SOLAR POWERED BOREHOLE PUMPS

Electricity generated by solar "photovoltaic" (PV) modules has been used for powering pumps for almost half a century, but in the past scaling up solar powered pumping systems was hampered by high capital costs, lack of versatility and limited pumping capacity. The cost of PV modules has reduced by 85% in the last decade triggering technological advancements of robust and reliable solar pumping equipment. The development of variable frequency inverters has extended the solar pump performance range tenfold since they work with standard electric motors and so any electric pump can be solarised. **These developments have made solar the preferred choice and the first option that all Oxfam projects should consider for off grid pumping.** In recent years, there has been an emergence of a vibrant private sector with good technical knowledge and offering quality solar pumping products in most countries where Oxfam works. At the time of writing, the largest solar pumping system implemented by Oxfam is a 30kW borehole pump powered by a 51kW PV generator and designed to provide 450m3/day of water for a population of 21,000 people in rural Kenya. PV pump systems require a higher initial investment, but this is compensated by large reductions in operation and maintenance costs which can be passed on to water users through lower tariffs.

Types of Photovoltaic (PV) Modules

There are three main types of photovoltaic modules widely available on the market - Monocrystalline (Mono-Si), Polycrystalline (Poly-Si) and Thin-film (TFPV). Currently Mono-Si and Poly-Si are used for the majority of water pumping applications because of their higher efficiencies. The main difference between the two is in the purity of the silicon which affects the efficiency. Mono-Si contains a higher purity silicone, resulting in the highest efficiency (15-20%) it is consequently the most space efficient and produces more power for an equivalent surface area but is also the most expensive. Poly-SI, sometimes also referred to as multicrystalline, is simpler to produce and therefore slightly cheaper, however it tends to have lower output efficiency (13-16%). Mono-Si is easily recognizable by an external even colouring and uniform look. A good way to distinguish mono and polycrystalline solar modules is that Poly-Si solar cells look perfectly rectangular without rounded edges. The choice is typically dependent on what is available in the local market, cost and space efficiency.

