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Review

Factors influencing the performance and efficiency of solar water pumping systems: A review

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The world is having an energy crisis and currently there is a strong drive towards renewable energy. A renewable energy option is solar energy, where by means of photovoltaic (PV) modules electrical energy can be produced. A residential as well as industrial application for these PV modules is solar water pumping systems. Disadvantages of solar water pumping systems are low performance and low energy efficiency. This paper provides a review on the factors that influence the performance and efficiency of solar water pumping systems, with a specific focus to South Africa. The principle factors discussed include: 1) environmental conditions, 2) PV panels, 3) controllers, 4) energy storages, 5) converters and inverters, and 6) pumps and motors.

Key words: Solar water pumping, photovoltaic, performance, efficiency.

INTRODUCTION

This paper provides a review on the factors that influence the performance and efficiency of a solar water pumping system, with a specific focus to South Africa. A solar water pumping system is typically constructed of: 1) photovoltaic (PV) module(s), 2) controller(s), 3) water and/or energy storage, 4) converter(s) or inverter(s) and 5) motor/-pump combination, as shown in Figure 1. When analyzing the performance and efficiency of a solar water pumping system, the environmental conditions must be considered. For this paper, a selection of the factors with the largest impact on the performance and efficiency of the system are discussed, but other factors of lesser impact are not.

The most important environmental factors are: 1) solar irradiation, 2) meteorological data and 3) air mass and indirect radiation. The factors influencing the performance and efficiency of the PV panel are: 1) the type of PV material used, 2) the tilt angle and azimuth, 3) characteristics of the PV cell, and 4) PV array arrangement (for example, how many modules in the panel are in series and how many panels in the array are in parallel?). The type of controller and storage medium used influences the performance and efficiency of the system. The controllers are therefore divided into: 1) maximum power point tracking (MPPT), 2) charge controllers and 3) other controllers. The energy storages are divided into: 1) water storage and 2) batteries and other storage. The pump motor of the solar water pumping system can run either on direct current (DC) or on alternating current (AC), so the converters/inverters are divided into: 1) DC-DC converters and 2) DC-AC inverters. The pump/motors are divided into: 1) DC borehole pumps, 2) AC swimming pool pumps and 3) other water pumps. For this paper, the focus is specifically on DC borehole pumps and AC swimming pool pumps.

Average solar-radiation levels in South Africa are between 4.5 and 6.5 kWh/m^2 in one day and most areas average more than 2500 h of sunlight per year in South Africa (Department of Energy, 2012). Solar power is increasingly being used for water pumping through the rural water-provision and sanitation programme of the Department of Water Affairs and Forestry (Department of Water, 2012). Solar water disinfection projects in areas where people do to not have access to safe drinking water and solar powered waste water management systems are currently been overseen by the department

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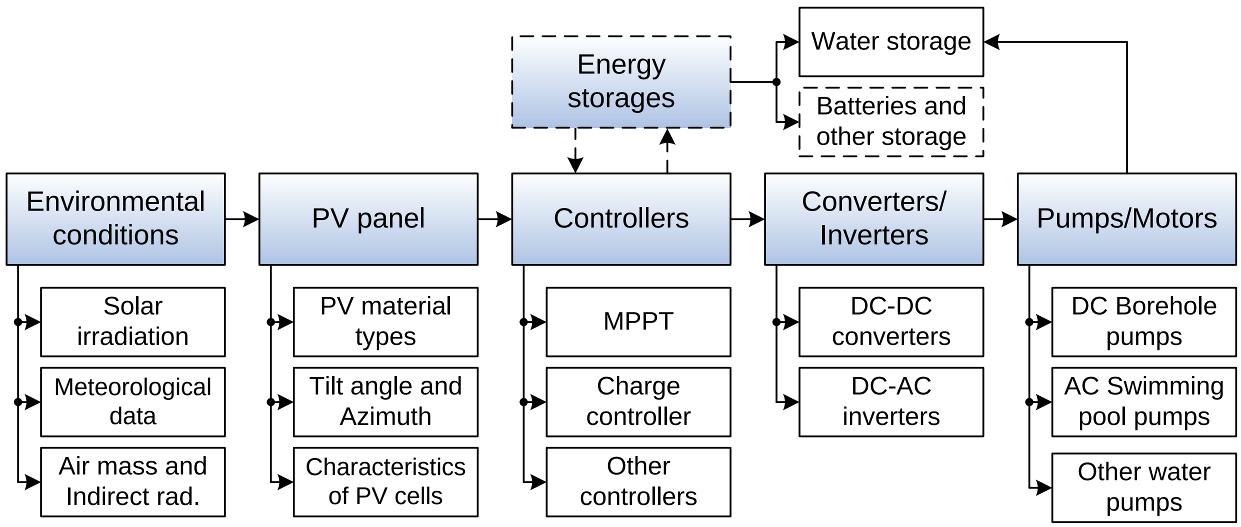

