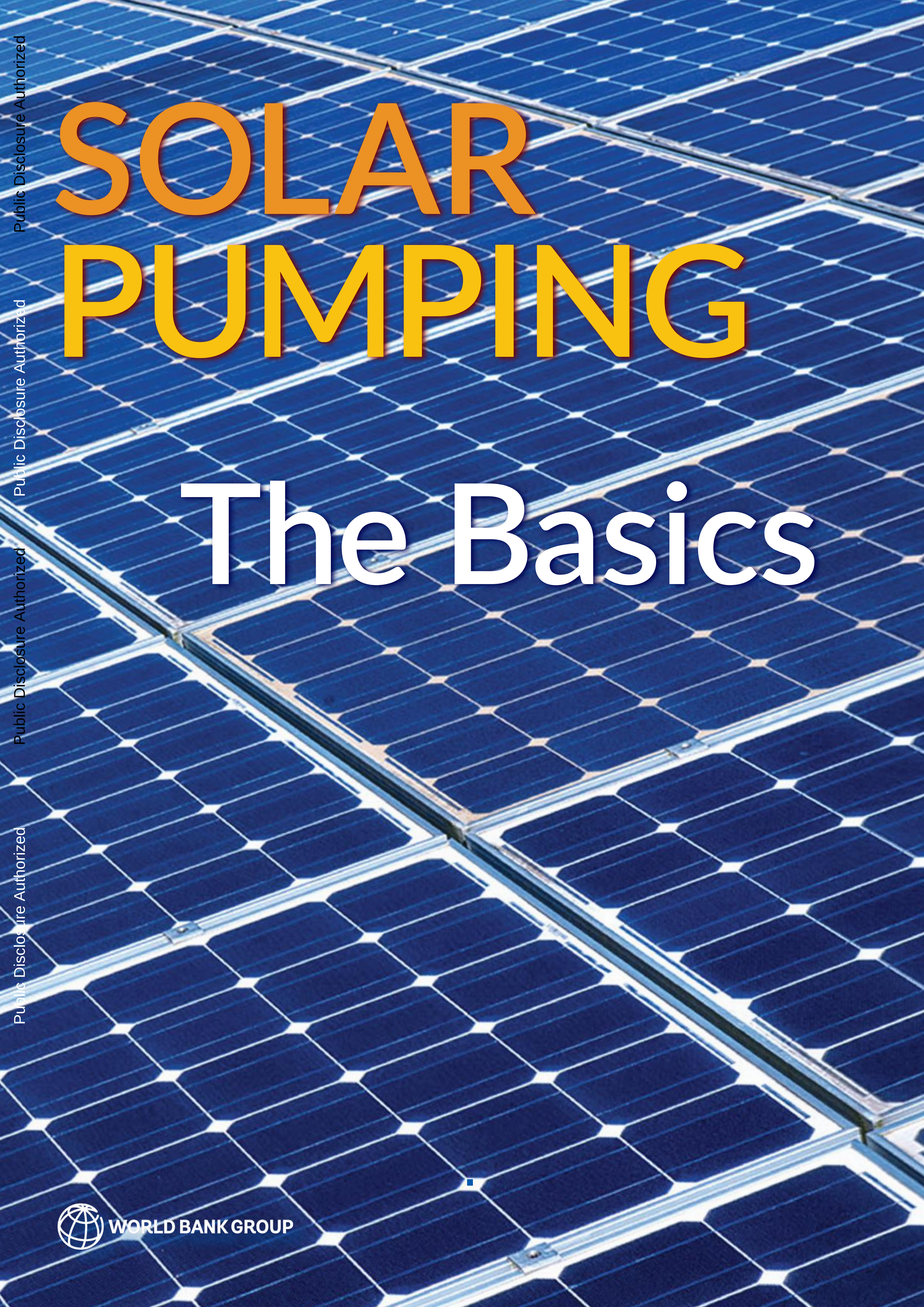

SOLAR PUMPING

The Basics

WORLD BANK GROUP

1818 H Street NW
Washington, DC 20433
Telephone: 202-473-1000
Internet: www.worldbank.org

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The advice and overview contained in this document are intended as a general introduction to the basic components of solar pumping. They are not presented as a substitute for consultation with technical experts and close adaptation to local situations. They are in no way intended as an instruction manual for infrastructure project implementation.

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The Basics

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This report was coauthored by Kristoffer Welsien (Water and Sanitation Specialist), Christopher Purcell (Renewable Energy Consultant), Reuben Kogi (Renewable Energy Consultant) and Carlos Batarda (Consultant). The Team wishes to thank Bill Kingdom (Global Lead for Water Supply and Sanitation in the Water Global Practice) and Miguel Vargas-Ramirez (Senior Water and Sanitation Specialist) for their valuable inputs and guidance. The Team is grateful for the thoughtful comments and feedback from peer reviewers Pierrick Fraval (Senior Water Resources Management Specialist) and Malcolm Cosgrove-Davies (Lead Energy Specialist), and appreciates the graphic design and layout by Helena Goldon (Consultant).

Abbreviations

AC	alternating current
BOS	balance of system
BS	British Standards
CAPEX	capital expenditure
CBA	cost-benefit analysis
DC	direct current
DWL	dynamic water level
IEC	International Electrotechnical Commission
IRR	internal rate of return
kW	kilowatt
kWh	kilowatt-hour
kWh/m^2/day	kilowatt-hours per square meter per day of solar resource
kWp	kilowatt peak
LCC	life-cycle costs
LCCA	life-cycle costs analysis
OEM	original equipment manufacturer
O&M	operation and maintenance
PV	photovoltaic
STC	standard test conditions
SWP	solar water pumping
TDH	total dynamic head
Wp	Watt-peak
VSD	variable speed drive

Table of Contents

1 WHAT IS SOLAR PUMPING?

1.1 Why is solar pumping exciting?

Solar photovoltaic water pumping (SWP) uses energy from solar photovoltaic (PV) panels to power an electric water pump. The entire process, from sunlight to stored energy, is elegant and simple.

1.2 The revolution of solar pumping

Over last seven years, the technology and price of solar pumping have evolved dramatically - and hence the opportunities it presents.

• *SWP system capacity and ability have expanded.* Early solar pumps had limited performance and were restricted to pumping installations with a shallow water source and a low water demand. Today, pumps can reach deeper wells (500 meters (m), compared to the previous 200 m) and push larger volumes of water (1,500 m^3/day, compared to the previous 500 m^3/day at low head). Efficiencies have also increased considerably. New pump and motor designs have increased water outputs over the entire pump range, as Figure 1 illustrates.

• *Prices of photovoltaic (PV) panels have dropped exponentially.* High demand for PV modules for grid-tied applications has resulted in massive economies of scale in production as well as competition among vendors. The commodity price of silicon, the key material, has also dropped substantially.

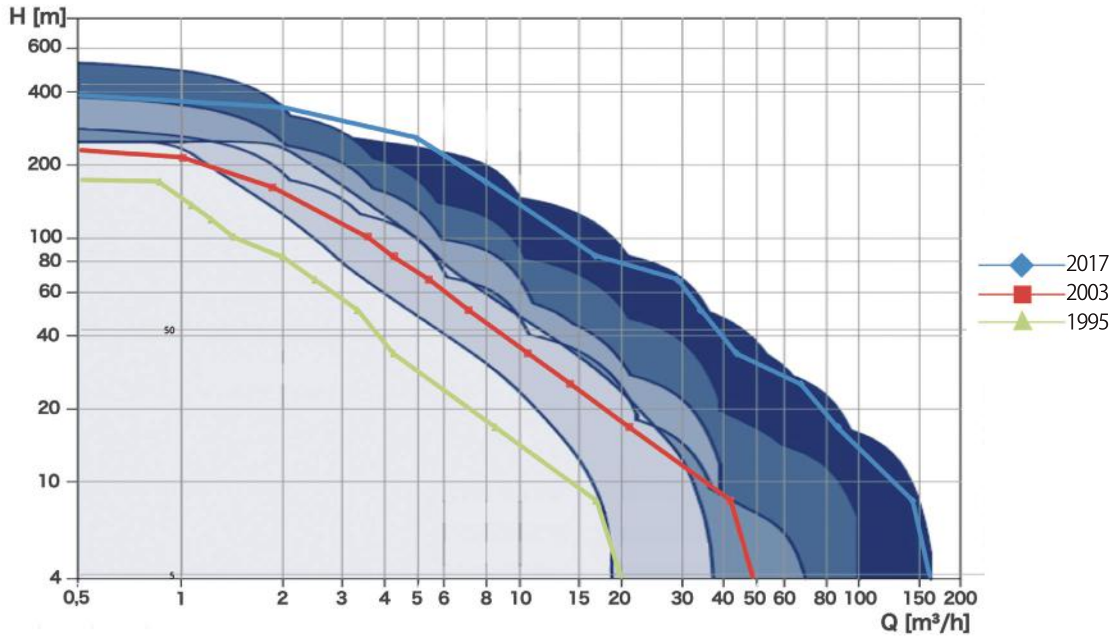


Figure 1. Solar pump capacity has increased due to technology innovations. Image credit: Grundfos.