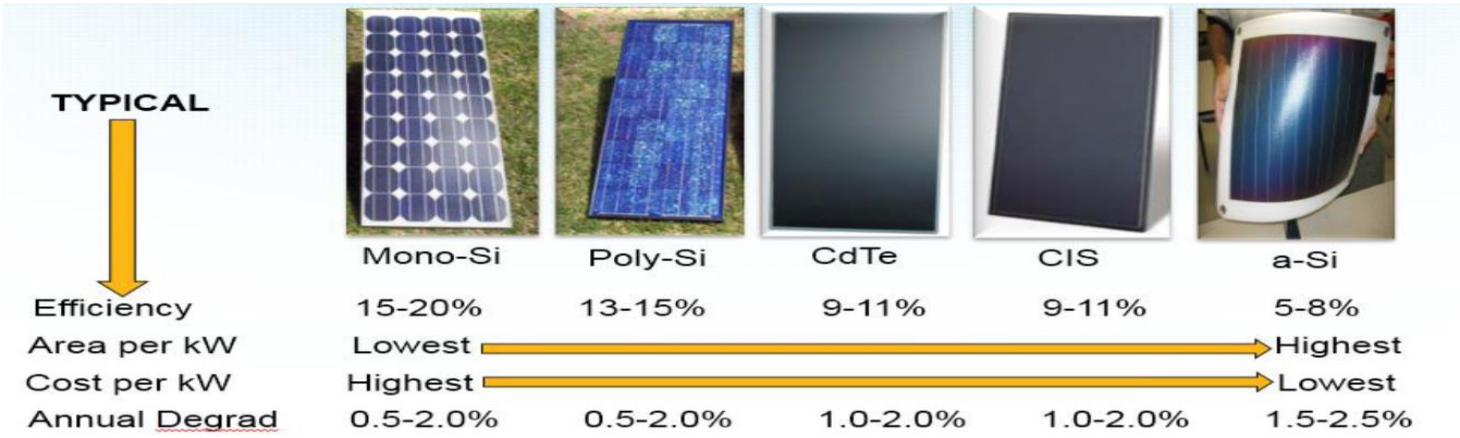

Fig 1: Different types of PV modules

Thin-film photovoltaic cells (CdTe, CIS, a-Si) are cheaper to produce but much less space efficient therefore needing a larger support structure and more cabling. A monocrystalline module of equivalent area can typically produce four times the amount of electricity. The current lifespan of thin-film is also lower. However thin-film technologies are evolving and it has enormous potential in the future as efficiency improves and costs reduce.

All PV panels produce DC current. Small capacity (1-4KW) solar pumps such as Grundfos SQFlex and Lorentz PS range are designed to run off DC. However most electric submersible pumps run on AC so require an inverter to convert DC to AC.

Choice of PV Module

There are many types of solar modules worldwide, some of the leading manufacturers currently being Canadian Solar, Trina Solar, First Solar, Jinko Solar, JA Solar, Sunpower, Yingli Green Energy, Sharp Solar, Renesola, Hanwha SolarOne, Kyocera, SolarWorld among others. The industry is competitive and dynamic and being the largest manufacturer does not necessarily guarantee the highest quality module as some of the smaller manufacturers may also offer premium products. That said, a company's proven ability to produce and sell a large amount of product is testimony to its brand's credibility.

Some of the considerations to make when choosing a solar module include:-

⇒ A system manufacturer who operates a quality management system that is ISO 9001 or equivalent and have recognised third party verification

⇒ Solar modules that meet the necessary CE / international standards for safety and where applicable functionality

⇒ PV modules that are approved to IEC/EN 61215 and 61730 or UL 1703 certified and listed, as indicators of quality and adherence to safety standards

⇒ Manufacturer who can provide a 20-25 year power output guarantee with a maximum degradation of 2% per annum

⇒ Modules of robust design and modules that have been successfully used in prior off grid applications

Note: The choice of panel should not be left to the procurement team without a technical review.

It is also important to take into consideration the performance characterises of a particular solar module such as power rating (Watts [W]), voltage (Volts [V]), current (Amps [A]), *[Fig 2]*. These characteristics will determine the module configuration in terms of series and parallel connections. Several modules electrically connected in series or parallel constitute an array, and several arrays, electrically connected in parallel to generate the required power, constitute the PV generator. The configuration will be determined by the characteristics of the pump. For modules in series the amperage remains constant but the voltage increases with each module added, while for modules in parallel, the voltage remains constant and amps increase with each additional module *[Fig 3]*. **It is critical to get the wiring correct and this is a common problem that can lead to sub optimal pump performance or damage of equipment.** Always double check the complete wired solar generator against the manufacturer's specification.

ELECTRICAL DATA (AT STC)

		ND-R250A5
Maximum power	P_{max}	250
Open-circuit voltage	V_{oc}	37.6
Short-circuit current	I_{sc}	8.68
Voltage at point of maximum power	V_{mpp}	30.9
Current at point of maximum power	I_{mpp}	8.10
Module efficiency	η_m	15.2