Figure 1. Factors influencing the performance and efficiency of a solar water pumping system.

of water affairs and forestry (Department of Water, 2012).

Most solar PV water pumping systems store water instead of electricity. Adding batteries usually doubles the cost of the system due to the battery cost, short battery life, and the additional maintenance with batteries. For water storage, the only additional expense is the storage tank. Usually, the storage tank is sized for most number of days without sunshine (enclosed tank will prevent evaporation). Another option is to oversize PV array, so water is pumped on cloudy days with no need for storage at all. Another effect on performance is fixed versus passive and motorized tracking for PV panels. The sections in Figure 1 provide a review on each of the factors mentioned.

Environmental conditions

This section provides a review on the environmental conditions that influence the performance and efficiency of a PV system or solar water pumping system. The environmental conditions must be used as input data during the design of a PV system. The following factors are discussed in this section: 1) solar irradiation, 2) meteorological data and 3) air mass and indirect radiation.

SOLAR IRRADIATION

Sunshine is the most important component for a PV system. Solar radiation is the term that refers to photons (or electromagnetic waves) generated by the sun. It is important to note that solar radiation is in units of energy. Solar irradiation on the other hand is the solar power incident per unit area on the earth's surface in units of watts per square meter (W/m^2). The amount of the solar irradiance for a specific location is important in the optimization of a PV system (Markvart and Castaner, 2003). Different parts of the world have different solar irradiance levels.

In South Africa, the solar irradiation average is highly compared to the USA and Europe, who are the leading continents in solar power generation. The amount of sunshine in South Africa is estimated at 2500 h/year and the annual 24 h solar radiation average is estimated at 220 W/m^2 compared to 100 and 150 W/m^2 for the USA and Europe, respectively (Department of Energy, 2012). Figure 2 provides a map of the average radiation of South Africa expressed in Wh/m^2 (Swera, 1998). The data was obtained from satellite observations and was captured by the United States National renewable energy laboratory (NREL). From this figure, it can be seen that the western half of South Africa has the highest solar irradiation. The number of PV panels required in a solar power system is calculated from the power required by the load and the solar irradiance of that specific area. The higher the solar irradiance, the higher the power produced by the PV panels, therefore, reducing the number of PV panels required. Solar irradiation therefore has an influence on the performance of the solar power system.