Solar modules once cost around $5/Wp (watt-peak); now, they are less than $0.75/Wp (ex-factory) as Figure 2 indicates. These reductions have made larger SWP systems possible where previously the capital cost priced them out of range.

• *The number of SWP manufacturers and suppliers has increased.* Old monopolies have been broken, and although the technology leaders continue to innovate, competition is fierce on price, performance, and quality.

• *SWP is cost-competitive with diesel and wind pumps in all size ranges.*

• *SWP is being mainstreamed and awareness is growing.* Good news travels fast, and markets are already demanding SWP in place of conventional pumping solutions. Further opportunities are arising as intensive awareness campaigns support and elaborate on the details of system performance and savings. Retrofits to diesel pump systems represent a market for further potential savings.

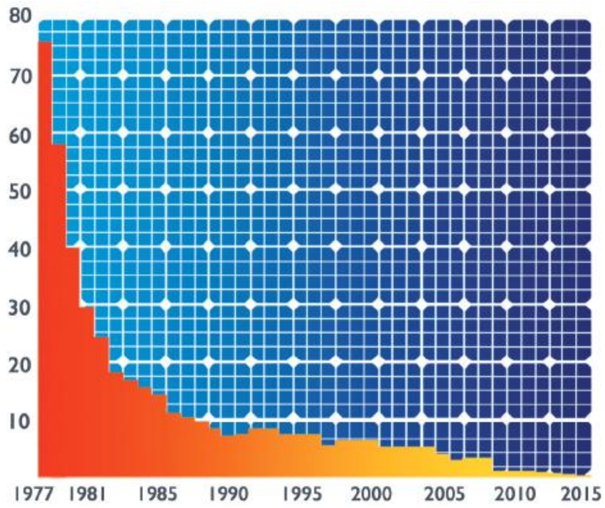


Figure 2. Falling prices PV cells (in $/watt) over time.

1.3 What are solar pumping's current applications?

The highest demand is within rural off-grid areas, currently underserved, or served by costly fossil fuel-driven pumps. The potential applications include:

- Potable water supply for institutions (traditional niche market for schools and health clinics)
- Community-scale water supply schemes (larger village schemes)
- Livestock water supply (individual or communal)
- Small-scale irrigation (individual farmers or cooperatives)

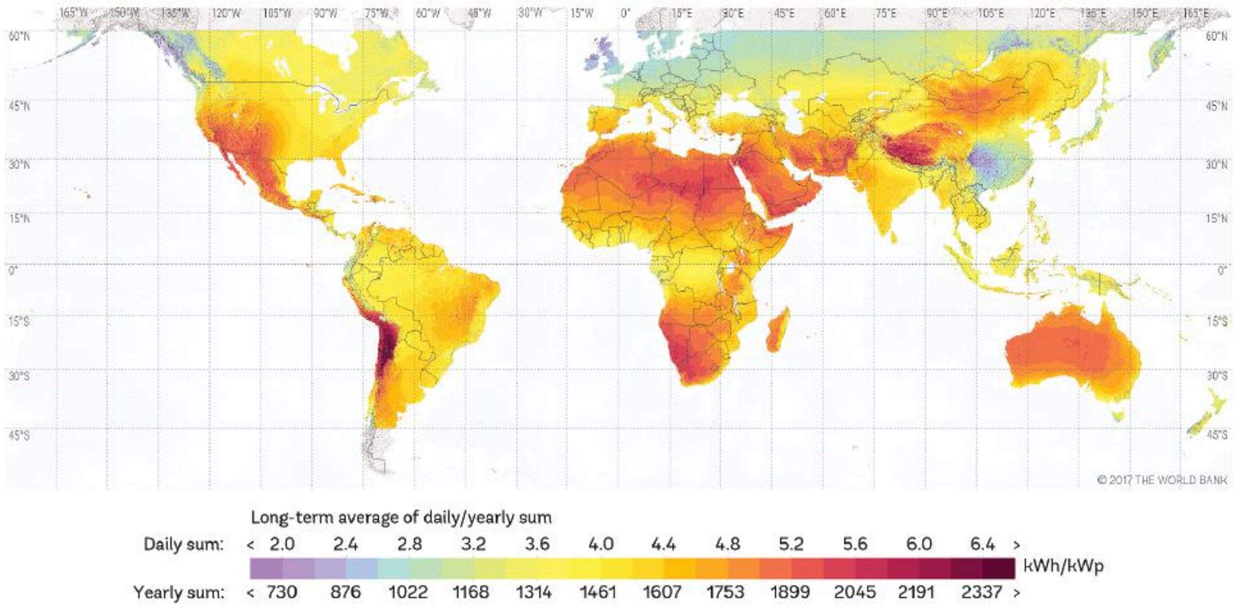


Figure 3. Global solar radiation map. Source: The World Bank.

Solar pumping is most competitive in regions with high solar insolation, which include most of Africa, South America, South Asia, and Southeast Asia. Although these regions all have high radiation (see Figure 3), the availability and depth of water resources vary significantly.

Advantages of solar pumping
• SWP systems consume little to no fuel. By using freely available sunlight, they avoid the constraints of weak or expensive rural fuel supply networks. • Unlike diesel-based systems (i.e., where a diesel generator powers the pump), solar pumping produces clean energy with zero or much reduced exhaust gases and pollutants. • Solar pumping systems are durable and reliable. PV panels have a design life of over 20 years, and solar pumps have few moving parts and require little maintenance (unlike diesel pumps). • Solar pumping systems are modular so can be tailored to current power needs and easily expanded by adding PV panels and accessories. • Properly installed solar systems are safe and low risk due to low system voltage. Adequate protection minimizes fire risk.
Possible disadvantages and mitigation
• Solar pumping systems have high initial capital costs, which can be discouraging. However, component prices are dropping substantially and investment payback is quick thanks to vast reductions in fuel usage (as detailed in Chapter 2). • Water tank storage is preferable to batteries, but still expensive. Hybrid solar/diesel pumping can reduce the need for storage and hence costs. • Solar pumps still require some servicing, and specialized technicians/providers may be difficult to access in some areas. This is gradually improving. • Panel theft can be circumvented by sensitizing communities and providing simple antitheft measures. • SWP can lead to excessive groundwater extraction because operators face near zero marginal-cost of pumping groundwater.

Table 1. The pros and cons of solar water pumping.

1.4 Basic configuration and advantages of solar pumping systems

A solar-powered water pumping system is like any other pumping system, except its power source is solar energy. Solar pumping technology covers the entire energy conversion process, from sunlight, to electrical energy, to mechanical energy, to stored energy. The process is elegant and simple.