Fig 2: Example of PV module electrical characteristics

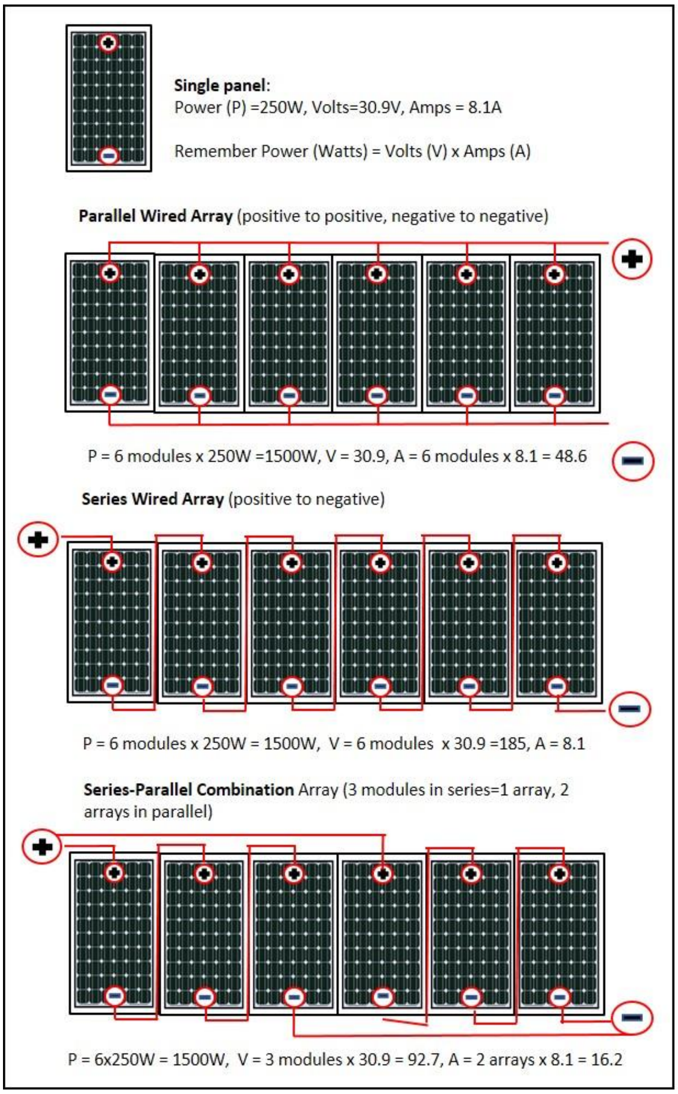

Fig 3: Example of PV wiring configurations

Factors affecting Solar Energy Production

There are three factors that affect the availability of solar energy: **location on the globe, season of the year, and time of the day**. Therefore a module rated at 100W will have different outputs depending on where it is installed, which season of the year it is and what time of day it is. Modules are rated against controlled laboratory conditions referred to as Standard Test Conditions (STC) i.e. an incoming solar irradiance of 1000W/m^2 and module temperature of 25^{0}C, and parameters outside of these will result in different power output.

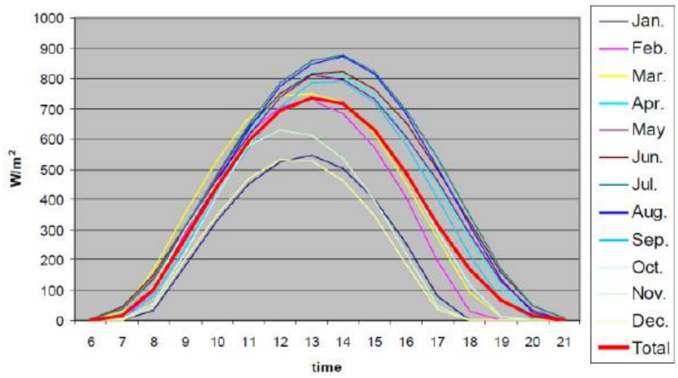

Fig 4: Solar irradiance variations

The rating and actual performance of a module will also differ depending on actual field conditions such as solar irradiation, temperature (efficiency reduces as temperature increases [1]*[Fig 3]*), dirt losses, cable losses, tolerance, reflectance etc. Other factors that affect power output from the modules (and which are in our control) are shading, tilt and orientation.

