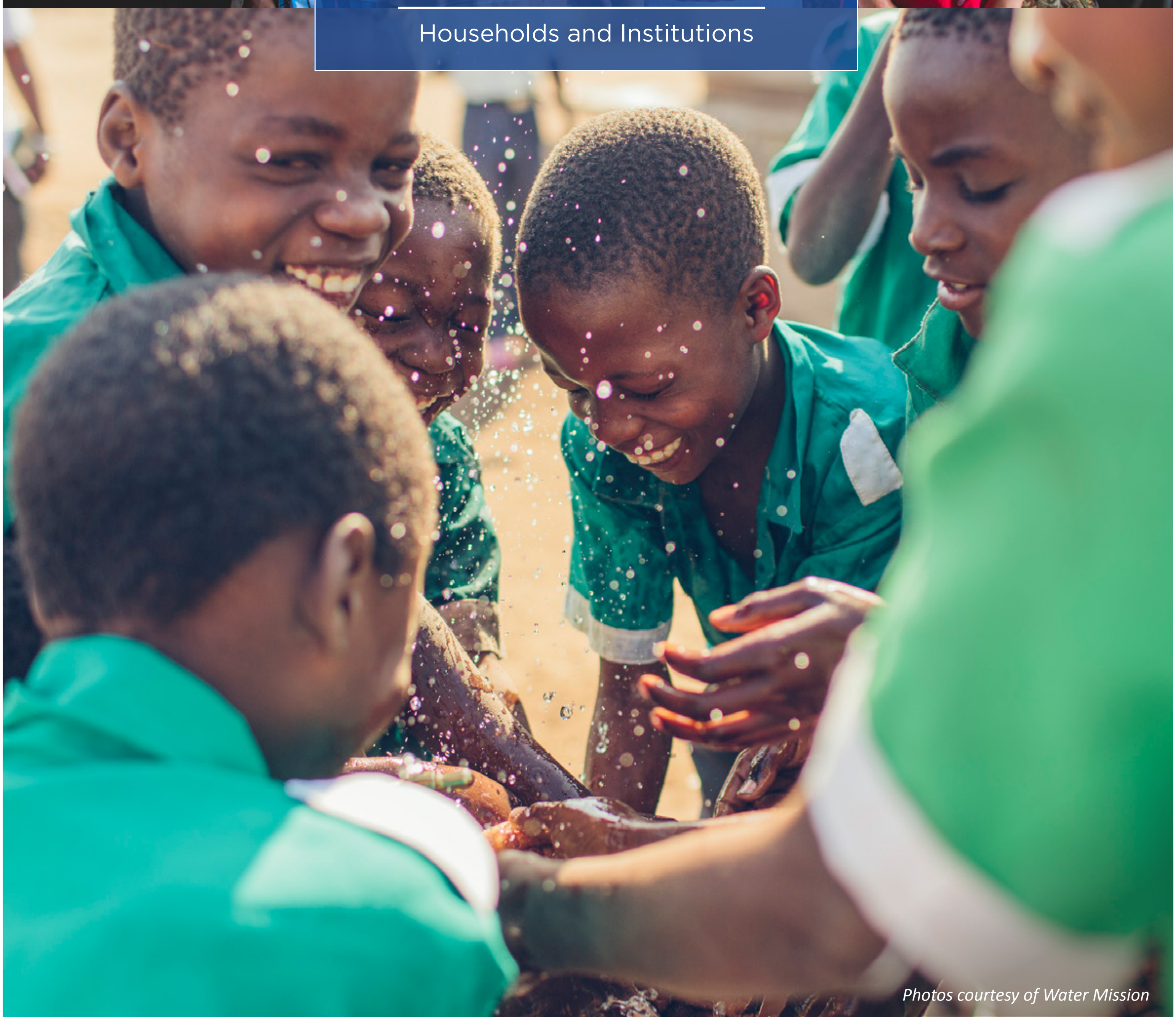
The presence of institutions in the community should be considered. Both the number of people who will be served and the water usage requirements of institutional facilities should be included. The way in which the project's total water demand will account for the additional water demand of these populations must be clearly defined in the project's design documentation. This may be accomplished in one of two ways. Before discussing the two methods, it should be recognised that the requirements of governing entities regarding the inclusion of institution populations must be followed.

The first method requires adding an estimate of the population serviced by local institutions to the population determined by the number of households to calculate the total population served by the project. However, judgment must be used when examining the effect that institutions will have on water demand. For example, suppose a community has a school that serves 500 children. If half of the students are residents of the community, they will already have been accounted for in the population determined by the number of households. The remaining 250 students that travel into the village specifically for school would add demand to the water system. Thus, these 250 students could be added to the household population (see **2.2.1.1. Population Types – Households**).

The second method involves determining (or estimating) the amount of water regularly used by the institution, regardless of the institution's population. For example, if a medical clinic has enough hospital beds to accommodate 25 patients at any one time, then the clinic will need access to water for 25 patients (regardless of whether the 25 beds are always in use by patients). In this scenario, the amount of water needed daily by the clinic can be calculated using a water usage per patient bed rate. In this method, the institutional population would not be added to the estimated household population. Instead, this would be a second usage demand to include in the total daily water demand calculation. This institutional daily water demand would be added to the household daily water demand.

Population Types:

Households and Institutions



Photos courtesy of Water Mission

2.2.3. Area of Service Water Usage

Once the total service area population has been determined, the next step is to estimate the individual water usage. As discussed above, any institutional water usage must also be counted. Additionally, it is important to consider any other uses not accounted for in the household or institutional calculations, such as livestock, irrigation, commercial and industrial activities, and recreational use.

In the international development field, there has been much discussion over how much water individuals and other users (institutions, irrigation, etc.) should be provided per day. Individual demand includes many considerations, such as consumption, hygiene, cooking, and other uses. Ideally, all of these uses would be met by the project (but doing so may not be practical). Below, various agencies' guidelines for determining how much water must be provided to individuals and other users are given. These guidelines can be helpful where there is uncertainty in the actual usage. However, it is important to note that the actual usage per person (as well as institutions and other uses) will not necessarily be consistent with these guidelines. Additionally, in the experience of the writers of this guide, solar powered water system designs based on meeting the full recommendation of agency or government guidelines, typically lead to systems designed for an unnecessary large capacity. A system designed this way may lead to financial constraints unless the parties involved in the project are prepared to meet those costs.

The amount of water used for all purposes can vary greatly, both by region and by individual practice. Thus, practical knowledge of a community's water usage patterns, which is typically gained only by interaction with community members, will greatly benefit the solar powered water system designer. If data exists or can be gathered, detailing the actual water usage of a community, this will typically be of even greater value to the designer.

It must also be recognised that water usage patterns can, and often do, vary throughout the year. Thus, using a daily average over the year may lead to an inadequate amount of water available during the season when water usage is highest. Therefore, it is also important to determine the seasons of the year during which the solar powered water system will be required to provide water, which may or may not be the entire year. This determination must be agreed upon by all involved parties in the project.

Even after uses of water are determined, it is quite possible that these figures will not be reflected in actual water usage of the solar powered water system. One of the reasons for this is that the service area population may continue to collect water from sources other than the solar powered water system. This may be because of familiarity with a water source, distance to the water collection point, or other potential reasons. Positioning a water collection point in close proximity to users will typically boost the usage of that water, whereas distance typically detracts (this means that the usage is typically influenced by the water distribution system in a community, but this guide does not cover distribution system design).

As discussed in **2.2.6. Design Demand**, the daily water demand on the solar powered water system alone will be critical to the design of the system. In other words, the water collected from other sources should not be counted in the design demand upon which the system design will be based.

Before presentation of the guidelines from various agencies, it should also be noted that all governmental authority codes, standards, or regulations regarding water usage rates must be followed in all water projects implemented within the governing authority's area of enforceable jurisdiction. If the governing authority does not have enforceable jurisdiction over the project area, or if the authority does not have stated requirements, then the guidance herein can be used.

World Health Organization

The World Health Organization (WHO) defines hydration requirements as the minimum daily fluid intake needed to sustain human life based on physical, environmental, and lifestyle factors. Using this definition, WHO recommends providing approximately three litres of safe drinking water per person per day.

WHO Hydration Requirements (WHO, 2003):

PERSON	NORMAL CONDITIONS (LITRES/DAY)	MANUAL LABOUR OR HIGH TEMPS (LITRES/DAY)
Adult Male	2.9	4.5
Adult Female	2.2	4.5
Child (10 years)	1.0	4.5

Other uses of water that affect demand include cooking, hygiene, and sanitation. The amount of safe water needed for cooking may differ based on the types of food that are common to different cultures. According to WHO, the average amount of water needed for cooking rice is between 1.6 and 2 litres per person per day. This estimate is used as a very basic guideline for cooking water needs, but in many places, the actual requirements vary greatly. Based on a study conducted in Kenya, Uganda, and Tanzania, WHO determined a baseline demand for hygiene and sanitation needs, such as hand and dishwashing, as well as bathing. For hand and dishwashing in these places, WHO determined the demand to be 6.6 L with an additional 7.3 L for bathing.

In a disaster situation, these standards are adapted to provide enough safe water to meet every person's most basic needs. In this case, WHO suggests a minimum of 7.5 L per person per day (2003), which is consistent with the Sphere Project standard (see The Sphere Project below).

Additionally, WHO recommends minimum quantity of water for different health care applications.

WHO Minimum Water Quantities Required in the Health-Care Setting (WHO, 2008):

INDICATOR	
Outpatients	5 litres/consultation
Inpatients	40-60 litres/patient/day
Operating theatre or maternity unit	100 litres/intervention
Dry or supplementary feeding centre	0.5-5 litres/consultation (depending on waiting time)
Wet supplementary feeding centre	15 litres/consultation
Inpatient therapeutic feeding centre	30 litres/patient/day
Cholera treatment centre	60 litres/patient/day
Severe acute respiratory diseases isolation centre	100 litres/patient/day
Viral haemorrhagic fever isolation centre	300-400 litres/patient/day

The Sphere Project

As an average minimum standard for humanitarian response, the Sphere Project has determined that the amount of water needed for drinking, cooking, and basic hygiene is between 7.5 to 15 litres per person per day (2018). The 2018 edition of the Sphere Handbook lists different water needs, the approximate amount of water required for each need, and water usage in various institutions. Please note that these quantities vary greatly according to regional, social, and cultural norms.

Basic Water Needs from the Sphere Project (from Sphere, 2018):

NEED	WATER REQUIRED	FACTORS
Survival needs: water intake (drinking and food)	2.5-3 litres per person per day	Depends on the climate and the individual physiology
Basic hygiene practices	2-6 litres per person per day	Depends on social and cultural norms
Basic cooking needs	3-6 litres per person per day	Depends on food type and social and cultural norms
Total Basic Water Needs:	**7.5-15 litres per person per day**	

In addition to personal use (as discussed previously), institutions surrounding a water system will affect the overall water demand on that system. The Sphere Project also provides guidance on typical water demands from different institution types.

Water Requirements for Institutions from the Sphere Project (Sphere, 2018):

INSTITUTION	WATER REQUIREMENTS
Health centres and hospitals	5 litres per outpatient per day; 40–60 litres per inpatient per day; additional quantities may be needed for laundry equipment, flushing toilets, etc.
Cholera centres	60 litres per patient per day; 15 litres per caretaker per day
Therapeutic feed centres	30 litres per inpatient per day; 15 litres per caretaker per day
Reception and transit centres	15 litres per person per day for persons staying more than one day; 3 litres per person per day for persons staying less than one day
Schools	3 litres per pupil per day for drinking and handwashing (use for toilets not included; see public toilets below)
Mosques	2–5 litres per person per day for drinking and handwashing
Public toilets	1–2 litres per user per day for handwashing; 2–8 litres per cubicle per day for toilet cleaning
Flushing toilets	20–40 litres per user per day for conventional flushing toilets connected to sewer; 3–5 litres per user per day for pour-flush toilets
Anal washing	1–2 litres per person per day
Livestock	20–30 litres per large/medium animal per day; 5 litres per small animal per day

UNHCR (United Nations High Commissioner for Refugees)

UNHCR uses a set of water, sanitation, and hygiene (WASH) Standards and Indicators by which to monitor a programme's effectiveness in meeting basic needs and targets. Included in these are standards for water quantity for individuals and communal buildings. It should be noted that the UNHCR WASH Standards and Indicators address water quantity, water access, water quality, sanitation, hygiene, and solid waste. However, this guidance document will refer only to the standards and indicators regarding water quantity.

UNHCR WASH Standards and Indicators – April 2018 (from UNHCR, 2018):

INDICATOR	EMERGENCY[1] STANDARD	POST EMERGENCY STANDARD
Average litres of potable[2] water available per person per day (L/p/d)	≥ 15	≥ 20
Per cent of households with potable water storage capacity of at least 10 litres/person	≥ 70%	≥ 80%

[1] An emergency is defined as the first six months after the population movement has stabilised. However, this definition is context-specific and should only serve as general guidance.

[2] Potable water: safe for drinking

UNHCR WASH Standards for Communal Buildings (from UNHCR, 2018):

INDICATOR	
Schools	Average 3 litres of potable water available per pupil per day
Health Clinics / Nutrition Feeding Centre	Average 10 litres of potable water available per outpatient per day Average 50 litres of potable water available per inpatient/bed per day

UNHCR also states that "where appropriate the standards should be adapted based on context or existing national standards.

Other Local Design Standards and Codes

If a water system location is under the jurisdiction of a local ruling body that has an enforceable code, standard, or regulation regarding the amount of water that shall be provided to each person per day (and to local institutions or other uses), then that requirement must be followed.

2.2.4. Predicting Demand from Individuals

Once the water usages for the area of service are reasonably determined, the daily project water demand for the solar powered water system can be calculated. To start Water Mission recommends calculating the individual daily water usage three different ways:

Photo courtesy of UNICEF

1. Maximum demand at system commissioning
2. Anticipated demand at system commissioning
3. Anticipated future demand

These three calculated demands will then be used to select the daily water usage from individuals. Following the equation in **2.2. Daily Project Water Demand**, the selected daily water usage from individuals will then be added to the other daily water uses and to the daily system water losses to determine a daily project water demand.

2.2.4.1. Maximum Demand at System Commissioning

The maximum demand at system commissioning is calculated by assuming that 100% of the members of the service population will each use the full individual usage amount previously determined. In order to calculate the maximum demand at system commissioning, the equation below can be applied:

MAXIMUM DEMAND

Maximum Demand at System Commissioning
= Total Service Population × Full Individual Usage Amount

2.2.4.2. Anticipated Demand at System Commissioning

However, it is recognised that 100% of the people in a community may not use the solar powered water system upon commissioning. Thus, it can be necessary to predict the percentage of the population that will use the safe water or the "anticipated population penetration." Additionally, those that do collect water from the system may not use the full individual usage amount determined. Thus, it may be decided that, in the time period just after commissioning the system, the individual usage might be less than the full amount. In order to calculate the anticipated demand at system commissioning, the equation below can be applied:

ANTICIPATED DEMAND

Anticipated Demand at System Commissioning
= Total Service Population × Anticipated % of Population to Use System × *Anticipated Individual Usage at Commissioning*

2.2.4.3. Anticipated Future Demand

In order to keep the water system sustainable and serving the community as long as possible, it is useful to estimate an anticipated future demand. This will indicate whether the system has the capacity to meet the demand of an estimated future population. Yet it is important to note that future demand can be hard to predict because of population growth, migration, trade, urbanization, and humanitarian disaster events.

This guide does not give approximate growth rates for population. Instead, these rates should be determined using governmental data (or requirements) for specified locations. Once determined, the growth rate (r) can be used in the following equation (Mihelcic, 2009). To calculate the future population (PN) in N years:

Photo courtesy of Water Mission

$$P_N = P_0 \times (1 + \frac{r}{100})^N$$

It is important to note that this calculation is solely a projection. In addition, it is typical (but not required) for solar powered water systems to use a value of 20 years for N.

Once the predicted future population is determined, it can be multiplied by the anticipated population use percentage (if less than 100% of the people will be using the system in the future) and individual usage amount to determine the anticipated future demand. This is shown in the following equation:

ANTICIPATED FUTURE DEMAND

Anticipated Future Demand = Total Service Population × Anticipated % of Population to Use System × *Anticipated Individual Usage Amount*

2.2.5. System Water Losses

There is one last consideration of daily project water demand that needs to be considered before deciding on a design demand. Water losses are common to water systems for a variety of reasons. Common reasons are water spilled or wasted at distribution points, overflow within storage tanks, and leaks in supply and distribution piping. Even in the developed world, it is a common practice to account for a certain amount of water loss, especially when utilising aged infrastructure. A certain amount of reoccurring waste should be accounted for in the design flow of the system. To account for this loss, either a known amount of daily loss can be added to the daily water demand, or a percentage of the daily water demand can be added to the demand calculation. As a benchmark, a daily loss of five (5) to ten (10) per cent is considered acceptable. If the water loss is higher due to aged or improperly installed infrastructure, consideration should be given to the repair or replacement of the leaking components in the system.

2.2.6. Design Demand

All three calculated individual daily water usage demands will impact the daily project water demand and, subsequently, the design demand. In keeping with the equation in **2.2 Daily Project Water Demand**, the other daily water uses and the system water losses per day will need to be added to the individual daily water usage demands to select a final design demand.

It is recommended that the system be initially designed to meet the anticipated individual demand at system commissioning. Once that design is complete, it can be compared to the maximum individual demand at system commissioning and the anticipated future individual demand. If the designed system can meet all three calculated demands, this increases the confidence level of the design.

If the design cannot meet the maximum individual demand at system commissioning and the anticipated future individual demand, this does not necessarily mean that the design should be revised. Instead, the design engineer can determine what changes would need to be made in order to meet these two demands. If these alterations would take a minimal amount of additional equipment and capital expenditure, then doing so may be appropriate. However, if meeting the other two demands would drastically increase the capital expenditure, then it may not be practical or economically prudent. The recommendation of this guide is for this decision to be discussed and agreed upon at the onset of the project by all parties involved in the project.

Additionally, it must be recognised that the selected design demand may not necessarily equal the daily project water demand calculated according to **2.2. Daily Project Water Demand**. This may be for several reasons, including phasing of a water system for a service area, inadequate funding for complete capital expenses, exclusion of certain water uses from the proposed system, or other reasons.

The chosen design demand will form the basis of the design of the rest of the system. It is critical to the success of a completed solar powered water system that the design demand be clearly stated and agreed upon by all parties involved in the planning and future ownership of the system, including documentation of the agreement. Many existing solar powered water systems today are deemed to be under-performing due to the lack of a clear calculation, selection, and subsequent agreement on the design demand. It should be noted that this dissatisfaction with these systems is typically not due to improper performance of the equipment but to improper planning and designing.

The following example details the data collection and deliberation that goes into calculating the daily project water demand.

Example: Calculating Daily Project Water Demand

(reference IEC 62253 – 6.2 Customer data, d. Water demand)

A community in rural Kenya currently collects drinking water from three sources: a borehole fitted with a handpump, a river, and seasonal streams that have no flow during the dry season. The population of the community has grown, and there are always long queues at the handpump. In addition, the river is not easily accessible by everyone as it is on the far west side of the community. A funding source has become available to design and install a solar powered water system to better serve the community's safe drinking water needs.

The community is made up of 350 households, and the average number of people per household is six. Additionally, there is a school in the community with 700 students, and all 700 students reside in the community.

After discussing the water needs with the community leaders, it is determined that the daily water use per person has the following pattern.

WATER USE	PER PERSON PER DAY
Drinking and Cooking	4 to 6 litres
Basic Hygiene	2 to 4 litres
Productivity (livestock, irrigation, laundry, other uses)	0 to 6 litres
TOTAL DAILY WATER USE:	6 to 16 litres

Step 1: Determine the total population intended to be served by the system.

Before we use the equation provided in **2.2.1.1. Population Types – Households,** we need to ask the question if all 350 households are intended to be served by the system. Will these households truly have access to the water provided? For this example, it is determined that all 350 households are intended to use the water from this project. Therefore, applying the equation:

Approximate Population = *Number of Households* × *Average Number of Persons per Household*
2,100 *people* = 350 *households* x *6 people per household*

Step 2: Add any other people that will use the water.

This community has a school of 700 students. If all or some of these students were not accounted for by the previous calculation, then these students could be added to the population figure, or the total amount of water usage for this institution could be added later to the demand. However, for this example, we will assume that all 700 students reside in the community. Therefore, they are already accounted for in the previous equation.

Step 3: Determine how much water each person will collect from the system each day.

The table above gave a range of 6 to 16 litres per person per day based on different uses and different amounts for each use. However, it is important that the solar powered water system is designed to supply only the amount of water intended to be collected from the system. In this community, people will collect all their water used for drinking and cooking from the system. They will only collect some of the water they use for hygiene from the system, and they will not collect any of their productivity water from the system. Using this information, it is determined that the average person in the community will collect six to eight litres from the system per day. (For additional information, see **2.2.3. Area of Service Water Usage**)

Step 4: Calculate the individual water demand.

In **2.2.4. Predicting Demand**, the calculation for three different types of individual demands is presented. Using the above information for this community, we now calculate all three.

Calculating Maximum Demand at System Commissioning is done using information already provided.

Maximum Demand at System Commissioning =
Total Service Population × *Full Individual Usage Amount*

16,800 liters per day = *2,100 people* x *8 liters per person per day*

For the Anticipated Demand at System Commissioning calculation, a determination needs to be made as to the percentage of the population that will collect water from the system. It is rare that 100% of the population will collect water from the system. For this community, we determined that 85% of the population will use the system upon commissioning. In addition, for this calculation, if there is a reason to believe that people will collect less than the full individual amount of water per day, then a lesser figure should be used. As discussed above for this community, it is believed that people will collect between six and eight litres per day. We will average this to seven litres per day for the calculation.

Anticipated Demand at System Commissioning =
Total Service Population × Anticipated % of Population to Use
System × Anticipated Individual Usage at Commissioning

12,495 liters per day = 2,100 people x 85% x 7 liters per person per day

To calculate Anticipated Future Demand, a future population needs to be determined. Using government data for this region of Kenya, it is determined that the region grows at a rate of 2% annually, and we would like to make the analysis for 20 years from now. Using the equation provided in 2.2.4.3 Anticipated Future Demand for calculating future populations:

$$2{,}100 \; people \; x \left(1 + \frac{2(\%)}{100}\right)^{20} = 3{,}120 \; people$$

Then similarly, to the Anticipated Demand at System Commissioning calculation, a determination to the percentage of the population that will collect water from the system is needed, as well as an anticipated individual usage. These two figures can be different from the ones used in the Anticipated Demand at System Commissioning calculation if there is reason to believe they will be different. For this example, we will still use 85% and seven litres per person per day.

Anticipated Future Demand =
Future Population × Anticipated % of Population to
Use System × Anticipated Individual Usage Amount

18,564 liters per day = 3,120 people x 85% x 7 liters per person per day

Section **2.2.6. Design Demand** recommends for the system to be designed using the Anticipated Individual Demand at System Commissioning (unless all involved parties agree that another demand is more applicable to a project's objectives). In this example, that demand is 12,495 litres per day.

Step 5: Consider other daily water uses and system water losses per day.

In Step 2, we determined that the school population was already accounted for in the population calculation of Step 1. Section **2.2.5. System Water Losses** states that a daily loss of five to ten per cent is considered acceptable. Since this system will use all new components and be installed by qualified contractors, we will use 5%.

12,495 *liters per day* + 5% *due to water loss daily* = 13,120 *liters per day*

Section **2.2. Daily Project Water Demand** states that the basic components of calculating water demand include:

- calculating the total population and the daily water consumption of the individuals,

- determining any other water usages that will be provided by the proposed water system, and
- assessing any existing system water losses.

Section **2.2. Daily Project Water Demand** also gives the following general equation:

Daily Project Water Demand = Individual Daily Water Usage × Service Area Population
+ Other Daily Water Uses (institutions, livestock, commercial, industrial, recreational, etc.)
+ System Water Losses per Day

In the example above, we went through each of these components to determine that the Daily Project Water Demand will equal 13,120 litres per day.

2.3. Water Source

(reference IEC 62253 – 6.2 Customer data, c. Specific local conditions)

Designing any water system is largely defined by the water source that the system will utilize. Both the source type and the amount of water available from the source (or source yield) will impact the system's design. Historically, groundwater has been the most typical water source for solar powered water systems. However, in many cases, surface water sources have also been utilized, as solar pump manufacturers have full lines of equipment to fit different surface water sources as well.

When choosing a water source, it is critical to the quality of the water that any sewage disposal be a minimum distance of 30 meters from the source (from Sphere, 2018). Sewage disposal closer than 30 meters from the water source not only places the users of the water in harm's way but also impacts the design and performance of the final water system. Additionally, the chosen water source should not be downgradient from any potential source of contamination.

2.3.1. Source Yield

Knowing the available yield, or flowrate, from a water source is crucial for designing any water system. Unfortunately, it is not uncommon for an estimate of the yield not based on testing to be used to design and select equipment. This typically leads to significant challenges with the actual performance of the equipment and the water source. Project equipment needs to be sized to the specific source yield. Additionally, the source yield needs to meet, and preferably exceed, the project's calculated water demand to ensure that enough water is provided for the community. An accurate source yield will not only inform the pump and motor selection but the design of the solar array as well.

The best method for determining the source yield of a borehole will be discussed first, followed by comments regarding the yield of a surface water source. Finally, other considerations concerning the water source yield when planning and designing a solar powered water system will be addressed.

2.3.1.1. Water Source Yield of a Borehole

It is impossible to know the yield of a borehole simply by looking at it or by monitoring the drilling process. Two boreholes of the same depth and diameter may produce different amounts of water based on geological formations, surrounding aquifers, and other water abstractions. Boreholes can provide only a limited flow rate over an extended period. Thus, it is essential to perform a yield test on any borehole that may be used as a source. The purpose of a yield test is to determine the flow rate that can be sustainably pumped from the borehole. Additionally, any potential change in the yield test results due to seasonal fluctuations of the area ground water conditions and other water abstractions must also be taken into account.

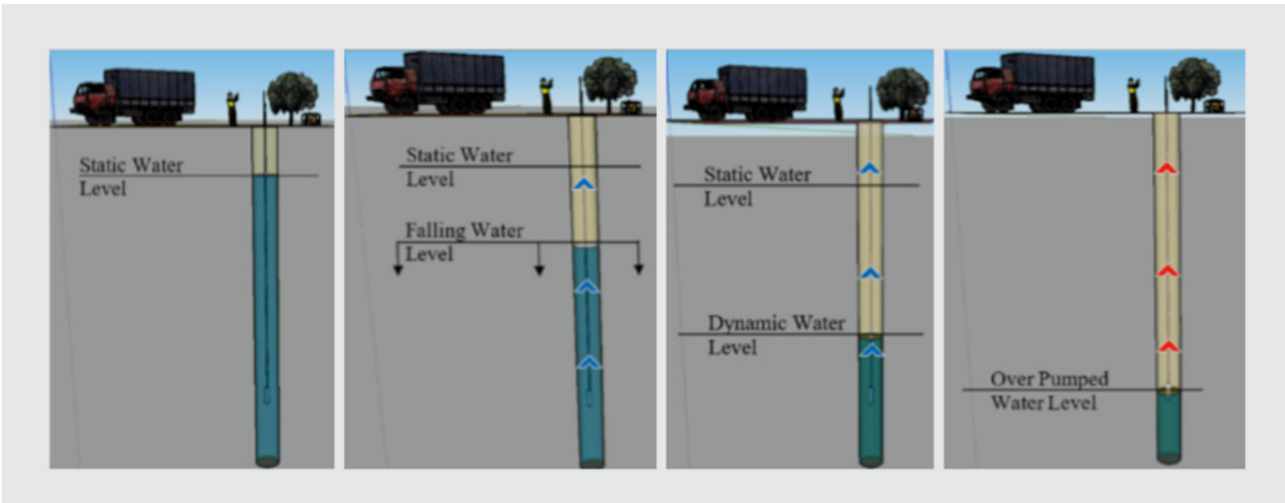
Water Source Yield of a Borehole

Two boreholes of the same depth and diameter may produce different amounts of water based on geological formations and surrounding aquifers. Boreholes can provide only a limited flowrate over an extended period.

Photo courtesy of Water Mission

2.3.1.1.1. Understanding Drawdown

When performing a yield test, the technician should record these primary parameters: time, flowrate, water level, and drawdown. While time, flowrate, and water level are commonly measured, drawdown can be more difficult to comprehend. Drawdown is the difference between the static water level (when no water is being pumped) and the dynamic water level when water is being pumped from the borehole. While the technician cannot see inside the borehole, it is important to visualize what is happening during the yield test to measure the drawdown properly. The following figure illustrates what happens to the water level as water is pumped out of the borehole



.**Figure 2.3.1.1.1. – Water Level During Pumping**

Stage 1: Static Water Level (no pumping)

Before the pump is turned on, the level of the water in the borehole is at its static water level.