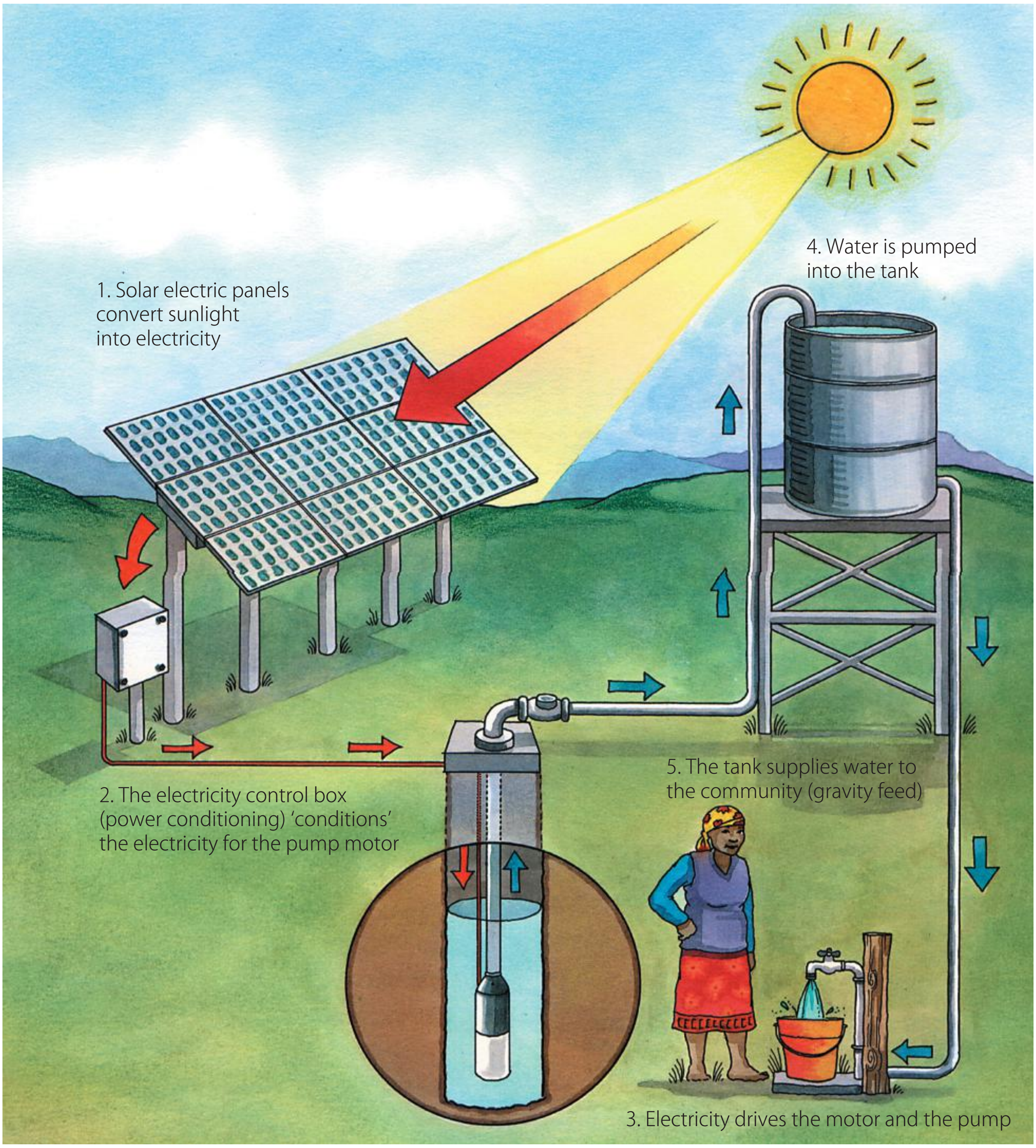


Figure 4. Solar water pumping system. Image credit: Energy and Development Group.

2 ECONOMIC BENEFITS

2.1 Life-cycle cost analysis

There are several technically viable options for new pumping systems, generally distinguished by their energy source—diesel pump, wind, solar, etc. Cost-benefit analysis (CBA) is often used to assess the economic merits of alternative investment options.

Pumping systems typically have a 20-year lifespan, and over that period they incur various costs, some at the outset, and others at different times throughout the system lifetime. Consideration of all costs incurred during the system lifetime is often referred to as a life-cycle cost analysis (LCCA). LCCA is particularly important for renewable energy projects because of the high initial investment costs. More conventional options based on fossil fuels may appear cheaper due to lower initial costs; however, operating costs can be considerable over the project life.

Although pumping systems have myriad costs during their lifetime, a proper LCCA would assess at least four key cost elements:

- *Initial costs with capital expenditures (CAPEX) and installation/commissioning.* These mostly consist of the acquisition of equipment for the solar pump system: PV panels, pump, control system, pipes and fittings, wiring, etc. Initial costs also include design engineering, system installation, commissioning testing and inspection.

- *Operation and maintenance (O&M).* Operation costs are labor and energy costs related to a pumping system's operation. They can vary widely depending on the system's complexity and duty. For example, a hazardous duty pump may require daily checks for emissions and operational performance, whereas an automated nonhazardous system may only require limited supervision. Security and managerial costs are also included here. Maintenance costs comprise all costs entailed in keeping the system functional, including routine activities (e.g., cleaning solar panels) and small repairs to faulty components. System design can influence O&M costs through construction quality, components used, and ease of access to spare parts.

- *Energy*. System energy consumption is often one of the largest cost elements in the LCC, especially if the pump runs more than 2,000 hours per year. Solar pumping systems have lower energy supply costs than systems based on fossil fuels, such as diesel.

- *Capital replacements.* Some major parts of a pumping system have a shorter design lifetime than that of the overall system (often 20 years), requiring capital replacements along with the associated costs. The pump, for example, often needs to be replaced after 7–10 years.

2.2 Example from Tanzania

An example from Tanzania illustrates the economic benefits of solar pumping. Exactly 418 existing operational diesel pump water schemes (i.e., water pumps running on diesel generators) in rural areas were identified. Data were collected on these schemes to compare the LCC of a typical system with the LCC of solar pumping. Figure 5 shows the yearly costs of a typical diesel generator pump system.

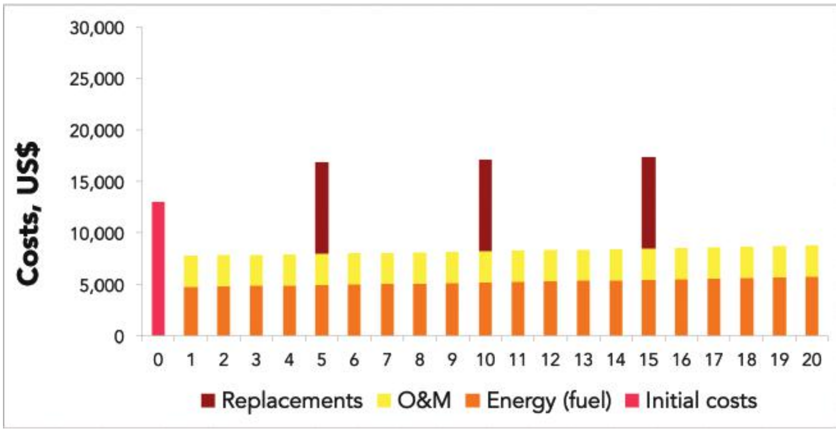


Figure 5. Yearly costs of a diesel-based pumping system.

The initial system costs are around US$13,000. Thereafter, the system incurs substantial annual costs for diesel fuel (the average yearly expenditure in fuel is over US$5,000, or 40% of initial costs), as well as periodic replacement costs.

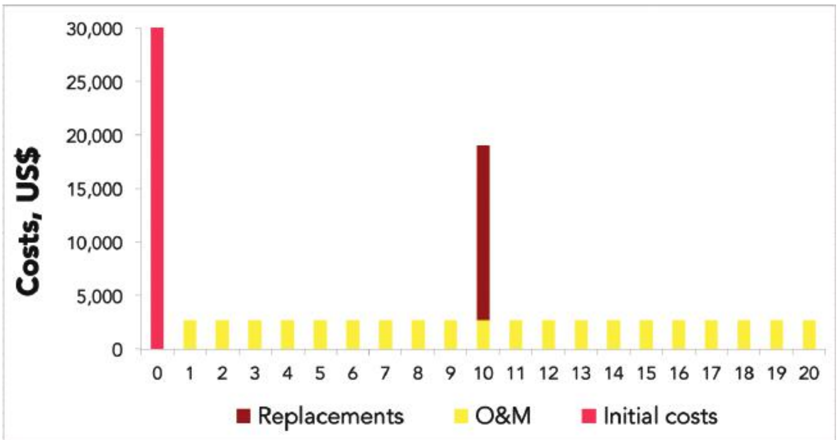
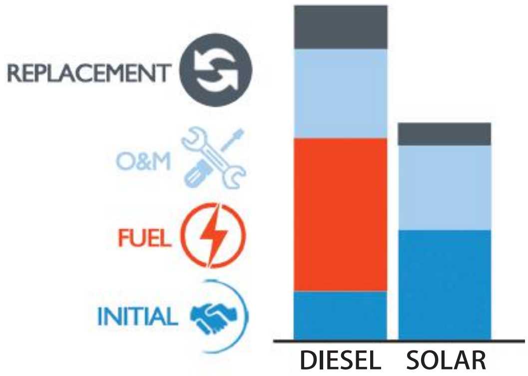


Figure 6. Yearly costs of a hypothetical solar pumping system.