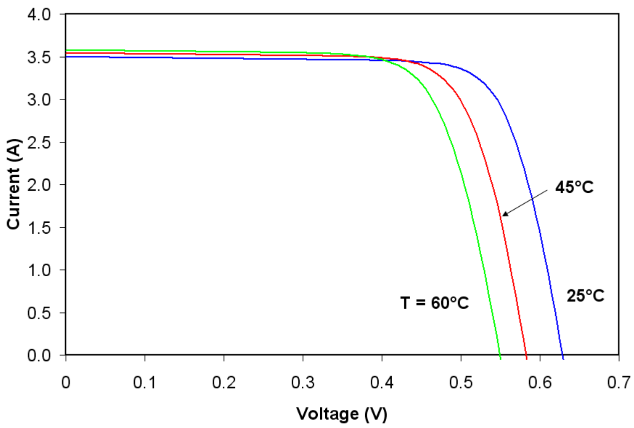

Fig 5: The higher the module temperature, the less power generated

The performance ratio (PR) expresses reduction in generation of solar energy due to these factors. The lower the PR is the more modules will be needed to compensate for losses. Pump design tools take these factors into consideration and typically the size of PV generator is significantly bigger than the size of motor being powered by a factor ranging from 1.1 to 2.5. It is recommended to use solar sizing tools to get the actual factor for your location and requirement.

Where is Solar Viable?

How can we know whether we have enough energy to power a pump in my location? The PV system size needed to meet the pump's energy requirements depends on a site's solar resources, which are calculated in daily peak sun hours (PSH). PSH is the number of hours per day during which solar irradiance averages 1000W/m^2. For example, a location that receives 8kWh/m^2 per day can be said to have received 8 hours of sun per day at 1000W/m^2.

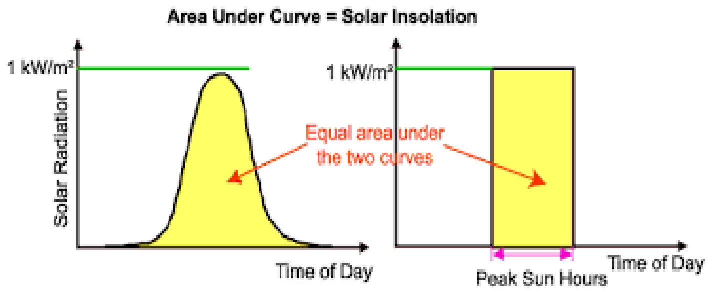

Fig 6: Graph of peak sun hours

A pump will run as if connected to a generator for as many hours as the PSH. PSH hours can be confirmed at the Atmospheric Science Data Centre or European Commission PV GIS.

Rule of thumb:

- ⇒ **If PSH is less than 3.5, discard solar option**
- ⇒ **Solar application is viable in countries within the solar belt (area of the world between 35^{0}N and 35^{0}S that receive the highest amount of solar irradiation)**

The other consideration for viability is the power requirement of the pump. Currently the largest motor that can be powered using solar is 37kW (from Grundfos) but bigger solutions are in development from both Grundfos and Lorentz. Other circumstances where solar may not be appropriate include isolated locations where solar pumps are prone to vandalism and/or theft.

Contexts that show clear advantages should be strongly considered for solar, such as; camps which are anticipated to remain longer than 2-3 years, locations which have no

[1] On a clear day a solar panel in N. Europe will be more efficient than at the equator. Even in freezing temperatures the panel warms up and may reach the controlled temperature of 25^{0}C whereas the operating temperature near the equator could be 60 degrees or higher.

electrical grid connection and places where diesel is expensive or supply is irregular.

Types of PV Pumping Systems

Solar solutions are available for both submersible borehole and surface applications. This brief focuses on ground water application though the design and application principle is the same. The best type of solar pump for a particular pumping application depends on the daily water requirement and the pumping head. Generally pumps are categorized into two:

(i) Helical Rotor (positive displacement) pumps: they operate efficiently over a wide speed range and can pump water at low solar irradiation levels. They are suitable for higher heads and low flows applications.

(ii) Centrifugal (rotor dynamic) pumps: these are suitable for relatively lower heads and higher flow applications. Development of DC-AC inverters has allowed use of centrifugal pumps to provide performances of more than 200m^3/hr and heads of up to 450m.