Stage 2: Falling Water Level (pumping rate exceeds rate of water entering borehole)

As the pump starts pumping water, the water level in the borehole begins to drop. Water from surrounding aquifers will begin to flow into the borehole, slowly at first, but increasing in speed as water continues to be withdrawn. Initially, if more water is being pumped out than is flowing back in, the water level in the borehole will continue to fall.

Stage 3: Dynamic Water Level (pumping rate equals rate of water entering borehole)

As the water level continues to fall inside the borehole, the rate at which water enters the borehole from the surrounding aquifer will begin to increase. At first, the drawdown and the flow are directly proportional to each other. As one increases, so does the other. As the rate of water flowing into the borehole becomes equal to the rate of water being pumped out, the water level in the borehole will reach equilibrium. When this happens, the level of the water is called the dynamic water level. The dynamic water level in a borehole will change depending on the pumping rate. For example, if the pumping rate were very low compared to the yield of the borehole, the dynamic water level may be close to the static water level. If the pumping rate were increased, the borehole might reach a new equilibrium with a lower dynamic water level. The dynamic water level that corresponds to the maximum yield of the borehole is called has the maximum dynamic water level.

Stage 4: Over Pumped Water Level (rate of water entering borehole cannot meet pumping rate)

If the pumping rate is allowed to increase beyond the maximum yield of the borehole, the water level will continue to drop. This will lead to an over-pumped condition, which could lead to negative effects on the surrounding aquifer and biofouling of the borehole. Additionally, this condition could lead the water system and pump to fail, causing a lack of water supply to the water system users. A properly designed water system and a well-selected pump will never allow the pumping rate to exceed the maximum yield of the borehole.

2.3.1.1.2. Maximum Yield Test for Boreholes

The maximum yield test specification expands on a traditional step-drawdown yield test to determine the borehole's hydraulic characteristics and establish the maximum yield of the source. The test description and procedure follow, and a full example of this test is contained in **Appendix c. Performing a Maximum Yield Test.** Additional standards for yield testing procedures can be found in ISO 14686:2003

2.3.1.1.2.1. Description

During this test, water will be pumped from the source, and the flowrate will be adjusted in steps (or intervals that increase flowrate and corresponding drawdown) until the maximum dynamic water level is reached. The position of the pump in the borehole (i.e., the elevation of the pump) during this test is crucial for determining the true maximum yield of the borehole. The pump should be set as low as possible for the construction of the borehole, which is typically around half a meter above the bottom of the borehole. If the pump is set too high during the test, then the water level will drop to the determined minimum level before the maximum yield can be found. The determined minimum level is a few meters above the elevation of the pump (or a few meters above the pump's run-dry sensor, if so equipped), which will provide for adequate submergence of the pump.

For a maximum yield test, proper pump selection is also crucial, because the test pump capacity must be greater than or equal to the anticipated maximum yield of the borehole (with the anticipated maximum yield based on hydrogeologic projections, drilling information, the yield of other boreholes in the area, or other pertinent data). Other components, including the rising main, fittings, gate valve used at ground surface for throttling flow, flow meter, etc., must be sized appropriately for the intended objective and provide for the maximum yield.

At the beginning of the test, the throttling valve at the borehole discharge is almost fully closed and then opened in intervals of 60-minutes (or longer time interval, if desired or needed for water level stabilization). With each interval, the throttling valve is opened to increase discharge to the target flowrate while the water level in the borehole and the discharge flowrate are monitored. The goal is to record the dynamic water level and discharge flowrate at each interval to find the flowrate that corresponds to the maximum dynamic water level.

2.3.1.1.2.2. Test Procedure

A. Design the test:

a. Estimate the minimum and maximum flowrates of the borehole. The maximum flowrate can be approximated from estimates of yield developed during drilling/construction, records of yield tests and/or pumping rates from the source in the past, yield from similar sources in the area, etc. The minimum flowrate should be small compared to the estimated maximum flowrate, but still enough to provide for adequate water flow through the pump to prevent overheating, loss of lubrication, etc.

b. Divide the difference between the minimum and maximum flowrates into four to six equal amounts. The target flowrate will be increased by this amount during each interval.

c. Using the interval amount, define the target flowrates for the test defined as follows:

i. **Target flowrate 1** = Minimum flowrate

ii. **Target flowrate 2** = Target flowrate 1 + interval amount calculated in A.b

iii. **Target flowrate 3** = Target flowrate 2 + interval amount calculated in A.b

iv. **Target flowrate 4** = Target flowrate 3 + interval amount calculated in A.b

v. **Target flowrate 5** = Target flowrate 4 + interval amount calculated in A.b

vi. **Continue increasing the target flowrate as many times as necessary until the maximum yield is determined.**

B. Remove the existing pump, rising main, etc., if necessary.

C. Clean and disinfect all components to be placed in the source to keep it from becoming contaminated by test equipment.

D. Measure and record the diameter and total depth (depth to the solid bottom) of the borehole.

E. Install the test pump at the desired depth/ location and assemble piping, wiring, meter, gate valve, and any required hoses and/or pipe.

F. Measure and record the static water level.

G. Adjust the gate valve to almost fully closed.

H. Start the generator and turn on the pump. All water abstracted must be discharged away from the borehole so as to not be allowed to flow back into the borehole. A location to properly discharge all abstracted water shall be agreed upon with the owner of the project and the other parties involved in the project.

I. Target flowrate 1

a. Adjust (open) the gate valve to achieve target flowrate 1.

b. Record the discharge flowrate and water level in 1-minute intervals for the first 15 minutes, and then at 5-minute intervals for the remainder of the 60-minute step (or longer time interval, if desired or needed for water level stabilization).

c. If the flowrate changes by more than 10% at any point during the 60-minutes, adjust the gate valve to try to maintain the target flowrate within 10%, being very careful not to over-adjust.

J. Target flowrate 2

a. At the 60-minute mark, adjust (open) the gate valve to achieve target flowrate 2.

b. Record the discharge flowrate and water level in 1-minute intervals for the first 15 minutes, and then at 5-minute intervals for the remainder of the 60-minute step.

c. If the flowrate changes by more than 10% at any point during the 60-minutes, adjust the gate valve to try to maintain the target flowrate within 10%, being very careful to not over-adjust.

K. Repeat Step J for target flowrates 3, 4, and 5.

a. If the water level drops to the determined minimum level at any point during these intervals, reduce the flowrate so that the water level does not go below the minimum. The goal is for the discharge flowrate and dynamic water level to stabilise at or as close to the determined minimum level as possible. Slowly adjust the flowrate until this goal is reached. Then proceed to Step M.

L. **If the determined minimum level has not been reached, continue to increase the target flowrate by the interval amount every hour. Record the discharge flowrate and water level as described in Step J.** If the water level drops to the determined minimum level at any point during these intervals, reduce the flowrate so that the water level does not go below the minimum. The goal is for the discharge flowrate and dynamic water level to stabilise at or as close to the determined minimum level as possible. Slowly adjust the flowrate until this goal is reached. Then proceed to Step M, or N per the option described below.

M. **As an option, it is also permissible to skip Step M and proceed to Step N, if M will be performed on a different day. If Step M is performed on a different day, Steps N through P need to be completed after Step L (i.e., on the first day of testing) and after Step M (i.e., on the second day of testing). To complete this step, maintain the maximum dynamic water level and discharge flowrate determined in Step K or L for the reminder of the 24-hour test. 24-hours is the minimum length of time. If desired, or necessary due to other reasons, the test can exceed 24-hours.**

   a. Continue to make small adjustments to the gate valve as necessary to maintain the discharge flowrate within 10% of the flowrate determined in Step K or L.

   b. Record the discharge flowrate and dynamic water level in 1-hour increments until a 24-hour period has passed since the beginning of Step H (or the beginning of Step M if being performed on a different day).

   c. If the discharge flowrate and dynamic water level continue to remain steady and to remain at or above the determined minimum level, then this discharge flowrate is the maximum yield.

N. **At the conclusion of the test pumping period, turn off the pump (and generator as applicable).**

O. **The water level in the borehole will being to recover as soon the pump is turned off.** This recovery period is just as important as the pumping period, as this period also indicates the transmissivity of the aquifer surrounding the borehole. The water level must be recorded every minute for the first fifteen minutes after the pump being turned off. Then the water level must be recorded every five minutes until 60 minutes has passed since the pump was turned off. After this the water level must be recorded every ten minutes until the water level recovers to the static water level, or to within 10% of the static water level. If the water level fails to recover to within 10% of the conditions prior to the test, then the yield test results cannot be considered conclusive and further testing (or repeat testing) is necessary.

P. **At the conclusion of the test, remove all test equipment and clean and restore the site to its original condition, remembering to clean and disinfect any pump, piping, wiring, etc.**2.3.1.1.3. Borehole Yield Testing Options

Water Source Yield of a Surface Source

Many surface water sources may not need to be tested for available yield, due to the large amount of available water. This would apply to large lakes, rivers, and high capacity springs.

Photo courtesy of Water Mission

2.3.1.1.3. Borehole Yield Testing Options

The maximum yield test outlined above is the recommended option for determining the maximum yield of a borehole. However, there are two other options for determining borehole characteristics. The first, called a specific yield test, is to target a yield lower than the maximum yield of the borehole. The main reason to perform such a test would be if the design flow (see **3.1. Design Flow**) for the proposed water system will be significantly less than the maximum yield of the borehole. There may still be interest in knowing the maximum yield (e.g., comparison with boreholes in the surrounding area, gathering data on the aquifer, possible future use of borehole). Conducting a specific yield test is similar to the maximum yield test. The main change in the test procedure is to stop increasing the discharge flow rate when the desired specific flow rate is reached. The decision to perform this type of test needs to be made by the engineer of record for the project.

The second option is to perform the yield test for less than 24 hours. The main reason for this option would be if there is a serious concern or limitation to performing the test for the full duration as previously described. At a minimum, the yield test should last as long as the anticipated daily production of the water project. For example, a pump powered solely by solar may only produce water for around 7 to 8 hours per day. In this case, a 7 to 8-hour test may be enough, if a 24-hour test cannot be performed. However, it is important to note that just because a borehole produces a certain flow for an hour or two does not mean that it can sustain that flowrate for extended periods of time. Also, as stated in the Steps above, testing can be accomplished over two days with Step M being performed on a different day. Again, the decision of what type of yield test to perform needs to be made by or be acceptable to the engineer of record for the project.

2.3.1.2. Water Source Yield of a Surface Source

Many surface water sources may not need to be tested for available yield, due to the large amount of available water. This would apply to large lakes, rivers, and high capacity springs. However, in the case of small streams and low-capacity springs, a means of determining the available water yield is crucial. Regardless of the method used, it is critical to the success of the solar powered water system to know the yield of the source.

Another factor to consider when designing is whether the surface water source experiences a low yield season on a yearly basis or only during dry seasons. Additionally, if there are other water users downstream of the water source, maintaining the flow needed by the downstream users is also a necessary design consideration.

Photo courtesy of Water Mission

2.3.1.3. Safe Yield or Allowable Yield

One of the common concerns of using any type of mechanised or solar powered pump is over-pumping or over-abstraction. This is one of the reasons that a properly conducted yield test on the water source is critical to the design of a solar powered water project. A permanently installed oversized pump will damage the natural hydrology and the pump itself over time. An undersized pump may lead to frustration on the part of users who expected a higher water production rate. The reason for a properly performed yield test is to choose a pump that balances the available yield of the source with the needs of the water users.

It is also important to recognize that the source yield may change seasonally (e.g., a lower yield in the dry season and a higher yield in the rainy season). If this is the case, it is advisable to test the source at the time of year when the yield will be the lowest. If the project at hand cannot wait for a yield test to be performed during the season with the lowest yield, then research should be done to make the best possible estimate of the low yield condition to keep the project moving forward. This methodology must have the full agreement of all parties involved in the project before advancing.

Also, it is not uncommon for governing entities to require newly constructed solar powered water systems to use only a percentage of the yield test amount. This is deemed an allowable or safe yield and is commonly held at 80% to 90% of the yield test results (though some entities require this to be held as low as 60%). Additionally, as previously discussed, if there are other users of the same water source, the percentage of the yield that may be used by the solar powered water system needs to be determined and agreed upon by all involved parties before the water system design can continue forward.

2.3.2. Source Conditions

Additional conditions of the water source will have various potential effects on the design of the solar powered water system.

2.3.2.1. Borehole Conditions

If the system utilizes groundwater via a borehole, then the casing size (diameter) of the borehole will have a direct effect on the size of the pump and motor that can be selected. Additionally, the casing type, screening location, and total depth of the borehole will be necessary information to the system design.

2.3.2.2. Water Source Elevation

Upon completion of the yield test on the water source, the static water level and dynamic water level on the source will be known (see **2.3.1.1. Water Source Yield of a Borehole**). The difference in elevation of these levels to the water storage tank (and to any water treatment system used) will have a direct effect on the design of the water system components (see **3.2. Pump and Motor Selection (or PV Pump Aggregate Selection)**).

It is also important to recognize that similar to seasonal change of the source yield (see **2.3.1.3. Safe Yield or Allowable Yield**), the static and dynamic levels may also change seasonally. If this is the case, it is advisable to test the source at the time of year when the levels will be at their lowest. If the project at hand cannot wait for a test to be performed when the levels will be at their lowest, then research should be done to make the best possible estimate of the lowest levels to keep the project moving forward. This methodology must have the full agreement of all parties involved in the project before advancing.

2.3.2.3. Water Quality

Water treatment is not specifically addressed in this design guide. However, the water quality of the water source may nonetheless influence the solar powered water system design. The first potential effect is when the water quality of the source is harmful to humans upon consumption. It is possible that the water is of such poor quality that the source is rejected from being used for any project for human consumption. However, if a treatment system is available that will effectively remediate the water quality issues, then this treatment will need to be included in the overall water system design. If the decided means of water treatment will be an in-line treatment system on the supply line, then this will require a certain amount of power from the pump and motor, which must be accounted for in the design of the photovoltaic array supplying power to the motor and pump.

Water Quality

The water quality of the source is likely to influence the design of a solar powered water system.

Photo courtesy of Water Mission

The other water quality consideration is when the source has a characteristic that would be corrosive to the pump, motor, and/or other components of the water conveyance system. A significant amount of suspended solids in the source water, indicated by a high turbidity measurement, will cause over-wearing in some pumps and may even render certain pumps unusable. A project drawing from source water with high turbidity should either employ some type of pre-sedimentation process prior to the pump or utilize a pump designed to handle water flow with high turbidity.

Additionally, high chloride content, high conductivity, high TDS, and acidic pH levels of the source water can cause corrosion of certain metals, leading to damaged pumps and piping. Very hard water may cause carbonate deposits (scaling) to build up and reduce a pipe's capacity. If these conditions are present in a water source, they must be addressed during the design. The use of certain materials or pre-treatment of the water can mitigate the conditions, or an alternate water source can be secured to avoid these conditions altogether.

If the system's water is ultimately meant for human consumption, then a full range of water quality testing must be performed on the water source. A high-quality solar powered water supply system will still fail to meet the needs of the end-users if the water quality renders the water unusable. In this case, the use of a water treatment method designed to make the water safe for human consumption is essential. Indeed, a key advantage of solar powered pumping (or any mechanised pumping) over hand pumping is the ability to include in-line treatment in the water supply system.

IEC 62253 (6.2 Customer data) states that water quality "shall be according to international or national regulations."

2.3.2.4. Geographic Conditions

The distance from the water source to the water storage tank (and to any water treatment system used) will have a direct effect on the system components (see **2.4. Water Supply System Design Layout**). Additionally, there may be security concerns, potential hazards, and construction obstacles (such as existing rock and tree root obstructions to pipe routes) that need to be planned for during the layout and design of the water system. These considerations would pose challenges to the design of any water project, but solar powered water projects, in particular, may face additional obstacles because of the power required to make appropriate accommodations.

2.4. Water Supply System Design Layout

(reference IEC 62253 – 6.2 Customer data, a. Geographical, c. Specific local conditions)

A design layout refers to the location and arrangement of all components of the water system. The design layout of the water supply system will include all information for the water conveyance system, including pipe routing, pipe material, pipe size(s), and pipe wall thickness (outer diameter and inner diameter). The design layout of a water supply system will directly affect the selection of the pump and motor and the design of the photovoltaic array and power supply system. In addition, further planning and designing are needed to accommodate all changes in elevation between each system component. This would include elevation differences between the dynamic water level of the water source, the elevation of the water storage tank, and the elevation of any water treatment included in the system. If a certain amount of water pressure is also required at the point of discharge, as in the case of irrigation sprinklers, this will also need to be taken into account. In addition, all piping should be routed to avoid areas prone to erosion from rainwater runoff.

All these items will contribute to the TDH of the water system, which corresponds to the amount of energy required of the pump in order for water to flow at the design flow rate. With the assumptions that pressure energy can be neglected and kinetic energy is non-existent in the system (typical of rural water supply projects), then the TDH is a summation of potential energy (elevation difference between beginning and final water level), friction head loss (due to friction with the pipe), and minor head losses (of the piped system components). This design guide does not present the methods of calculating TDH, because the methods of calculating TDH for a solar powered pumping system do not change from the methods used with any other mechanised pumping system.

At the beginning of the design, the layout may be preliminary and only able to be confirmed at the end of the design. Thus, it is common for the design layout to be an iterative process. The location of the major components and the pipe information advise the selection of the pump and motor and the design of the solar array. Subsequently the pump, motor, and solar array provide confirmation of, or revision to, the location of the major components and the pipe information.

Regarding the location for major components of the water system, this guide cautions against the use of small, hand-held geographical positioning system (GPS) devices for elevation data. GPS devices are typically only accurate with regard to longitude and latitude and do not have the same level of accuracy for elevation readings. Unless the GPS manufacturer's specifications state that the device is accurate for elevation readings, this method is not recommended. However, some GPS-based surveying systems are accurate for taking elevation readings. These survey systems usually track elevation differences between multiple points in a survey. Any similar survey system that can measure elevation differences at an accuracy of less than a meter, and preferably less than half a meter, will be appropriate.

Some projects may not be appropriate for installing the largest capacity system that the water source yield can accommodate. This could be due to a design demand that is smaller than the maximum source yield, limited available capital funds, or other political or social constraints. The system design layout for these projects will reflect this limitation by necessity. However, thought should be given to the supply system layout of a possible future expansion (e.g., if additional funds become available at a future date). In this case, the piping system installed initially should be adequate for both a lower- and higher-capacity design flow, and adequate space for a future solar array expansion would need to be planned. Additional water storage volume may be needed at that future date as well.

2.5. Project Location

(reference IEC 62253 – 6.2 Customer data, a. Geographical, b. Climatic data)

The project location will directly affect the design of the photovoltaic array that will provide power to the water system. In general, solar panels convert energy from the sun into usable power. The rate at which solar energy falls onto a panel is known as solar irradiance, and it is measured in units of power per area (e.g., W/m^2). The intensity of solar irradiation depends on several factors, including location, time of year, time of day, as well as weather and atmospheric conditions. The amount of power a solar panel can convert from solar energy is known as photovoltaic production. IEC 62253 also gives allowance for a design where specific location data is not given or known. In this case, the design must follow default data given in IEC 62124.

2.5.1. Daylight Hours and Irradiance Data for Project Location

Figure 2.5.1.a shows how solar irradiance changes throughout the day. The actual amount of irradiance in each hour (discussed in the next section) and the number of hours per day when irradiance is present vary widely based on location. Figure 2.5.1.b provides a graphical representation of the amount of irradiation in different regions worldwide.

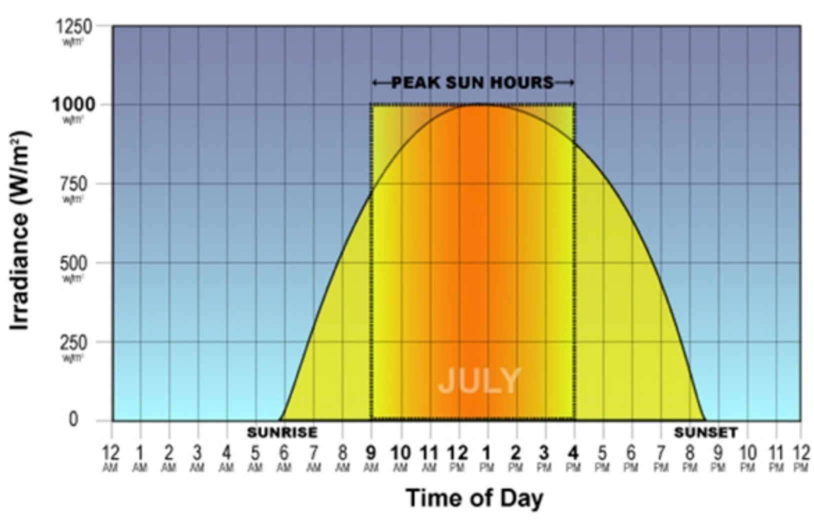


Figure 2.5.1.a – Solar Irradiance Based on Time of Day

Source: http://allbaysolar.blogspot.com/2013/04/peak-hours-vs-sun-hours.html

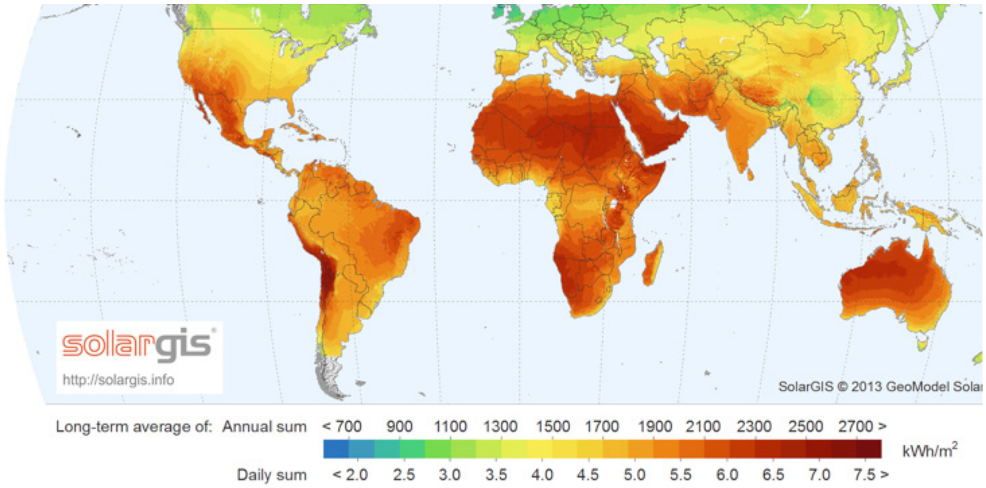


Figure 2.5.1.b – Solar Irradiation Based on Worldwide Location

Source: https://commons.wikimedia.org/wiki/File:SolarGIS-Solar-map-World-map-en.png

2.5.2. Temperature and Irradiance Data for Project Location

The two main factors that affect photovoltaic power production are temperature and solar irradiance. Increases in temperature have a negative impact on power produced by irradiation. In other words, increasing temperature results in a decrease in power production. This is because rising temperatures cause a decrease in voltage, as shown in Figure 2.5.2.a. With the understanding that the product of voltage times current is equal to power, a decrease in voltage will lead to a decrease in power.

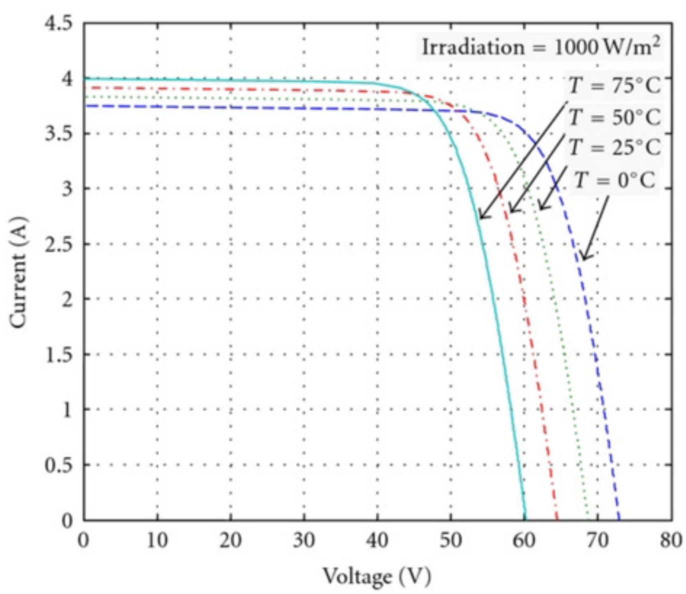


Figure 2.5.2.a – The Effect of Temperature on Photovoltaic Production

Increases in solar irradiance will have a positive impact on power produced by irradiation. As shown in Figure 2.5.2.b, increasing irradiance corresponds to an increase in current. With the understanding that the product of voltage times current is equal to power, an increase in current will result in an increase of power. Therefore, increases in solar irradiance lead to an increase in power production.

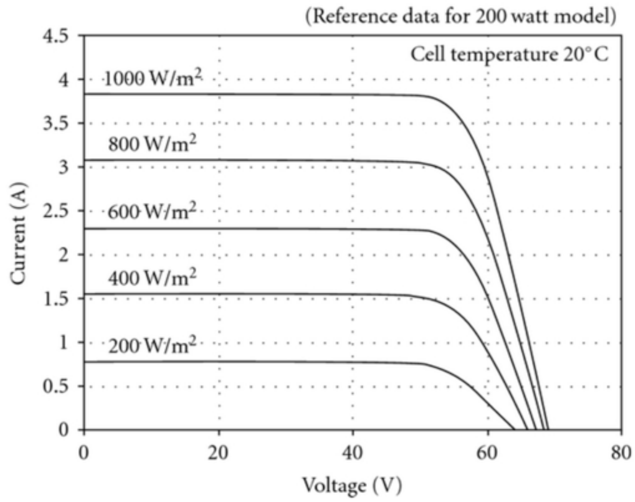


Figure 2.5.2.b – The Effect of Solar Irradiance on Photovoltaic Production

2.5.3. Monthly Temperature and Irradiance Data

Ambient temperature and incident irradiance are the only environmental factors needed to estimate the output of a given solar panel. As **2.5.1. Daylight Hours and Irradiance Data for Project Location** shows, irradiance will increase from zero at sunrise to the daily maximum at solar noon and then decrease back down to zero at sunset. Irradiance can be approximated as a parabolic function with respect to time if irradiation and daylight hours are known.

However, since the sun's position in the sky above a given location shifts over the course of the year, irradiance for that location usually changes each month. Additionally, overcast weather will block energy from the sun, so rainy seasons typically experience less intense irradiation. Ambient temperature and solar irradiance data are available from the United States' National Aeronautics and Space Administration (NASA) for any location in the world, every month of the year (*reference IEC 62253 – 6.2 Customer data, b. Climatic data, 6.3 System characteristics*). Similar data are also available from the European Commission's Photovoltaic Geographical Information System and on the Global Solar Atlas from World Bank Group, ESMAP, and Solargis.

The temperature and irradiance data values used to design the solar array for a given project should be based on one of the following monthly data sets:

- The month with the lowest irradiance values
- Any individual set of monthly data that is of interest because of a project's conditions or desired performance
- The average of all monthly data over the entire year

If the solar powered water system will be relied upon to produce a set amount of water during every month of the year, then the month with the lowest irradiance value data set should be used for the system design. This is because the solar array will need to provide enough power for the pump to perform at a design flow rate during the worst irradiance conditions. However, designing a solar powered water system to the lowest irradiance conditions, is not necessarily the "worst condition" as discussed in section 6.2.d) of IEC 62253. IEC 62253 also mentions a worst condition date and water head.

For example, the lower irradiance condition may take place during the rainy season. However, the water demand during the rainy season may be less than it is during the rest of the year due to rainwater harvesting or other water collection practices. Therefore, the worst condition date may be during a month when the irradiance conditions are average, or are peaked, but when the water demand is highest due to lack of rain. Determining this type of condition takes a thorough understanding of the water usage patterns in a community over a whole year (for more information see **2.2.3. Area of Service Water Usage**).

Additionally, the worst condition for water head will typically be during a month when the aquifer water level drops to seasonal low. However, it is possible that this condition does not correspond to the month with the lowest irradiance values. Hydrogeologic data and thorough yield and drawdown testing (see **2.3.1 Source Yield**) will be required to determine the seasonal low water level.