By comparison, Figure 6 represents the yearly costs of the average solar pumping system. Although initial costs are higher (around US$30,000) and there would be significant expenditure in year 10 to replace the pump, these costs are more than compensated for by the vast reduction in energy costs. If the diesel powered pumping scheme in Figure 5 converted to solar, **the life-cycle cost would be about US$59,000, 36% down from US$93,000** for the diesel pumping (see Figure 7).

This would translate into a **price reduction from US¢40/m³ to US¢25/m³** for water extracted. Investment in solar pumping for these schemes would yield an **internal rate of return (IRR) of 34% and be paid back within 3.6 years**. A more thorough LCCA that includes environmental costs from carbon dioxide (CO_2) emissions and lost production costs from system downtime would demonstrate even higher benefits since solar pumping is more attractive than diesel on both counts.



	DIESEL	SOLAR
LCC (US$)	93,000	59,000
LCC water	40¢/m³	25¢/m³
IRR	-	34%
Payback	-	3.6y

Figure 7. Economic comparison of diesel with solar pumping.

Although this is only an example, the findings of the analysis are in line with those from other studies regarding the economic benefits of solar pumping, in particular, compared with diesel pumping. Such benefits will tend to increase further as the price of solar components drops due to technological advances.

3 MAJOR SYSTEM COMPONENTS

A solar pumping system consists of PV modules, a pump set, a storage tank, electronic components, and interconnected cables (see Figure 8). Electronics normally include an inverter, power conditioner or pump controller, controls/protections, and water sensors. This chapter describes in more detail the major components used in solar pumping systems.

3.1 PV modules

The energy and power for driving an SWP system comes directly from an array of solar modules of the correct size and specification. The elementary component of a solar module is the **solar photovoltaic (PV) cell**. The cell directly converts solar radiation into electric current, through the **photoelectric effect**. The ratio of electric power produced to radiation received is the solar PV cell's **efficiency**. For example, if a cell generates 0.15 kW of power for each kW received from the sun, its efficiency is 15%. The semiconductor materials most commonly used in commercial PV cells are **crystalline silicon**. These modules are either **monocrystalline** silicon modules, where each PV cell has a single silicon crystal; or **polycrystalline** modules, where each cell has multiple crystals (see Figure 9).

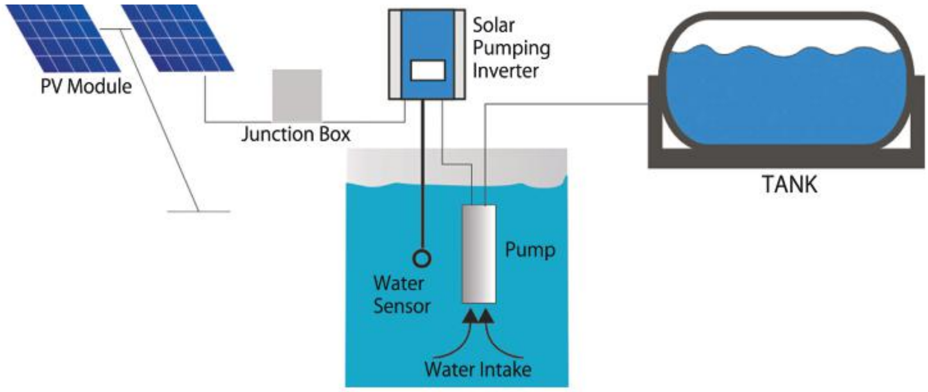


Figure 8. Basic elements of a solar pumping system, Source: Zhuhai MNE Technology Co., Ltd.

Mono-crystalline modules are more efficient than polycrystalline ones (16–17% compared to 14–16% in commercial applications).

PV modules are rated according to their power output, based on a solar irradiance of 1,000 W/m^2 at a specified module temperature. Panel output data includes the **peak power** (maximum power generated by the panel, often referred to as watt-peak [Wp]), voltage (volts [V]), and current (amps [A]). In addition to irradiance, PV module temperature affects the amount of power produced, with higher temperatures decreasing power output. It is therefore a good design practice to ensure good ventilation of the modules to limit their temperature increase.

A challenge in many countries has been the lack of quality regulation, leading to an influx of cheap, substandard, and counterfeit products in the local market. Purchasers of solar panels should thus seek quality assurance, as there are now well-developed global standards and testing procedures for panels, notably from the **International Electrotechnical Commission (IEC)** or similar organizations.

The main global standard for crystalline silicon modules is IEC 61215, which, like similar standards, is awarded largely based on tests administered to samples of modules produced. Since modules cannot be tested throughout their 25-year lifetime, accelerated stress testing is performed. One of the main tests is the verification of the nominal peak power that a PV module can deliver under **standard testing conditions (STC)**, which include 1 kW/m^2 of insolation perpendicular to the panels and 25°C of PV cell temperature.

Quality of solar modules, and matching of solar module performance is especially important in SWP systems consisting of large arrays of modules connected in series, where array performance, hence SWP performance, depends on the performance of the weakest module. Even one module with inferior output can have a devastating effect. The commissioning of a SWP system should identify such weaknesses through I-V curve scanning of the array.

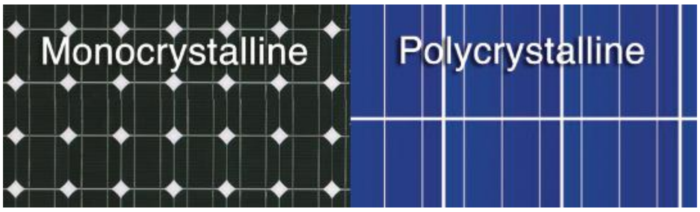


Figure 9. Mono- (left) and poly- (right) crystalline solar panels; Source: York Solar.

3.2 Pumps and motors

Pumps physically lift water from source to point of use/storage. Technological progress has radically improved pump performance over the years, with pumps now available for pumping ranges up to 500 meters deep or 150 m^3/h, as represented in Figure 10.

Water pumps are driven by **electrical motors**, which convert electrical energy (produced, in the case of solar pumping, by PV panels) into mechanical energy. Most motors typically run on either **direct current (DC)**, where the electrical flow does not switch direction periodically in the wires; or **alternating current (AC)**, where it does.

DC motors are appealing for solar pumping because PV modules producing direct current can be directly coupled to the motor with limited power conditioning. This makes them an economical option for systems with low water demand and a short cable distance between the PV panel array and the motor. For long-distance cabling, however, low-voltage DC motors are not suitable because of power loss in the cable. DC motors are currently not available beyond the 5 kW threshold.

AC motors can be used in larger SWP systems, although they require a DC/AC inverter.

Solar pumping systems use two main types of pumps: **positive displacement** and **centrifugal**. Positive displacement pumps are further divided into volumetric and helical rotor pumps. Broadly speaking, positive displacement pumps are suitable for lower flow rates and medium to high pumping heads (30–250 m), whereas centrifugal pumps are suitable for high flow rates and lower pumping heads (10–120 m). Within positive displacement pumps, helical rotor pumps are especially suitable for operation with low and variable solar radiation levels, since they can pump at low speed without loss of efficiency, unlike centrifugal pumps, which do not produce any water below a threshold speed and are thus much less efficient at low or fluttering irradiation.

It should be noted that these are generalizations for illustration. The most suitable pump and motor type for any situation should be determined based on manufacturers' catalogues and motor pump manuals, and specifically on pump/motor pair performance curves similar to Figure 10 (characterized to the IEC 62253 standard) to ensure that the pump/motor pair can deliver the required flow against the total dynamic head (TDH)[1].