METEOROLOGICAL DATA

Table 1 provides the meteorological data for Potchefstroom (South Africa) as obtained by the NASA Langley research centre - atmospheric science data centre (Gaisma, 2012). It can be calculated from Table 1 that the average daily solar energy in Potchefstroom is 5.5 kWh/m^2/day, which translates to 5.5 h of sunshine per

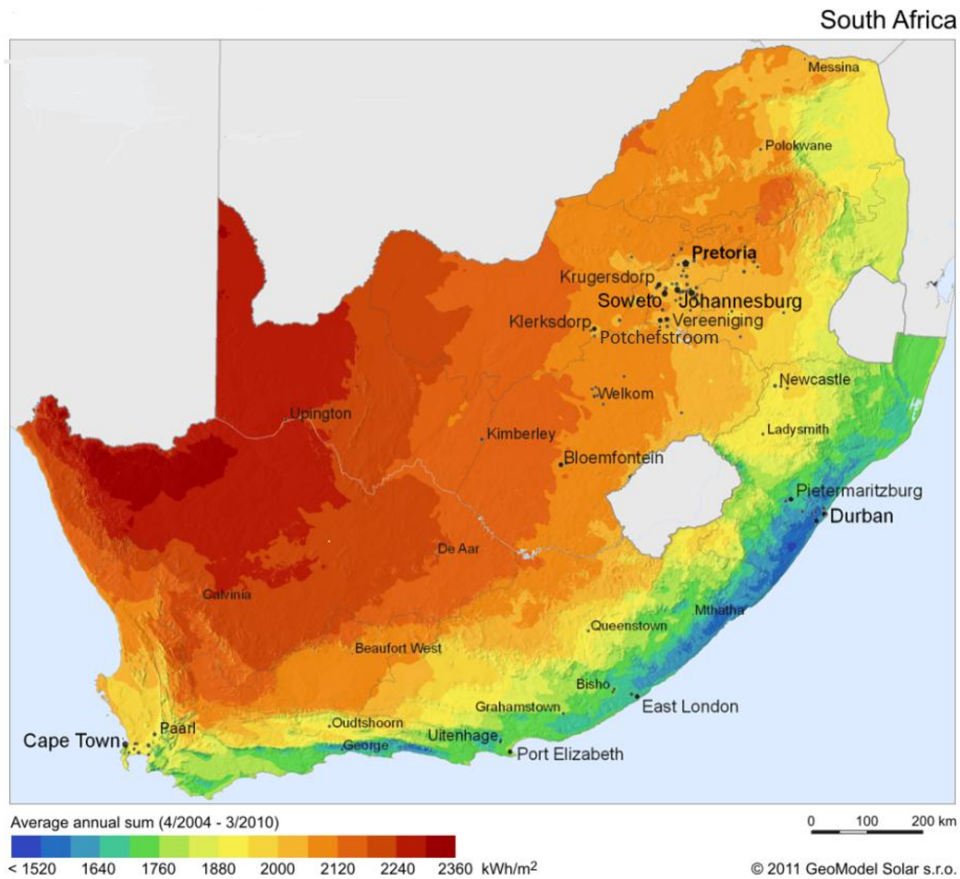

Figure 2. Solar irradiation map of South Africa (Swera, 1998).

Table 1. Meteorological data for Potchefstroom (South Africa) (Gaisma, 2012).

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual average
Irradiation (kWh/m^2/day)	6.55	5.92	5.24	4.58	4.04	3.64	3.92	4.67	5.57	5.86	6.36	6.57	5.24
Irradiation (kWh/m^2/month)	203	172	162	137	125	113	122	145	173	182	197	204	161.25
Clearness (0 - 1)	0.56	0.54	0.54	0.58	0.63	0.64	0.65	0.65	0.63	0.57	0.55	0.55	0.59
Temperature (°C)	22.4	22.1	21.1	18.7	14.8	10.8	10.9	14.2	18.3	20.1	20.9	21.3	17.97

day, since PV modules are tested and designed at the standard test condition of 1000 W/m^2.

