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# PRACTICAL GUIDANCE FOR DESIGNING AND IMPLEMENTING FIELD TESTING FOR SOLAR WATER PUMPS

Guidance on solar water pump performance monitoring in the field

**JUNE 2022**
EFFICIENCY FOR ACCESS COALITION

Photo Credit: Bimala Colavito

# CONTEXT

Efficiency for Access is developing a series of field-testing resources to help practitioners design and implement field testing projects that focus on performance monitoring and measurement of appliances and equipment designed for use in off-grid weak-grid contexts.

We define field testing as the process of collecting, measuring, and analysing a product's data, often but not necessarily used by end-users in real-world settings over an extended period. Successful field testing provides information about the product's performance and user experience and informs on why the product performs the way it does and its impacts on the user's life or livelihood. In addition, the data and intelligence gathered from field testing inform decisions about design, financing, business models and more.

The first guide, published in January 2022, provides generic guidance on performance monitoring for any solar appliance and productive use equipment in the field. Following the first guide, this document focuses on specific design and implementation considerations for solar water pumps (SWPs) and resources that can be easily customised based on the field testing needs. The learnings and examples are drawn from Efficiency for Access' experience in testing SWPs in laboratory settings and the field through ongoing SWP field monitoring projects in Kenya, Tanzania, and Senegal. This guide is also published in parallel to a field-testing guide for off- and weak-grid refrigerators, which can be accessed here.

CLASP, Co-Secretariat of the Efficiency for Access Coalition, developed this field-testing guide as part of the Low Energy Inclusive Appliances (LEIA) programme, a flagship programme of Efficiency for Access. Efficiency for Access is a global coalition working to promote affordable, high-performing, and inclusive appliances that enable access to clean energy for the world's poorest people. It is a catalyst for change, accelerating the growth of off and weak-grid appliance markets to boost incomes, reduce carbon emissions, improve quality of life, and support sustainable development. Current Efficiency for Access Coalition members have programmes and initiatives spanning 54 countries and 26 key technologies. It is co-chaired by UK aid and the IKEA Foundation. This report was authored by Michael Maina, Elisa Lai, Makena Ireri and Michael Spiak of CLASP.

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# ABBREVIATIONS

| | |
|---|---|
| **AC** | Alternating Current |
| **BLDC** | Brushless Direct Current Motor |
| **DC** | Direct Current |
| **EforA** | Efficiency for Access |
| **W** | Watts |
| **Wh** | Watt Hours |
| **MC4** | Manufacturer Multi-Contact 4-millimetre diameter contact pin |
| **MPPT** | Maximum Power Point Tracking |
| **PAYGO** | Pay as You Go |
| **PWM** | Pulse Width Modulation |
| **PV** | Photovoltaic |
| **PVoC** | Pre-Export Verification of Conformity |
| **M** | Metres |
| **RMS** | Root Mean Square |
| **RPM** | Revolutions per Minute |
| **SWP** | Solar Water Pump |
| **VAT** | Value Added Tax |