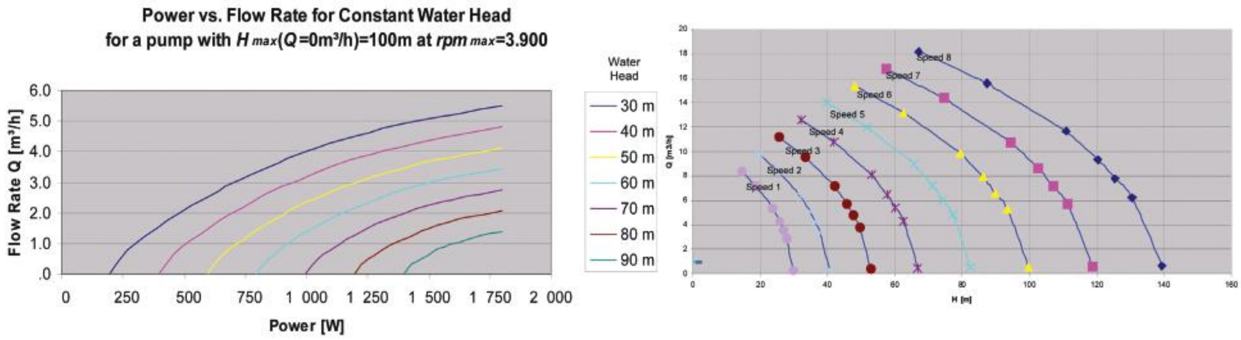


Figure 10. Pump motor characteristic P-Q curve and H-Q curve. Image credit: International Electrotechnical Commission, IEC.

3.3 Power conditioners

Power conditioners convert DC power from the solar panels to match the pump motor's requirements. Power conditioners can take several formats: a simple **DC-DC converter**, a simple fixed-frequency **inverter** for an AC pump, or a more complex **variable speed drive** (VSD) in single or three-phase AC power. In general, the power conditioner is matched to a specific pump and optimized to suit the pump performance for array voltage and power. Pump kits from larger pump manufacturers provide an optimized power conditioner and motor/pump as a matched set. Such power conditioners provide change-over between solar supply and diesel engine supply, **enabling use in hybrid systems or systems with back-up**.

System integrators are increasingly combining third-party power conditioners or programmable VSDs with other third-party motor/pump pairs, and branding them as their own or offering them as original equipment manufacturer (OEM) solutions. Although these solutions may be just as efficient, they have likely been less well tested and the performance depends entirely on the programming setup. In particular, the performance of the controller/motor/pump under intermittent sunshine solar conditions may be substantially lower if not properly set up. For that reason, the testing and characterization of the entire set under the IEC 62253 standard, which can include three test conditions (clear day, cloudy day, and intermittent sunshine), can yield valuable comparative results.

[1] Examples of major solar pump manufacturers include **Grundfos** (www.grundfos.com), **Lorentz** (www.lorentz.de), and **Mono** (www.mono-pumps.com). Suppliers of VSD include:

- ABB ACS355 solar pump drive: www.abb.com
- Vacon 100X drive: www.drives.danfoss.com
- Altivar 312 solar: www.schneider-electric.com
- Solartech solar pumping inverter: www.solartech.cn
- JFY solar pumping inverter: www.jfy-tech.com
- Grundfos renewable solar inverter (RSI): www.grundfos.com
- Lorentz PSK2 solar pump controller: www.lorentz.de
- Invt solar water pump inverter: www.invt.com

4 SYSTEM DESIGN CONSIDERATIONS

The conceptual design of solar pumping systems is best accomplished by analyzing the following seven key parameters:

- Water demand
- Water source
- Design flow rate
- Water storage
- Total dynamic head
- Location of PV panels
- Solar resource

This design process is complemented by deeper awareness of the equipment to be used in the system, which is described in more detail in chapter 3.

Thereafter, it should be possible to do a rough SWP system sizing and costing calculation as in Chapter 5.

4.1 Water demand

The design capacity of the solar water system depends primarily on water demand, measured in m^3/day or liters/day (see Table 2). Water is considered for human and/or livestock consumption or for irrigation.

Potable water for human consumption in a village/town is estimated from population size and daily per capita water consumption. For example, if the system is to serve a population of 2,000 and the supply standard is 30 liters per capita per day, then system design capacity should be at least 60,000 liters/day or 60 m^3/day. Similarly, **water demand for livestock** will depend on livestock type and quantity.

Irrigation water demand assessment is considerably more complex, and depends on area, soil hydration and properties, evaporation rates, crop selection, spacing, crop seasons, irrigation type, etc., and is best determined by an agronomist, to avoid over- or under-estimating water needs, and to determine optimal cropping seasons. The standards used in determining the water demand can usually be obtained from the ministry or government agency for water in the country. Designs typically allow for population growth and seasonality of demand.

4.2 Water source

Fresh water is generally obtained through open sources or surface water, such as rivers, streams, and dams; or protected ground water sources such as boreholes and wells. Each is characterized with respect to security of supply, water quality, and replenishment. In general, groundwater is preferred for potable water.

In assessing surface water sources, the following aspects must be carefully considered:

- *Water availability and pumping levels.* Accounting for seasonal variations is critically important, since some sources may dry up, while others may be prone to flooding and high risk. Water level may vary considerably between seasons, affecting pumping head.
- *Water quality.* Debris, silt, and sediment can cause damage to the pump if not properly screened at pump intake.

Human consumption (litre/capita/day)	
Urban user	130
Rural household	80
Rural minimum standard	20-35

Notes:
- Design standards vary from country to country and the needs from location to location.
- Irrigation water requirements are especially variable and dependent on local climatic conditions, crop selection, and seasonality.

Livestock			
Cattle	Cattle	40-50	l/head/day
	Calf	15-25	l/head/day
Sheep	Pig	8-11	l/head/day
	Lactating sow	20	l/head/day
	Piglet	5	l/head/day
Birds	Layers	40	l/100 birds/day
	Broiler	10	l/100 birds/day
	Chicks	8	l/100 birds/day

Irrigation at crop (m^3/ha/day)	
Banana, sunflower	40
Maize, beans, kale, cabbage, lettuce, onion, tomato	15-17
Potato	10

Irrigation efficiency	
Floor or open channel	40%
Sprinkler	80%
Drip irrigation	98%

Table 2. Illustrative water requirements use to estimate water demand.

Groundwater is a commonly used water source. Groundwater is contained in **aquifers**, natural underground water reservoirs accessed by **wells** or **boreholes**. A **pumping test** is conducted to evaluate the amount of water that can be pumped from a particular aquifer. The test determines the **maximum yield** (in m^3/h) as well as the **drawdown**, or depth to which the water level in the borehole will fall for a given yield and duration (yield per meter of drawdown), while being dynamically replenished by the aquifer. Obviously, a low drawdown is desirable.

Water demand that exceeds an aquifer's yield can lead to **overpumping**. Overpumping is evident from deeper drawdown. This can lead to precipitation of heavy metals and oxidation of iron compounds, potentially causing infiltration of nitrate and pesticides in the water and the formation of ochre, which may clog the pump. This vicious cycle leads to increased service costs for the pump, a need for water treatment, longer-term aquifer depletion, and possibly reduced aquifer life.

4.3 Design flow rate

In conventional engineering design, a pump's **design flow rate** is derived by dividing the daily water demand by the total number of pumping hours in a day. Solar pumping applications, however, use the number of peak sun hours to estimate the daily pumping hours.

For example, in a solar resource that averages 7.0 kWh/m^2/day, peak sun time is 7 hours/day. For a daily water requirement of 70 m^3/day, the design flow rate is 70,000 liters/day/7 hours/day = 10,000 liters/hour. The design flow rate should not exceed the maximum water source pumping rate or **yield**. The design flow rate is used for future water pressure drop calculations and pipe sizing.

4.4 Water storage

Most solar pumping systems require water storage capacity to improve performance and reliability. Reliability is improved when a **storage tank** is used to store water extracted during sunshine hours to meet water needs at night, or in the event of cloudy weather or system downtime.

In general, SWP tanks should be sized to store at least a 2–3-days of water supply (daily demand (m^3/day) x 3 days = storage volume (m^3). Field survey data indicate that many SWP storage tanks are too small, and experience water overflows in the daytime and shortages in the evening. Optimal tank sizing must account for the hourly water demand pattern as well as possible insolation variations supplying the tank.