The condition that requires the highest flow and pressure demands on the pump when the available power from solar irradiance is low is the "worst condition". If a month other than that with the lowest irradiance values is determined to be the worst condition month, then the system is best designed using that specific month's temperature and irradiance data set.

Alternatively, if a solar powered water system will be used only during a particular season, then the system should be designed for the monthly data sets of that season.

Regardless of which month the solar powered water system is designed to, it is good practice to check the design using the average monthly temperature and irradiance data. Performance under average monthly conditions will increase confidence in the equipment selections.

It is also noted that IEC 62253 gives allowance for a design where specific location temperature and irradiance data is not known. In this case, the design must default to the data given in IEC 62124 and to a default average ambient temperature of 30°C.

3. Pump and Motor Selection (or PV Pump Aggregate Selection)

3.1. Design Flow Rate

The design flow rate of the water system is based on the design demand (see **2.2.6 Design Demand**). At a simplified level, the design flow rate required of the pump can be expressed as a daily total volume divided by the average number of daylight (or peak sun or full solar irradiance) hours where the project is located (see **2.5.3. Monthly Temperature and Irradiance Data**). However, this will only be true if enough power is provided to the pump to produce a specified amount of water during each daylight hour. In actuality, the amount of power provided to the pump by the solar array will increase as the sun rises and decrease as the sun sets. Thus, during the period of time between when the sun rises and sets, there may not be enough power for the pump to produce to the full design flow rate.

During the design phase, there are two ways to handle the disparity in power supplied by the solar array and the power required of the pump to produce to the design flow rate. The first option is to assume that water is only produced during the peak sunlight hours. This option is the most conservative. If this option is chosen, the designer must ensure that the pump is not allowed to be powered on until an adequate amount of power to begin a flow water is supplied. If a pump is allowed to power on but is not supplied enough power to move water through it, the pump will overheat and may eventually fail. This condition is typically avoided by proper use of the manufacturer's pump controls (or proper inverter settings).

The second option is to design the array with enough solar panels to generate the necessary amount of power even during the hours of the day with lower irradiance. In this case, the pump would produce at least the minimum amount of flow during every hour of sunlight. However, this option is only practical where the necessary area and finances are available for a larger solar array.

Regardless of which option is chosen, the completed solar powered water system design must always be checked to ensure that the design demand will be fulfilled (see **4.8. Checking System Design to Daily Project Water Demand**). It should also be noted that if the yield, or allowable yield, of the water source is less than the design flow rate, then the design flow rate must be decreased to be equal to or less than the source yield.

3.1.1. Energy Supplementing

The design process for supplying secondary energy sources to the pump and motor is not covered in this guide, with the exception of direct solar. Secondary energy sources would include AC grid power, generators, and batteries (including stored solar). However, if additional forms of energy are to be used, then the design flow rate of the pump will be different from the design flow rate required from a system powered by direct solar alone. Instead of dividing the total volume by the average number of daylight (or full solar irradiance) hours, the total volume would be divided by the total hours that power will be provided to the pump.

Secondary modes of energy will also influence the sizing of water storage by mitigating the risk of emergencies and weather variations and providing off-hour pumping (see **5. Water Storage**).

3.2. Pump and Motor Selection (or PV Pump Aggregate Selection)

3.2.1. Pump Types Based on Water Source

Identifying the project's water source is an essential factor in choosing the right pump. Section **2.3. Water Source** discusses source considerations, but the first determinant of pump selection is whether the water source is groundwater or surface water.

3.2.1.1. Groundwater Source

If the source is a borehole (or a well), typically a submersible pump will be used. Most current solar pumping applications use submersible pumps. Logically, submersible pumps must be installed below the water level, fully submerged. If the pump runs while exposed to air, air may be introduced into the pump, causing significant damage. Therefore, most submersible pumps have run-dry sensors that turn off the pump if it is not fully submerged. Manufacturer recommendations on the depth to which a pump should be submerged within a water column must be followed.

It must also be recognized that pump selection is constrained by the inner diameter of the borehole casing. This also means that if the casing was installed poorly or has been damaged, any narrowing of the casing at any point in the borehole column will also affect the size of the pump suitable to be installed in the borehole. The inner diameter of the borehole casing must meet the pump manufacturer's requirement and recommendations. Similarly, a borehole must be vertically plumb to appropriately accommodate a submersible pump and riser pipe installation.

Additionally, submersible pumps are very sensitive to solid particles, so they should be used primarily in boreholes where turbidity is low. Submersible

Pump Curves

Pump selection depends heavily on the design demand (see 2.2.6 Design Demand) and the hydraulic design.

Photo courtesy of Water Mission

pumps are not typically recommended in turbulent rivers, lakes, or areas that are prone to flooding unless means of protecting the pump from silt and high turbidity are provided. Typically, a hand-dug well (or unprotected borehole) is also prone to turbidity, silt, and solids due to the well construction and from run-off surface water. For these reasons, unless protection to the pump can be facilitated, submersible pumps are not recommended for hand-dug well installations.

3.2.1.2. Surface Water Source

If surface water is the best available water source, then a surface pump is typically most appropriate. Surface pumps are recommended for use in many water sources, including rivers, lakes, pools, and tanks. However, surface pumps have low suction lift and cannot draw water from deep sources (like a deep borehole or well) or from deep within a surface water source. Therefore, boreholes are commonly avoided when using a surface pump (unless the net positive suction head requirement can be met). It is also important to know that a surface pump typically requires priming before use.

If a surface pump is being used, net positive suction head (NPSH) must be considered. Each water system will have a certain amount of NPSH available (NPSHA). For a surface pump to operate properly, the NPSHA must be high enough to prevent vaporization as water enters the impeller eye. Each impeller design has its own minimum NPSH requirement (NPSHR). If the NPSHA (determined by the system) is not greater than the NPSHR (determined by the pump), water will vaporize as it enters the pump. The result is loss of head and efficiency; cavitation; pitting and erosion of the impeller; and eventual pump failure (Grundfos, 1999). This design guide does not present the methods by which to calculate NPSHA, because the methods are the same for a solar powered pumping system as for any other mechanised pump. It should also be recognised that when using a surface water source, it is common for the water level of the source to change throughout the year. This will need to be accounted for within the NPSH calculations to ensure proper pump operation.

3.2.2. Pump Curves

(reference IEC 62253 – 6.3 System characteristics)

The purpose of both surface and submersible pumps is to add energy to the water within a system to create flow. Thus, pump selection depends heavily on the design demand (see **2.2.6. Design Demand**) and the hydraulic design. In other words, the pump and motor will be selected based on the design flow rate and subsequent TDH demanded of the pump by the water system. The pressure (or energy per unit volume) a pump can supply is known as pump head and is given as an amount of elevation lift. The minimum amount of elevation lift that a pump must supply for a water system to produce water is equal to the TDH (see **2.4. Water Supply System Design Layout**).

The design flow rate and TDH of the system can be compared to specific pump models using performance curves (or "pump curves"). A pump curve describes the relationship between flow and head for a pump. In general, pump selection will require matching the system's flow rate and required TDH to a pump's performance curve. Pump curves are available from pump manufacturers and suppliers.

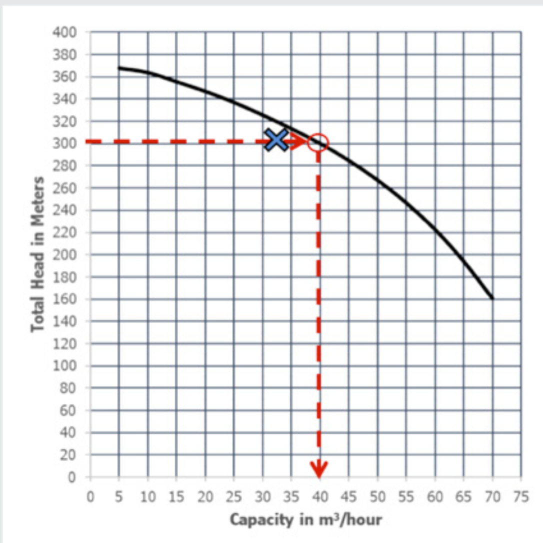
3.2.2.1. Selecting an AC Pump Using a Traditional Pump Curve

Before discussing the selection of solar pumps, we will present how to select an AC pump using a traditional pump curve (note: the term AC pump here is used to refer to pumps that can only accept AC power, as opposed to DC). This is important to the presentation of solar pumps for two reasons. First, the process for reading solar pump performance curves, which display performance under variable amounts of power, builds upon the method of selecting a pump with a traditional pump curve. Traditional pump curves assume a constant amount of supplied power. Second, many AC pumps can also be powered by solar through the use of an inverter (see **3.5.2. Inverters**). This is important to note because AC powered pumps have a higher range of performance as compared to solar pumps. Some water system designs will require this higher performance.

The power required by an AC pump is determined by the pump itself. Therefore, a traditional pump curve shows only one curve of TDH versus flow rate at the required power. The first step in selecting an AC pump is to find one where the designed TDH intersects the pump curve. The point where the designed TDH meets the curve corresponds to the potential flow rate on the x-axis. This is the flow the pump can achieve given the specified TDH and ideal conditions. This potential flow should be greater than the design flow rate. If the pump is unable to produce water at the design flow rate (i.e., the potential flow is less than the design flow rate), another pump must be chosen. The following example details the process of selecting an AC pump with a traditional pump curve.

Example: Selecting an AC Pump

Select an AC pump for a system designed with a flow rate of 33 m^3/hr and a TDH of 300 m.



AC Pump Performance Curve

Step 1: Find a pump that can achieve the designed TDH.

The pump performance curve indicates a TDH range of approximately 160-370 m. Therefore, the pump is capable of the designed TDH of 300 m.

Step 2: Find the potential flow rate of the pump at the designed TDH.

Find the point on the pump curve that corresponds to a TDH value of 300 m. Then find the value on the x-axis (i.e., the potential flow rate) that corresponds to this point. Based on the AC pump performance curve, the pump can generate 40 m^3/hr at a TDH of 300 m.

Step 3: Make sure the potential flow rate exceeds the designed flow rate.

Step 2 determined that the potential flow rate is 40 m^3/hr at a TDH of 300 m, which exceeds the designed flow rate of 33 m^3/hr.

Step 4: Determine the power requirement.

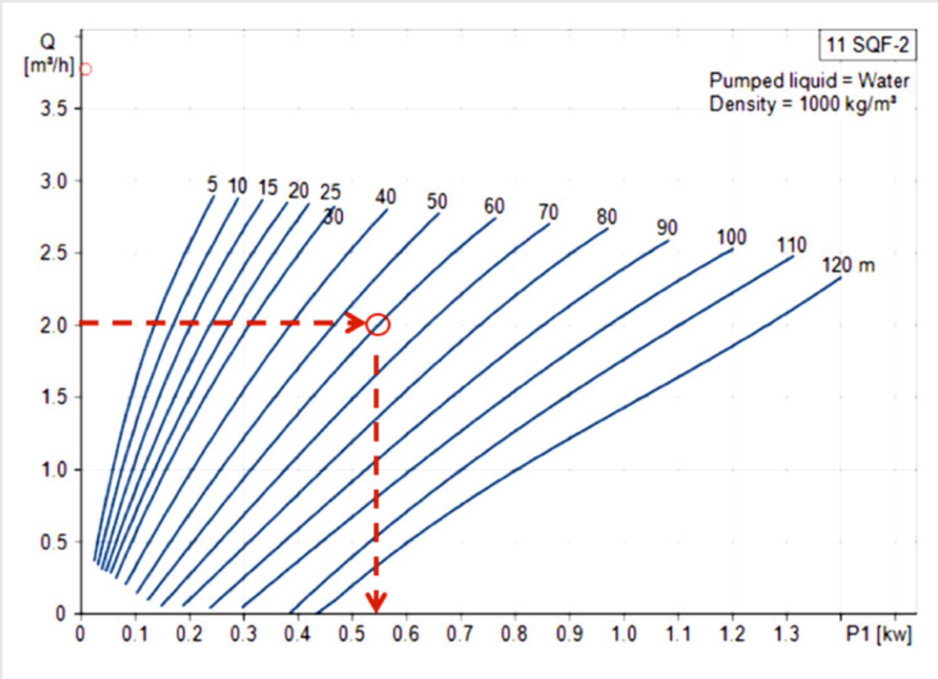
After selecting the pump, the amount of power needed will depend on the pump and motor requirements. This information should be available in the specifications from the manufacturer.

3.2.2.2. Selecting a Pump using Solar Pump Performance Curves

Each solar pump will have a range of TDH and flow conditions that it can meet based on the amount of power supplied. Therefore, a solar pump will have multiple performance curves to cover a range of conditions. The corresponding flow rates are graphed on the y-axis, while the power required is graphed on the x-axis. The first step is to find a pump with a pump head capacity that encompasses the value calculated for the system. In other words, one of the pump's performance curves will correspond to the designed system's TDH. Next, the design flow rate on the y-axis should intersect that performance curve. The point on the graph where the designed flow and TDH intersect will correlate to the power required on the x-axis. This process is illustrated in the following example.

Example: Selecting a Solar Pump

Select a submersible solar pump for a system with a flow rate of 2 m^3/h and a TDH of 60 m.



Solar Pump Performance Curve for the Grundfos 11 SQF-2

Step 1: Find a pump that can achieve the system's designed TDH.

Use the performance curves to determine the range of TDH that each pump model can achieve. Based on the curve, the Grundfos 11 SQF-2 ranges in TDH from 5-120 m, which includes the system's design of 60 m.

Step 2: Make sure the pump in question can achieve the system's designed flow rate.

The y-axis of the performance curve graph shows the flow rates it can produce. Looking at the graph, the 11 SQF-2 can pump approximately 0–3 m^3/h, which encompasses the system's design of 2 m^3/h. More specifically, the 2 m^3/h mark intersects the 60 m performance curve. This indicates that the Grundfos 11 SQF-2 can meet the system design.

Step 3: Determine the power requirement.

Find the point on the graph where the 2 m^3/h mark intersects the 60 m TDH curve. Then, drop straight down to the x-axis to determine the power requirement. Based on the graph, the Grundfos 11 SQF-2 requires approximately 550 W to achieve the system design.

Multiple pump models may be able to achieve the flow rate and TDH designed for the system. If this is the case, determine the power required for each of the pumps that could be used. Then, the recommendation is to select the one with the highest efficiency rating for the required flow and TDH or the lowest power requirement.

If the project being designed does not have the available capital funds for the largest capacity pump, motor, and solar panel array, it is possible to install a lower capacity system for which the capital funds are available. As mentioned in **2.4. Water Supply System Design Layout**, the recommendation would be to install a piping system that is adequate for both a lower and higher capacity flow and to ensure that there is adequate space for a possible future solar array expansion to go with a larger capacity pump. Additional water storage volume may be needed as well.

3.2.2.3. Manufacturer Selection Software

Many leading solar pump manufacturers provide online and computer-based tools that can be used in the design and selection process (e.g., Grundfos, Lorentz, and Franklin each offer these tools to assist in the selection of their respective products). Users input design criteria such as water demand, water source yield, water source type, water system information, site location, and irradiance conditions. The tools then return multiple equipment configurations that can achieve the design criteria, which can then be evaluated by the user.

With a skilled user, these tools can lead to an effective and efficient selection of equipment and design of the system. However, without accurate design data and adequate knowledge of the underlying principles, the tools can result in inadequately sized equipment. The user needs to understand the design criteria inputs to use the tools accurately. Proprietary selection tools are not able to evaluate the appropriateness of certain equipment selections beyond the input criteria or beyond the product offerings of the manufacturer. The user must be able to provide this evaluation. The Engineer of Record must still ensure that the requirements of IEC 62253 are fulfilled by the design.

3.3. Power Required

It is critical to supply the correct amount of power (wattage) for the pump (and inverter, if applicable) to perform at the design flow and TDH requirements.

3.3.1. Power Required by the Pump Motor

The energy the pump is ultimately able to add to the water will depend on the power supplied to the pump motor. The power required by a pump motor can quickly be identified by the manufacturer-supplied pump curve and accompanying information.

3.3.2. Power Required by the Inverter

If an inverter is being used (see **3.5.2. Inverters**), it is important to recognize that the inverter will also have inefficiencies. Thus, the power input required by the inverter will be greater than the motor power (see **4.1.3. Power Losses**).

3.4. Manufacturer Specifications

3.4.1. Of the Motor

After the motor power is identified, it is important to identify the input voltage range and the maximum current draw of the motor. The voltage supplied by the solar array will need to exceed the minimum voltage required by the pump motor, or the pump will not start. In addition, the voltage from the solar array must not exceed the maximum voltage acceptable to the pump motor, or it will damage the motor. Most pump motors are equipped with overvoltage (and undervoltage) protection, meaning that the motor and pump will shut off automatically if the supplied voltage falls outside of the accepted range.

Regarding current, the pump motor will only draw up to a certain number of amps identified in the pump motor specifications. If the solar array supplies a current greater than the maximum amperage draw of the pump motor, the actual wattage used by the motor will be based on the maximum amperage of the motor and not on the amperage supplied by the solar array.

3.4.2. Of the Inverter

If an inverter is being used, the inverter itself will have an acceptable input voltage range (VDC). If the voltage supplied by the solar array does not fall within the voltage range acceptable to the inverter, the inverter will not operate.

Regarding current, an inverter will only be able to supply a certain number of amps to the pump motor. If the solar array supplies an amperage to the inverter that exceeds the amount that the inverter will supply to the pump motor, the useable wattage will be based on the maximum amperage that the inverter can supply to the pump motor and not on the amperage supplied by the solar array.

Design and use of an inverter must comply with IEC 62109-1 and IEC 62109-2.

3.5. Ancillary Pump and Motor Equipment

Based on the pump and motor make and model, identify all ancillary equipment needed for the pump and motor to function properly. These may include but are not limited to control units, inverters, switches or breaker boxes, float switches, and run-dry sensors/switches. It is critical in the selection

Ancillary Pump and Motor Equipment

It is critical in the selection of all ancillary equipment that the pieces of equipment be rated for the form of power that they will be used to convey.

Photo courtesy of Water Mission

of all ancillary equipment that the pieces of equipment be rated for the form of power that they will be used to convey (i.e., equipment used to convey DC power shall be rated for DC, and equipment used to convey AC power shall be rated for AC).

Design and use of an inverter or other power conditioning unit must comply with IEC 62109-1 and IEC 62109-2.

3.5.1. Control Units

Some pump manufacturers have recommended control units that accompany certain pump models. These are typically recommended for proper controlling of the pump and motor.

3.5.2. Inverters

An inverter converts DC output from solar panels into AC. Thus, with the correct inverter, most AC pumps can be powered by a solar array. Inverters are typically used in a solar powered water system when the pump capacity needed exceeds the capacity of the pump and motor combinations (or PV pump aggregates) that can take DC input. Pump and motor combinations that require AC input commonly have much higher capacities.

The appropriate inverter must be selected to power the pump required for the project. The critical parameters to determine an inverter's compatibility and ability to power a specific pump are:

- inverter nominal power rating (AC kW),
- inverter output phase,
- inverter output voltage (AC volts),
- inverter maximum output current (AC amps),
- inverter minimum input voltage (VDC), and
- inverter maximum input voltage (VDC).

If these values are in conflict with those of the selected pump, then the inverter is not compatible with the pump. Typically, the information gathering and decision-making process can be expedited by using a pump manufacturer's recommended inverter for the particular pump needed for a project. After the inverter has been selected, the minimum and maximum input DC voltage acceptable to the inverter will be needed during the solar array design (see **4. PV System Design**).

3.5.3. Float Switches

Float switches are used to turn a pump on or off based on the water level in a storage tank. For water storage tanks after the pump, the float switch is installed so that it turns the pump off when the tank is full. Therefore, the float switch is installed so that it floats horizontally on the water's surface when the tank is full. In the horizontal position, an electrical contact within the float closes, which sends a signal to the pump control unit. This signal turns off the pump. As water exits the tank, the water level lowers and the float shifts toward a vertical position. This reopens the contact and resumes pump operation until the tank is refilled.

There are also float switches available that can be used to drain tanks. These float switches turn on the pump when the tank is full, and then turn off the pump once the tank reaches a set low point (without letting the pump run in a dry condition). They are typically used in water systems where water needs to be stored in advance of t he pump.

It should also be noted that all float switch wiring will have a maximum distance that can be accommodated between the switch and the pump control unit. Float switches are typically available for any mechanised pump system. They are particularly advantageous in a solar powered system where the full power of the midday sun is used to pump water to fill storage tanks that will be drained during the time of day when the sun is down (see **5. Water Storage**).

3.5.4. Run-Dry Sensors/Switches

A run-dry sensor or switch is an accessory that prevents the pump from operating when water is not present. Operating a pump in dry conditions increases heat and friction within the pump, causing damage, and potentially failure, to the pump. Additionally, operating a pump dry in a borehole can cause biofouling within the water source. Therefore, the use of run-dry protection is critical to the ongoing success of any water system using a mechanised pump, including solar powered systems.

Some pumps come equipped with a sensor embedded in the motor cable that transmits signals directly to the pump's control unit to turn off the pump when the sensor is exposed to air instead of water. If a pump does not come equipped, the run-dry sensor can typically be supplied as an ancillary piece of equipment. The sensor is typically placed approximately 0.5 m above the pump.

3.6. Pump and Motor Installation Design

The placement and installation requirements for the pump and motor must be determined during the design. These include, but are not limited to pump location in relation to the water level (or dynamic water level); net positive suction head requirements of the pump (if a surface pump is being used); wiring requirements (including grounding); any pump priming requirements; and any requirements pertaining to the installation of ancillary equipment.

Additionally, the installation design must provide adequate protection to the pump and motor to ensure good performance throughout the expected lifespan. As such, measures must be designed to protect the pump and motor from environmental, animal, or human hazards. These include but are not limited to prolonged exposure to direct sunlight; any possibility of negative impacts to the quality of the water being pumped; exposure to hazardous weather events common to the location; and tampering or vandalism by animals or humans. In the case of a submersible pump in a borehole, proper protection includes a properly grouted and cased borehole that has a high-quality well cap with sanitary seal. For pump installations using surface water sources, proper protection includes a properly screened intake in accordance with the pump manufacturer's requirements.

For submersible pumps installed in boreholes, the installation design must also include a safety line, as well as means for removing the pump for future maintenance. A polypropylene rope or stainless-steel braided cable is recommended for use as a safety line.

4. PV System Design

4.1. Solar Array Design

The selected solar panel and solar array configuration shall supply the power required by the selected pump and motor, or inverter, if applicable (see **3.3. Power Required**), and shall satisfy all specifications of the pump and motor manufacturer (see **3.4. Manufacturer Specifications**). Thus, the power to be supplied by an array must be estimated to verify whether the array design is appropriate for the pump and motor required by the water system. Estimating the power output of a solar array design involves:

- calculating the power outputs of the solar panels to be used for the irradiance and ambient temperature conditions of the project location (see **4.1.1. Solar Panel Selection**);
- calculating the power output of the array due to the configuration of the panels (see **4.1.2. Solar Array Configuration**);
- and then adjusting the calculated power output of the array based on the power losses of the system (see **4.1.3. Power Losses**).

All solar array design and installation must comply with IEC 62548 Design requirements for photovoltaic (PV) arrays.

Pump and Motor Installation Design

Solar Panel Selection

Photos courtesy of UNICEF (top) and Water Mission (bottom)

4.1.1. Solar Panel Selection

The amount of energy converted by solar panels will depend on their design and specifications. Solar panels have several characteristics that are important in order to estimate their power output. These characteristics are provided on the solar panel specifications and datasheets from the manufacturer (though the information given and the terminology may differ between manufacturers).

Maximum power point (P_{max}) is the maximum possible output wattage of the panel (this may also be referred to as peak or nominal power by different manufacturers).

Maximum power point voltage (V_{mpp}) is the voltage that corresponds to the maximum power point.

Maximum power point current (I_{mpp}) is the current that corresponds to the maximum power point.

Open circuit voltage (V_{oc}) is the voltage that occurs when there is no load on the array.

Short circuit current (I_{sc}) is the maximum current the solar panel can handle in short circuit conditions.

The temperature coefficient (TC V_{oc}) is used to estimate a solar panel's open circuit voltage as the cell temperature rises. TC Voc is measured in V/°C.

Normal operating cell temperature (NOCT) is the expected operating temperature of a cell measured at an irradiance of 800 W/m^2 and an ambient temperature of 20°C.

The values for these characteristics will vary for each model of solar panel. All solar panels used in an array should have the same characteristics. (For discussion of the effect of connecting solar panels of different voltage and/or current rating, **see 4.1.2. Solar Array Configuration**.) Additionally, it is advantageous to the array construction for the solar panels to be of the same length and width.

The maximum power point, maximum power point voltage, maximum power point current, open circuit voltage, short circuit current, and temperature coefficient are the primary characteristics of the panels, and are provided by manufacturers at standard test conditions (STC) of 1,000 W/m^2, air mass of 1.5, and a cell temperature of 25°C. However, these standard conditions rarely, if ever, occur in reality. Therefore, most solar panels will not output the maximum rated wattage when installed in the field.

Calculating a solar panel's estimated performance in field conditions is presented in **4.1.1.1. Calculating a Panel's Estimated Performance for the Project Location**. Any solar panel selected must comply with IEC International Standards:

- IEC 61215-1 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1: Test requirements
- IEC 61215-1-1 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1-1: Special requirements for testing of crystalline silicon photovoltaic (PV) modules
- IEC 61215-1-2 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1-2: Special requirements for testing of thin-film Cadmium Telluride (CdTe) based photovoltaic (PV) modules
- IEC 61215-1-3 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1-3: Special requirements for testing of thin-film amorphous silicon-based photovoltaic (PV) modules
- IEC 61215-1-4 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1-4: Special requirements for testing of thin-film Cu(In, GA) (S, Se)2 based photovoltaic (PV) modules
- IEC 61215-2 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures

4.1.1.1. Calculating a Panel's Estimated Performance for the Project Location

(reference IEC 62253 – 6.3 System characteristics)

The estimated power (wattage) output of the solar panel shall be calculated for the ambient temperature and solar irradiance of the project location (see **2.5.3. Monthly Data** to determine which monthly ambient temperature and irradiance data set to use for these calculations).

As mentioned previously, solar panel specifications are provided at standard test conditions. However, these conditions are rare in the field. Generally, irradiance will increase from zero at sunrise to the daily maximum at solar noon and then decrease back down to zero at sunset. Temperature will also fluctuate during the day. Due to these variations in ambient temperature and irradiance, solar panels do not typically perform to their STC specifications. The actual output of a given solar panel can be calculated if the ambient temperature and irradiance are known. To calculate the power (wattage) output of a solar panel, follow the steps below.

Step 1: Calculate the cell temperature. This is the temperature of the solar panel cells as a function of irradiance and ambient temperature at the specific project location.

$$\text{Cell temp (°C)} = \text{Ambient temp (°C)} + (\text{NOCT} - 20°\text{C}) \times \frac{\text{Irradiance}\ (\frac{W}{m^2})}{800\ \frac{W}{m^2}}$$

Step 2: Calculate the open circuit voltage at the cell temperature. The open circuit voltage will vary as a function of the cell temperature in accordance with the TC Voc value.

$$V_{oc} = \text{STC } V_{oc} + (\text{Cell temp} - 25°\text{C}) \times \text{STC } V_{oc} \times \text{TC } V_{oc}$$

Step 3: Calculate the short circuit current at the given incident irradiance. This adjusts the standard short circuit current for the actual irradiance at the project location.

$$I_{sc} = \text{STC } I_{sc} \times \frac{\text{Irradiance}\ (\frac{W}{m^2})}{1{,}000\ \frac{W}{m^2}}$$

Step 4: Calculate the maximum power point current at the given irradiance. This adjusts the standard maximum power point current for the actual irradiance at the project location.

$$I_{mpp} = \text{STC } I_{mpp} \times \frac{\text{Irradiance}\ (\frac{W}{m^2})}{1{,}000\ \frac{W}{m^2}}$$

Step 5: Calculate the solar panel output under the given conditions. This adjusts the standard maximum power point for the actual ambient temperature and irradiance experienced at the project location.

$$P_{max}\ (W) = V_{oc} \times I_{sc} \times \frac{\text{STC } I_{mpp} \times \text{STC } V_{mpp}}{\text{STC } I_{sc} \times \text{STC } V_{oc}}$$

Step 6: Calculate the maximum power point voltage of the panel. This adjusts the standard maximum power point voltage for the actual ambient temperature and irradiance experienced at the project location.

$$V_{mpp} = \frac{P_{max}}{I_{mpp}}$$

IEC 62253 - *6.3 System characteristics*, requires that the power output of the solar array be evaluated for a minimum of four different temperature and irradiance condition data sets for the project location, specifically 100%, 80%, 60%, and 40% of the maximum power conditions. This means that the above calculations must be worked to assess an individual solar panel's power output performance for these four conditions at a minimum.