# 1. Technology scope & objectives

## 1.1 Solar water pump technology scope

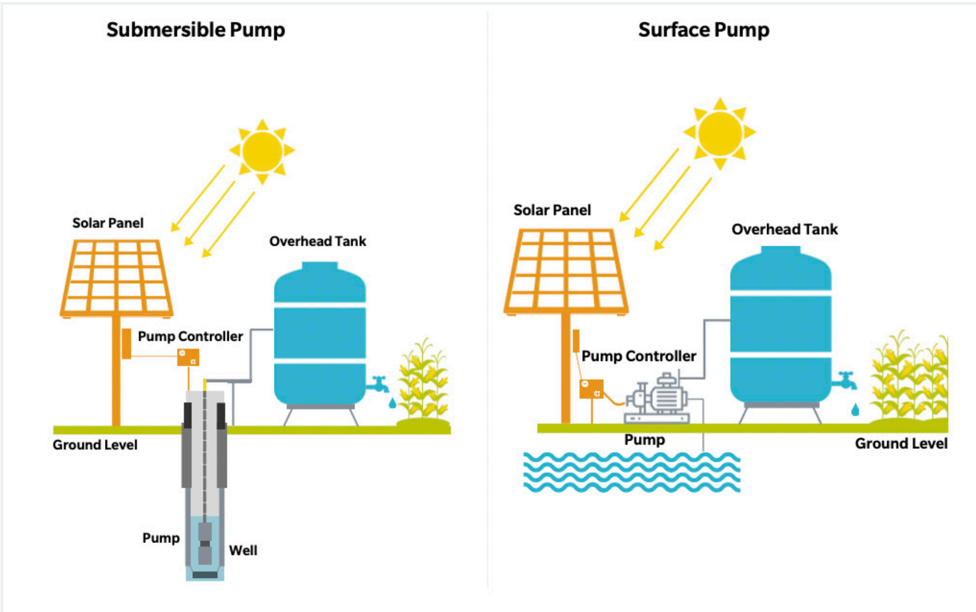
A solar water pump (SWP) is a pumping technology that uses solar energy to move water. It enables users, such as smallholder farmers, to access water for irrigation needs, households to access clean water for drinking and sanitation, water vending and, in some cases, water for small construction projects. SWPs can be categorised by several metrics, including:

- **Pump type**: surface or submersible
- **Motor type**: AC or DC motor
- **Pumping mechanism type**: centrifugal pump or positive displacement pump
- **Power System**: solar direct drive pumps or battery enabled pumps

While various metrics can categorise SWPs, this guide primarily focuses on small-scale (less than 2 kilowatts of power input) off-grid SWPs ideal for smallholder farmers irrigating up to 5 acres of land. Two broad categories of pumps, defined by their orientation to the source of water (Figure 1), are within the scope of the SWP guide:

- **Surface pumps** draw water from surface sources, such as streams and ponds. The pump itself is designed to be situated outside of the water source.
- **Submersible pumps** are designed for underwater installation, like in boreholes and wells.