Solar pumping systems can be installed in three configurations:

(i) Stand alone DC solar system: Pumps powered by DC motor connected to the PV generator via a control box. Such systems are available up to 4kW motor size and are suitable for small applications. They are more efficient than equivalent AC systems and should be preferred for requirements within this range.

(ii) Stand alone AC solar system: Pumps powered by AC motor connected to the PV generator via a DC-AC inverter. Such systems are available from 1.1kW to 37kW motor size.

(iii) Hybrid pump system which can be either a DC or AC pump powered by solar, with an alternative source of power (electric grid or fossil fuel generator) that allows for supplementary pumping during cloudy days and at night. Switching between solar and generator/grid is through a changeover switch.

Lorentz and Grundfos are the market leaders of solar pumping technology and provide equipment of sound design and quality coupled with a 2 year warranty. Pump inverters are now fitted with a data logger that makes it possible to remotely switch on/off and monitor key parameters of the pump (where GSM network is available) from any location in the world making it an interesting feature for systems in remote and security sensitive locations.

Oxfam's experience in Horn and East Africa since 2012 is predominantly based on Lorentz pumps. Prior to this DC-AC Grundfos SQFlex were the dominant type of solar pump and focus of Oxfam's first technical brief on solar. Whilst SQFlex are still appropriate for small applications, the higher water demands for most humanitarian situations limits their use. Lorentz has recently expanded its capacity to 30kW AC pumps powered by solar. Grundfos (which has been playing catch up with Lorentz) has introduced an advanced range of up to 37kW. The technology is improving and evolving very quickly with bigger sizes being developed by both manufacturers. Oxfam will need to keep abreast with the technology as it advances.

Components of a PV Pumping System

The main components in a PV water pumping system are PV modules, pump, inverter/control box and module support structure. Other parts include disconnect switch, sun sensor module, combiner box, surge protector, lightning arrestor, earthing, water level sensors, cables and pipes.

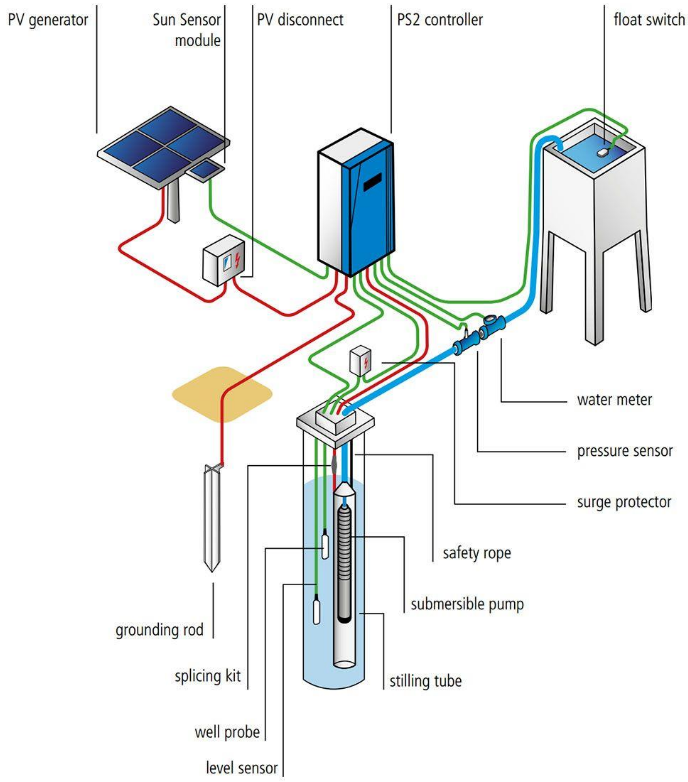

Fig 7: Major Components of a PV Pumping system

Controller: Incorporates an inverter that transforms the DC power produced from the solar generator to AC power which can power standard electric motors. It can be retrofitted into existing generator/grid powered AC pumping systems. They have integrated protective features against over/under voltage, overload, short circuit, dry running, reverse polarity, high temperature fault indication and controlled start-up.