4.1.2. Solar Array Configuration

A solar panel will have limited photovoltaic production based on its design. In most situations, a single panel will not provide enough power for a water project. Therefore, multiple panels are wired together in an array to increase the overall power (wattage) output.

Power can be increased in two ways: through an increase in voltage or through an increase in current. The wiring configuration of the solar array has a direct impact on whether the voltage or current increases. There are two possible wiring configurations, series or parallel, which are illustrated in figure 4.1.2. below.

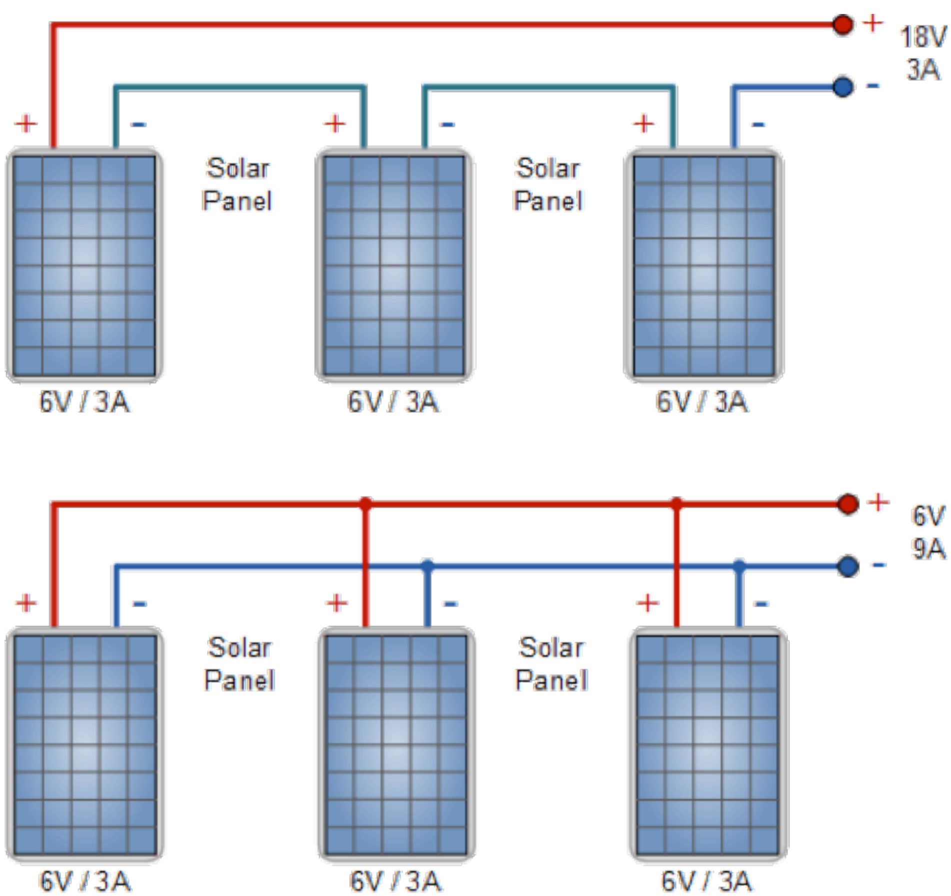


Figure 4.1.2. – Comparison of Solar Panels Wired in Series (top) and Parallel (bottom)

Wiring solar panels in series increases the voltage, while the current remains the same. If wired in series, the total voltage (VT) of the array will be the sum of each panel's individual voltage (Vi). This is represented by the following equation, where n is the total number of panels.

$$V_T = n \times V_i$$

This equation is only valid if all the panels have the same voltage. It is also possible to use panels with different voltages, but the panels wired in series should have the same current (AET, 2017). If the panels do not have the same current, the array will be limited to the lowest current value of the individual panels.

Alternatively, wiring panels in parallel increases the current, rather than the voltage. In parallel, the total current (IT) for a solar array will be equal to the sum of each panel's individual current (Ii), as represented in the following equation, where n is the total number of panels.

$$I_T = n \times I_i$$

This equation is only valid if all the panels have the same current. It is also possible to wire panels with different currents together in parallel. However, if the panels do not have the same voltage, the array will be limited by the lowest voltage value of the individual panels.

While a solar array is defined as a group of solar panels wired together in series or in parallel, typically panels are wired together to increase voltage and achieve the maximum wattage with the least number of solar panels. However, it should be noted that a solar array can also consist of multiple strings of solar panels. Each string is comprised of a number of solar panels connected in series, and each string is connected in parallel. Use of multiple strings is typical for pump motors that require high wattage.

The known output of the individual solar panels and the array configuration can be used to estimate the output of the solar array using the following equations:

$$\text{Array } V_{oc} = V_{oc} \text{ per panel} \times \text{number of panels in series}$$

$$\text{Array } V_{mpp} = V_{mpp} \text{ per panel} \times \text{number of panels in series}$$

$$\text{Array } I_{mpp} = I_{mpp} \text{ per panel} \times \text{number of parallel strings}$$

$$\text{Array } P_{max} (W) = \text{Array } I_{mpp} \times \text{Array } V_{mpp}$$

It is important to note that the Voc per panel, Vmpp per panel, and Impp per panel used in the equations above must be the values adjusted for the temperature and irradiance conditions for the location and not the STC values taken from the solar panel manufacturer specifications. Adjusting these values for temperature and irradiance conditions is detailed in **4.1.1.1. Calculating a Panel's Estimated Performance for the Project Location**.

The total output power (wattage) of a solar array should be calculated for a range of ambient temperatures and irradiances to confirm that the array will meet the needs of the project under a variety of conditions. Specifically, the monthly temperature and irradiance data that the designer has decided is the "worst condition" must be evaluated to confirm that an acceptable amount of water will be delivered by the selected pump and array under those conditions (see **2.5.3. Monthly Temperature and Irradiance Data**).

IEC 62253 - *6.3 System characteristics*, requires that the power output of the solar array be evaluated for a minimum of four different temperature and irradiance condition data sets for the project location, specifically 100%, 80%, 60%, and 40% of the maximum power conditions.

4.1.3. Power Losses

(reference IEC 62548)

Additionally, when evaluating the solar array, it is important to consider system losses of power. A derate factor should be applied to an array's estimated power output to account for any expected sources of power loss in the system.

System losses occur for many reasons:

Nameplate rating: Not all solar panels are rated accurately, meaning that the actual measurement of an individual panel's electrical characteristics may vary from the nameplate rating. The true performance of an individual panel may be lower, and at times even higher, than the panel's rating. The derate factor for this consideration has an accepted range of 0.80 to 1.05. If specific panel information is unavailable, the recommended value is 0.99.

Mismatch: Manufacturing imperfections between individual panels (or modules) in an array can cause slight differences in current and voltage characteristics

Power Losses

When evaluating the solar array, it is important to consider system losses of power. A derate factor should be applied to an array's estimated power output to account for any expected sources of power loss in the system.

Photo courtesy of Water Mission

of the panels. The derate factor for this consideration has an accepted range of 0.97 to 1.0. If specific panel information is unavailable, the recommended value is 0.98.

Connections: The connectors used in a system have resistive losses. The derate factor for this consideration has an accepted range of 0.99 to 0.997. If specific connector information is unavailable, the recommended value is 0.995.

Wiring: The wiring used for the array also has resistive losses. The derate factor for this consideration has an accepted range of 0.97 to 0.99. If specific wire information is unavailable, the recommended value is 0.98. (See **4.3.1. From Solar Panels to Pump** for discussion on voltage drop through wiring.)

Soiling: Any accumulation of dirt and debris on the surface of solar panels can prevent solar radiation from reaching the panel cells and cause a decrease in power generation. This accumulation depends on the array location conditions and maintenance regimen, as well as local weather patterns. High-traffic and high-pollution areas will experience the highest potential for soiling losses. The frequency of rain and washing of the panels will influence the impact of soiling on power generation. For design purposes, the recommended derate factor value is 0.98, with responsible planning and maintenance.

System availability: Both scheduled and unscheduled system shutdowns (i.e., maintenance or outages) will cause a reduction in the system's power output. For design purposes, the recommended derate factor value is 0.97.

Shading: When nearby trees, buildings, or other obstructions create shadows on the surface of array panels, the power output of the array will be less than full capacity. Thus, all possible measures should be taken to ensure that shading will not be experienced at any time during the year when the array will be expected to produce power (see **4.6. Solar Array Location**). It should also be noted that if an array is arranged in multiple rows of panels, it is important that the individual rows themselves do not create shadows on the panels. Additionally, as surrounding vegetation grows, part of the maintenance of the solar array should include management of this growth to avoid future shading. For design purposes, the recommended derate factor value is 0.97.

Age: Weathering of the solar panels will eventually affect the array's performance. A derate factor does not need to be used for this consideration unless already aged panels will be used to construct the array (which is not a recommendation of this guide).

Light-induced degradation: During the first few months of operation, some solar panels will experience a reduction in performance because of light-induced degradation. For design purposes, the recommended derate factor value for this consideration is 0.985.

Inverter losses: If the solar system will use an inverter (see **3.3.2. Power Required by the Inverter**), then the efficiency of the inverter will also need to be taken into account. If specific inverter efficiency information is unavailable, the recommended derate factor value for this consideration is 0.96.

Taking all potential power losses together, the recommendation of this guide is to apply an overall derate factor between 0.85 and 0.90 for a system without an inverter or between 0.82 and 0.85 for a system with an inverter.

$$\text{Array } P_{derated}\ (W) = \text{Array } P_{max}\ (W) \times \text{derating factor}$$

4.1.4. Supplied Wattage Check

The final calculated estimate of the solar array power (wattage) supplied to the pump motor shall meet the power required by the pump motor (and/or inverter, if applicable) for the pump to perform to the design flow rate and TDH conditions. In addition, it is important to remember that irradiance varies throughout the day (see **2.5. Project Location**). This means the amount of power supplied by the solar array to the pump will change over the course of the day.

If the above calculations for the array do not yield enough power to the pump and motor for a sufficient length of time each day to produce the desired amount of water from the system, then the PV array will need to be redesigned.

4.1.5. Supplied Voltage and Amperage Check

The voltage supplied by the solar array will need to exceed the minimum voltage required by the pump motor, or the pump will not start. In addition, the calculated solar array Voc should be less than the maximum voltage accepted by the pump motor. Most pump motors are equipped with overvoltage (and undervoltage) protection, meaning that the motor and pump will shut off if the supplied voltage falls outside of the accepted range.

Regarding current, the pump motor will only draw up to a certain amperage identified in the pump motor specifications. If the solar array supplies a current greater than the maximum amperage draw of the pump motor, the actual wattage used by the motor will be based on the maximum amperage draw of the motor and not on the amperage supplied by the solar array.

Additionally, if an inverter is being used, the inverter itself will also have an input voltage range acceptable to the inverter. If the voltage supplied by the solar array does not fall within the voltage range acceptable to the inverter, the inverter will not operate.

Regarding current, an inverter will only be able to supply a certain amperage to the pump motor. If the solar array supplies an amperage to the inverter that exceeds the amount that the inverter will supply to the pump motor, the usable wattage will be based on the maximum amperage that the inverter can supply to the pump motor and not on the amperage supplied by the solar array.

4.2. Further Installation Requirements

4.2.1. Solar Array Tilt Angle

Solar panels should never be installed at a 0° tilt angle, as this would encourage the collection of dust, soil, and debris that will have a negative effect on the panel's power production. Additionally, the optimal tilt angle for the panel to receive the maximum amount of incident irradiance will typically be greater than 0°. Generally, it is best to set the tilt angle of all the solar panels in the array to match the latitude of the location of the project for optimum irradiance year-round. For example, an array installed at 20° north (or south) should be installed with a 20° tilt angle.

However, some deviations could be considered. If the latitude of the project location is below 15°, then the recommendation of this manual is to set the tilt angle at 15°. This is because 15° is a minimum tilt angle to promote washing by rainfall or wash water, allowing water to fall down the panel to clear away dust, soil, and debris from the panel's surface (Solar World Technical Bulletin, 2016). In addition, if the solar powered pumping system is not being designed to operate every month of the year, but only during certain months, then it may be appropriate to tilt the solar panels at an angle that will maximize the incident irradiance received by the panels during those months only.

The tilt angle should be established during the design of the PV array, and the construction of the solar array must match the designed tilt angle.

4.2.2. Solar Array Cardinal Direction

If the project is in the Northern Hemisphere, the panels should face true south. If the project is in the Southern Hemisphere, the panels should face true north. In general, these orientations based on location will maximize the incident irradiance received by the solar panels. However, if the solar powered pumping system is not being designed to operate every month of the year, but only during certain months, then it may be appropriate to face the solar panels in a slightly different direction to maximize the incident irradiance received by the panels during those months only. In addition, there are some solar array designs that use east- and west-facing arrays to maximize solar power production as the sun rises and sets. This is merely an optional, atypical configuration.

The direction the array will face should be established during the design of the PV array, and the construction of the solar array must match the designed direction.

Solar Array Tilt Angle

An optimal tilt angle will allow for the maximum amount of incident irradiance to be received by the solar array.

Photo courtesy of Water Mission

4.3. Electrical Wire Requirements

4.3.1. From Solar Panels to Pump

The allowable ampacity of the material type and size of the wire used must be appropriate for the current being transmitted, including any applied factor due to required adherence with electrical codes relevant to the project location (such as IEC 60947-1, 62253, and 62548, as well as applicable NEC codes). Wiring would include, but is not limited to, the wiring between solar panels, the wiring from the combined solar panels to the pump controller, and the wiring to the pump motor. In addition, if any secondary sources of power will be used, all wiring from these power sources to the pump motor must be rated appropriately for the current being transmitted.

All wire to be used in the system, and the routing of each length of wire, must be identified during the design. The construction of the system must adhere to the design of all wiring.

In addition, it is recommended that the DC voltage drop (VD) due to the length, material type, and size of the wire not exceed 5%. Calculating DC voltage drop over the wires is an important step in designing solar arrays. Voltage drop is the reduction in electrical potential that occurs as electricity travels through resistive materials like wires. For DC wiring, VD is calculated using the following equation, where L is the length of the wire (in meters or feet) and R is the resistance of the wire (in Ω/km or Ω/kft):

$$VD = 2 \times L \times R \times \frac{I}{1000}$$

Resistance is determined by the material and cross-sectional area (CSA) of the wire. The resistance for different sizes of copper-coated wire is shown in the table below.

Resistance for Copper Wires at 75°C (from NEMA)

WIRE SIZE	CSA		RESISTANCE	
	Circular Mils	mm^2	Ω/KM	Ω/kft
18 AWG	1620	0.823	27.700	8.450
16 AWG	2580	1.31	17.300	5.290
14 AWG	4110	2.08	10.700	3.260
12 AWG	6530	3.31	6.730	2.050
10 AWG	10380	5.261	4.226	1.290
8 AWG	16510	3.867	2.653	0.809
6 AWG	26240	13.3	1.671	0.510
4 AWG	41740	21.15	1.053	0.321
2 AWG	66360	33.62	0.661	0.201

Resistance also depends on temperature, so the numbers from the table above should be adjusted for temperatures other than 75°C. These adjustments can be made using the equation below, where T2 is the temperature of the conductor, R2 is the resistance at T2, and R1 is the resistance at 75°C.

$$R_2 = R_1 \; [1 + 0.00323 \, (T_2 - 75)]$$

Once the DC voltage drop is known, it can be used to calculate the final voltage and wattage of the solar array. To determine the final voltage, subtract the voltage drop from the array's Vmpp (i.e., the voltage at the start of the wire). For the final wattage, multiply the final voltage by the solar array's I_{mpp}.

4.3.2. Grounding (or Earthing)

(reference IEC 60347-7-712 and 62548)

Every solar powered pumping system must be grounded appropriately. Typically, the manufacturer of each component of the system will publish requirements and recommendations for proper grounding. These include, but are not limited to, the solar panel frames and rack, the pump motor and control unit, and the inverter (if applicable).

4.4. Identify Supplement Solar Array Components

4.4.1. Disconnect Switch (or Circuit Breaker)

Disconnect switches, or circuit breakers, must be used in compliance with electrical codes relevant to the project location (such as IEC or NEC codes). Additionally, they must be used in accordance with solar panel manufacturers' and motor manufacturers' requirements and recommendations. All disconnect switches used must be rated appropriately for the power they are used to convey. Thus, disconnect switches conveying DC shall be rated for DC, and disconnect switches conveying AC shall be rated for AC. Failure to use the proper switch can lead to overheating and failure of the switch and can potentially cause a fire.

Additionally, each disconnect switch must have a maximum amperage rating that exceeds the amperage that it will convey, including any applied factor due to required adherence with electrical codes relevant to the project location (such as IEC or NEC codes). It should be noted that some pump manufacturers' control units also serve as a disconnect switch.

4.4.2. Combiner Box

A combiner box is used to connect multiple strings of a solar array. As previously discussed, each string will consist of a number of solar panels connected in series, and then each string will be connected in parallel. Many solar powered pumps will only require a single string of solar panels connected in series, which means that a combiner box will not be needed. However, some pump motors that require a high wattage to run (e.g., most systems requiring an inverter) will need multiple strings of solar panels combined in parallel. Typically, a combiner box is necessary when four or more strings are to be combined.

Combiner boxes must be used in compliance with electrical codes relevant to the project location (such as IEC or NEC codes). Additionally, they must be used in compliance with solar panel manufacturers' and motor manufacturers' requirements and recommendations. All combiner boxes used must be rated appropriately for the form of power and the amount of amperage that they are used to convey.

4.5. Solar Array Rack Design

(reference IEC 60364-7-712 and 62548)

Photo courtesy of Water Mission

Structural Rack Design

Most solar racks are constructed using structural steel (or aluminium, or another structural metal) with a steel-reinforced concrete foundation.

4.5.1. Structural Rack Design

Structural racking to support the solar array must be designed in accordance with local building codes. At a minimum, the rack shall be designed to support the weight of the solar array and to withstand wind, seismic, and snow loads common to the solar array's location. Additionally, the tilt angle (see **4.2.1. Solar Array Tilt Angle**), the cardinal direction of the solar array (see **4.2.2. Solar Array Cardinal Direction**), and the desired height of the array above the ground must be accommodated for and clearly noted in the structural rack design.

Most solar racks are constructed using structural steel (or aluminium, or another structural metal) with a steel-reinforced concrete foundation. Additionally, it is typical for structural steel to be used to frame and hold the solar panels themselves. If this is the case, then the final steel frame design must not be allowed to obstruct or cast a shadow upon the cells of the solar panels. This will negatively affect the production of power from the solar panel array.

4.5.2. Other Rack Design Considerations

As mentioned above, the height of the solar rack above the ground needs to be identified as a part of the solar rack design. Large solar array fields that are constructed purely for power production are typically less than a meter above the ground (taken from the lowest edge of the panels). However, in rural water supply settings, it is more common to elevate the panels 1.5 m or higher (taken from the lowest edge). There are a few different reasons for elevating the height of the solar rack to 1.5 m or higher. An elevated solar rack will avoid the overgrowth of any ground vegetation. It will, at times, reduce the accumulation of dust, soil, and debris on the solar panels. It can deter animals and children (and perhaps adults) from climbing onto the solar panels. Applying pressure, such as walking on the surface of the panels, may cause damage and should always be avoided. Finally, elevation can also discourage theft of the panels. (More theft prevention measures are discussed in **4.5.3. Security of the Solar Panels**.)

As with any exterior structure, solar racks must be protected from corrosion and weathering and/or be made from corrosion-resistant materials. In the case of structural steel, all exposed steel surfaces must be treated appropriately to resist corrosion, whether by galvanization, painting, or other appropriate surface treatments. Failure to protect all structural elements from corrosion and weathering will affect the structural integrity of the solar rack.

In addition, if steel is used to frame the solar panels, and if that steel is not protected from corrosion, the corrosion may cause an obstruction or cast a shadow upon the cells of the solar panels. This will negatively affect the production of power from the solar array and should not be allowed.

4.5.3. Security of the Solar Panels

It is also advisable to provide a means of securing the solar panels against theft or vandalism. As stated above, the height of the solar rack above the ground can offer a deterrent. Using structural steel to build a frame around the solar panels is typically done in order to secure the panels. Another common means of securing the panels is with security bolts that cannot be removed without special tools. Bolts can also be welded in place or protected from tampering by welding a small piece of steel over the bolt to restrict access. Finally, in some cases, a perimeter fence around the entire solar array can be used as a security measure and/or used in conjunction with other methods.

Additionally, it is common to consider the use of a lightning rod or arrestor in the vicinity of a solar array to protect the array from possible damage. It is advisable to compare the cost of potential damage from lightning to the cost of the lightning protection equipment before proceeding with the procurement and installation of the equipment.

If desired, these security measures should be identified during the design of the solar array rack.

4.6. Solar Array Location

(reference IEC 62253 – 6.2 Customer data, e. Project description)

The location of the solar array must be chosen to avoid shading on the solar panels by trees, buildings, and other obstructions. As discussed in **4.1.3. Power Losses**, shading on the solar array will cause the output of power at less than full capacity.

Additionally, it is recommended that the array be installed as close to the pump and motor as possible. Doing so will keep the voltage drop to a minimum (see **4.3.1. From Solar Panels to Pump**). However, this recommendation must also be balanced with the requirement to avoid potential shading, as well as any security concerns.

4.7. Solar Array Maintenance

The design of an array should consider and provide means for the maintenance plans necessary to support the ongoing production of power. Solar array maintenance plans typically consist of regularly washing the solar panels to clear all dust, soil, and debris; routinely inspecting all wire and wire connections; and reapplying paint or other corrosion-resistant materials to the structural steel of the rack. Any rack design that makes such routine maintenance overly difficult should be avoided. Solar racks that are overly cumbersome to maintain on a routine basis run the risk of non-routine or non-existent maintenance practices.

As discussed in **4.5.2. Other Rack Design Considerations** and **4.5.3. Security of the Solar Panels**, raising the panels 1.5 m or higher can deter animals and people from climbing on the panels and can also help guard against theft. However, when considering the structure's design, these benefits should be weighed against the consequences of putting the panels at a height that would make maintenance overly cumbersome. Raising the panels to a height that is difficult to access will likely discourage washing.

As previously mentioned, a solar array with a minimum 15° tilt angle will experience some natural washing of the panels during a rain event. However, at times and in certain locations, it will be necessary to wash the surface of the solar panels to ensure that they continue to produce the desired amount of power. See **4.1.3. Power Losses** for a discussion of the power loss effects of dust, soil, and debris on solar panels. Washing the solar panels can typically be accomplished with lots of water and a soft cleaning device. The use of a cleaning agent is discouraged, as is the use of any abrasive cleaning device. Any cleaning procedure that may scrape, scratch, or otherwise damage the solar panels should not be allowed. In addition, it is advisable to clean solar panels in the morning or late in the day, but not during the middle hours of the day when the temperature of the solar panels will be the highest. Washing during the middle hours of the day could cause cracking. However, at no time during a cleaning process should pressure be applied to the surface of the panels, for instance, by walking on the panels or using a pressure washer.

4.8. Checking System Design to Daily Project Water Demand

(reference IEC 62253 – 6.3 System characteristics, 6.6 Design check of the PV pumping system in respect to the daily water volume)

Before the solar array design can be considered complete, the anticipated water production must be compared to the daily project water demand. The power supplied by the array to the pump motor will enable the pump to produce a certain amount of water. IEC 622*53 - 6.4 Design check of the PV pumping system in respect to the daily water vol*ume, requires that the volume flow rate be evaluated for a minimum of four different solar power condition data sets for the project location, specifically 100%, 80%, 60%, and 40% of the maximum power conditions.

For pump and motor combinations (or PV pump aggregates) that can take DC power input, the amount of water produced can be approximated by referring to the pump curve supplied by the manufacturer (for an example see Figure 4.8.a below). The power required by the pump motor is found by locating the point on the pump curve where the desired flow rate meets the calculated TDH, and then reading the power required at this point. Working backwards, a flow rate can be approximated for the power supplied by the array at each hour of the day. To do this either an assumption is made that the TDH will remain roughly constant, or the TDH can be recalculated at each flow rate for greater accuracy (or to confirm the assumption).

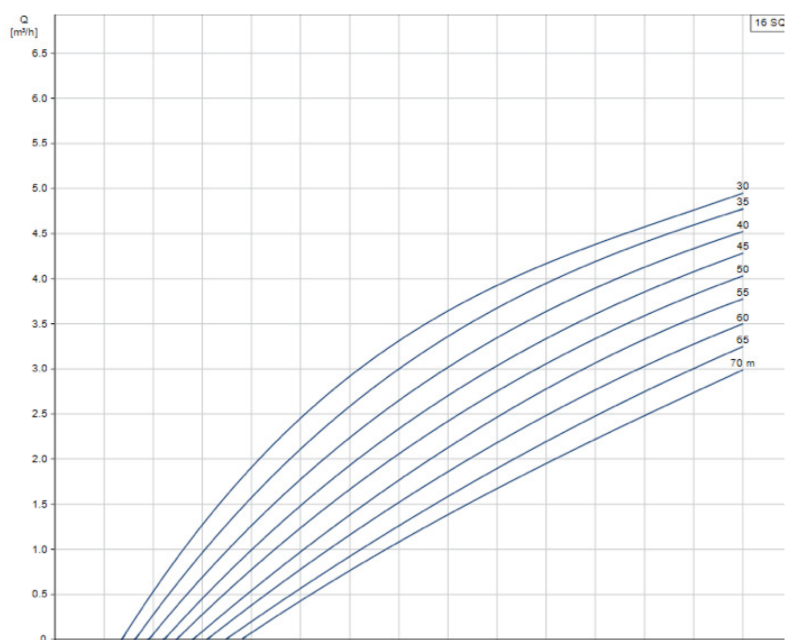


Figure 4.8.a – Solar Pump Performance Curve for Grundfos 16 SQF-10

Checking System Design to Daily Project Water Demand

Before the solar array design can be considered complete, the anticipated water production must be compared to the daily project water demand. The power supplied by the array to the pump motor will enable the pump to produce a certain amount of water.

Photo courtesy of Water Mission

However, in a design using an AC powered pump and inverter, it is typically not true for the TDH to hold roughly constant. This is because the hourly fluctuation of power for these types of systems is much greater. Instead, we can use the affinity laws, which are applicable to standard centrifugal pumps to calculate how the pump will perform at the different amount of power supplied by the solar array. The affinity laws are expressed as follows:

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3$$

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1}$$

$$\frac{H_2}{H_1} = \left(\frac{N_2}{N_1}\right)^2$$

P = Power; N = Speed; Q = Flow; H = Head

In submersible pumps, speed changes are commonly accomplished by means of a variable frequency drive. Most inverters used in pumping applications supply power to the pump motor using a variable frequency drive. Since frequency (Hz) can be interchanged with speed, the frequency can be used in the place of speed in the affinity laws shown above. Thus, these laws can be used to calculate how the hourly amount of power supplied translates to pump performance. This is displayed as multiple performance curves for the pump (for an example, see Figure 4.8.b below).