**Figure 1: Basic components of submersible and surface pumps**



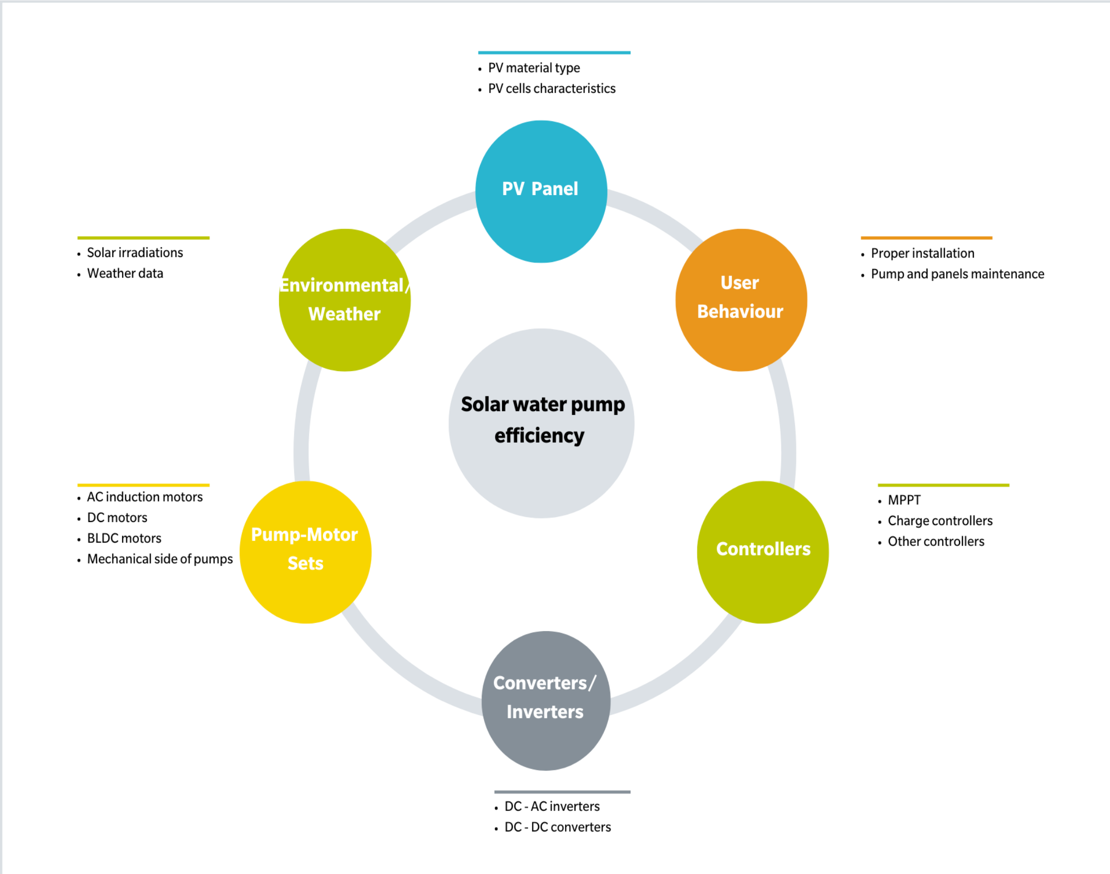

Although different pump types have varying components, the factors affecting the performance of a SWP are:

- **Environmental conditions** include solar irradiation and weather patterns in the specific geography, wind, ambient temperature, and cloud cover. The environmental factors may also have other variables based on particular locations where the pumps are installed, such as the distance to the water source and water characteristics in terms of salinity and turbidity.
- **Solar PV Module** - the capacity of a PV array determines how much electrical energy can be generated to power the pump system in rated conditions. In addition, the performance and efficiency of the PV panel -which is dependent upon the type of PV material used, the tilt angle and azimuth, and the characteristics of the PV cells also affect how well the pump system functions.
- **Pump motor sets** - brushed AC, brushed DC, or brushless DC (BLDC) motors- are the key energy-consuming component in electric pumps. Therefore, the type of motors used and motor efficiency can be the main contributors to the overall pump system efficiency.
- **Controllers** - solar pump controllers regulate the amount of current and voltage drawn from the solar panels and feed power into the pump. The type of algorithms used in the design, including charge controllers, may include Maximum Power Point Tracking (MPPT) and Pulse Width Modulation (PWM). If the controllers are not well designed, it can lead to power losses or over or or underpowering the pump, damaging the motor or leading to sub-optimal performance. Note that some pumping systems do not include solar charge controllers.
- **User behaviour**, such as installation process and maintenance, contribute to pump performance and durability over time. Installation and maintenance of SWPs can also be impacted by the amount and conciseness of information from the manufacturer.

- **Batteries** – Oversizing or under-sizing batteries can bring about pump inefficiency. This inefficiency can occur due to irregular charging cycles affecting the battery life and its ability to provide the necessary electrical power to the motor.
- **Converter or inverter efficiencies** are also important, especially for AC/DC compatible pumps. In some cases, solar charge controllers serve as inverters for AC motors.

Figure 2 below provides an overview of the various factors/components that may affect pump efficiency.

**Figure 2: Key factors influencing the performance of a solar water pump**




## 1.2 Field testing objectives

Before initiating field testing, it is essential to establish the objectives of the project and research questions that you plan to answer through this work. Some of these research objectives and questions may include examples listed on the next page. While data collected through performance monitoring can help answer some of the questions, it is essential to deploy user surveys or questionnaires to collect additional user feedback and observations that supplement and help explain performance monitoring data.