Sun sensor/module: is an automatic solar level switching device that ensures pump starts only when there is sufficient solar irradiation, avoiding frequent stop-starts and premature wear of pump. Ensure sensor is never shaded and correctly calibrated.

PV disconnect: a string connection box that also allows the DC current from the solar generator to be isolated before reaching the control unit. For a large solar generator, multiple PV disconnects may be required depending on the type of disconnect switch and the number of strings to be terminated.

Well probe / low level sensor: installed with every system for dry run protection.

Sizing of a PV Pumping System

The selection of a suitable solar pump follows the same principle as with traditional water system designs but is more complex due to the additional variables involved and in order to design the system accurately, use of software-based design tools is recommended. User friendly solar pump design tools are available from both Lorentz (Compass) and Grundfos (Grundfos Product Center) and parameters required for design include:

⇒ Application (surface vs. submersible)
⇒ Water consumption per capita per day
⇒ Total population and projected population growth
⇒ Maximum yield of water source (m^3/hr)
⇒ Distance from source to solar panels
⇒ Distance from source to water tank
⇒ Elevation from source to tank
⇒ Static and dynamic water level
⇒ Inner borehole casing diameter
⇒ Seasonality of water demand
⇒ GPS location (longitude and latitude)

Since solar energy is only available during sunlight hours and performance is dependent on season and time, it is critical to dimension solar pumps based not on hourly requirement but on daily demand such that water is pumped during sunlight hours, stored and made available when needed. *Fig 8* shows an example of pump output variations – seasonally and daily.

Where the daily water supply is critical (i.e. need to ensure a minimum supply per day, no matter the conditions), it is recommended to design the system based on month with least output so that demand is met in the worst case, meaning in all the other days of the year, you will get more water than what you need.

Where demand exceeds the capacity of a stand-alone solar pump, an alternative power source can be connected via an external change over switch, pumping using solar energy during the day and switching to grid /generator power during the night or during periods of overcast weather. This applies also in cases where the borehole capacity is limited and meeting the demand requires prolonged pumping or where constant water supply is critical.

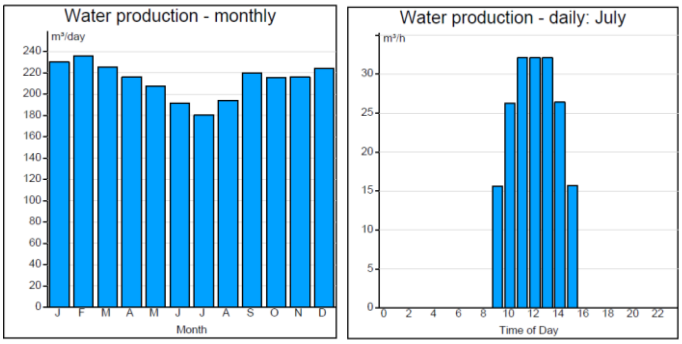

Fig 8: Seasonal and daily variation of pump output

The use of batteries for storage is strongly discouraged and direct systems are preferred due to improved efficiencies of PV modules and DC-AC inverters. Instead of storing energy, we store water hence keeping the system simple and efficient. In a pure solar PV pump systems, ideally, the tank should be sized to store at least a three-day water supply. In practice this will not always be possible so you need to think through, with users, the implications and management/mitigation measures that can be put in place such as rationing.

The most common failure of solar pumps witnessed in the field is not unique to solar issues but is rather due to improper system dimensioning. Therefore, solar design tools should not replace the need for technical staff in the field as they are designed to be used by people who are proficient in the design of water supply systems to ensure coherency. Proper siting/construction of water point, coherent dimensioning, sound installation and backed up with a post-installation maintenance plan is critical for the success of any water system. Contrary to popular belief that solar systems have zero maintenance costs, they have high potential repair costs and a cost recovery mechanism should be put in place to ensure system sustainability.