Diesel pump systems, or SWP switchable with diesel back-up, on other hand, allow for much smaller tanks for back-up storage since the diesel pump may be run at any time.

4.5 Total dynamic head

In pumping systems, "head" refers to the height to which water must be pumped relative to its normal level (e.g., underground). **Total dynamic head (TDH)** or total pumping head is the sum of three components, as represented in Figure 11.

Dynamic water level (DWL) is the depth of the surface of the aquifer. This gradually increases due to drawdown, hence the term "dynamic."

Discharge head corresponds to the height above the ground of the water surface inside the storage tank (usually 5–10 m). This water is discharged to users through gravity, thus the name "discharge."

Friction head accounts for the friction of the water against the inside of the pipes (both vertical and horizontal). It is typically 10% of the DWL plus discharge head.

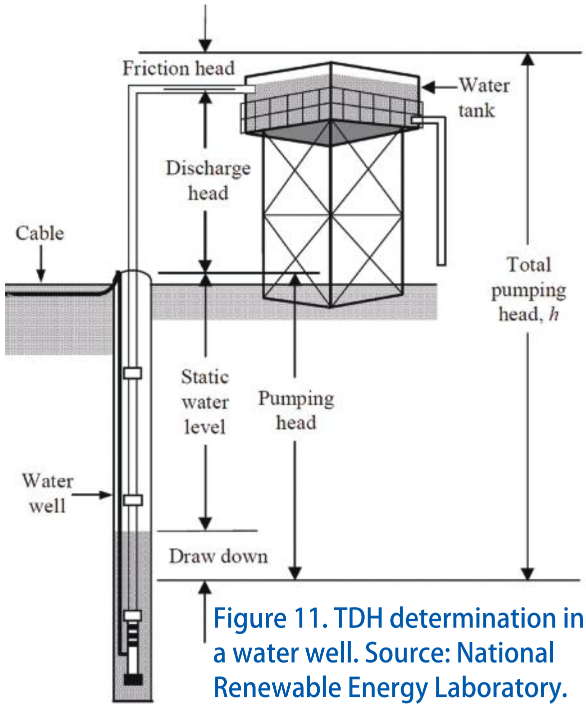


Figure 11. TDH determination in a water well. Source: National Renewable Energy Laboratory.

A pumping test can provide information on the DWL and the discharge head, whereas the friction head can be more accurately obtained from head loss charts for pipes at the required flow rate and pipe characteristics.

4.6 Location of PV panels

Although not critical to the initial system sizing, PV panels should be installed close to the pump and water source, equator-facing, at optimal tilt angle to the horizon, and unshaded in any part of the solar array for the solar day. Panels should generally be situated in a secure and safe location. These issues can be fine-tuned during final design and installation, but for purposes of preliminary design, it is conceivable that the solar array would not be closely located to the pump, and thus longer array cables are required, with possible energy losses. This scenario calls for a high allowance for power loss in array cables.

4.7 Solar resource

Solar insolation is a measure of the cumulative irradiance received on a specific area over a period of time. It is a measure of energy (rather than power), normally expressed in kilowatt-hours (kWh/m^2/day). The characteristics of the solar resource at the site are critical to system design. Sunshine reaches the earth through radiation. **Solar irradiance** is the power of solar radiation received per unit area. Irradiance is the instantaneous measurement of power, in watts or kilowatts per square meter (W/m^2

or kW/m^2). Irradiance is affected by the angle of sun, and at any time of day it is highest when a solar module is perpendicular to the incident sun rays. Since the sun's position in the sky changes during the day, irradiance increases during the morning until noon (when it is highest), and then decreases until sunset, since the sun's rays must penetrate more of the atmosphere to reach the earth (see Figure 12).

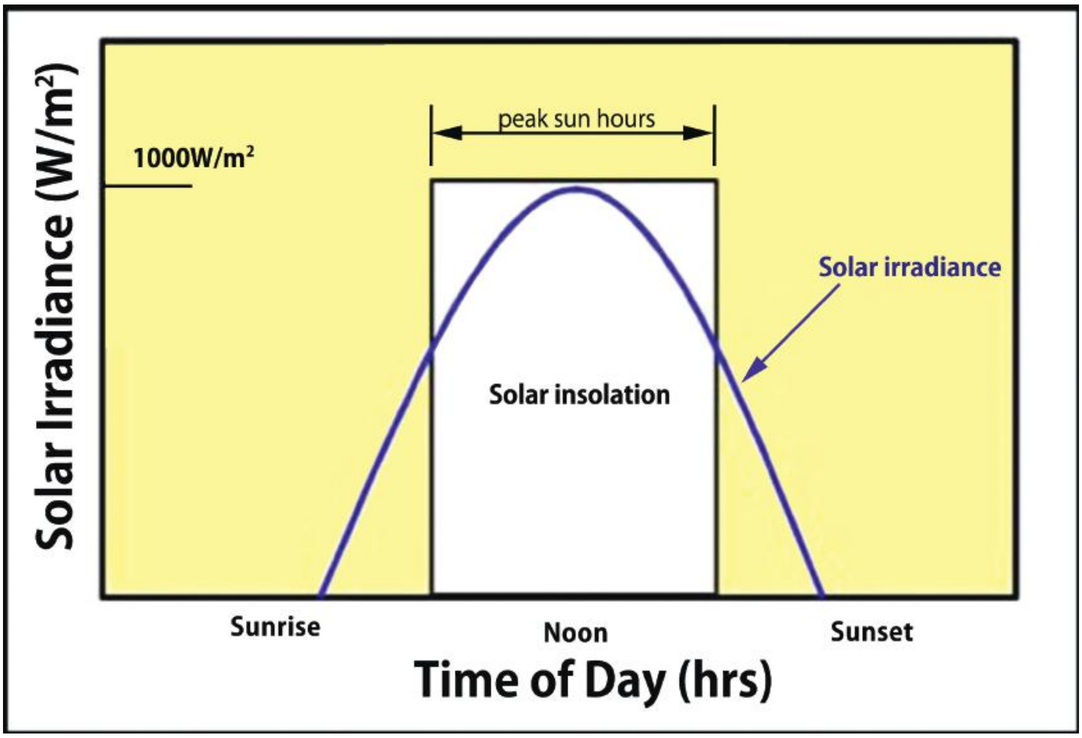


Figure 12. Solar irradiance on a given site during the day, Source: Renewable Energy Primer-Solar.

Solar insolation is effectively equal to the area under the solar irradiance curve. **Peak sun hours per day** is just another term for solar insolation and is always measured in kWh/m^2/day.

Solar resources vary from area to area. As Figure 3 illustrates, **solar radiation is generally higher in regions near the equator.** Factors that affect the amount of solar radiation on a particular area include latitude, prevalence of cloudy periods, humidity, atmospheric clarity, and seasonal variations.

Long-term statistical weather data from meteorological stations is usually provided in the form of monthly averaged data for insolation on a horizontal surface, and includes daily variations of this insolation. Since sizing of SWP systems requires further adjustments and optimizations to this data to account for nonhorizontal or tilted solar arrays orientated toward the equator, the complex nature of these calculations and statistical basis of the data suits computer-based sizing approaches.

5 SIZING GUIDANCE

The use of **sizing software is highly recommended**; nonetheless, this section outlines various sizing considerations.

5.1 Rules of thumb

The sizing of SWP system can naturally be estimated using simple formulae, the understanding of which is appropriate for SWP 101. The basic principle for sizing is to create an "energy balance." Energy balance for a solar SWP system is determined by:

Electrical energy (solar resource, solar array, power conditioner) × motor-pump efficiency = hydraulic energy (volume delivered, head, friction losses). Electrical energy yield to the motor-pump can be estimated as follows:

$$E_{sys} = P_{array\_STC} \times f_{man} \times f_{dirt} \times f_{temp} \times H_{tilt} \times \eta_{pv\_inv} \times \eta_{inv} \times \eta_{inv\_sb}$$

where:

E_{sys} = average yearly energy output of the PV array, in kWh

P_{array_STC} = rated output power of the array under standard test conditions, in kWp

f_{man} = de-rating factor for manufacturing tolerance, dimensionless (100%)

f_{dirt} = de-rating factor for dirt, dimensionless (95%)

f_{temp} = temperature de-rating factor, dimensionless (95%)

H_{tilt} = daily insolation value (kWh/m^2/day) for the selected site

η_{pv_inv} = efficiency of the subsystem (cables) between the PV array and the inverter (98%)

η_{inv} = efficiency of the inverter, dimensionless (95%)

η_{inv_sb} = efficiency of the subsystem (cables) between the inverter and the switchboard (95%)

Overall efficiency is therefore about 77.4%. Note that cloud cover will further reduce output.