**Table 1: Sample objectives and research questions for SWP field testing**

| Research Aims | Example Questions |
|---|---|
| **To ensure that SWPs perform optimally or as advertised in varied real use.** | How much water is pumped per solar day in different solar conditions?<br>How does water quality impact pump performance and durability?<br>How much energy is consumed to move a measured volume of water?<br>Is the water source consistent or is the water level always changing, impacting the pump performance and durability? |
| **To rank the field performance of two or more design options or competing appliances** | Do surface pumps or submersible pumps function better in location X? |
| **To monitor how performance varies with seasonality or over time** | What is the amount of water pumped over an average solar day and/or in various solar day conditions (sunny, partly cloudy, and fully cloudy |
| **To investigate the frequency and intensity of pump breakdown cases** | How many breakdowns occur in a month?<br>Which parts of the SWP break down the most?<br>Can the breakdowns be associated with user behavior, environmental conditions or product design factors? |
| **To investigate field performance of certain ancillary or associated equipment** | Does the use of different types of pipes, level switches, cables or introduction of flow meters affect the pump service delivery?<br>How does usage of additional electrical appliances connected to the solar PV module affect pump performance? |
| **To determine how energy consumption varies with situation, user, or other factors** | What environmental factors (e.g., water quality, distance from the water source, etc.) impact the performance and durability of pumps. |
| **To determine 'real' appliance usage patterns by measuring/ observing user behavior** | What is the frequency of pump use (once day, a couple of times a week, weekly, etc.);?<br>How long is the duration of water pumping, etc.<br>How is the SWP maintained and does the user manual have access to maintenance and troubleshooting information? |
| **To evaluate adequacy of packaging for shipping (protecting the appliance in transit)** | Do products and/or components arrive with damages? |
| **To evaluate end user comprehension of product documentation, e.g., installation instructions, user manuals, troubleshooting and repairs, warning labels, etc.** | How well do SWP distributor or consumers understand the instructions for installation and operation? |
| **To identify any software issues for pumps reliant on various software** | Are there options to bypass the pump sensors in case they fail?<br>How long does the PAYGO controller respond after token top-up? |
| **To evaluate pump durability over extended use periods in varied water quality scenarios and varying use cases** | How does the pump performance vary when pumping saline water for over 1000 hours? |
| **To validate or develop new laboratory test methods from field testing learnings** | How can various user behaviors be factored in or useful in laboratory simulations? |

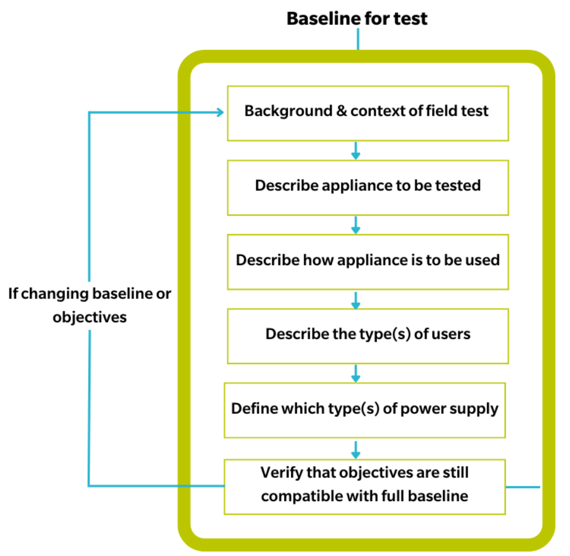
# 2. Collecting baseline data for solar water pump field testing

Collecting baseline data is an important second step as the data help crystalize the equipment to be tested (power, capacity, type of controls, etc.). These details also inform the selection of appropriate monitoring equipment to use in field testing projects.

## 2.1 Template to define the solar water pumps under test

To establish a good baseline of the pumps under test, Table 2 (annexe) can capture details of each specific product. The list is not exhaustive, and not all sections are relevant for all tests. In addition to filling in the table, take photos of the products (front, rear, sides, rating plate, battery, packaging, user controls, special features, controller, pump component, PV module, damages or observed deficiencies, and all included items).

**Figure 3: Steps for collecting baseline data.**




The pump's maximum voltage and current ratings are critical to determining the monitoring equipment's capacity. It is also helpful to consider the solar energy system capacity and whether it is generating sufficient electrical energy to power the pumps and the remote monitoring equipment. In cases where flow meters will be used to measure flow rate, pump diameter/size of the outlet pipes should be recorded before selecting the appropriate flow meter and any resulting errors.

## 2.2 Template to define solar water pump condition, situation, and usage at start and end of test

Table 3 in the annexe provides considerations regarding the set up and condition of the solar water pump in its test location as the test begins.

# 3. Solar water pump technical performance measurements

Monitoring the performance of SWPs can be categorised into two main categories; energy performance and service delivery/ throughput. Energy performance requires monitoring the input power and the power drawn by the SWP. On the other hand, the service delivery of a SWP can be measured by the flow rate (litre per minute, (lpm)) or volume per day (cubic meter per day, (m3 / day)).