The fraction of insolation at the top of the atmosphere, which reaches the surface of the earth, can be defined as the clearness index. Solar radiation data are often also presented in a dimensionless form called the clearness index. Clearness and temperature has a direct influence on the irradiation levels. When designing a PV system, the meteorological data of the specific area must be taken into account, since the data has a direct influence on the performance of PV system. According to Nakada et al. (2010), the clearness index and air mass strongly affect the intensity of solar irradiation and the spectral irradiance distribution, and the average photon energy increases when the clearness index increases and the air mass decreases. The amount of solar irradiation in a specific area has a direct influence on the temperature of that same area. The temperature data provided in Table 1 is the average temperature for each month of the year for the Potchefstroom area. If the solar irradiation levels for a specific area are unknown, the temperature values can be used during the design of the solar PV system.

AIR MASS AND INDIRECT RADIATION

The three main types of radiation are direct, diffuse and reflected radiation (Demain et al., 2012). Reflected

Table 2. PV material efficiencies (Gosse et al., 2007).

Material	Typical efficiencies (%)	Laboratory efficiency (%)
Gallium arsenide	20	32
Mono-crystalline silicon	14 - 17	25
Polycrystalline silicon	11.5 - 14	20
Copper Indium gallium selenide (CIGS)	9 - 11.5	19
Cadmium telluride (CdTe)	8 - 10	16.5
Amorphous silicon	5 - 9.5	13

radiation by the earth's surface can increase the PV panel's power output. Diffuse radiation is solar radiation, which has been scattered by particles in the atmosphere before impacting the PV panels. All these contribute towards the total irradiation for a specific area. Various factors affect the sun's rays before they reach the surface of the earth. The amount of solar radiation received by a surface that is always held vertical to the rays that come in a direct line from the path of the sun is defined as direct normal irradiance (DNI). The amount of radiant energy released by the sun that fall each second on 1 m^2 outside the earth's atmosphere over all wavelengths is defined as total solar irradiance (TSI).

The sun's radiation is scattered and absorbed as it passes through the atmosphere, which reduces the intensity. All this depends on the temperature and the water vapour content of the air in a particular area, which is referred to as air mass. The maximum radiation is received when the sun is directly above a specific area; this is called zenith and it is the shortest distance from the sun to that specific area. The sun angular position affects the performance of the PV panels. The standard test and design condition for PV panels is performed at an air mass factor of 1.5. This standard test and design condition is applicable for the Potchefstroom area, but recalculation is required for areas with a lower or higher air mass factor. Shnishil et al. (2011) presented the influence of air mass on the performance of many types of PV modules in Baghdad. According to Shnishil et al. (2011), the performance of triple-junction amorphous National Institute of Standards and Technology (NIST) insulated modules and triple-junction amorphous Sandia National Laboratories (SNL) uninsulated modules are the best type at a small air mass, while at a large air mass other types give larger maximum output power.

Indirect radiation has an influence on the performance of the solar panels and therefore has an influence on the performance of the complete solar water pumping system. Indirect radiation therefore cannot be studies separately.

PhotoVoltaic panels

This section provides a review on the factors that influence the performance and efficiency of the PV panels. The factors mentioned in this section are variables and must be optimally selected in order to maximize the performance and efficiency of the PV system. The factors discussed in this section: 1) PV material types, 2) tilt angles and azimuth and 3) characteristics of PV cells.

PV modules are used for the conversion of solar energy into electric energy. PV modules consist of solar cells, which are made up of two layers of semiconductor materials. Electric field is built in the p-n junction between the semiconductor materials. The absorption of photons of energy greater than the band gap energy of the semiconductor promotes electrons from the valence band to the conduction band, creating hole-electron pairs throughout the illuminated part of the semiconductor (Markvart and Castaner, 2003). DC power is generated in the external contacts when the electron and hole pairs flow in different directions in the p-n junction. Solar cells typically produce low voltages of around 0.5 V each; a combination of solar cells is therefore connected in series to form a PV module with a higher voltage and power output (Markvart and Castaner, 2003).

PV MATERIAL TYPES

Solar cells are manufactured as crystalline or thin film. Crystalline type PV cells are higher in efficiency than thin film, but some thin film (like cadmium-telluride) is also popular, because they have lower cost. Table 2 provides the efficiencies of the most used PV cell materials (Gosse et al., 2007).