Hydraulic energy out of the pump output can be calculated as follows:

$$E_{hydraulic} = Q \text{ x TDH x } \rho \text{ x } g \text{ / 3,600,000 (J/kWh)}$$

where:

$E_{hydraulic}$ = hydraulic energy in kWh

Q = daily water output (m^3/day)

TDH = total dynamic pumping head (m)

ρ = density of water = 1,000 kg/m^3

g = 9.8 kg.m/s^2

Pumping system efficiency[2] = hydraulic energy / electrical energy yield:

$$\eta\text{motor x }\eta\text{pump} = E_{hydraulic} / E_{sys}$$

5.2 Sizing example

A SWP system for a rural community of 2,000 people must be designed to deliver potable water at the standard 30 liters/capita/day. The tested water source level is at 100 m static head below ground level. Borehole drawdown is 5 m at 5 m^3/hour, and 10 m at 10m^3/hr. Gravity head, or elevation of the storage tank, must be 10 m above ground level. The solar resource on site averages 4.5 kWh/m^2/day at a tilt of 20° from horizontal, orientated toward the equator, which optimizes the solar yield in the worst month. What is the indicative SWP system size?

A: First pass sizing:

1. Key inputs

- Q = 30 liters/capita x 2,000 persons = 60 m^3/day
- Design flow = 60(m^3/day) / 7(pumping hours/day) = 8.5 m^3/hour
- TDH = 100 m static + 8.5m drawdown + 10 m elevation + 10% dynamic losses = 118.5m × 110% = 130 m

2. Total hydraulic energy required = 60 m^3/day x 130 m x 1,000 × 9.8 / 3,600,000 = 21.23 kWh

3. Assume that pump motor is optimally sized at its operating point of 60% wire-to-water efficiency

4. Electrical energy required = 21.23 kWh/day/60% = 35.4 kWh/day

5. Array size required: 35.4 kW/day = array kWp x 77.4% x 4.5 kWh/m^2/day

Therefore: **array size = 10.16 kWp**

6. Water tank storage volume should be approximately 120–180 m^3 and is calculated as follows:
= Q (m^3/day) x 2-3 days = 120-180m^3

5.3 Costing parameters

SWP system ex-works cost is typically less than $1.75/Wp ($1,750/kWp). A 10.18-kWp system would cost about $18,500.

The total installed costs would typically be less than $3.2/Wp (or $32,000 in the example). This pricing would apply to larger systems (>10 kWp), or large numbers of small systems. Once-offs in remote locations would naturally attract much higher installation charges. Prices of $2.2/Wp are likely once large programs are implemented. The price breakdown is more or less as follows:

[2] A typical pumping system would have a maximum efficiency of 60% at optimal operating point. See Chapter 4 for some typical motor pump combinations.

- PV modules: < $ 0.75/Wp including mounting, for certified modules ($7,500)
- Pump and controller or power conditioner: $1.1/kW ($11,207).
- Balance of system (BOS), cables, etc.: 20%: ($3,668)
- Installation and related services: 25% ($5,501)
- Total: ($27,507)
- Grand total (with profit of 20%): $32,900
- Not included
    - o Borehole and water source development
    - o Storage tanks
    - o Water reticulation, stand pipes, and/or water metering

5.4 What affects SWP performance in real life?

The simplified SWP sizing algorithm presented is adequate for understanding the sizing dynamics, and good for static design conditions. In reality, there are several input variables that are not constant and thus affect SWP performance over the course of a year. Therefore, to be rigorous, sizing algorithms must evaluate the conditions over the course of a whole year to determine when the limiting design conditions occur. Below are some of the key variables:

- *Seasonal changes in solar radiation.* Essentially, SWP water output is more or less proportional to irradiation. First-pass sizing is usually based on average insolation for the year, or perhaps the worst month of the year. It is necessary to assess the output for days when radiation will be less than the annual average, and less than the monthly average. Tilt angle optimization is required.

- *Seasonal changes in pumping head.* Similarly, drops in water levels will affect pump output. Water output is more or less indirectly proportionate to pumping head. Too conservative an estimation of water level will result in system oversizing.

- *Sunny versus cloudy days.* Average insolation is insufficient. A key variable is the amount of cloud cover and intermittency of the sunshine. Especially, variable speed drives coupled with AC pumps tend to suffer degraded performance under stop-start solar conditions, since they require minimum power conditions start-up, and take considerable time to spool up once threshold levels are reached. So while 2 days might have the same amount of cumulative insolation, a clear morning with zero sun in the afternoon is likely to yield far higher water output than an intermittently cloudy day. Derating for this kind of local variability is important for certain motor pump types in particular.

• *Seasonal changes in water demand.* Experience shows that demand is not constant throughout the year. For human consumption, the variations are low (25%), but for livestock and irrigation the variations can be significant, up to 80%, with zero demand in very wet seasons. The analysis of these variables can be cumbersome.

5.5 Sizing software

The combinations of variations in seasonal water demand, seasonal solar radiation, and seasonal changes in pumping head make for a considerably more complex optimization, which is best suited for computer-based iterations.

Further, while basic sizing can be accomplished on simple spreadsheets, optimizations and **final designs are best done using proven software**, examining actual motor pump sets and their specific operating points. In general, this will be done by suppliers, who must present their predicted system performance with their offers. Examples of some sizing and simulation software:

- COMPASS™, specific to solar pump manufacturer Lorentz™.
- Grundfos Product Centre™, specific to pump manufacturer Grundfos™.
- PVSyst™, which can be used to size and simulate any PV system but requires engineering knowledge of individual components in case of SWP.
- HOMER™, which can be used to do basic energy balances, without knowledge of the specific components, and performs annual simulations.

6 SYSTEM INSTALLATION AND OPERATIONS AND MANAGEMENT

In a PV system, the "balance of system" or BOS refers to all hardware components other than the main components. In a solar pumping system, the main components are the PV panels, pump, and pump controller, with the BOS comprising the PV array mounting structure, cables/wires, switches, fuses, piping, water meters, data loggers, etc. Installation and related services, on the other hand, include engineering design, transport to site, site preparation, installation services, commissioning, training, and maintenance. The BOS installation and related services can account for 30–50% of total capital costs, and are an important part of setting up a solar pumping system.

6.1 Installation and commissioning

Although a detailed description of equipment installation procedures is outside the scope of this document, key considerations include:

- Inventory of equipment
- Array location and safety
- Safety standards
- Equipment protection standards, including earthing
- General security
- System performance

Array location. Maximized solar energy production depends on panel location and orientation. Panels should be equator-facing, with panel tilt predetermined based on latitude and local weather conditions to maximize incident insolation and facilitate panel cleaning during the rainy season. Shading at any time of day should be avoided. Because many solar pumping systems are located in remote areas, the risk of vandalism and theft can be significant, and panels should not be easily accessible by the public. If the use of trees and vegetation for shielding is deemed acceptable, then adjustment to sizing may be required if this reduces the amount of available solar radiation due to shading, especially in early morning and late afternoon. This should be decided before installation.

Safety standards. PV systems present a unique combination of hazards and risks, which must be addressed by sound design and specifications followed by proper installation, operation, and maintenance of the system. In large pumping systems, high-voltage DC arrays require special cabling, switch gear, and clear labelling.

Equipment protection. Protecting equipment against faults on both the DC and AC sides requires careful attention to earthing design and protective components. Risk of lightning damage is addressed by grounding (giving electrical lightning surges a direct path to the ground that bypasses valuable equipment) and by installing lightning arrestors and surge protectors.

Another major risk is that of **vandalism and theft**. Measures to curb this risk include:

- Build **community ownership**.
- Locate the solar array in a populated area with regular foot traffic.
- Fence the array to make access more difficult.
- Arrange for security guards.
- Install motion-detecting sensors and alarms whenever possible.
- **Spot-weld bolts** or use **tamper-proof** bolts, screws, and fasteners.
- Use anti-theft array mounting frames. These metallic structures hold the panels and are designed to withstand strong winds. There are three types of frames: ground, roof, and post (see Figure 13).