In a refugee context (off-grid), solar should be Oxfam's default option.

Solar for Agricultural Use

Solar pumping for irrigation applications follows similar principles of solar design as with submersible water supply applications. Irrigation pumps can either be submersible or surface mounted. Surface mounted pumps are available from Grundfos and Lorentz and use the same solar controllers/inverters as for submersible pumps. Installation configuration can be solar stand alone or hybrid. To prevent suction problems such as cavitation, surface pumps have to be installed as close to the water source as possible and are often installed with a floating suction which allows the suction pipe to rise and drop as the water level changes. Submersible pumps can also be installed in surface water sources and installed on a floating pontoon.

Fig 9: Submersible pump installed on a floating pontoon

A wide range of surface pumps are available from domestic use to large scale applications with capacities ranging from 0.3kW DC pumps to 37kW AC pumps. Performances range from as low as 0.25m^3/hr to as high as 450m^3/hr, with heads of up to 200m.

Module Orientation and Tilt

To maximize the solar system's energy production, the modules should always face the equator i.e. face south if in the northern hemisphere and face north if in the southern hemisphere. They should be mounted at a tilt equal to the latitude but not less than 15^{0}C for self cleaning when it rains.

The support for the modules can be ground-mounted, pole-mounted or roof mounted, made of galvanized steel or aluminium frames and choice will depend on system size, environmental conditions and security factors. A pole-mount is subject to wind loading and correctly analyzing these loads is essential for determining the correct foundation design and mounting pole size. The structure itself needs to be properly coated and protected against environmental factors such as rain, humidity, corrosion, and other conditions. The modules should be secured in a manner that will deter theft/vandalism, prevent them from being blown off in high winds and avoid accidental damage from wandering wildlife or livestock. This can be achieved through perimeter fencing, installing alarm systems, spot welding bolts/tamper-proof bolts, welding of angle iron over the frame of the modules (taking care not to shade the edge of the actual PV cells), installing motion detector lights, engraving identification on the modules etc.

Fig 10: Ground mounted support structure in Rhino Camp, Uganda

Fig 11: Pole mounted structure in Turkana, Kenya

For tracking, the modules have to be pole mounted. In the equatorial regions PV tracking is not necessary as the orientation of the sun does not vary as much compared to higher latitudes. In order to minimize voltage drop and lower installation costs, location of PV modules should ideally be close to the pump while taking into consideration security factors such as potential theft and vandalism.

Equipment Costs

In comparison to fossil-based pump systems, solar systems have higher capital costs but are cheaper over the life of the system. Evidence shows that the breakeven point (at which solar becomes advantageous over diesel) is on average 2-4 years and for small systems sometimes less than 1 year, and this will continue to improve as solar prices continue to come down. A few indicative prices for Oxfam solar systems in East Africa region are shown in ***fig. 12.***

Location	Motor Size [kW]	PV Generator Size [kW]	Max Output [m3/day]	TDH [m]	Cost (£)
Kenya, Nablon	30	51	450	100	61,400
Kenya, Songot	4	3.5	35	85	12,225
Kenya, Lodwar	0.9	1.4	18	70	6,565
Tanzania, Nyarugusu	26	54	350	150	81,700
Tanzania, Makere	0.7	1.5	25	30	4,880

Fig 12: Solar system prices

Advantages of solar

- ⇒ Low life cycle costs due to minimal running costs.
- ⇒ Short return on investment for small and medium sized systems
- ⇒ Little routine maintenance required (other than keeping the modules clean)
- ⇒ Low requirement for operation
- ⇒ Potential to provide water at lower user tariff
- ⇒ Environmentally friendly and sustainable
- ⇒ Efficient, versatile, durable

Constraints to solar

- ⇒ Higher capital cost
- ⇒ Can only operate during daylight hours
- ⇒ Reduced output when cloudy
- ⇒ Potential for theft if not well secured and elevated.
- ⇒ Capacity constraints as available inverters are up to 37 and 30KW for Grundfos and Lorentz respectively
- ⇒ Lack of sector professionalism in some markets
- ⇒ For rapid response and short term water supplies solar may not be as cost effective as other power sources.