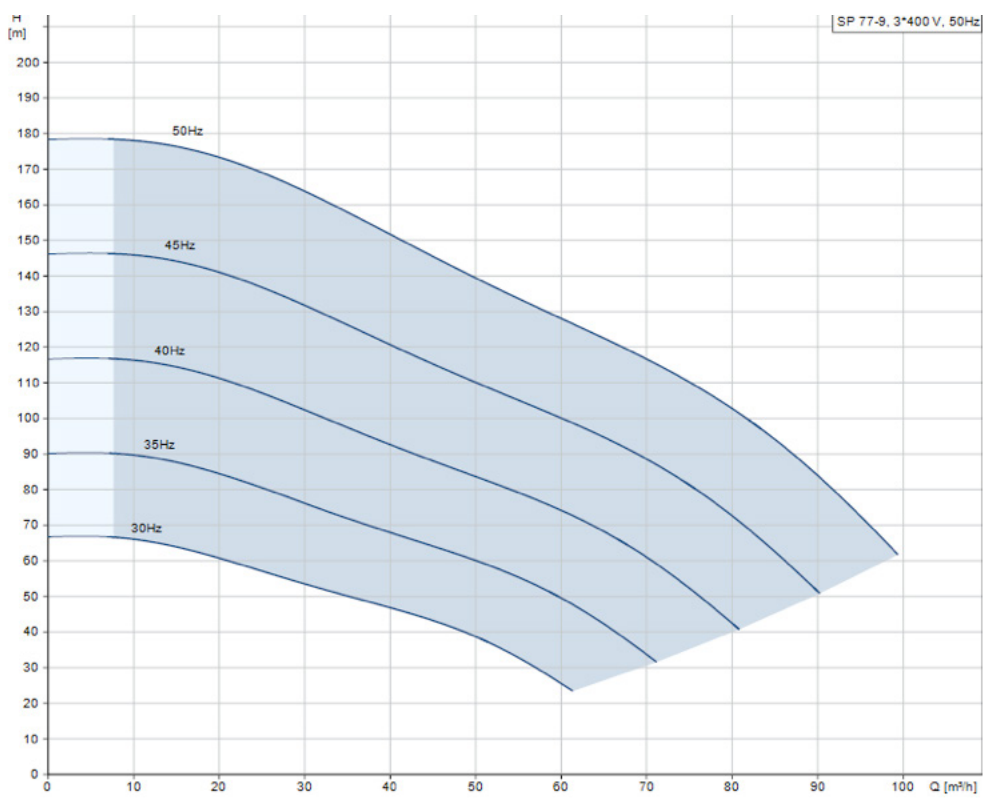


Figure 4.8.b – Pump Performance Curve for Grundfos SP 77-9 at Different Frequencies

These performance curves can then be used to show how the pump with a variable frequency drive will perform (flow and TDH) for the system being designed. This process is detailed in a design example that follows this section (and in Appendix g.). The approximated total amount of water to be produced daily, found by adding together the approximate amount produced each hour, is compared to the daily project water demand (see 2.2 Daily Project Water Demand). If the total is significantly greater or lower than the daily project water demand, then the array must be redesigned. IEC 62253 states that supplied total should be within a tolerance of -5% to +20% of the daily project water demand. If the supplied total is outside of this tolerance, then a redesign is necessary by using either a different size solar panel, a different number of panels, or a different array configuration. If the supplied total is within the tolerance, further confidence in the design could be attained by analyzing the same redesign options.

However, under certain project conditions, it is possible that the -5% to +20% tolerance cannot be achieved. This could be due to many possible causes, such as a restricted amount of area for the solar array installation, inaccessibility of the optimal size or quantity of solar panels, or inaccessibility of the optimal size pump and motor. In this case, an agreement must be made between the water system owner and designer to modify the daily water project demand to match the amount of water that the most optimal system will be able to produce. Failure to do so will lead to a solar powered water system installation that will never be able to meet the expected demands of the users.


Photo courtesy of UNICEF

Example: Designing the PV System for a Solar Pump

(reference IEC 62253 – 6.3 System characteristics, 6.6 Design check of the PV pumping system in respect to the daily water volume)

In a previous example, we determined that the Daily Project Water Demand for a community in rural Kenya was 13,120 litres per day. In a separate example we selected a pump that could supply a desired flow rate of around 2 m^3/hour at a TDH of 60 meters (a Grundfos 11 SQF-2 was selected). After consulting the pump curves for this pump, it was determined that the pump motor will require about 550 W of power to achieve the desired performance. On further review of the manufacturer specifications, it was noticed that the motor has an input voltage range of 30 to 300 VDC and a maximum current draw of 8.4 A.

Step 1: Determine the ambient temperature and solar irradiance conditions for the project site (see Section 2.5.2).

As discussed in **2.5.3. Monthly Temperature and Irradiance Data**, the ambient temperature and solar irradiance fluctuate throughout the year. In order to ensure that the water system will meet the water demand during every month of the year, the PV system will be designed using the data from the month with the lowest irradiance values. After looking at the data available online from National Aeronautics and Space Administration (NASA), we see that during the lowest irradiance month the project location has a daytime average ambient temperature of 20.9 °C and a daily irradiance profile as shown below:

HOUR	IRRADIANCE (W/m^2)
8	327
9	430
10	503
11	551
12	565
13	551
14	503
15	430
16	327

Step 2: Calculate the panel's estimated performance for the project location.

The solar panels most readily available for the project have the following performance under standard test conditions (STC):

- Maximum power point (Pmax): 290 W
- Maximum power point voltage (Vmpp): 31.9 V
- Maximum power point current (Impp): 9.2 A
- Open circuit voltage (Voc): 39.6 V
- Short circuit current (Isc): 9.75 A
- Temperature coefficient (TC Voc): -0.29%/C
- Normal operating cell temperature (NOCT): 46°C

Calculating the panel's estimated performance for the project location is done by working through the equations in **4.1.1.1. Calculating a Panel's Estimated Performance for the Project** Location for each hour of the day. Below we will show the detailed calculations for the irradiance conditions at 12 o'clock.

Step 2a: Calculate the cell temperature.

$$\text{Cell temp } (°C) = \text{Ambient temp } (°C) + (\text{NOCT} - 20°C) \times \frac{\text{Irradiance } \left(\frac{W}{m^2}\right)}{800\ \frac{W}{m^2}}$$

$$39.3°C = 20.9°C + (46°C - 20°C) \times \frac{565\ \frac{W}{m^2}}{800\ \frac{W}{m^2}}$$

Step 2b: Calculate the open circuit voltage at the cell temperature.

$$V_{oc} = \text{STC } V_{oc} + (\text{Cell temp} - 25°C) \times \text{STC } V_{oc} \times \text{TC } V_{oc}$$

$$38.0\text{ V} = 39.6\text{ V} + (39.3°C - 25°C) \times 39.6\text{ V} \times -0.29\%/C$$

Step 2c: Calculate the short circuit current at the given incident irradiance.

$$I_{sc} = \text{STC } I_{sc} \times \frac{\text{Irradiance } \left(\frac{W}{m^2}\right)}{1{,}000\ \frac{W}{m^2}} \qquad 5.51\text{ A} = 9.75\text{ A} \times \frac{565\ \frac{W}{m^2}}{1{,}000\ \frac{W}{m^2}}$$

Step 2d: Calculate the maximum power point current at the given irradiance.

$$I_{mpp} = \text{STC } I_{mpp} \times \frac{\text{Irradiance } \left(\frac{W}{m^2}\right)}{1{,}000\ \frac{W}{m^2}} \qquad 5.2\text{ A} = 9.2\text{ A} \times \frac{565\ \frac{W}{m^2}}{1{,}000\ \frac{W}{m^2}}$$

Step 2e: Calculate the solar panel output under the given conditions.

$$P_{max}\ (W) = V_{oc} \times I_{sc} \times \frac{STC\ I_{mpp} \times STC\ V_{mpp}}{STC\ I_{sc} \times STC\ V_{oc}}$$

$$159.2\ W = 38.0\ V \times 5.51\ A \times \frac{9.2\ A \times 31.9\ V}{9.75\ A \times 39.6\ V}$$

Step 2f: Calculate the maximum power point voltage of the panel.

$$V_{mpp} = \frac{P_{max}}{I_{mpp}} \qquad 30.6\ V = \frac{159.2\ W}{5.2\ A}$$

By following the same steps, the conditions for each hour of the day can be calculated. The results of those calculations are presented in the following table:

HOUR	IRRADIANCE (W/m²)	CELL TEMPERATURE (°C)	VOC (V)	ISC (A)	IMPP (A)	PMAX (W)	VMPP (V)
8	327	31.5	38.9	3.19	3.0	94.3	31.4
9	430	34.9	38.5	4.19	4.0	122.6	30.7
10	503	37.2	38.2	4.90	4.6	142.3	30.9
11	551	38.8	38.0	5.37	5.1	155.1	30.4
12	565	39.3	38.0	5.51	5.2	159.2	30.6
13	551	38.8	38.0	5.37	5.1	155.1	30.4
14	503	37.2	38.2	4.90	4.6	142.3	30.9
15	430	34.9	38.5	4.19	4.0	122.6	30.7
16	327	31.5	38.9	3.19	3.0	94.3	31.4

Step 3: Design the configuration of the solar array.

Now that we know the power output on a single solar panel being considered in this project location, we can take a preliminary estimate of the number of solar panels needed for the array. As stated in a previous example, a target of the design is to produce water during the seven middle hours of the day at a minimum (this will be checked at the end of the example). Therefore, we can divide the required amount of power (550W) by the lowest amount of power per panel during the middle seven hours of the day (122.6W). Doing this roughly tells us that the array will need to consist of about four panels (550 W ÷ 122.6 W ≈ 4).

As discussed in **4.1.2. Solar Array Configuration**, wiring solar panels in series will increase the voltage, and wiring in parallel will increase the current. Also, panels are typically wired in series to achieve the maximum wattage with the least number of solar panels. Thus, the next step would be to check the power output from the array during each hour of irradiance with four panels wired in series (using the equations given in **4.1.2. Solar Array Configuration**). As done previously, we will show the detailed calculations for the irradiance conditions at 12 o'clock.

$$Array\ V_{oc} = V_{oc}\ per\ panel \times number\ of\ panels\ in\ series$$

$$152\ V = 38.0\ V \times 4$$

$$Array\ V\_mpp = V\_mpp\ per\ panel \times number\ of\ panels\ in\ series$$

$$122\ V = 30.6\ V \times 4$$

$$Array\ I_{mpp} = I_{mpp}\ per\ panel \times number\ of\ parallel\ strings$$

$$5.2\ A = 5.2\ A \times 1$$

$$Array\ P_{max}\ (W) = Array\ I_{mpp} \times Array\ V_{mpp}$$

$$634\ W = 5.2\ A \times 122\ V$$

Step 4: Derate the power output from the array.

This calculated power output from the array should be derated to account for power losses (as discussed in **4.1.3. Power Losses**). We will use a derate factor of 0.90 as recommended for a system without an inverter.

$$Array\ P_{derated}\ (W) = Array\ P_{max}\ (W) \times derating\ factor$$

$$571\ W = 634\ W \times 0.90$$

By using the same equations, the conditions for each hour of the day can be calculated. The results of those calculations are presented in the following table:

HOUR	ARRAY V_{OC} (V)	ARRAY V_{MPP} (V)	ARRAY I_{MPP} (A)	ARRAY P_{MAX} (W)	ARRAY $P_{DERATED}$ (W)
8	156	126	3.0	378	340
9	154	123	4.0	492	443
10	153	124	4.6	570	513
11	152	122	5.1	622	560
12	152	122	5.2	634	571
13	152	122	5.1	622	560
14	153	124	4.6	570	513
15	154	123	4.0	492	443
16	156	126	3.0	378	340

Step 5: Verify that the array voltage and amperage satisfy the pump motor specifications.

The supplied voltage and amperage need to be checked against the pump motor specifications. As previously stated, the pump motor has an input voltage range of 30 to 300 VDC and a maximum current draw of 8.4 A. As can be seen in the table above, the array Voc is greater than 30 but less than 300 V. Additionally, since the solar panels are to be connected in series, the current of the array will be equivalent to the current of a single panel, which is less than the maximum current draw of the pump.

Step 6: Confirm that the designed array enables the pump to supply the daily project water demand.

The final check on the design is to see if the power supplied by the array to the pump motor will enable the pump to supply the daily project water demand of 13,120 litres per day. This can be approximated by referring to the pump curve supplied by the manufacturer. As shown in **3.2.2.2. Selecting a Pump using Solar Pump Performance Curves**, the power required by the pump motor is found by locating the point on the pump curve where the desired flow rate meets the TDH line, and then reading the power required at this point. Working backwards, a flow rate can be approximated for the power supplied by the array at each hour of the day. (To do this an assumption is made that the TDH will remain roughly constant, or the TDH can be recalculated at each flow rate for greater accuracy.) Using the pump curves for the Grundfos 11 SQF-2, the following conditions are observed:

HOUR	ARRAY PDERATED (W)	APPROXIMATE FLOW RATE AT 60 M TDH (m^3/HOUR)	HOURLY WATER PRODUCTION (L)
8	340	1.2	1,200
9	443	1.5	1,500
10	513	1.8	1,800
11	560	2.0	2,000
12	571	2.1	2,100
13	560	2.0	2,000
14	513	1.8	1,800
15	443	1.5	1,500
16	340	1.2	1,200
TOTAL DAILY WATER PRODUCTION (L):			15,100

Thus, an approximate of the total daily water produced is 15,100 litres per day. If this number was significantly greater or lower than the daily project water demand (13,120 litres per day), then the array should be redesigned. IEC 62253 states that supplied total should be within a tolerance of -5% to +20% of the daily project water demand. Our approximate total daily water produced (15,000 litres) is 15% greater than the daily project water demand (13,120 litres), so our design meets the requirement. If the supplied total was outside of the tolerance, then a redesign is necessary by using either a different size solar panel, a different number of panels, or a different array configuration.

Example: Designing the PV System for an AC Pump with Inverter

(reference IEC 62253 – 6.3 System characteristics, 6.6 Design check of the PV pumping system in respect to the daily water volume)

This example uses a similar location, with the same temperature and irradiance conditions, and the same solar panel selection of the previous example. This will show the difference in designing a system with an AC powered pump and inverter, as opposed to a pump and motor combination that can take DC power input.

A yield test has been completed on a borehole in a large community in rural Kenya. The test results show that the maximum yield of the borehole is 39 m^3/hour with a dynamic water level of 94.5 meters below the ground. The community would like to access 90% of the maximum yield to produce a daily water volume of 295,000 liters per day from the borehole. Using a design flow of 35 m^3/hour (90% of the 39 m^3/hour yield), hydraulic calculations were performed to find that the TDH of the planned water system will be 102.2 meters. After seeing that all available pump and motor combinations (or PV pump aggregates) that can take DC power input could not perform to the desired capacity, an AC powered pump with an inverter was considered. An AC powered pump and motor was selected that can perform at a duty point of 34.9 m^3/hour and 102.1 meters of head at a required motor power of 14.3 kW. The motor is a 50 Hz, three phase, nominal 380 V motor. The pump and motor manufacturer's literature suggests that an 18.5 kW inverter be used, which matches the power requirements of the motor (50 Hz, nominal 380 V). The inverter has an input voltage range of 400 to 800 VDC and a maximum current output of 38.0 A and is equipped with a variable frequency drive. The appropriateness of the inverter will be checked during the design.

Using the same 290 W solar panels as in the previous example, the performance of an individual panel during the sunlight hours at the project location is as follows (for calculation details, see previous example):

HOUR	IRRADIANCE (W/m^2)	CELL TEMPERATURE (°C)	V_{OC} (V)	I_{SC} (A)	I_{MPP} (A)	P_{MAX} (W)	V_{MPP} (V)
8	327	31.5	38.9	3.19	3.0	94.3	31.4
9	430	34.9	38.5	4.19	4.0	122.6	30.7
10	503	37.2	38.2	4.90	4.6	142.3	30.9
11	551	38.8	38.0	5.37	5.1	155.1	30.4
12	565	39.3	38.0	5.51	5.2	159.2	30.6
13	551	38.8	38.0	5.37	5.1	155.1	30.4
14	503	37.2	38.2	4.90	4.6	142.3	30.9
15	430	34.9	38.5	4.19	4.0	122.6	30.7
16	327	31.5	38.9	3.19	3.0	94.3	31.4

Step 1: Design the configuration of the solar array.

When it is evident that multiple strings of solar panels will be used, the voltage and current parameters of the motor or inverter need to be taken into consideration. For the inverter being considered, the solar panels will need to be combined in such a way that the voltage is greater than 400 V and less than 800 V with a current no greater than 38.0 A. Using these parameters, we can see that the array will have somewhere between 11 (400 V ÷ 38.0 V = 11) and 21 (800 V ÷ 38.0 V = 21) solar panels in series and seven (38.0 A ÷ 5.51 A = 7) or less strings. A thorough design will check different combinations to achieve the power supply required by using the smallest number of solar panels. The remainder of this example will use seven strings of 18 solar panels for a total of 126 panels.

Step 2: Check the power output from the array.

The output of the array should be checked during each hour of irradiance (using the equations given in **4.1.2. Solar Array Configuration**). We show below the detailed calculations for the irradiance conditions at 12 o'clock.

$$\textit{Array } V_{oc} = V_{oc} \textit{ per panel} \times \textit{number of panels in series}$$

$$684.0\text{ V} = 38.0\text{ V} \times 18$$

$$\textit{Array } V_{mpp} = V_{mpp} \textit{ per panel} \times \textit{number of panels in series}$$

$$550.8\text{ V} = 30.6\text{ V} \times 18$$

$$\textit{Array } I_{mpp} = I_{mpp} \textit{ per panel} \times \textit{number of parallel strings}$$

$$36.4\text{ A} = 5.2\text{ A} \times 7$$

$$\textit{Array } P_{max} \textit{ (W)} = \textit{Array } I_{mpp} \times \textit{Array } V_{mpp}$$

$$20.0\text{ kW} = 36.4\text{ A} \times 550.8\text{ V}$$

Step 3: Derate the power output from the array.

This calculated power output from the array should be derated to account for power losses (as discussed in **4.1.3. Power Losses**). We will use a derate factor of 0.85 as recommended for a system with an inverter.

$$\textit{Array } P_{derated} \textit{ (W)} = \textit{Array } P_{max} \textit{ (W)} \times \textit{derating factor}$$

$$17.0\text{ kW} = 20.0\text{ kW} \times 0.85$$

By using the same equations, the conditions for each hour of the day can be calculated. The results of those calculations are presented in the following table:

HOUR	ARRAY V_{OC} (V)	ARRAY V_{MPP} (V)	ARRAY I_{MPP} (A)	ARRAY P_{MAX} (kW)	ARRAY $P_{DERATED}$ (kW)
8	700.2	565.2	21.0	11.9	10.1
9	693.0	552.6	28.0	15.5	13.2
10	687.6	556.2	32.2	17.9	15.2
11	684.0	547.2	35.7	19.5	16.6
12	684.0	550.8	36.4	20.0	17.0
13	684.0	547.2	35.7	19.5	16.6
14	687.6	556.2	32.2	17.9	15.2
15	693.0	552.6	28.0	15.5	13.2
16	700.2	565.2	21.0	11.9	10.1

Step 4: Verify that the array voltage and amperage satisfy the inverter.

Before estimating the amount of water to be produced in these power conditions, the table above can be used to check the appropriateness of the inverter that was suggested by the manufacturer's literature. The suggested inverter is an 18.5 kW, 50 Hz inverter with an input voltage range of 400 to 800 VDC and a maximum current output of 38.0 A. The calculation results in the table above meet the voltage and current conditions of the inverter, and power to be conveyed is appropriately close to the nominal power rating of the inverter.

Step 5: Confirm that the designed array enables the pump to supply the daily project water demand.

By use of the affinity laws and the pump performance curves (see **4.8. Checking System Design to Daily Project Water Demand**), we can now calculate an anticipated amount of water produced each hour. The first step is to calculate the frequency by using the affinity law relationship between power and speed. Note that as stated in section 4.8, frequency can be used interchangeably with speed. The calculation for the conditions at 8 o'clock is shown here.

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3$$

$$N_2 = \left(\frac{10.1kW}{14.3kW}\right)^{1/3} \times 50Hz = 44.5Hz$$

However, as previously stated, the pump motor and inverter are 50 Hz. Thus, the frequency will never exceed 50 Hz. The calculated frequency for each is presented in the following table:

HOUR	ARRAY $P_{DERATED}$ (kW)	FREQUENCY (Hz)
8	10.1	44.5
9	13.2	48.7
10	15.2	50
11	16.6	50
12	17.0	50
13	16.6	50
14	15.2	50
15	13.2	48.7
16	10.1	44.5

Next, performance curves for each calculated frequency are determined. This is done by calculating several points along the performance curve by use of the affinity laws. By taking each calculated frequency and the affinity law relationships between flow and speed, and between head and speed, points along the corresponding pump performance curve for each calculated frequency can be determined. Below are the calculations for a single point along the performance curve that corresponds to a frequency of 44.5 Hz.

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1}$$

$$Q_2 = \frac{44.5Hz}{50Hz} \times 3.2\, m^3/hr = 2.8\, m^3/hr$$

$$\frac{H_2}{H_1} = \left(\frac{N_2}{N_1}\right)^2$$

$$H_2 = \left(\frac{44.5Hz}{50Hz}\right)^2 \times 195.1m = 154.5m$$

(P = Power; N = Speed; Q = Flow; H = Head)

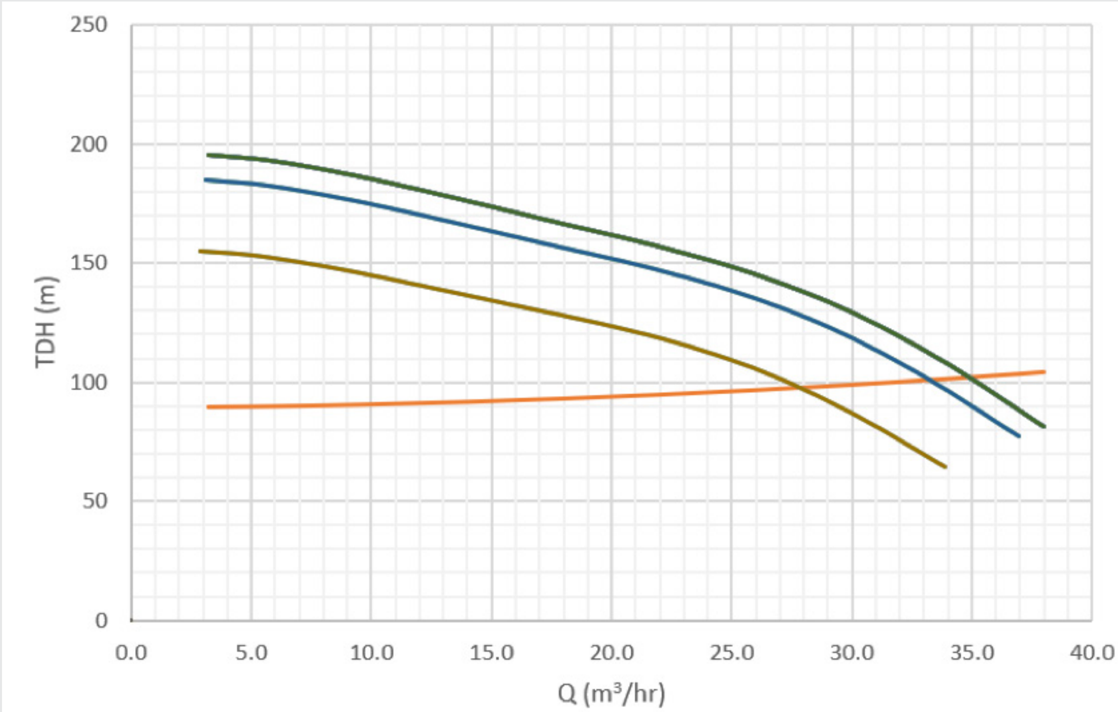
Several points along the performance curve for each frequency will need to be calculated. The calculation results for ten points along the curve are shown below. More or less points will correspond to more or less accuracy, respectively, for the final results. In the table below, we have calculated ten points on the performance curve corresponding to 44.5 Hz by starting with ten points along the full power, or 50 Hz, performance curve.

Points on Performance Curve for 50 Hz	
Q_1 (m^3/hr)	H_1 (m)
3.2	195.1
6	192.4
10	185.0
18	166.2
22	156.7
26	145.1
30	129.3
34	107.7
34.9	102.1
38	81.5

Points on Performance Curve for 44.5 Hz	
Q_2 (m^3/hr)	H_2 (m)
2.8	154.5
5.3	152.4
8.9	146.5
16.0	131.6
19.6	124.1
23.1	114.9
26.7	102.4
30.3	85.3
31.1	80.9
33.8	64.6

These same calculations will need to be performed for the 48.7 Hz performance curve as well.

It is important to recognize that the points (Q_2, H_2) in the table above represent points along a performance curve for the pump, and not points along the system curve for the proposed water system. On the graph below, the green and blue curves are the performance curves for the pump at 50 Hz, 48.7 Hz, and 44.5 Hz.



The orange curve on the graph represents the system curve for the proposed water system. The system curve is determined by calculating the TDH for multiple flow values (As previously stated, this design guide does not present the methods of calculating TDH, because the methods of calculating TDH for a solar-powered pumping system do not change from the methods used with any other mechanized pumping system).

The intersections of the system curve and each performance curve represent the flow rate of the system at the corresponding frequency for each hour of the day. The flow value at each intersection can be observed graphically and can be calculated by the following method. The table below shows the flow and head values along the 44.5 Hz performance curve and the TDH of the proposed water system for each flow.

Q_2 (m^3/hr)	**H_2** (m)	**TDH** (m)
2.8	154.5	89.6
5.3	152.4	89.9
8.9	146.5	90.5
16.0	131.6	92.5
19.6	124.1	93.8
23.1	114.9	95.4
26.7	102.4	97.2
30.3	85.3	99.2
31.1	80.9	100.1
33.8	64.6	101.4

Note in the graph above that the system curve intersects the 44.5 Hz performance curve between 25 m^3/hr and 30 m^3/hr. Additionally, the table above shows that the TDH for 26.7 m^3/hr is below the head of the performance curve, but the TDH for 30.3 m^3/hr is above the head of the performance curve. By using a method of interpolation, we can use these flow rates and the corresponding TDH and performance curve head values to calculate the flow rate where the corresponding TDH of the proposed water system and the head on the performance curve are equal.

$$\frac{(30.3 - 26.7)}{[(99.2 - 85.3) - (97.2 - 102.4)]} = \frac{(Q_{at\ intersection} - 26.7)}{[0 - (97.2 - 102.4)]}$$

$$Q_{at\ intersection} = 27.7\ m^3/hr$$

Note that this flow rate could be checked by calculating the TDH of the proposed water system for this flow rate and checking the head on the pump performance curve to see that the two values are equal.

HOUR	ARRAY PDERATED (kW)	FREQUENCY (Hz)	FLOW (m^3/hour)	HOURLY WATER PRODUCTION (L)
8	10.1	44.5	27.7	27,700
9	13.2	48.7	33.2	33,200
10	15.2	50	34.9	34,900
11	16.6	50	34.9	34,900
12	17.0	50	34.9	34,900
13	16.6	50	34.9	34,900
14	15.2	50	34.9	34,900
15	13.2	48.7	33.2	33,200
16	10.1	44.5	27.7	27,700
			TOTAL DAILY WATER PRODUCTION (L):	**296,300**

The approximate total daily water produced (296,300 liters) is less than 1% greater than the daily project water demand (295,000 liters), so our design meets the requirement of IEC 62253 to be within a tolerance of -5% to +20% of the daily project water demand.

5. Water Storage

5.1. Water Storage Considerations

Most rural water supply systems, including solar powered systems, use a water storage tank to balance the daily water production of the system with the daily water demand of the users. For this reason, use of a water storage tank is recommended.

Water Storage

Most rural water supply systems, including solar powered systems, use a water storage tank to balance the daily water production of the system with the daily water demand of the users.

Photo courtesy of Water Mission

5.2. Water Storage Tank Volume

(reference IEC 62253 – 6.2 Customer data, e. Project description)

It is common practice to store water in a tank prior to distributing the water to consumers. Regardless of the water distribution design after the storage tank (a design process that is not discussed as a part of this guide), the size of the water storage is typically based on the water system's daily demand volume and pattern. For solar powered systems, the variance in water produced throughout the day should also be considered, as water production will be restricted to hours of sunlight and may be limited by overcast weather. Therefore, water storage tanks can be used to supply water during non-pumping hours or on days when weather may affect the production of safe water.

Though this guide does not specify a particular method for determining a water storage tank size, the final choice should be made by comparing the daily water demand pattern with the daily water production of the system. The minimum recommendation of this guide is that the storage tank be sized such that the water supplied to users is not disrupted by daily (and monthly) fluctuations in the water produced by the solar powered supply system. However, it is also recommended that excessive water storage be avoided. The capital costs associated with construction and installation of water storage are typically high. Thus, inclusion of a large storage volume that is not needed on a project will lead to significant costs which are unjustified and unnecessary. Additionally, excessive water storage should be avoided, because prolonged water storage typically leads to deterioration in water quality.

Additional considerations in determining a water storage tank size could include:

Emergency storage: Supply interruptions can happen for multiple reasons, including contamination of a source, maintenance of the water system, and extreme weather events. For these breaks in service, communities rely on water storage during the supply interruption caused by the emergency. The amount of emergency water storage is dependent on the probability and potential consequences of a break in service.

Peak days: Tank sizing should consider abnormal days that may require especially large quantities of water. While it may not be practical to design an entire system for a peak day, extra storage can provide enough water for a particular day or days of increased demand.

Existing water system losses: If an existing system is used as a part of a water system, existing losses should be considered. A certain amount of waste should be accounted for the design flow of the entire system, including the water storage tank. The tank will need to store this water even if it is ultimately lost.