As shown in Table 2, gallium arsenide has the best efficiency, but it is the most unpopular due to its high cost (Gosse et al., 2007). Mono-crystalline and polycrystalline silicon are the most popular materials because of their low costs compared to gallium arsenide (Gosse et al., 2007). The efficiency of mono-crystalline and polycrystalline silicon is higher than thin film materials. Mono-crystalline has a slightly higher efficiency when compared to polycrystalline, but there is almost no difference in cost. Mono-crystalline silicon PV panels are therefore a good option for a solar water pumping system. Murata et al. (2003) proposed a new type of PV

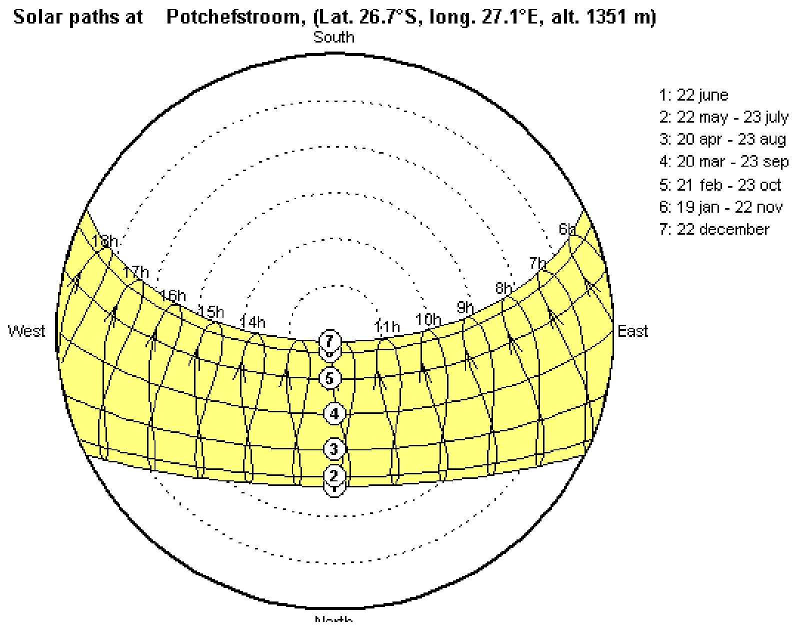

Figure 3. Sun paths at Potchefstroom (Mermoud, 2012).

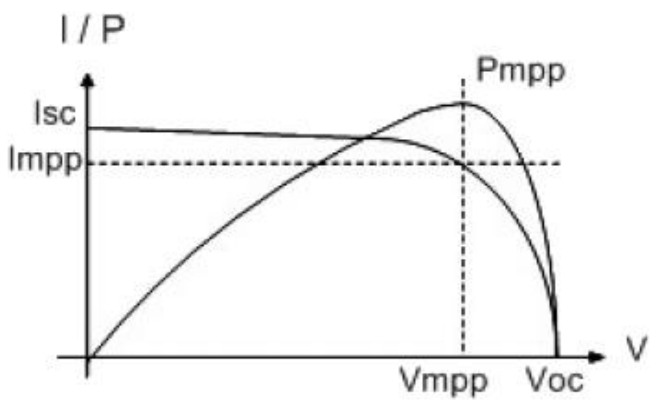

Figure 4. Characteristics curves of a PV cell (Rakotomananandro, 2011).

module integrated with roofing material, which is a highly fire-resistant PV tile. According to Murata et al. (2003), it offers a lower cost, simpler construction, better design, and a greater fire resistance PV module. There are however several reasons why higher voltage PV modules are preferable over lower voltage modules.