## 3.1 Define Technical Parameters

Table 4 provides an overview of the various parameters to be monitored for both energy performance and service delivery.

## 3.2 Assessing the flow rate and yield

Flow rate refers to the amount of water that a system can move within a given period and is usually measured in litres per minute or gallons per minute. Pumps are often marketed with the volume of water moved per day ($m^3$/day), indicating the cumulative amount of water moved in a given solar day condition.

On the other hand, yield refers to the flow rate of a well or the amount of water the well/water source can yield in a day.

Measuring the flow rate during field testing can be done through direct measurements using monitors or inferred approaches. Approaches and parameters can be combined to fully assess service delivery for a solar water pump field test, although relative importance will vary by situation, technical capability, and budget.

- Direct measurement: Flow rate can be measured directly through flow meters and sensors or volume and time measurements. This measurement type does not use proxies to estimate flow rate.

  **Flow meters**: A range of flow meters can be used (Coriolis meters, ultrasonic meters, magnetic meters, vortex meters, multiphase meters, hall sensor meters and turbine flow meters) to measure the flow. The choice of a flow meter is heavily dependent on cost, availability, level of accuracy required, the preferred mode of data logging and relay, indicative maximum flow rate from the source, and the quality of water being monitored. The Beta Testing of Remote Monitoring Solutions report highlights provision for selecting an ideal flow meter. As a best practice, it is important to compare or validate the readings provided by the flow meter through other methods such as volume and time calculations since some flow meters reduce the pipe diameter as the water passes through the flow meter.

  Volume and time – This flow measurement method is done by recording the time it takes for a SWP to fill a known volume container.

- **Inferred approaches**: When a direct measurement is impossible, the flow rate can also be measured using implied methods by measuring pressure difference and motor speed. While test results from the inferred approach are likely to be less accurate than direct measurement, the measurement accuracy could be improved by comparing results with direct measurements and calibrating equipment before deploying these methods for field testing and repeated trials.

  **Motor speed** - Direct measurements may be possible where a motor is accessible, but this is not always the case. For example, for solar water pumps, the speed of the motor can be measured by revolutions per minute (RPM) using detectors such as magnetic hall sensors or a digital tachometer.

  Using the motor's speed, one can infer the volume and flow rate of the liquid (water) from a displacement pump as the flow rate is directly proportional to the motor speed. However, the head should also be measured alongside the RPMs for centrifugal pumps to determine the flow rate accurately. For brushed DC motors, the motor speed is closely related to the power that it draws from the solar power system, so monitoring the motor's input voltage may be sufficiently accurate to estimate the water output of a pump.

  **Pressure difference** – Differential pressure flow measurement is a tested and reliable way to estimate fluid flow along a pipe. This approach uses an orifice plate to reduce the fluid flow and two pressure gauges retrofitted on either plate side to measure the pressure difference. Using water flow can be calculated from the known pressure difference and water velocity. Bernoulli's principle, water flow can be calculated from the known pressure difference and water velocity.

**Table 4: Technical parameters that can be measured in the lab, field, or through user surveys.**

| Category | Parameters | Data Source | | |
|---|---|---|---|---|
| | | Lab testing | Field testing | User survey |
| **Energy Performance** | Minimum-maximum voltage input (V) | x | x | |
| | Minimum-maximum current input (A) | x | x | |
| | Minimum-maximum power input (W) | x | x | |
| | Average Power/day | x | x | |
| | Maximum head (m) | x | | x |
| | Head range (m) | x | | x |
| | Type of pipe included | | | x |
| | Length of pipe provided (m) | | | x |
| | Diameter of included pipe (cm) | | | x |
| | Pump type (Centrifugal, helical rotor, etc.) | x | | x |
| **Service Delivery / Pump Performance** | Hours of Operation (h) | x | x | x |
| | Minimum-maximum flow rate (lpm) | x | x | |
| | Volume of water moved per day (m3 /day) | x | x | x |
| | Average wire-to-water efficiency (%) | x | | |

## 3.3 Measuring solar water pump energy performance

As well as the flow rate factors set out in section 3.2, the following parameters should be measured to assess solar water pump energy performance:

1. The voltage at solar water pump input
2. Root Mean Square (RMS) current drawn over time, including the measurement of instantaneous start-up/inrush current when the unit is switched on, which is highly likely to be recognisable when data is recorded in a time series at a high sampling frequency
3. Instantaneous power (W);
4. Energy consumption (Wh) in a typical day
5. Pump head in meters (m)

## 3.4 Calculating wire-to-water efficiency

Wire-to-water efficiency, expressed in %, is the commonly used metric to determine the overall efficiency of a solar water pump. It is calculated by hydraulic power output (Wh) divided by the PV power input (Wh) for each head tested:

$$\boldsymbol{n} = \frac{pgHQ}{IV}$$

Where;
$n$ is the efficiency (%)
$p$ is the density (kg/m$^3$)
$g$ is the gravity
$H$ is head (m)
$Q$ is flow (l/s)
$I$ is PV current (I)
$V$ is PV Voltage (V)

The wire-to-water efficiency indicates the efficiency of the pump, pump motor, connecting wires, and controller in the case of AC pumps. The wire-to-water efficiency metric also accounts for the losses in the pipe fittings that surround the pump. Essentially, it is the ratio of the hydraulic energy of the water delivered from the pipe outlet to the energy supplied to the pump through the electrical wires from the PV array or PV module.

# 4. Design for remote monitoring and data logging

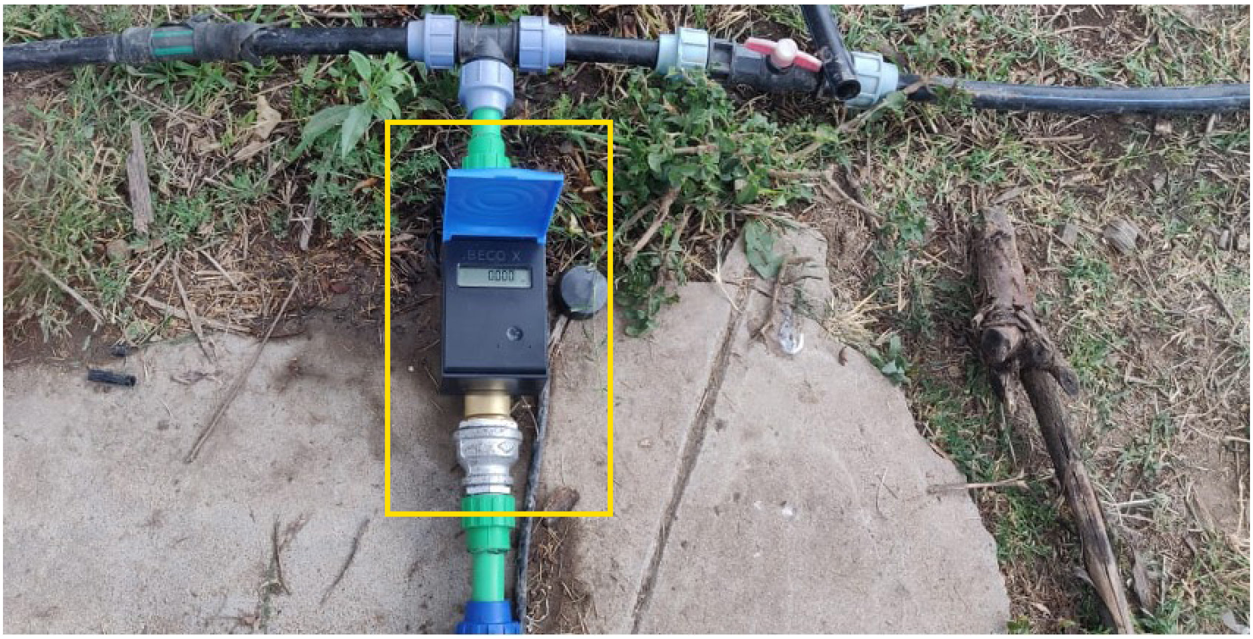
Table 5 provides an overview of the sensors recommended for field testing of solar water pumps, including their recommended accuracy and measurement resolution.