If any of the above are of concern in a project, storage capacity should be added to the minimum storage calculation. The capacity added should be based on sound engineering judgment that assesses the likelihood and severity of these factors.

5.3. Tank Support Design

If a water storage tank is to be part of the system, a proper tank support must be identified and designed as a part of the full water system design. Any elevated support structure for the tank must be designed to support the weight of the tank at full storage capacity and to withstand wind, seismic, and snow loads common to the water system's location. Since the calculated TDH of the water system is dependent on the height of the water storage tank, it is critical that the height remain in accordance with the original calculation of the system TDH.

6. Design Documentation

(reference IEC 62253 – 6.5 Documentation)

All solar powered water system designs must be well documented to provide a reference of the design to all project parties. Each step of the design including the data used, the assumptions made, the design process and calculations performed, and the complete results must be included in the documentation. This documentation is commonly used for the following purposes:

- To verify to all governing authorities and involved parties that the design meets the relevant requirements and agreements for the solar powered water system
- To inform the requirements of the project installation and construction
- To serve as a lasting record for any future inquiry into the design of the system

INSTALLATION

Photo courtesy of Water Mission

C. INSTALLATION

7. Installation and Construction Safety

The project entity assigned to the management of the project construction is responsible for providing, maintaining, and enforcing safety standards among all parties involved in the construction and installation.

In addition to the safety of the workers on the project, any safety concerns that observers of the project may face must also be addressed and mitigated. People in a rural community, especially children, may have a lot of curiosity about the construction of a solar powered water system. It is the responsibility of the project entity assigned to the management of the construction project to ensure the safety of the general public around the project.

7.1. Electrical Safety

Working with electricity in an unsafe manner may cause burns, shocks, or electrocution (death). Working with solar-generated electricity is no different, and measures must be taken to keep workers safe. In addition, since the topic of this guide is solar powered water supply systems, it must also be stressed that all electrical components and all work on those components must be guarded from contact with water. The necessary exception to this rule is any piece of equipment specifically designed to be in contact with water (such as the pump and pump motor). All components must be handled per all manufacturers' requirements and recommendations.

Other general rules when working with electricity include:

- All electrical work should be performed by qualified and authorized electricians.
- All electrical equipment must be grounded per manufacturer requirements and recommendations.
- All contact with energized electrical circuits must be avoided.
- All electrical devices should be assumed to be energized until proof of disconnection is made evident.
- Power must be disconnected prior to installing or servicing any electrical system component.
- If it is necessary to handle equipment that is energized, measures should be taken to protect the worker, such as using only tools with non-conductive handles, keeping hands and the work area dry and free of water, and wearing non-conductive clothing (e.g., shoes and gloves).
- If water is ever spilled onto an electrical component, immediately disconnect the power to the component.
- Finally, enclose all electrical contacts, conductors, and components to keep others safe.

7.2. Safety Working at Heights

If the design of the solar array rack includes placing the solar panels at a height of 1.5 m or higher (taken at the lowest edge of the panels), then the safety of those installing the racks and solar panels must be considered. Any risk of workers falling must be addressed and mitigated.

8. Supervision and Inspection

All installation and construction activities must be supervised to ensure quality workmanship. Additionally, each component of the system must be inspected upon completion of the installation or construction of the component. The purpose is to ensure that every component of the solar powered water system is installed according to the system design and according to the equipment manufacturer's specifications. This includes, but is not limited to, the initial mobilization of each contractor, the make and model of each system component, the routing and location of each component, the installation and construction methods, the proper protection of each component, the system organization and cleanliness, etc. The recommendation of this guidance document is for the engineer of record, the owner of the water system, or their appointed representative to provide this supervision and inspection.

9. Water System Installation

9.1. All System Components

All construction and installation must be performed in accordance with all local codes and standards (see **2.1. Water System Compliance**).

Every component of the water system constructed must match the water system design. This includes but is not limited to the water source, the piped system, the water treatment system (if applicable), the pump, the water storage tank, and the location of each component. The TDH required of the pump by the constructed water system must match the TDH used in the selection of the project pump and motor during the design. As such, all pipe routing, pipe lengths, pipe diameters, pipe materials (and roughness factors), pipe components, treatment systems, locations, and elevations of key items in the system must match those used in the design of the water system.

Any deviation from the system design in the installation of the system will affect the final performance of the water supply system. Therefore, these deviations may very well lead to a different daily water production than what the system was intended to supply. For that reason, any deviation from the design, for any reason, shall only be made in consultation with, and with approval from, the design engineer of record for the project.

Upon completion of the entire water system installation, the site must be clean and free of all soil and debris that may have accumulated during construction. Additionally, all construction equipment, construction spoils, and by-products must be removed from the site. Accumulated soil and debris left unmanaged at a solar powered water system site could negatively impact the proper operation of the water system. This could include worsened water source quality (if soil and debris enter the water source), poor production of power from the solar array (if dust and soil accumulate on the solar panels), and unnecessary complications to the ongoing system maintenance routines. The construction contract documents must assign ownership and responsibility for the removal of construction equipment and the removal and/or disposal of soil, debris, construction spoils, and by-products.

Photo courtesy of Water Mission

Piping

All buried piping must be properly backfilled to provide adequate support and protection to the pipe.

9.2. Piping

All piping installed as a part of the water system must be free of leaks upon completion of construction. To ensure adherence to this requirement, it is recommended that all pipelines be pressure tested prior to backfilling the pipeline trench to check for leaks. Additionally, all completed pipelines must be disinfected with chlorine and flushed prior to being placed into service as part of the water supply system.

All piping must be buried a minimum a 1 meter (3.3 feet) below grade, except in the following locations or circumstances:

- Transition from the water source intake
- Transition to any system water treatment components
- Transition to a water storage tank
- Transition to any other above-grade component necessary to the water system design

Additionally, if rocks or other obstacles are encountered during construction, causing difficulty with or preventing installation according to the design and specification, a description of the encountered obstacle and the subsequent difficulty should be submitted to the design engineer of record for review. This gives the design engineer the opportunity to analyse how a revision in the pipe routing would affect the system design. Approval from the design engineer of record must be granted before the change is implemented by the contractor. Along with the approval of the revision, additional measures to protect the pipe may be deemed necessary, such as encasing the pipe in concrete or using a casing pipe.

All buried piping must be properly backfilled to provide adequate support and protection to the pipe. Additionally, all trenching excavations must be backfilled and compacted. After burial of the pipeline, if any pipeline leaks are made evident by soft, moist soil along the pipe route and/or ponding water above a pipeline (not due to rainfall), the leaks must be corrected by the contractor responsible for the installation of the pipeline.

All above-ground piping must be installed plumb and level. All above-grade piping must be strapped and secured to the structural components of the water system (e.g., structural members, platforms, or buildings). Under no circumstance shall piping be required to support its own weight or the weight of the water it carries. Supports must be installed to avoid any sag or movement of the piping during operation of the water system.

10. Pump and Motor Installation

10.1. Pump and Motor Installation

The pump and motor installed must match the selection made during the design phase. The flow and TDH required of the pump used must match the flow and TDH used in the design. Use of an alternate pump and motor shall only be permitted with approval of the design engineer of record on the project.

10.2. Pump Installation

10.2.1. Water Source

The water source used in the construction of the water system must be the source used in the design of the system. Use of a different water source would change the design of the solar powered water system. For this reason, the use of an alternate water source for any reason will not be permitted without a review of the water system design by the design engineer of record on the project.

10.2.1.1. Source Yield

If a yield test on the water source was not completed prior to selecting a pump and motor, then a yield test must be completed prior to the pump and motor being installed. For a complete presentation of yield testing, see **2.3.1. Source**

Yield. The yield, or allowable yield, of the source must exceed, or be equal to, the design flowrate. If the yield, or allowable yield, of the water source is less than the design flowrate, the water system design must be reviewed, and perhaps redesigned, by the design engineer of record on the project before installation can proceed.

10.2.1.2. Source Protection

The water source must be secured against any potential negative impacts on the quality of the water. This includes protection during construction of the solar powered water system, as well as measures to protect water quality in the future. Degradation in water quality could have possible negative effects on the pump and motor. (It should also be noted that degradation in the water quality could require a change in water treatment method, which could then change the flow and TDH of the system. This may require use of a different pump and motor and solar array configuration.)

During construction of the solar powered water system, rainfall runoff must be controlled to ensure that it does not run over disturbed soil and construction materials and into the water source. This could introduce sediment, chemicals, construction materials, and other contaminants into the water source. Instead, rainfall runoff must be routed past the water source, and/or the water source must be fully protected from allowing the entrance of any flow of water from the construction site. In the case of a submersible pump in a borehole, proper protection includes a high-quality well cap with sanitary seal.

As previously discussed, at the completion of the water system construction, the site must be clean and free of all soil and debris that may have accumulated due to the construction. Additionally, all construction equipment, construction spoils, and by-products must be removed from the site. Amassed soil and debris left unmanaged at a solar powered water system site could negatively impact the water quality of the source water if they are allowed to enter the water source.

10.2.2. Pump and Motor Installation Requirements

The pump and motor must be installed per the manufacturer's requirements and recommendations and according to the instruction of the project's design engineer of record. This includes but is not limited to: the pump location in relation to the water level (or dynamic water level); the net positive suction head requirements of the pump; all wiring requirements of the pump; any run-dry sensor requirements; any pump priming requirements; any protection measures; and any future maintenance measures.

All wire connections to the motor must be installed in accordance with the manufacturer's requirements and recommendations, including wire type and terminal connection location(s).

10.3. Ancillary Pump and Motor Equipment Installation

All ancillary components installed with the pump and motor, including disconnect switches (or circuit breakers), control units, inverters, float switches, and run-dry sensors (or switches), must match the selections made in the design of the system. Use of any alternates shall only be permitted with approval from the design engineer of record on the project.

Additionally, all ancillary equipment must be installed in compliance with the requirements and recommendations of the component manufacturer and according to the instruction of the design engineer of record for the project. All supplemental components must be securely fastened to a structural surface (e.g., the interior wall of a building) in the proper orientation according to the manufacturer's requirements and recommendations. All wire connections to these components must conform to the manufacturer's requirements and recommendations, including wire type and terminal connection location. All wire grips used on wiring entering or leaving a component must be properly tightened to guard against unprotected openings in the component. All electrical components must be properly grounded per the component manufacturer's requirements.

10.4. Ancillary Pump and Motor Equipment Wiring

(Note: Refer to **7. Installation and Construction Safety** regarding safety of all electrical construction tasks.)

All electrical wiring must be installed in congruence with all electrical codes relevant to the project location (such as IEC or NEC codes). All wiring used in conjunction with the pump and motor and ancillary equipment, including wiring between the motor and the control unit, wiring associated with a float switch or run-dry sensor/switch, and all grounding wiring, must be in accordance with the wire identified in the design of the system (see **4.3. Electrical Wire Requirements**). Use of any alternatives shall only be permitted with approval from the design engineer of record on the project.

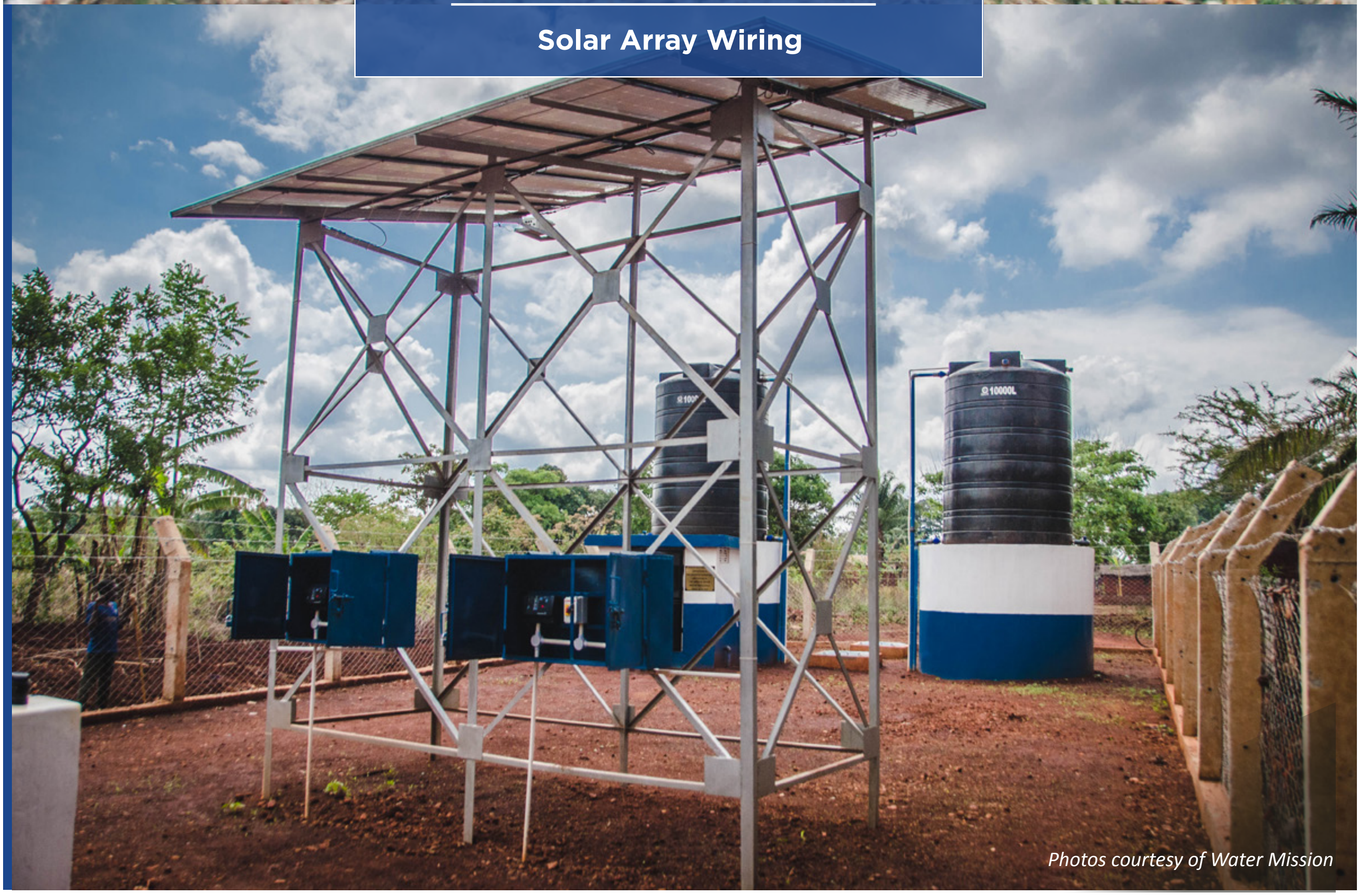
All buried wiring must be rated for direct burial and buried a minimum of 1 meter (3.3 feet) below grade. All buried wiring not rated for direct burial must be enclosed in electrical rated conduit. Additionally, all trenching excavations must be backfilled and compacted. If rocks or other obstacles are encountered, causing difficulty with or preventing installation according to the design and specification, a description of the encountered obstacle and the subsequent difficulty shall be submitted to the design engineer of record for review. Approval from the design engineer of record must be granted before any deviation from the design (and construction specification) is enacted by the contractor. Along with the approval of the revision, additional measures to protect the wire and/or conduit may be deemed necessary, such as encasing it in concrete or using a casing pipe.

All non-buried wiring must be enclosed in electrical conduit (except for the vertical section of wire in a borehole for a submersible pump discussed above). All above-ground conduit must be installed plumb and level. All conduit must be firmly strapped and secured to structural components of the water system (e.g., structural members, platforms, or surfaces of buildings). Under no circumstance shall conduit be installed in a manner in which it is supporting its own weight or the weight of the wiring it carries. Supports must be installed to avoid any sag or movement of the conduit. Protect all unenclosed conduit ends from intrusion of water, insects, or other unwanted material.

Photo courtesy of Water Mission

PV System Installation and Construction

Solar Array Wiring



Photos courtesy of Water Mission

All wiring must be properly connected. Under no circumstance shall bare wire remain exposed. Accordingly, stripped wire ends must be kept to a minimum to make a proper connection. Connections made inside of electrical equipment or associated components and boxes must keep stripped lengths of bare wire to a minimum. Use properly sized splices and connectors according to the size and type of wire.

11. PV System Installation and Construction

(reference IEC 60364-7-712)

11.1. Solar Panel

The solar panel used in the construction of the solar array must match the nominal rating and specifications selected during the design (see **4.1.1. Solar Panel Selection**). Use of an alternate solar panel shall only be permitted with approval of the design engineer of record on the project. All panels in the solar array should adhere to the same specifications, including maximum power point voltage (Vmpp), maximum power point current (Impp), open circuit voltage (Voc), short circuit voltage (Isc), temperature coefficient at Voc (TC Voc), and normal operating cell temperature (NOCT). Additionally, the dimensions of the solar panels installed must match the dimensions needed to comply with the design of the solar array rack (see **11.5. Solar Array Rack**).

Any solar panel selected must comply with IEC International Standards:

• IEC 61215 Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval

• IEC 61646 Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval

• IEC 61730-1 Photovoltaic (PV) module safety qualification – Part 1: Requirements for construction

• IEC 61730-2 Photovoltaic (PV) module safety qualification – Part 2: Requirements for testing

11.2. Solar Array

The solar array configuration (i.e., the number of solar panels in series and the number of parallel strings) must match the design configuration (see **4.1.2. Solar Array Configuration**). The tilt angle of the solar array and the cardinal direction that the solar array faces must match the design requirements (see **4.2. Further Installation Requirements**). Any deviation in the configuration, tilt angle, or cardinal direction of the solar array, for any reason, will necessitate review and approval by the design engineer of record on the project.

All solar array design and installation must be in compliance with IEC 62548 Design requirements for photovoltaic (PV) arrays.

11.3. Solar Array Wiring

(reference IEC 60364-7-712)

All wiring used in the construction of the solar array, including wiring between individual solar panels, wiring from the solar array to the pump and motor, and all grounding wiring, must be in conformance with the wire identified in the design of the system (see **4.1. Solar Array Design**). Use of any alternatives shall only be permitted with approval from the design engineer of record on the project.

All buried wiring must be rated for direct burial and buried a minimum of 1 meter (3.3 feet) below grade. All buried wiring not rated for direct burial must be enclosed in electrical rated conduit. Additionally, all trenching excavations must be backfilled and compacted. If rocks or other obstacles are encountered, causing difficulty with or preventing installation according to the design and specification, a description of the encountered obstacle and the subsequent difficulty shall be submitted to the design engineer of record for review. Approval from the design engineer of record must be granted before any deviation from the design (and construction specification) is enacted by the contractor.

Along with the approval of the revision, additional measures to protect the wire and/or conduit may be deemed necessary, such as encasing it in concrete or using a casing pipe.

All non-buried wiring must be enclosed in electrical conduit (except for sections of individual solar panels discussed below). All above-ground conduit must be installed plumb and level. All conduit must be firmly strapped and secured to structural components of the water system (e.g., solar rack members or surfaces of buildings). Under no circumstance shall conduit be installed in a manner where it is supporting its own weight or the weight of the wiring it carries. Supports must be installed to avoid any sag or movement of the conduit. All unenclosed conduit ends must be protected from the intrusion of water, insects, or other unwanted material.

The only non-buried, non-conduit enclosed wire shall be the horizontal sections to the leads of individual solar panels. This wiring must be kept directly beneath the solar panels and securely fastened to the solar panel frames and solar array rack. Vertical sections of wire from the solar array rack to the ground must be enclosed in electrical conduit.

All wiring sections must be properly connected. Under no circumstance shall bare wire remain exposed. Accordingly, in order to make a proper connection, stripped wire ends must be kept to a minimum. Connections made inside of electrical equipment or associated components and boxes must keep stripped lengths of bare wire to a minimum.

Connectors used to connect the solar panel leads to the solar array wiring must be the same make and model as the connectors that come installed on the solar panel by the solar panel manufacturer. Use of any alternates shall only be permitted with approval from the design engineer of record on the project. The installation of a connector onto a wire must always be made in accordance with the connector manufacturer's requirements and recommendations.

The solar array must be properly grounded per the design requirements and the solar panel manufacturer's recommendations.

All wiring must be in compliance with IEC 60364-7-712, 60947-1 and 62253.

11.4. Supplemental Solar Array Components

All ancillary components used in the construction of the solar array, including all disconnect switches (or circuit breakers), combiner boxes, and other elements that conduct power, must be in conformance with the components identified in the system design (see **4.4. Identify Supplement Solar Array Components**). Use of any alternates shall only be permitted with approval from the design engineer of record on the project.

All ancillary components must be properly oriented and securely fastened to a structural surface (e.g., the interior wall of a building) according to manufacturers' requirements and recommendations. All wire connections to these components must be in accordance with the design requirements and the manufacturers' recommendations. All wire grips used on wiring entering or leaving a component must be properly tightened to guard against unprotected openings in the component. All electrical components must be properly grounded according to the design requirements and the component manufacturer's recommendations.

11.5. Solar Array Rack

The solar array rack must accommodate the requirements set forth in **4.5. Solar Array Rack Design** (including configuration, tilt angle, and cardinal direction). The rack shall be constructed per the design for the PV system (see **4. PV System Design**). This includes the location, the height of the solar panels above the ground, measures to prevent or resist corrosion of the rack, any security measures to deter theft and vandalism of the solar panels, and any future maintenance plans. Any deviation in the design shall only be permitted with approval from the design engineer of record on the project.

As discussed in **4.5.2. Other Rack Design** Considerations, the rack structural members must be painted, galvanized, or made of material that resists or prevents rust, corrosion, and other damage. This includes providing means to prevent water from entering the interior of hollow structural members that would encourage rust.

Similarly, all fasteners and hardware shall be composed of corrosion-resistant material.

12. Water Storage Construction

12.1. Storage Tank Installation

If a water storage tank is part of the water system design, then the water storage tank must match what was specified in the design, including volume and location (see **5. Water Storage**). Use of any alternative shall only be permitted with approval from the design engineer of record on the project. Water storage tanks installed as a part of the water system must be free of leaks upon completion of construction. Additionally, completed water storage tanks must be disinfected with chlorine and flushed prior to being placed into service as a part of the water supply system.

12.2. Tank Support Structure Construction

All structures used to support the water storage tank must be constructed in accordance with the design of the water system (see **5.3. Tank Support Design**). Any deviation from the design shall only be permitted with approval from the design engineer of record on the project.

Photo courtesy of Water Mission

COMMISSIONING

Photo courtesy of Water Mission

The structure must provide a level surface to support the tank. If concrete is to be used as a part of the tank support structure, it is recommended that the concrete be allowed to cure for a minimum of seven days prior to the placement of the storage tank on the structure.

D. COMMISSIONING

13. System Testing

(reference IEC 62253 – 6.6 Design check of the PV pumping system in respect to the daily water volume)

Upon completing the installation of all major components of the project, each component shall be commissioned by the installer of that component in the following manner. In the presence of the design engineer of record or owner's representative, the component must be operated and must perform according to the design of that component. This includes commissioning of the PV system, pump and motor, piping, and water storage. Any failure to meet required performance shall be rectified by the installer of that component. The component commissioning must then be repeated. All components are required to perform according to the design of the system. IEC 62253 allows for a maximum uncertainty of 3% in the measurement used to assess performance.

13.1. PV System Testing

The following tests must be conducted, with the results included in the installer's report of completion:

- Measure the voltage coming into the pump motor controller from the solar array. The measured voltage must be within 5% of the design.
- If a disconnect switch (or circuit breaker) has been installed with the solar array, place in the disconnect (or circuit broken) position, and measure the voltage coming into the pump motor controller from the solar array. The measured voltage must be zero.

14. Documentation

(reference IEC 62253 – 6.5 Documentation)

Final documentation must be provided to the solar powered water system owner before the project is considered complete and ready for full operation. This documentation shall include:

a. Design Documentation (see **6. Design Documentation**)
b. Installation Records
c. Operation and Maintenance Handbook
d. Warranty Information

Installation records consist of drawings depicting the full system including location, identification, sizes, and routing (including, but not limited to, pump, motor, pump controls, solar array, wiring, piping, water storage tanks, etc.). All differences between the design documentation and the installation documentation shall be clearly noted, with the installation documentation being the actual record of all components installed.

The operation and maintenance handbook must cover the following topics in a manner that is clear and easy to comprehend:

- The standard operation of all equipment, including troubleshooting measures and interpretation of status and error indicators
- Instructions for correcting or reinstating after system errors or faults
- Instructions on all necessary safety measures
- Instructions on all maintenance measures, including recommended service schedules
- All necessary referencing to the installation records

Warranty information provided must consist of all equipment warranties provided by the equipment manufactures. This may include, but is not limited to, the pump, motor, pump controls, solar panels, etc. Product supplier are generally responsible for managing manufacturer warranties on equipment. Typical equipment warranties are:

- Solar panels: 25 years on performance and 10 years on manufacturing defects
- Power conditioning equipment and inverters: 5 years
- Pumps and motors: 2 to 5 years

Additionally, warranties on the installation and construction of the major components of the project must be provided. This would consist of a warranty on the materials, components, and quality of workmanship. The duration of warranties covering installation and construction must be agreed upon between the owner of the solar powered water system and the party responsible for the installation or construction of each component. A two-year warranty duration from the final system commissioning date is recommended (one-year warranty duration is the minimum required).

15. Equipment Replacement Information or Spares

Information required to procure and replace major system components must be supplied to the solar powered water system owner for future use. All parties should understand that when the lifetime of components and equipment has passed, it is possible that the procurement and replacement information will be obsolete. Yet obsolete information is preferable to zero information.

In addition, it is recommended for the solar powered water system owner to consider procuring spares of the major equipment components at the time of the initial system commissioning, if future procurement of those items will be problematic. This is particularly the case in countries or regions where supply chains of the components of a solar powered water system are not robust or present. However, procurement of any piece of equipment that will be set aside until a future use date should also be considered in light of the relevance of that piece of equipment to the future requirements of the system as a whole. For example, if a second pump of the same model installed in the original system is purchased to keep for the future date when the current pump is no longer functional, the potential growth of the daily project water demand due to increase in population or increase in water usage will need to be supplied by that pump. Thus, any procurement of spare components to be used in the future must be carefully evaluated, but consideration of spare components is the recommendation of this guide.

E. SUPPLEMENTARY TOPICS

16. Introduction to Operation and Maintenance of Solar Powered Water Systems

The focus of this guidance document is on design and installation. However, there are other topics within solar powered water systems that are of high importance. One of those topics is operation and maintenance. To give recognition to this importance, the following section is included here as an overview of the roles and responsibilities that are necessary to sustainably operate and maintain solar powered water systems from a technical and financial perspective.

Before we discuss the ongoing activities that are required to operate and maintain solar powered water systems, it is important to acknowledge that the feasibility of proper operation and maintenance for these systems is critically dependent on the service delivery arrangements that are in place, even more so than on the durability of the technology itself. The fundamental question that should be addressed before a solar powered water system is commissioned is: who will own the water system assets over the long-term? The answer to this question will then determine who has the liability to maintain the system and the authority to delegate this responsibility. The division of all ongoing responsibilities, whether technical or non-technical, must be clearly articulated in contractual agreements, and all actors must have the capacity to meet their commitments. This means that community-based actors, such as water user committees, will need to be properly trained and professionalized. Additionally, some responsibilities may need to be delegated to higher skilled private sector entities. The service delivery arrangements should also establish and uphold warranty and defect liability periods ideally for two or more years (minimum requirement of one-year). The arrangements will also need to plan for eventual overhaul and replacement of equipment. Most importantly, a feasible plan for covering ongoing costs through a combination of funds from tariffs, taxes, and transfers needs to be in place.

Additionally, there are some common technical issues experienced by solar powered water systems, such as vandalism, theft, and electrical failures. Proper operation and maintenance can help to avoid or address these issues. As previously discussed in this guidance document, plans can be made during the design of the solar array to help ensure that the operation and maintenance will be successful (see **4.5.2. Other Rack Design Considerations, 4.5.3. Security of the Solar Panels**, and **4.7. Solar Array Maintenance**).

It is good practice to develop a day-to-day operation plan, so that all actors have a clear understanding of what activities will need to be conducted and at what frequency. Typical system maintenance consists of relatively simple activities that yield significant results when performed on a regular basis. These activities typically include providing security, cleaning the solar array, monitoring performance, collecting user payments or tariffs, making minor repairs, and keeping records. These activities are conducted on a daily, weekly, or less frequent basis. Other activities will take place on a quarterly, yearly, or once-per-system-life basis. This may include complex diagnostics and repairs, component replacement, and warranty issues. The importance of good record keeping of water volume produced, tariffs collected, changes in groundwater levels, repairs made, and other activities is of critical importance. This information can be used to prevent conflicts, indicate sustainability of groundwater withdrawals, and is usually necessary to fulfill product warranties. Failure to routinely perform these activities will result in costly repairs that could have been avoided and eventual system failure.