TILT ANGLE AND AZIMUTH

In order to optimize the performance and efficiency of a PV system, the tilt angle and azimuth need to be taken into account. The tilt angle is the angle between the earth's surface and the PV panel. Most panels are fixed in one position with the optimum tilt angle selected though simulation of the PV panels under specific area conditions. Some PV panels use a sun tracker to constantly change the tilt angle in order to receive maximum sunlight constantly. Azimuth is the angle measured between the true north and the position of the sun at a specific time. Figure 3 provides the path of the sun for the Potchefstroom area (Mermoud, 2012). The sun's path is used to get the perfect azimuth angle for a specific area. By adjusting the tilt angle and the azimuth angle, the PV panel can be positioned for optimum performance and efficiency. Yen et al. (2009) provided results on the performance evaluation of large tilt angle PV systems in Taiwan. According to Yen et al. (2009), the results show that the inclination (tilt) angle has more effects on the final yields than the azimuth. Motorized tracking can also increase the performance of the PV system, but could lead to an increase in maintenance. The gain in energy from a motorized tracking system therefore has to be compared with the gain in energy by just adding more modules in a fixed array.

CHARACTERISTICS OF PV CELLS

Figure 4 provides the current-voltage (I-V) and the power-voltage (P-V) characteristic curves for a PV cell (Rakotomananandro, 2011). From this figure, it can be seen that when the solar irradiation increases, the voltage and current also increases. When the cell temperature increases, the voltage decreases while the current slightly increases. The open circuit voltage (V_{oc}) is

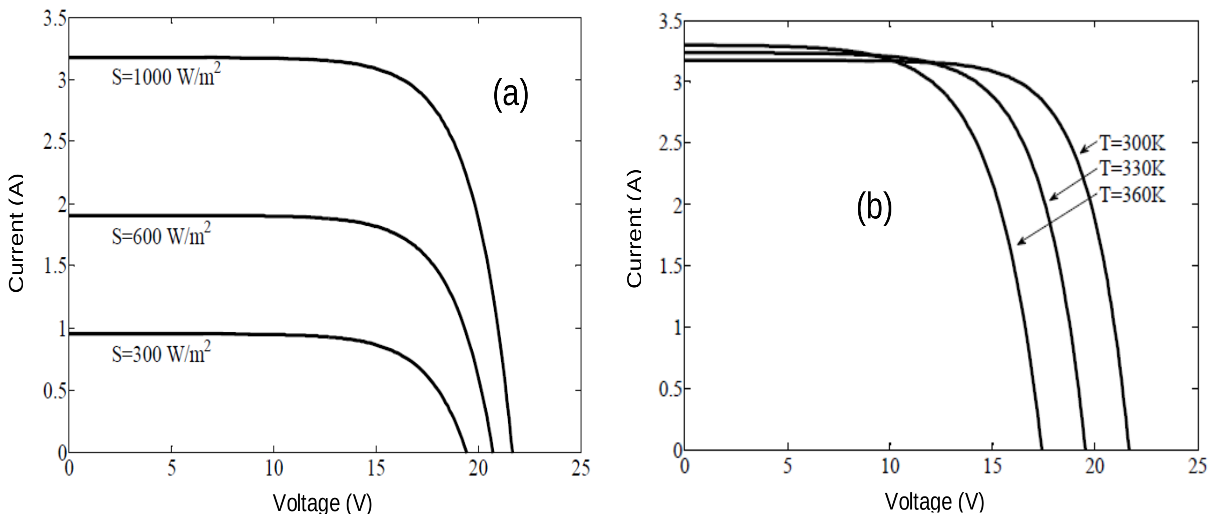

Figure 5. Effects of a) solar irradiance and b) cell temperature on the I-V curve (Park and Yu, 2004).

the maximum voltage supplied at zero current and the short circuit current (I_{sc}) is the maximum current supplied when the voltage is zero. The P-V profile shows that there is a maximum power point in the I-V curve where the solar cell can generate maximum power at any solar irradiance level ($P_{max} = V_{mpp} \times I_{mpp}$), where V_{mpp} is the maximum power voltage and I_{mpp} is the maximum power current. To optimize the performance of the PV panel, it must be operated where the solar cell can generate maximum power (P_{max}).