Preventive Maintenance

- ⇒ Depending on the level of dust, daily/weekly clean the modules with a cloth and water only (no soap or detergent), and clean at early hours when modules are not hot. For elevated pole mounted arrays, which are inaccessible to clean manually, a hose pipe arrangement is required to spray water across the modules for cleaning.
- ⇒ Ensure that nothing in the vicinity can shade modules, remove shrubs around the solar modules, do not allow the construction of structures that might shade the modules
- ⇒ Inspect components - check the cleanliness and connections of all visible equipment (modules, inverter, generator).
- ⇒ Once a week, check the cables whenever possible and seek possible damage (cuts, wear or insulation eaten by rodents).
- ⇒ Ensure there is no dew condensation, no peculiar smell, stable vibration, normal temperature of the body, no abnormal noise etc.
- ⇒ Ensure connections are firm (tighten loose terminals, nuts, cable glands etc). In case of a problem, consult an expert. Do not tamper with it.
- ⇒ Check mechanical stability, weathering, corrosion of the support structure
- ⇒ Periodically paint the module support structure to prevent corrosion.
- ⇒ Frequently monitor the flow output from the pump and the current consumed by the pump.
- ⇒ Keep a record of system performance so that problems can be identified easily.
- ⇒ Keep a record of all associated O&M costs to better understand the long-term real costs and benefits associated with the system.
- ⇒ Put in place a service contract with a qualified service provider for at least the first, most critical, 18-24 months.

Safety, Dos and Don’ts

- ⇒ Always remember that even a single solar module is a live circuit that can result in electrocution.
- ⇒ Two or more modules connected in parallel or series if connected incorrectly to a pump can damage or destroy the equipment.
- ⇒ All DC wiring should, if possible, be completed prior to installing a PV array. This will allow effective electrical isolation of the DC system while the array is installed; and effective electrical isolation of the PV array while the inverter is installed.
- ⇒ Your solar module consists of glass which can easily break. Do not throw objects at the solar module, stand or step on the module or try to repair your solar module if it breaks.
- ⇒ Do not carry out modifications on your system without technical guidance from your system supplier or a qualified technician.
- ⇒ Fix all modules securely onto the support structure before doing any wiring and minimise the risk of accidents by covering and shading modules with their packaging until the installation is complete.
- ⇒ Modules that have different characteristics in model, power, voltage and current should not be connected together in the same system (mismatching)
- ⇒ Shadowing should be avoided as it leads to significant power loss.

Further Information

1. Lorentz solar pump installation manual
2. World Bank Solar Technical Repository
3. Oxfam catalogue items (refer to catalogue for more details)

⇒ **BSS3L/1: Pump kit, Solar, Submersible** (£3,110)**,** 3" This 'low yield' kit is offered as a simple installation for a community water supply, school, health post or staff compound. The 3" pump enables the unit to be used in boreholes of 4" casing or greater. The kit is selected to be capable of delivering *approximately* =/>10 m^3/day at 10-30 m total head, based on general solar irradiation figures between 20° North and South of the Equator. The kit is designed to be powered using the Solar Panel kit included.

⇒ **BSS4/1: Pump kit, Solar, Submersible** (£3,550)**,** 4" multi stage submersible pump set supplied with rising main, wellhead assembly and control panel, Wide pumping range with output of upto 7m3/hr at 20 metres and 4m^3/hr at 70m head.. All tools and accessories are included for installation of the equipment. Electrical inverter/control/protection unit and Level control equipment low water and tank full switching, can operate off diesel genset as backup for night time operation.

4. Galvanized steel and aluminium support structure design and Bill of Materials (link to be added).