The simplest but most impactful ongoing maintenance activities associated with solar powered systems are routine cleaning of the solar panels and maintaining the site around the array. This is done to ensure that no shade is cast on the array at any point during the day. The power output of the array will decrease due to accumulation of dust (see **4.1.3. Power Losses**). Additionally, an array that becomes shaded during certain times of the day due to trees, buildings, or other obstructions, will not produce the full amount of power that it is capable of producing (see **4.1.3. Power Losses**).

17. Solar Powered Water Systems in Humanitarian Disaster Response

After a disaster the most important tasks, following search and rescue, fall into the categories of medical, shelter,

Photo courtesy of Water Mission

food, and water. When it comes to providing safe water for disaster victims and aid workers, the most common solutions are water trucking and water production powered by a generator. However, solar powered water systems present a viable option in humanitarian disaster response as well. The following section addresses some of the reasons that solar powered applications should be considered.

The first reason to consider is that solar powered water systems typically have lower operational and maintenance costs. These costs are typically lower, because solar powered systems do not use fuel and oil. After a disaster, fuel is often in short supply or difficult to procure. Civil unrest, damaged infrastructure, and physical barriers make transportation and delivery of fuel problematic. If fuel is accessible, it can often have a high cost due to the limited supply and difficult delivery. Additionally, before WASH responders can move on to other communities and locations, they must determine who will be responsible for the technical operation and the financial sustainability of the water system. If operational costs are high due to fuel costs, this can be a difficult burden to place on a recovering community or on other relief organizations. Using solar powered water systems eliminates these costs. Also, generator care and troubleshooting require a lot of time and attention. This also adds to the maintenance costs and commands a community members time that they could be using in other important areas after a disaster. In general, maintenance requirements and costs tend to be lower for solar systems as compared to generator systems.

The next reason to consider is the practicality of the power supply for a water system. When systems get above a certain size, mobility of the equipment needs to be taken into account. It is typically easier to move solar panels to a site, as opposed to a large generator. For example, a 50kw generator could weigh upwards of 1,500 lbs. (700 kg) and will require a truck for transportation. Solar panels can be hand-carried to a site individually. A team can hand-carry 50kw of panels, which is especially important for sites that are hard to access after a disaster. In addition, solar systems can be scaled depending on the project. This allows for greater flexibility among varying communities. Finally, solar panels are silent and give off no exhaust. Therefore, they do not create noise and air pollution as a generator does. This can be especially valuable after a disaster when people are on high alert and are potentially sleeping in camps or relief centers near water system equipment.

Finally, the long-term value and sustainability of solar powered water systems must be considered. Generators, especially small verities and those outfitted with wheels, tend to become targets of theft. Solar panels can be secured in a welded frame making them hard to steal without stealing the entire frame, which is heavy and usually bolted to a structure. In addition, the lifespan of a solar power system is longer than that of a generator. Therefore, a longer service life even well beyond disaster recovery is typical.

Solar powered water systems can be an excellent option for getting people safe water quickly in a humanitarian disaster response. Each disaster will be different, but operation and maintenance costs, practicality, and sustainability all need to be considered when determining how to power the water system.

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APPENDICES

Photo courtesy of Water Mission

H. APPENDICES

a. Appendix

BASIC STEPS TO DESIGNING A SOLAR POWERED WATER SYSTEM There are five basic steps involved in designing a solar powered water system.	
STEP 1 | Calculate the daily water demand for the project.	
Reference in Guidance Document:	2.2. Daily Project Water Demand
Question to answer:	What is the water demand that the solar powered water system will be designed to produce?
STEP 2 | Determine the yield of the water source available to the solar powered water system.	
Reference in Guidance Document:	2.3. Water Source
Question to answer:	Does the yield of the water source meet or exceed the demand calculated in Step 1?
STEP 3 | Determine the total dynamic head (TDH) of the water system at the chosen design flow.	
Reference in Guidance Document:	2.4. Water Supply System Design Layout 3.1. Design Flowrate
Question to answer:	What is the design flow and TDH that the pump will be required to meet?
STEP 4 | Select a pump and motor.	
Reference in Guidance Document:	3.2. Pump and Motor Selection (or PV Pump Aggregate Selection) 3.3. Power Required 3.4. Manufacturer Specifications
Question to answer:	What are the power requirements of the pump motor to achieve the desired pump performance?
STEP 5 | Design the PV system.	
Reference in Guidance Document:	4. PV System Design
Question to answer:	How will the solar array need to be configured to supply the power required by the pump motor?
As this Guidance Document shows, each system may have specific considerations that need to be accounted for in the system design details. However, these five steps constitute the major building blocks of each system, and no solar powered water system design is complete without them.	

b. Appendix

Example: Calculating Daily Project Water Demand

(reference IEC 62253 – 6.2 Customer data, d. Water demand)

A community in rural Kenya currently collects drinking water from three sources: a borehole fitted with a handpump, a river, and seasonal streams that have no flow during the dry season. The population of the community has grown, and there are always long queues at the handpump. In addition, the river is not easily accessible by everyone as it is on the far west side of the community. A funding source has become available to design and install a solar powered water system to better serve the community's safe drinking water needs.

The community is made up of 350 households, and the average number of people per household is six. Additionally, there is a school in the community with 700 students, and all 700 students reside in the community.

After discussing the water needs with the community leaders, it is determined that the daily water use per person has the following pattern.

WATER USE	PER PERSON PER DAY
Drinking and Cooking	4 to 6 litres
Basic Hygiene	2 to 4 litres
Productivity (livestock, irrigation, laundry, other uses)	0 to 6 litres
TOTAL DAILY WATER USE:	6 to 16 litres

Step 1: Determine the total population intended to be served by the system.

Before we use the equation provided in **2.2.1.1. Population Types – Households**, we need to ask the question if all 350 households are intended to be served by the system. Will these households truly have access to the water provided? For this example, it is determined that all 350 households are intended to use the water from this project. Therefore, applying the equation:

$$\textit{Approximate Population} = \textit{Number of Households} \times \textit{Average Number of Persons per Household}$$
$$2{,}100 \textit{ people} = 350 \textit{ households} \times 6 \textit{ people per household}$$

Step 2: Add any other people that will use the water.

This community has a school of 700 students. If all or some of these students were not accounted for by the previous calculation, then these students could be added to the population figure, or the total amount of water usage for this institution could be added later to the demand. However, for this example, we will assume that all 700 students reside in the community. Therefore, they are already accounted for in the previous equation.

Step 3: Determine how much water each person will collect from the system each day.

The table above gave a range of 6 to 16 litres per person per day based on different uses and different amounts for each use. However, it is important that the solar powered water system is designed to supply only the amount of water intended to be collected from the system. In this community, people will collect all their water used for drinking and cooking from the system. They will only collect some of the water they use for hygiene from the system, and they will not collect any of their productivity water from the system. Using this information, it is determined that the average person in the community will collect six to eight litres from the system per day. (For additional information, see **2.2.3. Area of Service Water Usage**)

Step 4: Calculate the individual water demand.

In **2.2.4. Predicting Demand**, the calculation for three different types of individual demands is presented. Using the above information for this community, we now calculate all three.

Calculating Maximum Demand at System Commissioning is done using information already provided.

Maximum Demand at System Commissioning =
Total Service Population × Full Individual Usage Amount

16,800 liters per day = 2,100 people x 8 liters per person per day

For the Anticipated Demand at System Commissioning calculation, a determination needs to be made as to the percentage of the population that will collect water from the system. It is rare that 100% of the population will collect water from the system. For this community, we determined that 85% of the population will use the system upon commissioning. In addition, for this calculation, if there is a reason to believe that people will collect less than the full individual amount of water per day, then a lesser figure should be used. As discussed above for this community, it is believed that people will collect between six and eight litres per day. We will average this to seven litres per day for the calculation.

Anticipated Demand at System Commissioning =
Total Service Population × Anticipated % of Population to
Use System × Anticipated Individual Usage at Commissioning

12,495 liters per day = 2,100 people x 85% x 7 liters per person per day

To calculate Anticipated Future Demand, a future population needs to be determined. Using government data for this region of Kenya, it is determined that the region grows at a rate of 2% annually, and we would like to make the analysis for 20 years from now. Using the equation provided in **2.2.4.3. Anticipated Future Demand** for calculating future populations:

$$2{,}100\ people\ x \left(1 + \frac{2(\%)}{100}\right)^{20} = 3{,}120\ people$$

Then similarly, to the Anticipated Demand at System Commissioning calculation, a determination to the percentage of the population that will collect water from the system is needed, as well as an anticipated individual usage. These two figures can be different from the ones used in the Anticipated Demand at System Commissioning calculation if there is reason to believe they will be different. For this example, we will still use 85% and seven litres per person per day.

Anticipated Future Individual Demand =
Future Population × Anticipated % of Population to
Use System × Anticipated Individual Usage Amount

18,564 liters per day = 3,120 people x 85% x 7 liters per person per day

Section **2.2.6. Design Demand** recommends for the system to be designed using the Anticipated Demand at System Commissioning (unless all involved parties agree that another demand is more applicable to a project's objectives). In this example, that demand is 12,495 litres per day

Step 5: Consider other daily water uses and system water losses per day.

In Step 2, we determined that the school population was already accounted for in the population calculation of Step 1. Section **2.2.5. System Water Losses** states that a daily loss of five to ten per cent is considered acceptable. Since this system will use all new components and be installed by qualified contractors, we will use 5%.

12,495 *liters per day* + 5% *due to water loss daily* = 13,120 *liters per day*

Section **2.2. Daily Project Water Demand** states that the basic components of calculating water demand include:

- calculating the total population and the daily water consumption of the individuals,
- determining any other water usages that will be provided by the proposed water system, and
- assessing any existing system water losses.

Section **2.2. Daily Project Water Demand** also gives the following general equation:

Daily Project Water Demand = Individual Daily Water Usage × Service Area Population
+ Other Daily Water Uses (institutions,livestock,commercial,industrial,recreational,etc.)
+ System Water Losses per Day

In the example above, we went through each of these components to determine that the Daily Project Water Demand will equal 13,120 litres per day.

c. Appendix

Example: Performing a Maximum Yield Test

(reference IEC 62253 – 6.2 Customer data, c. Specific local conditions)

It has been determined that a new borehole is the best water source to serve a rural community in Kenya. Other boreholes in the region range from 30 to 70 m deep and have yields of 2 to 7 m^3/hr. While setting up for the maximum yield test, the new borehole was measured and has a total depth of 60 m and a static water level of 44 m. The pump has been set so that the run-dry sensor is 55 meters below ground.

Step 1: Determine the minimum level.

See **2.3.1.1.2.1. Description**

The minimum level should be set a few meters above the pump's run-dry sensor, which is at 55 m for this example. Therefore, the water level during the yield test should not go below 52 m (3 m above the run-dry). This is equivalent to 8 m of drawdown considering the static water level is 44 m. When the water level reaches the determined minimum level and remains constant, the flowrate will not be increased but instead held through the remainder of the time of the test.

Step 2: Determine the target flowrates.

See **2.3.1.1.2.2. Test Procedure** Step A (b & c).

Based on other boreholes in the area, we estimate the minimum flowrate to be 4 m^3/hr and the maximum flowrate to be 7 m^3/hr. According to the test procedure, we divide the difference (3 m^3/hr) in to four to six intervals to use during the maximum yield test. Using six equal amounts, the interval will be 0.5 m^3/hr. We determine the target flowrates for the test as follows:

Target flowrate 1 = 4.0 m^3/hr

Target flowrate 2 = 4.0 m^3/hr + 0.5 m^3/hr = 4.5 m^3/hr

Target flowrate 3 = 4.5 m^3/hr + 0.5 m^3/hr = 5.0 m^3/hr

Target flowrate 4 = 5.0 m^3/hr + 0.5 m^3/hr = 5.5 m^3/hr

Target flowrate 5 = 5.5 m^3/hr + 0.5 m^3/hr = 6.0 m^3/hr

Again, if at any point during the test the water level drops to a constant 52 m below the surface, then the flowrate will not be increased. However, if the water level has not reached 52 m at Target flowrate 5, then the flowrate will continue to be increased by the same interval amount (0.5 m^3/hr) every hour until the determined minimum level is reached.

Step 3: Pump at target flowrate 1 for one hour.

See **2.3.1.1.2.2. Test Procedure** Steps H-I and Example Yield Test Drawdown Rows 1-24.

To begin the test, we will turn on the pump and adjust the gate valve to target flowrate 1, which was determined above to be 4 m^3/hr. We measure and record the water level every minute for the first fifteen minutes, and then every 5 minutes for the remainder of the first hour. We record the results shown below, which indicate that the water level stabilised at a drawdown of 4.5 m.

	TIME SINCE PUMPING STARTED (MINUTES)	MEASURED WATER LEVEL (m)	RESIDUAL DRAWDOWN (m)	CUMULATIVE DRAWDOWN (m)	MEASURED PUMPING RATE (m^3/hr)
1	0	44	0	0	0
2	1	45.5	1.5	1.5	4
3	2	46	0.5	2	4
4	3	46.5	0.5	2.5	4
5	4	46.8	0.3	2.8	4
6	5	47	0.2	3	4
7	6	47.1	0.1	3.1	4
8	7	47.3	0.2	3.3	4
9	8	47.5	0.2	3.5	4
10	9	47.7	0.2	3.7	4
11	10	47.9	0.2	3.9	4
12	11	48.1	0.2	4.1	4
13	12	48.2	0.1	4.2	4
14	13	48.2	0	4.2	4
15	14	48.3	0.1	4.3	4
16	15	48.3	0	4.3	4
17	20	48.3	0	4.3	4
18	25	48.4	0.1	4.4	4
19	30	48.4	0	4.4	4
20	35	48.4	0	4.4	4
21	40	48.5	0.1	4.5	4
22	45	48.5	0	4.5	4
23	50	48.5	0	4.5	4
24	55	48.5	0	4.5	4

Step 4: Pump at target flow rate 2 for one hour.

See **2.3.1.1.2.2. Test Procedure** Step J and Example Yield Test Drawdown Rows 25-48.

Since target flow rate 1 did not result in the determined minimum level, we can proceed to target flow rate 2. At 60 minutes, we open the gate valve until the pumping rate is now equal to target flow rate 2 (4.5 m^3/hr). Again, we will pump at this rate for one hour, recording the water level every minute for the first fifteen minutes and every five minutes for the remainder of the second hour. We record the results below, which indicate that the water level stabilised at a drawdown of 6.1 m.

	TIME SINCE PUMPING STARTED (MINUTES)	MEASURED WATER LEVEL (m)	RESIDUAL DRAWDOWN (m)	CUMULATIVE DRAWDOWN (m)	MEASURED PUMPING RATE (m^3/hr)
25	60	48.5	0	4.5	4.5
26	61	48.8	0.3	4.8	4.5
27	62	49	0.2	5	4.5
28	63	49.2	0.2	5.2	4.5
29	64	49.3	0.1	5.3	4.5
30	65	49.4	0.1	5.4	4.5
31	66	49.5	0.1	5.5	4.5
32	67	49.6	0.1	5.6	4.5
33	68	49.7	0.1	5.7	4.5
34	69	49.7	0	5.7	4.5
35	70	49.8	0.1	5.8	4.5
36	71	49.8	0	5.8	4.5
37	72	49.8	0	5.8	4.5
38	73	49.9	0.1	5.9	4.5
39	74	49.9	0	5.9	4.5
40	75	49.9	0	5.9	4.5
41	80	50	0.1	6	4.5
42	85	50	0	6	4.5
43	90	50	0	6	4.5
44	95	50	0	6	4.5
45	100	50.1	0.1	6.1	4.5
46	105	50.1	0	6.1	4.5
47	110	50.1	0	6.1	4.5
48	115	50.1	0	6.1	4.5

Step 5: Pump at target flow rate 3 for one hour.

See **2.3.1.1.2.2. Test Procedure** Step K and Example Yield Test Drawdown Rows 49-72.

Since target flow rate 2 did not result in the determined minimum level, we can proceed to target flow rate 3. At 120 minutes, we open the gate valve until the pumping rate is now equal to target flow rate 3 (5.0 m^3/hr). Again, we will pump at this rate for one hour, recording the water level every minute for the first fifteen minutes and every five minutes for the remainder of the third hour. We record the results below, which indicate that the water level stabilised at a drawdown of 7 m.

	TIME SINCE PUMPING STARTED (MINUTES)	MEASURED WATER LEVEL (m)	RESIDUAL DRAWDOWN (m)	CUMULATIVE DRAWDOWN (m)	MEASURED PUMPING RATE (m^3/hr)
49	120	50.1	0	6.1	5
50	121	50.3	0.2	6.3	5
51	122	50.4	0.1	6.4	5
52	123	50.5	0.1	6.5	5
53	124	50.5	0	6.5	5
54	125	50.6	0.1	6.6	5
55	126	50.6	0	6.6	5
56	127	50.7	0.1	6.7	5
57	128	50.7	0	6.7	5
58	129	50.7	0	6.7	5
59	130	50.8	0.1	6.8	5
60	131	50.9	0.1	6.9	5
61	132	50.9	0	6.9	5
62	133	50.9	0	6.9	5
63	134	51	0.1	7	5
64	135	51	0	7	5
65	140	51	0	7	5
66	145	51	0	7	5
67	150	51	0	7	5
68	155	51	0	7	5
69	160	51	0	7	5
70	165	51	0	7	5
71	170	51	0	7	5
72	175	51	0	7	5

Step 6: Pump at target flow rate 4 for one hour.

See **2.3.1.1.2.2. Test Procedure** Step K and Example Yield Test Drawdown Rows 73-96.

Since target flow rate 3 did not result in the determined minimum level, we can proceed to target flow rate 4. At 180 minutes, we open the gate valve until the pumping rate is now equal to target flow rate 4 (5.5 m^3/hr). Again, we will pump at this rate for one hour, recording the water level every minute for the first fifteen minutes and every five minutes for the remainder of the fourth hour. We record the results below, which indicate that the water level stabilised at a drawdown of 7.8 m.

	TIME SINCE PUMPING STARTED (MINUTES)	MEASURED WATER LEVEL (m)	RESIDUAL DRAWDOWN (m)	CUMULATIVE DRAWDOWN (m)	MEASURED PUMPING RATE (m^3/hr)
73	180	51	0	7	5.5
74	181	51.2	0.2	7.2	5.5
75	182	51.3	0.1	7.3	5.5
76	183	51.4	0.1	7.4	5.5
77	184	51.5	0.1	7.5	5.5
78	185	51.5	0	7.5	5.5
79	186	51.5	0	7.5	5.5
80	187	51.6	0.1	7.6	5.5
81	188	51.6	0	7.6	5.5
82	189	51.6	0	7.6	5.5
83	190	51.6	0	7.6	5.5
84	191	51.7	0.1	7.7	5.5
85	192	51.7	0	7.7	5.5
86	193	51.8	0.1	7.8	5.5
87	194	51.8	0	7.8	5.5
88	195	51.8	0	7.8	5.5
89	200	51.8	0	7.8	5.5
90	205	51.8	0	7.8	5.5
91	210	51.8	0	7.8	5.5
92	215	51.8	0	7.8	5.5
93	220	51.8	0	7.8	5.5
94	225	51.8	0	7.8	5.5
95	230	51.8	0	7.8	5.5
96	235	51.8	0	7.8	5.5

Step 7: Pump at target flow rate 5 for one hour.

See **2.3.1.1.2.2. Test Procedure** Step K and Example Yield Test Drawdown Rows 97-120.

Since target flow rate 4 did not result in the determined minimum level, we can proceed to target flow rate 5. At 240 minutes, we open the gate valve until the pumping rate is now equal to target flow rate 5 (6.0 m^3/hr). Again, we will pump at this rate for one hour, recording the water level every minute for the first fifteen minutes and every five minutes for the remainder of the fifth hour. We record the results below, which indicate that the water level stabilised at a drawdown of 8 m. This is the determined minimum level.

	TIME SINCE PUMPING STARTED (MINUTES)	MEASURED WATER LEVEL (m)	RESIDUAL DRAWDOWN (m)	CUMULATIVE DRAWDOWN (m)	MEASURED PUMPING RATE (m^3/hr)
97	240	51.8	0	7.8	6
98	241	51.9	0.1	7.9	6
99	242	51.9	0	7.9	6
100	243	51.9	0	7.9	6
101	244	52	0.1	8	6
102	245	52	0	8	6
103	246	52	0	8	6
104	247	52	0	8	6
105	248	52	0	8	6
106	249	52	0	8	6
107	250	52	0	8	6
108	251	52	0	8	6
109	252	52	0	8	6
110	253	52	0	8	6
111	254	52	0	8	6
112	255	52	0	8	6
113	260	52	0	8	6
114	265	52	0	8	6
115	270	52	0	8	6
116	275	52	0	8	6
117	280	52	0	8	6
118	285	52	0	8	6
119	290	52	0	8	6
120	295	52	0	8	6

Step 8: Hold at maximum allowable drawdown for the remainder of the 24-hour test.

See **2.3.1.1.2.2. Test Procedure** Step L-M and Example Yield Test Drawdown Rows 121-140.

Since target flow rate 5 resulted in the water level stabilising at the determined minimum level, we will not change the pumping rate. Instead, we will continue pumping at 6 m^3/hr and keep the water level at the determined minimum level to ensure the borehole can maintain this yield. We measure and record the water level every hour for the remainder of the 24-hour test.

	TIME SINCE PUMPING STARTED (MINUTES)	MEASURED WATER LEVEL (m)	RESIDUAL DRAWDOWN (m)	CUMULATIVE DRAWDOWN (m)	MEASURED PUMPING RATE (m^3/hr)
121	300	52	0	8	6
122	360	52	0	8	6
123	420	52	0	8	6
124	480	52	0	8	6
125	540	52	0	8	6
126	600	52	0	8	6
127	660	52	0	8	6
128	720	52	0	8	6
129	780	52	0	8	6
130	840	52	0	8	6
131	900	52	0	8	6
132	960	52	0	8	6
133	1020	52	0	8	6
134	1080	52	0	8	6
135	1140	52	0	8	6
136	1200	52	0	8	6
137	1260	52	0	8	6
138	1320	52	0	8	6
139	1380	52	0	8	6
140	1440	52	0	8	6
121	300	52	0	8	6
122	360	52	0	8	6
123	420	52	0	8	6
124	480	52	0	8	6
125	540	52	0	8	6
126	600	52	0	8	6
127	660	52	0	8	6
128	720	52	0	8	6
129	780	52	0	8	6
130	840	52	0	8	6

Step 8: (Continued)...

	TIME SINCE PUMPING STARTED (MINUTES)	MEASURED WATER LEVEL (m)	RESIDUAL DRAWDOWN (m)	CUMULATIVE DRAWDOWN (m)	MEASURED PUMPING RATE (m^3/hr)
131	900	52	0	8	6
132	960	52	0	8	6
133	1020	52	0	8	6
134	1080	52	0	8	6
135	1140	52	0	8	6
136	1200	52	0	8	6
137	1260	52	0	8	6
138	1320	52	0	8	6
139	1380	52	0	8	6
140	1440	52	0	8	6

Step 9: Monitor the recovery of the well.

See **2.3.1.1.2.2. Test Procedure** Steps N-P and Example Yield Test Recovery Rows 1-20.

At the end of 24 hours, we will turn off the pump and monitor the recovery of the borehole. We measure and record the water level in the borehole every minute for the first fifteen minutes. Then every five minutes until 60 minutes has passed. Then at every ten minutes until the water returns to the static water level. We record the results below, which indicate that it takes 30 minutes for this borehole to recover.

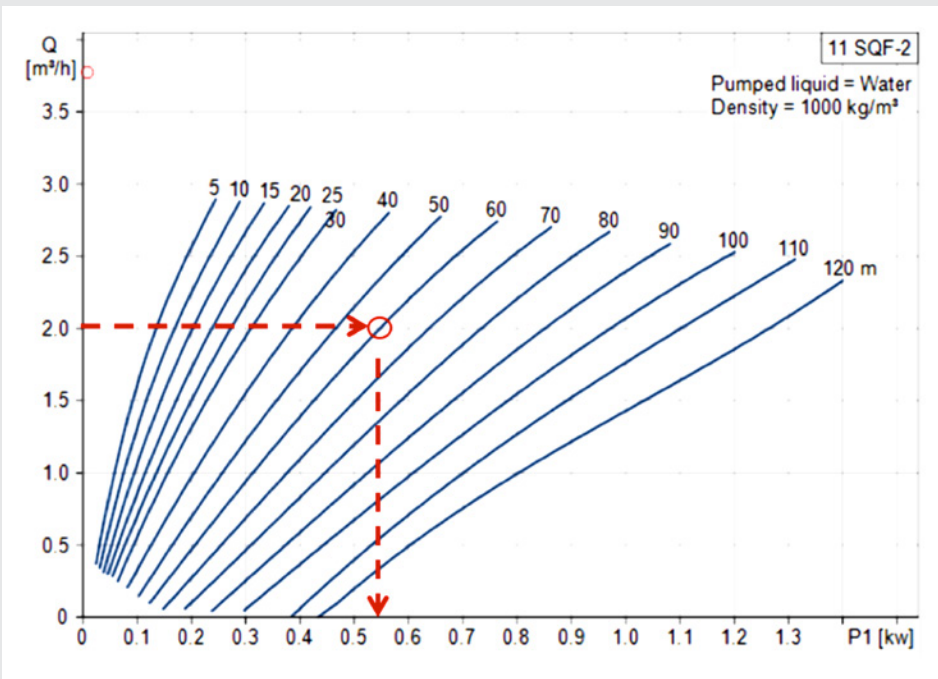
	TIME SINCE PUMPING STARTED (MINUTES)	MEASURED WATER LEVEL (m)	RESIDUAL DRAWDOWN (m)	CUMULATIVE DRAWDOWN (m)	MEASURED PUMPING RATE (m^3/hr)
1	0	52	0	8	0
2	1	51.7	-0.3	7.7	0
3	2	51.4	-0.3	7.4	0
4	3	51.0	-0.4	7.0	0
5	4	50.8	-0.2	6.8	0
6	5	50.6	-0.2	6.6	0
7	6	50.2	-0.4	6.2	0
8	7	49.9	-0.3	5.9	0
9	8	49.7	-0.2	5.7	0
10	9	49.3	-0.4	5.3	0
11	10	49.1	-0.2	5.1	0
12	11	48.9	-0.2	4.9	0
13	12	48.7	-0.2	4.7	0
14	13	48.4	-0.3	4.4	0
15	14	48.2	-0.2	4.2	0
16	15	47.9	-0.3	3.9	0
17	20	46.2	-1.7	2.2	0
18	25	45	-1.2	1	0
19	30	44	-1	0	0
20	35	44	0	0	0

d. Appendix

Note: The flow rate selected below is in response to the Daily Project Water Demand calculated in Appendix B (13,120 litres per day). By checking irradiance data for the location, it is noted that the project site receives an average of nine hours of sunlight per day with the middle seven hours of the day yielding the highest irradiance conditions (i.e., seven peak sunlight hours). It is decided that this project will target water production during these seven middle hours of the day at a minimum (this design target will be checked as part of the design process in Appendix E). Using this information gives us a rough estimate of flow rate that will be required of the pump (13,120 litres ÷ 7 hours = 1,874 litres/hour, or roughly 2 m^3/hour). Additionally, it is noted that the flow rate and the required head in the example below are supported by the yield test results of Appendix C.

Example: Selecting a Solar Pump

Select a submersible solar pump for a system with a flow rate of 2 m^3/h and a TDH of 60 m.



Solar Pump Performance Curve for the Grundfos 11 SQF-2

Step 1: Find a pump that can achieve the system's designed TDH.

Use the performance curves to determine the range of TDH that each pump model can achieve. Based on the curve, the Grundfos 11 SQF-2 ranges in TDH from 5-120 m, which includes the system's design of 60 m.

Step 2: Make sure the pump in question can achieve the system's designed flow rate.

The y-axis of the performance curve graph shows the flow rates it can produce. Looking at the graph, the 11 SQF-2 can pump approximately 0–3 m^3/h, which encompasses the system's design of 2 m^3/h. More specifically, the 2 m^3/h mark intersects the 60 m performance curve. This indicates that the Grundfos 11 SQF-2 can meet the system design.

Step 3: Determine the power requirement.