**Table 5: Overview list of sensors and placement guidance for field testing of refrigerators.**

| Equipment | Measurement | Minimum Instrument Accuracy | Measurement Resolution | Number and placement of equipment. |
|---|---|---|---|---|
| **Voltage sensor** | Voltage drawn (Volts) | ± 5% | 0.1 V | One sensor wired as close as possible to the appliance power input |
| **Current sensor** | Current drawn (Amperes) | ± 5% | 0.1 A | One sensor on the power input cable. This could be at the distribution board or closer to the appliance |
| **Power meter** | Energy consumption (Wh) | ± 5% | 0.1 Wh (at equal measuring intervals) | One energy meter with voltage measurement as close as possible to the appliance power input. Note: if using a power meter, voltage and current may be measured using this device instead. |
| **Flow meter** | Cubic meters/ hour or litres/ second or litres/ minute | ± 5% | 1 pulse per litre[2] | One flow meter placed along the main outlet pipe before any water is diverted. See figure 3. The flow meter should not be placed too close to the outlet as it causes backpressure due to the constriction it introduces. |
| **Motor Speed/ tachometer** | Revolutions per minute | <1% | N/A | For contact tachometers, the sensor needs to be placed on the motor enclosure. For contactless tachometer (infrared) point the infrared beam to the motor enclosure. |
| **Tape measure** | Pump head | ± 1% | N/A | To be measured once during installation |

2. Resolution of a flow meter also referred to as discrimination refers to the smallest amount of measurement that a flow meter can make. This varies according to the type of flow meter.

**Figure 3: Example of flow meter placement. Along the main outlet pipe and before any diversions**



# 5. Further guidance

## 5.1 Considerations when shipping solar water pumps

Efficiency for Access' product-agnostic field testing guide includes general guidance on considerations for shipping appliances. For some pumping systems with a battery, additional shipping paperwork may be required to ship batteries. If the product includes a lithium-ion battery, the shipper will need to obtain a UN 38.3 certification before shipment and provide specialised packaging and markings. This can take time, so it is essential to research the requirements of the shipping agent and the country of export and import in advance.

It is also important to understand additional quality standards or safety requirements required for importing SWPs into a country. In most cases, engaging a pre-export verification of conformity (PVoC) agency to obtain a certificate of compliance should be sufficient.

In certain countries, SWPs can benefit from taxes and duties exemption. For example, in Ethiopia, SWPs can be exempted from 15% Value Added Tax (VAT) and 2% withholding tax because the inputs are not directly used for commercial purposes.[3] In other countries such as Kenya, parts of the SWP system, like solar module and charge controller, can qualify for VAT exemption.[4]

For further guidance:

- The Efficiency for Access Guide to Shipping Appliances[5]
- Importation Guidelines for Solar PV Products and Systems in Kenya[6]

## 5.2 Other resources

Generic Guide for

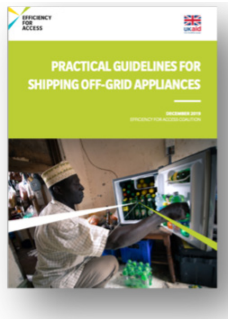
THE FIELD EVALUATION OF NEW TECHNOLOGIES

for

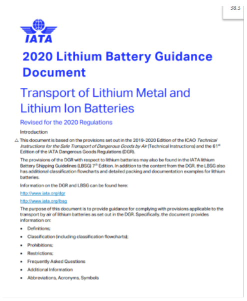
WHO PQS Prequalification

- Generic Guide for the Field Evaluation of New Technologies for World Health Organisation (WHO) Performance Quality Safety (PQS) Prequalification, WHO/PQS/GENERIC/GUIDE.1.1, March 01, 2016. Available from: https://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/catdocumentation.aspx?id_cat=17

3. https://www.ace-taf.org/wp-content/uploads/2019/10/ACE-TAF-UGANDA-SOLAR-WATER-PUMPING-REPORT-SCREEN-1.pdf
4. https://www.ace-taf.org/wp-content/uploads/2019/10/Importation-Guidelines-For-Solar-PV-Products-and-Systems-in-Kenya-2019-ACE-TAF.pdf
5. Available from: https://storage.googleapis.com/e4a-website-assets/EforA_ShippingGuide_Final.pdf.
6. https://www.ace-taf.org/wp-content/uploads/2019/10/Importation-Guidelines-For-Solar-PV-Products-and-Systems-in-Kenya-2019-ACE-TAF.pdf