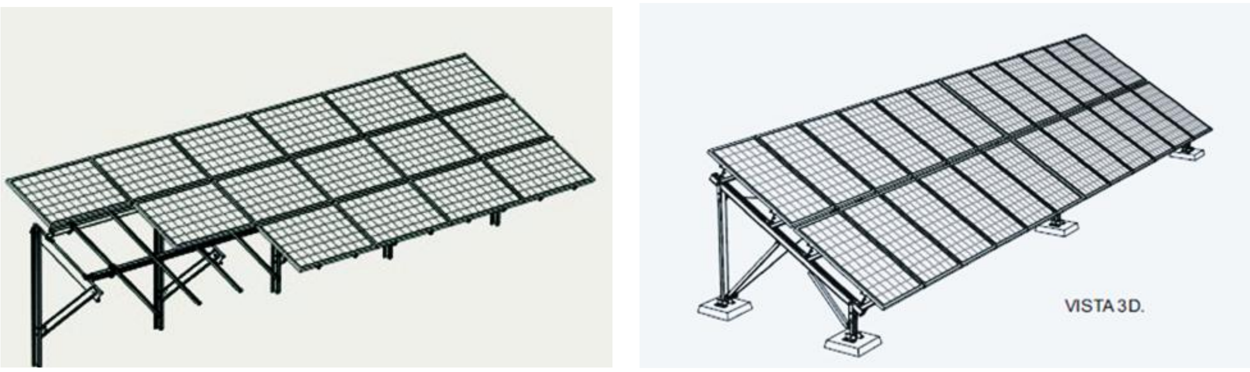


Figure 13. Models for post and ground mounts. Source: Hiasa.

Commissioning immediately follows installation and refers to the process of "handing-over" the system to the client, i.e., ensuring that all system components have been properly installed, are in good condition and that the system is operating as expected. Commissioning comprises three main elements: documentation, inspection, and testing, and should be carried out in accordance with the IEC/BS EN 62446 (for high-voltage DC arrays and earthing). General installation, including the AC side, should be in accordance with IEC 60364-9-1 (low-voltage electrical installations; installation, design and safety requirements for photovoltaic systems), and/or with British Wiring Standards BS 7671. Documentation should include single line diagram, individual component documentation, an O&M manual, and equipment warranty information. Testing benchmarks the system's performance against the design requirements and assumptions, notably by measuring the water output against solar radiation and pumping head (IEC 62253).

6.2 Operation and maintenance

After the system has been installed and commissioned, focus shifts to O&M throughout its lifetime. System operation can be optimized by closely monitoring and recording key system parameters (data logging), enabling operators to assess system performance or demand changes.

One crucial aspect of maintenance is **warranties**, usually against defective components or poor workmanship. Under the **defects period** of 1 to 2 years, any items that fail, are not installed to standard, or are damaged by natural calamities must be corrected on site at cost to the contractor/supplier/installer.

Component	Usual warranty period
Solar panels	25 years
Pump/motor	2-5 years
Inverter	5-10 years
Remaining components	1-2 years

Table 3. Illustrative warranty periods for solar pumping system components.

During the warranty period, the supplier is also expected to check system components and perform preventive maintenance at least quarterly (in any case, neither pumps nor panels require heavy maintenance, with panels only needing periodic cleaning) to attend to user complaints within a reasonable period of time, and to resolve any system breakdowns within 3 days. In addition to component warranties, the supplier may also provide a **performance warranty** on the system as a whole, ensuring that it will meet or exceed the design performance for a number of years. (See Table 3 for some example warranty time lines.)

Sustainability of solar SWP has been a challenge in many countries and especially in rural areas, with systems failing often within a short time after commissioning due to lack of proper O&M. It is therefore increasingly common for communities to establish **comprehensive maintenance contracts** with suppliers during warranty periods, and it is a good practice to extend such contracts beyond the warranty period. Suppliers should further secure system sustainability by **training** system operators, namely on basic plumbing skills useful for repairing leakages in the pipe network and on handling the advanced inverters and sensors common in modern solar pumping systems.

Since solar panels have no moving parts that could be affected by rust or break down, solar power requires very limited maintenance, other than regular dusting. Cleaning the solar panels with water is recommended to remove any dirt or dust.

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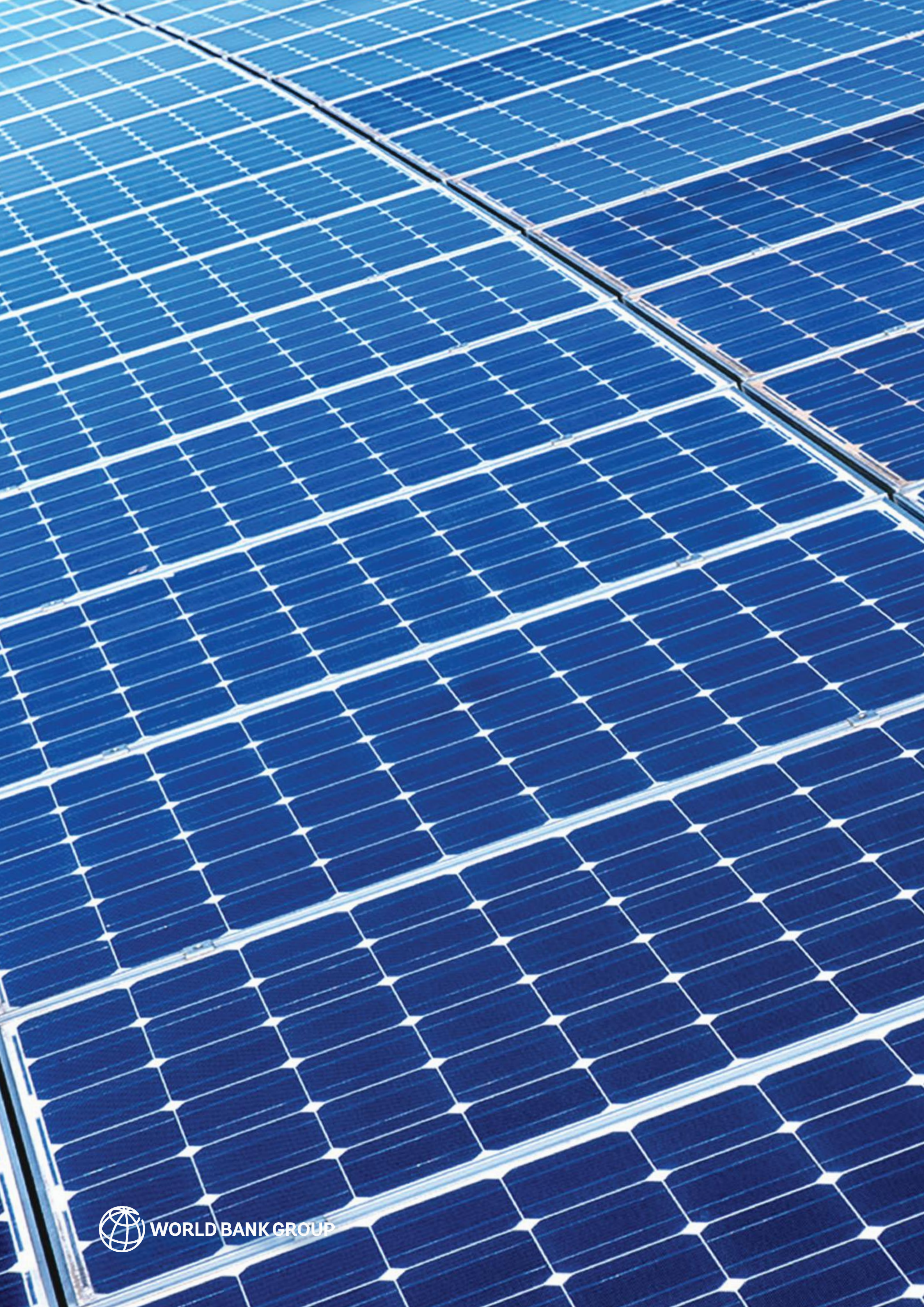
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