Find the point on the graph where the 2 m^3/h mark intersects the 60 m TDH curve. Then, drop straight down to the x-axis to determine the power requirement. Based on the graph, the Grundfos 11 SQF-2 requires approximately 550 W to achieve the system design.

e. Appendix

Example: Designing the PV System for a Solar Pump

(reference IEC 62253 – 6.3 System characteristics, 6.6 Design check of the PV pumping system in respect to the daily water volume)

In a previous example, we determined that the Daily Project Water Demand for a community in rural Kenya was 13,120 litres per day. In a separate example we selected a pump that could supply a desired flow rate of around 2 m^3/hour at a TDH of 60 meters (a Grundfos 11 SQF-2 was selected). After consulting the pump curves for this pump, it was determined that the pump motor will require about 550 W of power to achieve the desired performance. On further review of the manufacturer specifications, it was noticed that the motor has an input voltage range of 30 to 300 VDC and a maximum current draw of 8.4 A.

Step 1: Determine the ambient temperature and solar irradiance conditions for the project site (see Section 2.5.2.).

As discussed in **2.5.3. Monthly Temperature and Irradiance Data**, the ambient temperature and solar irradiance fluctuate throughout the year. In order to ensure that that water system will meet the water demand during every month of the year, the PV system will be designed using the data from the month with the lowest irradiance values. After looking at the data available online from National Aeronautics and Space Administration (NASA), we see that during the lowest irradiance month the project location has a daytime average ambient temperature of 20.9 °C and a daily irradiance profile as shown below:

HOUR	IRRADIANCE (W/m^2)
8	327
9	430
10	503
11	551
12	565
13	551
14	503
15	430
16	327

Step 2: Calculate the panel's estimated performance for the project location.

The solar panels most readily available for the project have the following performance under standard test conditions (STC):

- Maximum power point (Pmax): 290 W
- Maximum power point voltage (Vmpp): 31.9 V
- Maximum power point current (Impp): 9.2 A
- Open circuit voltage (Voc): 39.6 V
- Short circuit current (Isc): 9.75 A
- Temperature coefficient (TC Voc): -0.29%/C
- Normal operating cell temperature (NOCT): 46°C

Calculating the panel's estimated performance for the project location is done by working through the equations in **4.1.1.1. Calculating a Panel's Estimated Performance for the Project Location** for each hour of the day. Below we will show the detailed calculations for the irradiance conditions at 12 o'clock.

Step 2a: Calculate the cell temperature.

$$\text{Cell temp } (°\text{C}) = \text{Ambient temp } (°\text{C}) + (\text{NOCT} - 20°\text{C}) \times \frac{\text{Irradiance } \left(\frac{\text{W}}{\text{m}^2}\right)}{800\ \frac{\text{W}}{\text{m}^2}}$$

$$39.3°\text{C} = 20.9°\text{C} + (46°\text{C} - 20°\text{C}) \times \frac{565\ \frac{\text{W}}{\text{m}^2}}{800\ \frac{\text{W}}{\text{m}^2}}$$

Step 2b: Calculate the open circuit voltage at the cell temperature.

$$V_{oc} = \text{STC } V_{oc} + (\text{Cell temp} - 25°\text{C}) \times \text{STC } V_{oc} \times \text{TC } V_{oc}$$

$$38.0\text{ V} = 39.6\text{ V} + (39.3°\text{C} - 25°\text{C}) \times 39.6\text{ V} \times -0.29\%/\text{C}$$

Step 2c: Calculate the short circuit current at the given incident irradiance.

$$I_{sc} = \text{STC } I_{sc} \times \frac{\text{Irradiance } \left(\frac{\text{W}}{\text{m}^2}\right)}{1{,}000\ \frac{\text{W}}{\text{m}^2}} \qquad 5.51\text{ A} = 9.75\text{ A} \times \frac{565\ \frac{\text{W}}{\text{m}^2}}{1{,}000\ \frac{\text{W}}{\text{m}^2}}$$

Step 2d: Calculate the maximum power point current at the given irradiance.

$$I_{mpp} = \text{STC } I_{mpp} \times \frac{\text{Irradiance } \left(\frac{\text{W}}{\text{m}^2}\right)}{1{,}000\ \frac{\text{W}}{\text{m}^2}} \qquad 5.2\text{ A} = 9.2\text{ A} \times \frac{565\ \frac{\text{W}}{\text{m}^2}}{1{,}000\ \frac{\text{W}}{\text{m}^2}}$$

Step 2e: Calculate the solar panel output under the given conditions.

$$P_{max}\ (W) = V_{oc} \times I_{sc} \times \frac{STC\ I_{mpp}\ \times STC\ V_{mpp}}{STC\ I_{sc} \times STC\ V_{oc}}$$

$$159.2\ W = 38.0\ V \times 5.51\ A \times \frac{9.2\ A\ \times 31.9\ V}{9.75\ A \times 39.6\ V}$$

Step 2f: Calculate the maximum power point voltage of the panel.

$$V_{mpp} = \frac{P_{max}}{I_{mpp}} \qquad 30.6\ V = \frac{159.2\ W}{5.2\ A}$$

By following the same steps, the conditions for each hour of the day can be calculated. The results of those calculations are presented in the following table:

HOUR	IRRADIANCE (W/m^2)	CELL TEMPERATURE (°C)	VOC (V)	ISC (A)	IMPP (A)	PMAX (W)	VMPP (V)
8	327	31.5	38.9	3.19	3.0	94.3	31.4
9	430	34.9	38.5	4.19	4.0	122.6	30.7
10	503	37.2	38.2	4.90	4.6	142.3	30.9
11	551	38.8	38.0	5.37	5.1	155.1	30.4
12	565	39.3	38.0	5.51	5.2	159.2	30.6
13	551	38.8	38.0	5.37	5.1	155.1	30.4
14	503	37.2	38.2	4.90	4.6	142.3	30.9
15	430	34.9	38.5	4.19	4.0	122.6	30.7
16	327	31.5	38.9	3.19	3.0	94.3	31.4

Step 3: Design the configuration of the solar array.

Now that we know the power output on a single solar panel being considered in this project location, we can take a preliminary estimate of the number of solar panels needed for the array. As stated in a previous example, a target of the design is to produce water during the seven middle hours of the day at a minimum (this will be checked at the end of the example). Therefore, we can divide the required amount of power (550W) by the lowest amount of power per panel during the middle seven hours of the day (122.6W). Doing this roughly tells us that the array will need to consist of about four panels (550 W ÷ 122.6 W ≈ 4).

As discussed in **4.1.2. Solar Array Configuration**, wiring solar panels in series will increase the voltage, and wiring in parallel will increase the current. Also, panels are typically wired in series to achieve the maximum wattage with the least number of solar panels. Thus, the next step would be to check the power output from the array during each hour of irradiance with four panels wired in series (using the equations given in **4.1.2. Solar Array Configuration**). As done previously, we will show the detailed calculations for the irradiance conditions at 12 o'clock.

$$Array\ V_{oc} = V_{oc}\ per\ panel \times number\ of\ panels\ in\ series$$

$$152\ V = 38.0\ V \times 4$$

$$Array\ V\_mpp = V\_mpp\ per\ panel \times number\ of\ panels\ in\ series$$

$$122\ V = 30.6\ V \times 4$$

$$Array\ I_{mpp} = I_{mpp}\ per\ panel \times number\ of\ parallel\ strings$$

$$5.2\ A = 5.2\ A \times 1$$

$$Array\ P_{max}\ (W) = Array\ I_{mpp} \times Array\ V_{mpp}$$

$$634\ W = 5.2\ A \times 122\ V$$

Step 4: Derate the power output from the array.

This calculated power output from the array should be derated to account for power losses (as discussed in **4.1.3. Power Losses**). We will use a derate factor of 0.90 as recommended for a system without an inverter.

$$Array\ P_{derated}\ (W) = Array\ P_{max}\ (W) \times derating\ factor$$

$$571\ W = 634\ W \times 0.90$$

By using the same equations, the conditions for each hour of the day can be calculated. The results of those calculations are presented in the following table:

HOUR	ARRAY V_{OC} (V)	ARRAY V_{MPP} (V)	ARRAY I_{MPP} (A)	ARRAY P_{MAX} (W)	ARRAY $P_{DERATED}$ (W)
8	156	126	3.0	378	340
9	154	123	4.0	492	443
10	153	124	4.6	570	513
11	152	122	5.1	622	560
12	152	122	5.2	634	571
13	152	122	5.1	622	560
14	153	124	4.6	570	513
15	154	123	4.0	492	443
16	156	126	3.0	378	340

Step 5: Verify that the array voltage and amperage satisfy the pump motor specifications.

The supplied voltage and amperage need to be checked against the pump motor specifications. As previously stated, the pump motor has an input voltage range of 30 to 300 VDC and a maximum current draw of 8.4 A. As can be seen in the table above, the array Voc is greater than 30 but less than 300 V. Additionally, since the solar panels are to be connected in series, the current of the array will be equivalent to the current of a single panel, which is less than the maximum current draw of the pump.

Step 6: Confirm that the designed array enables the pump to supply the daily project water demand.

The final check on the design is to see if the power supplied by the array to the pump motor will enable the pump to supply the daily project water demand of 13,120 litres per day. This can be approximated by referring to the pump curve supplied by the manufacturer. As shown in **3.2.2.2. Selecting a Pump using Solar Pump Performance Curves**, the power required by the pump motor is found by locating the point on the pump curve where the desired flow rate meets the TDH line, and then reading the power required at this point. Working backwards, a flow rate can be approximated for the power supplied by the array at each hour of the day. (To do this an assumption is made that the TDH will remain roughly constant, or the TDH can be recalculated at each flow rate for greater accuracy.) Using the pump curves for the Grundfos 11 SQF-2, the following conditions are observed:

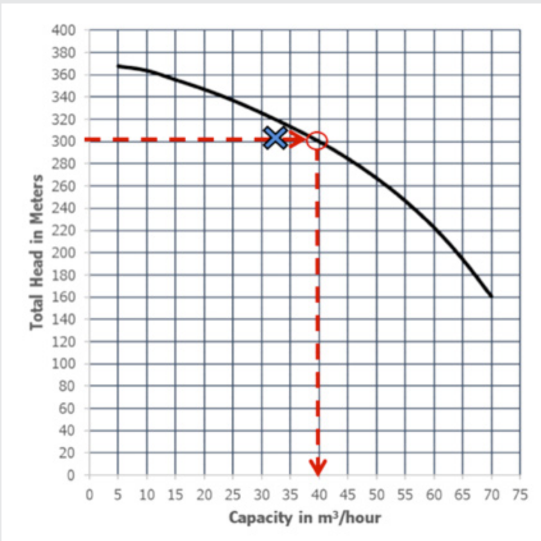
HOUR	ARRAY PDERATED (W)	APPROXIMATE FLOW RATE AT 60 M TDH (m^3/hour)	HOURLY WATER PRODUCTION (L)
8	340	1.2	1,200
9	443	1.5	1,500
10	513	1.8	1,800
11	560	2.0	2,000
12	571	2.1	2,100
13	560	2.0	2,000
14	513	1.8	1,800
15	443	1.5	1,500
16	340	1.2	1,200
TOTAL DAILY WATER PRODUCTION (L):			15,100

Thus, an approximate of the total daily water produced is 15,100 litres per day. If this number was significantly greater or lower than the daily project water demand (13,120 litres per day), then the array should be redesigned. IEC 62253 states that supplied total should be within a tolerance of -5% to +20% of the daily project water demand. Our approximate total daily water produced (15,000 litres) is 15% greater than the daily project water demand (13,120 litres), so our design meets the requirement. If the supplied total was outside of the tolerance, then a redesign is necessary by using either a different size solar panel, a different number of panels, or a different array configuration.

f. Appendix

Example: Selecting an AC Pump

Select an AC pump for a system designed with a flow rate of 33 m^3/hr and a TDH of 300 m.



AC Pump Performance Curve

Step 1: Find a pump that can achieve the designed TDH.

The pump performance curve indicates a TDH range of approximately 160-370 m. Therefore, the pump is capable of the designed TDH of 300 m.

Step 2: Find the potential flow rate of the pump at the designed TDH.

Find the point on the pump curve that corresponds to a TDH value of 300 m. Then find the value on the x-axis (i.e., the potential flow rate) that corresponds to this point. Based on the AC pump performance curve, the pump can generate 40 m^3/hr at a TDH of 300 m.

Step 3: Make sure the potential flow rate exceeds the designed flow rate.

Step 2 determined that the potential flow rate is 40 m^3/hr at a TDH of 300 m, which exceeds the designed flow rate of 33 m^3/hr.

Step 4: Determine the power requirement.

After selecting the pump, the amount of power needed will depend on the pump and motor requirements. This information should be available in the specifications from the manufacturer.

g. Appendix

Example: Designing the PV System for an AC Pump with Inverter

(reference IEC 62253 – 6.3 System characteristics, 6.6 Design check of the PV pumping system in respect to the daily water volume)

This example uses a similar location, with the same temperature and irradiance conditions, and the same solar panel selection of the previous example. This will show the difference in designing a system with an AC powered pump and inverter, as opposed to a pump and motor combination that can take DC power input.

A yield test has been completed on a borehole in a large community in rural Kenya. The test results show that the maximum yield of the borehole is 39 m^3/hour with a dynamic water level of 94.5 meters below the ground. The community would like to access 90% of the maximum yield to produce a daily water volume of 295,000 liters per day from the borehole. Using a design flow of 35 m^3/hour (90% of the 39 m^3/hour yield), hydraulic calculations were performed to find that the TDH of the planned water system will be 102.2 meters. After seeing that all available pump and motor combinations (or PV pump aggregates) that can take DC power input could not perform to the desired capacity, an AC powered pump with an inverter was considered. An AC powered pump and motor was selected that can perform at a duty point of 34.9 m^3/hour and 102.1 meters of head at a required motor power of 14.3 kW. The motor is a 50 Hz, three phase, nominal 380 V motor. The pump and motor manufacturer's literature suggests that an 18.5 kW inverter be used, which matches the power requirements of the motor (50 Hz, nominal 380 V). The inverter has an input voltage range of 400 to 800 VDC and a maximum current output of 38.0 A and is equipped with a variable frequency drive. The appropriateness of the inverter will be checked during the design.

Using the same 290 W solar panels as in the previous example, the performance of an individual panel during the sunlight hours at the project location is as follows (for calculation details, see previous example):

HOUR	IRRADIANCE (W/m²)	CELL TEMPERATURE (°C)	VOC (V)	ISC (A)	IMPP (A)	PMAX (W)	VMPP (V)
8	327	31.5	38.9	3.19	3.0	94.3	31.4
9	430	34.9	38.5	4.19	4.0	122.6	30.7
10	503	37.2	38.2	4.90	4.6	142.3	30.9
11	551	38.8	38.0	5.37	5.1	155.1	30.4
12	565	39.3	38.0	5.51	5.2	159.2	30.6
13	551	38.8	38.0	5.37	5.1	155.1	30.4
14	503	37.2	38.2	4.90	4.6	142.3	30.9
15	430	34.9	38.5	4.19	4.0	122.6	30.7
16	327	31.5	38.9	3.19	3.0	94.3	31.4

Step 1: Design the configuration of the solar array.

When it is evident that multiple strings of solar panels will be used, the voltage and current parameters of the motor or inverter need to be taken into consideration. For the inverter being considered, the solar panels will need to be combined in such a way that the voltage is greater than 400 V and less than 800 V with a current no greater than 38.0 A. Using these parameters, we can see that the array will have somewhere between 11 (400 V ÷ 38.0 V = 11) and 21 (800 V ÷ 38.0 V = 21) solar panels in series and seven (38.0 A ÷ 5.51 A = 7) or less strings. A thorough design will check different combinations to achieve the power supply required by using the smallest number of solar panels. The remainder of this example will use seven strings of 18 solar panels for a total of 126 panels.

Step 2: Check the power output from the array.

The output of the array should be checked during each hour of irradiance (using the equations given in **4.1.2. Solar Array Configuration**). We show below the detailed calculations for the irradiance conditions at 12 o'clock.

$$Array\ V_{oc}\ =\ V_{oc}\ \ per\ panel\ \times\ number\ of\ panels\ in\ series$$

$$684.0\text{ V} = 38.0\text{ V} \times 18$$

$$Array\ V_{mpp}\ =\ V_{mpp}\ \ per\ panel\ \times\ number\ of\ panels\ in\ series$$

$$550.8\text{ V} = 30.6\text{ V} \times 18$$

$$Array\ I_{mpp}\ =\ I_{mpp}\ \ per\ panel\ \times\ number\ of\ parallel\ strings$$

$$36.4\text{ A} = 5.2\text{ A} \times 7$$

$$Array\ P_{max}\ (W)\ =\ Array\ I_{mpp}\ \times\ Array\ V_{mpp}$$

$$20.0\text{ kW} = 36.4\text{ A} \times 550.8\text{ V}$$

Step 3: Derate the power output from the array.

This calculated power output from the array should be derated to account for power losses (as discussed in **4.1.3. Power Losses**). We will use a derate factor of 0.85 as recommended for a system with an inverter.

$$Array\ P_{derated}\ (W)\ =\ Array\ P_{max}\ (W)\ \times\ derating\ factor$$

$$17.0\text{ kW} = 20.0\text{ kW} \times 0.85$$

By using the same equations, the conditions for each hour of the day can be calculated. The results of those calculations are presented in the following table:

HOUR	ARRAY VOC (V)	ARRAY VMPP (V)	ARRAY IMPP (A)	ARRAY PMAX (kW)	ARRAY PDERATED (kW)
8	700.2	565.2	21.0	11.9	10.1
9	693.0	552.6	28.0	15.5	13.2
10	687.6	556.2	32.2	17.9	15.2
11	684.0	547.2	35.7	19.5	16.6
12	684.0	550.8	36.4	20.0	17.0
13	684.0	547.2	35.7	19.5	16.6
14	687.6	556.2	32.2	17.9	15.2
15	693.0	552.6	28.0	15.5	13.2
16	700.2	565.2	21.0	11.9	10.1

Step 4: Verify that the array voltage and amperage satisfy the inverter.

Before estimating the amount of water to be produced in these power conditions, the table above can be used to check the appropriateness of the inverter that was suggested by the manufacturer's literature. The suggested inverter is an 18.5 kW, 50 Hz inverter with an input voltage range of 400 to 800 VDC and a maximum current output of 38.0 A. The calculation results in the table above meet the voltage and current conditions of the inverter, and power to be conveyed is appropriately close to the nominal power rating of the inverter.

Step 5: Confirm that the designed array enables the pump to supply the daily project water demand.

By use of the affinity laws and the pump performance curves (see **4.8. Checking System Design to**

Daily Project Water Demand), we can now calculate an anticipated amount of water produced each hour. The first step is to calculate the frequency by using the affinity law relationship between power and speed. Note that as stated in section 4.8, frequency can be used interchangeably with speed. The calculation for the conditions at 8 o'clock is shown here.

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3$$

$$N_2 = \left(\frac{10.1kW}{14.3kW}\right)^{1/3} \times 50Hz = 44.5Hz$$

However, as previously stated, the pump motor and inverter are 50 Hz. Thus, the frequency will never exceed 50 Hz. The calculated frequency for each is presented in the following table:

HOUR	ARRAY PDERATED (kW)	FREQUENCY (Hz)
8	10.1	44.5
9	13.2	48.7
10	15.2	50
11	16.6	50
12	17.0	50
13	16.6	50
14	15.2	50
15	13.2	48.7
16	10.1	44.5

Next, performance curves for each calculated frequency are determined. This is done by calculating several points along the performance curve by use of the affinity laws. By taking each calculated frequency and the affinity law relationships between flow and speed, and between head and speed, points along the corresponding pump performance curve for each calculated frequency can be determined. Below are the calculations for a single point along the performance curve that corresponds to a frequency of 44.5 Hz.

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1}$$

$$Q_2 = \frac{44.5Hz}{50Hz} \times 3.2\, m^3/hr = 2.8\, m^3/hr$$

$$\frac{H_2}{H_1} = \left(\frac{N_2}{N_1}\right)^2$$

$$H_2 = \left(\frac{44.5Hz}{50Hz}\right)^2 \times 195.1m = 154.5m$$

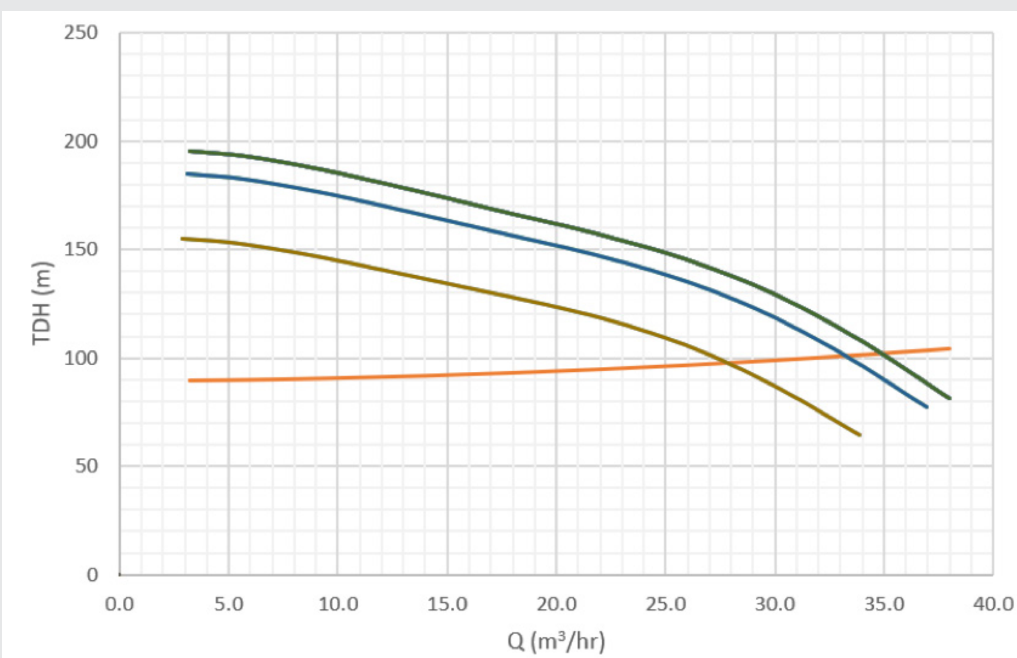
(P = Power; N = Speed; Q = Flow; H = Head)

Several points along the performance curve for each frequency will need to be calculated. The calculation results for ten points along the curve are shown below. More or less points will correspond to more or less accuracy, respectively, for the final results. In the table below, we have calculated ten points on the performance curve corresponding to 44.5 Hz by starting with ten points along the full power, or 50 Hz, performance curve.

Points on Performance Curve for 50 Hz		Points on Performance Curve for 44.5 Hz	
Q_1 (m^3/hr)	H_1 (m)	Q_2 (m^3/hr)	H_2 (m)
3.2	195.1	2.8	154.5
6	192.4	5.3	152.4
10	185.0	8.9	146.5
18	166.2	16.0	131.6
22	156.7	19.6	124.1
26	145.1	23.1	114.9
30	129.3	26.7	102.4
34	107.7	30.3	85.3
34.9	102.1	31.1	80.9
38	81.5	33.8	64.6

These same calculations will need to be performed for the 48.7 Hz performance curve as well.

It is important to recognize that the points (Q_2, H_2) in the table above represent points along a performance curve for the pump, and not points along the system curve for the proposed water system. On the graph below, the green and blue curves are the performance curves for the pump at 50 Hz, 48.7 Hz, and 44.5 Hz.



The orange curve on the graph represents the system curve for the proposed water system. The system curve is determined by calculating the TDH for multiple flow values (As previously stated, this design guide does not present the methods of calculating TDH, because the methods of calculating TDH for a solar-powered pumping system do not change from the methods used with any other mechanized pumping system).

The intersections of the system curve and each performance curve represent the flow rate of the system at the corresponding frequency for each hour of the day. The flow value at each intersection can be observed graphically and can be calculated by the following method. The table below shows the flow and head values along the 44.5 Hz performance curve and the TDH of the proposed water system for each flow.

Q_2 (m^3/hr)	**H_2** (m)	**TDH** (m)
2.8	154.5	89.6
5.3	152.4	89.9
8.9	146.5	90.5
16.0	131.6	92.5
19.6	124.1	93.8
23.1	114.9	95.4
26.7	102.4	97.2
30.3	85.3	99.2
31.1	80.9	100.1
33.8	64.6	101.4

Note in the graph above that the system curve intersects the 44.5 Hz performance curve between 25 m^3/hr and 30 m^3/hr. Additionally, the table above shows that the TDH for 26.7 m^3/hr is below the head of the performance curve, but the TDH for 30.3 m^3/hr is above the head of the performance curve. By using a method of interpolation, we can use these flow rates and the corresponding TDH and performance curve head values to calculate the flow rate where the corresponding TDH of the proposed water system and the head on the performance curve are equal.

$$\frac{(30.3 - 26.7)}{[(99.2 - 85.3) - (97.2 - 102.4)]} = \frac{(Q_{at\ intersection} - 26.7)}{[0 - (97.2 - 102.4)]}$$

$$Q_{at\ intersection} = 27.7\ m^3/hr$$

Note that this flow rate could be checked by calculating the TDH of the proposed water system for this flow rate and checking the head on the pump performance curve to see that the two values are equal.

HOUR	ARRAY $P_{DERATED}$ (kW)	FREQUENCY (Hz)	FLOW (m^3/hour)	HOURLY WATER PRODUCTION (L)
8	10.1	44.5	27.7	27,700
9	13.2	48.7	33.2	33,200
10	15.2	50	34.9	34,900
11	16.6	50	34.9	34,900
12	17.0	50	34.9	34,900
13	16.6	50	34.9	34,900
14	15.2	50	34.9	34,900
15	13.2	48.7	33.2	33,200
16	10.1	44.5	27.7	27,700
			TOTAL DAILY WATER PRODUCTION (L):	**296,300**

The approximate total daily water produced (296,300 liters) is less than 1% greater than the daily project water demand (295,000 liters), so our design meets the requirement of IEC 62253 to be within a tolerance of -5% to +20% of the daily project water demand.

h. Appendix

Hydraulic Power, Brake Power, and Motor Power

The energy that a pump is able to add to water is dependent on the power supplied to the pump motor. The power required by a pump motor can typically be identified by the manufacturer-supplied pump curve and accompanying information. The following equations for hydraulic, brake, and motor power are included to aid in the understanding of the requirements and performance of the motor that drives the pump.

Hydraulic Power (Ph)

Hydraulic power is the amount of energy that is transferred from the pump to the water. In SI units, hydraulic power is calculated using the following equation:

$$P_h\ (kW) = \frac{Q \times \gamma \times H}{1{,}000}$$

where: Ph = hydraulic power (kW)

Q = flow rate (m^3/s)

"γ" = specific weight of water (9,810 N/m^3)

H = pump head (m)

Brake Power (P2 or BP)

Brake power is the amount of energy that must be transferred from the motor to the pump to achieve the desired hydraulic power. Due to inefficiencies in the pump, the brake power will always be greater than hydraulic power. The main difference between calculating brake power and calculating hydraulic power is that the equation for brake power takes pump efficiency into account. In SI units, brake power is calculated using the following equation:

$$BP\ (kW) = \frac{P_h\ (kW)}{\eta_p} = \frac{Q \times \gamma \times H}{\eta_p \times 1{,}000}$$

where: BP = brake power (kW)

Ph = hydraulic power (kW)

ηp = pump efficiency (%)

Q = flow rate (m^3/s)

"γ" = specific weight of water (9,810 N/m^3)

H = pump head (m)

Motor Power (P1 or MP)

Motor power is the energy required by the pump motor in order to supply enough brake and hydraulic power. Motor power will always be greater than brake power (and hydraulic power) due to inefficiencies in the motor. Taking the motor efficiency into account is the main difference between calculating motor power and brake power. It is important to note that motor power is provided by a pump curve (though some pump curves will show motor power and brake power as P1 and P2,respectively). For SI units, motor power is calculated using the following equation:

$$MP\ (kW) = \frac{BP\ (kW)}{\eta_m} = \frac{P_h\ (kW)}{\eta_p \times \eta_m} = \frac{Q \times \gamma \times H}{\eta_p \times \eta_m \times 1{,}000}$$

where: MP = motor power (kW)

BP = brake power (kW)

ηm = motor efficiency (%)

Ph = hydraulic power (kW)

ηp = pump efficiency (%)

Q = flow rate (m^3/s)

"γ" = specific weight of water (9,810 N/m^3)

H = pump head (m)

Photo courtesy of Water Mission

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