- Practical Guidelines for shipping off-grid appliances, Efficiency for Access Coalition, December 2019. Available from: https://efficiencyforaccess.org/publications/practical-guidelines-for-shipping-off-grid-appliances




- 2020 Lithium Battery Guidance Document, IATA. Available from: https://www.dhl.com/content/dam/downloads/g0/express/shipping/lithium_batteries/lithium_battery_guidance_document.pdf

# 6. Annexe

**Table 2: Template to define the solar water pump under test.**

| |
|---|
| Appliance model number and name: |
| Manufacturer: |
| Brand: |
| Model number |
| Company purchased from (e.g., name of retailer or wholesaler, etc): |
| Product description: |
| Country of origin: |
| Unique serial number of the appliance: |
| Pump year of manufacture: |
| Outer dimensions: Height (cm): |
| Width (cm): |
| Depth (cm): |
| Weight (kg): |
| Power supply type (AC or DC, etc): |
| Motors type (AC, BLDC, DC etc): |
| Pump rated voltage range (V-V): |
| Pump rated power range (W-W): |
| Pump rated current (amps): |
| Rated frequency if product is AC (50Hz, 60Hz): |
| Rated/Maximum flow rate (litres/minute)[1]: |
| Advertised volume of water moved per day (M3/day): |
| Type of designation (surface vs submersible): |
| Type of pump (centrifugal, displacement etc.): |
| Maximum head (m) and/or Head range (m-m): |
| Pump curves (from technical specification documents): |
| Inverter or charge controller: |
| Battery capacity (Ah), if applicable: |
| Type of pipe included: |
| Length of pipe included (m): |
| Diameter of outlet pipe (mm): |
| Special features of the appliance that are relevant to the planned test such as water level sensors: |
| Other details from the rating plate |
| Pump and solar kit spare parts provided during purchase: |
| PV Module: |
| Maximum power: |
| Voltage (Vmp): |
| Current (Imp): |
| Voltage (Voc): |
| Current (Isc): |
| PV array configuration (number of PV modules in series/ parallel): |
| Maximum power of PV array: |

1. Include assumptions associated with stated value, such as power and energy input and head.

**Table 3: Template to define the condition of the solar water pump in its test location.**

| Consideration | Notes about the refrigerator and its set up |
|---|---|
| Description of the location of the appliance and what is located around it | *Example: Pump is located in a mixed fruit tree orchard approximately 100M from the owner's residence* |
| Photographs of the appliance in its test location | |
| What electricity supply connections are in place (include photographs)? | *Example: MC4 connectors, screw terminals, crude wire connections etc.* |
| What cable lengths and types are used for provision of power?<br>What types of pipes/hoses are used?<br>Were these cables and pipes provided by the manufacturer recommended? (for assessing sources of power loss leading to lower efficiencies that should be considered) | |
| What are the set charge controller settings? | |
| What monitoring equipment are in place, with photographs | *Example: Water level sensors* |
| Water source (river, pond, well) and water level at source | |
| Depth of water source (m) at installation date (if possible) | |
| Other shared appliances using PV energy system (in case of battery enabled pumps) | *Example: Lighting, TV, radio, or other appliances* |
| Water turbidity (directly measured or categorised) | |
| Is there a storage tank or direct pumping to field? | *Example: Elevated or underground tank, capacity, height from the ground (if elevated) and total vertical and horizontal distance from pumping level to calculate pump head.* |
| Water salinity (directly measured or categorised) | *Example: Parts per thousand (ppt) of dissolved salts.* |
| Depth of pump installation for submersible pumps | |
| Location and orientation of solar panels | |
| Check for visible damages to the SWP | |
| At or near the end of the test period, run through the above checks again to note what changes or damage (if any) has occurred.<br>At the end of the test, check also for any change to other electrical loads on the system, has power available to appliance under test been affected? | |