The maximum voltage (Voc) and the maximum current limit the power that can be produced by the solar cell (I_{sc}). The effects of the solar irradiation on the I-V characteristics are shown in Figure 5a. From this figure, it can be seen that the current increases as the irradiance level of the sun increases (Park and Yu, 2004).

The temperature of the solar cell itself affects the performance of the cell. From Figure 5b, we can see that an increase in the temperature of the cell decreases the open circuit voltage (V_{oc}), while the short circuit current (I_{sc}) slightly increases (Park and Yu, 2004). An increase in the cell's temperature therefore decreases the efficiency of the system (Park and Yu, 2004). Durgadevi et al. (2011) provided an article on PV modelling and PV characteristics. According to Durgadevi et al. (2011), the maximum power point varies with illumination, temperature, radiation dose and other aging effects.

Controllers

This section provides a review on the controllers for a solar water pumping system. The performance and efficiency of the system can be increased by selecting the appropriate controller. The following types of controllers are discussed in this section: 1) MPPT, 2) charge controllers and 3) other controllers.

MAXIMUM POWER POINT TRACKING

The MPPT controller operates the PV module at the maximum power point of the solar cells at all times despite the load requirements. Since the power harvested from the PV module is different at different operating points, it is important that the load is matched in such a way that maximum power is obtained from the PV module (Hussein et al., 1995). PV modules are expensive, it is therefore important to operate them at the maximum power point. If a load is directly connected to the PV module, the module will operate depending on the load voltage and current. The intersection between the I-V profile of the load and I-V profile of the PV module is the point at which the PV module operates (Sullivan and Powers, 1993). The load line therefore determines where the PV modules will operate when connected directly onto the PV module.

A MPPT controller is connected between the PV module and the load allowing the PV module to operate at the maximum power point. The control of a PV module can either be closed loop control or open loop control. Most MPPTs use the 'perturb and observe' (P&O) approach, which is implemented by a hill climbing algorithm usually on a microcontroller (Sullivan and Powers, 1993). This approach is complicated, can be slow, and become 'confused' if the irradiance conditions are changing rapidly and frequently (Hussein et al., 1995).

The P&O algorithm operates by varying the PV module voltage around the maximum power voltage (V_{pm}). The output power is assessed and the input voltage and current are adjusted accordingly. If the output provides an increase in power, the algorithm continues in the same direction and if the output gives a decrease in power, the algorithm changes to the opposite direction. Alternatives to the P&O approach have been suggested (Brambilla et al., 1999; Hussein et al., 1995; Midya et al., 1996).

CHARGE CONTROLLERS

Charge controllers are used to protect batteries from overcharging and excessive discharging, and are only applicable to solar water pumping systems that make use of batteries. Most solar water pumping systems do not have charge controllers or batteries and only store water in a tank. The charge controller is designed to prolong the lifetime of the battery. If the charging process continues when the battery is fully charged, it can damage the battery with the excessive voltage. Electrolyte loss and internal heating are some of the reasons the battery is damaged. The controller stops the charging of the battery as soon as the battery is fully charged by limiting the current flow. When the battery does not have enough capacity to supply the load and there is no current being generated by the PV module, the controller disconnects the batteries from the load because excessive discharge can also reduce battery life.

Most MPPT controllers incorporate the battery charge controlling function. When the power demand of the load is lower than the energy produced by the PV modules, the excess power is diverted to the charging of the batteries. Once the batteries are fully charged, the MPPT controller then has to move from operating at the maximum power point to producing only power that matches the demand. A charge controller can prolong the life cycle of a battery, which in turn has an effects on the performance and efficiency of the system.

Masheleni and Carelse (1997) proposed a microcontroller-based charge controller for a stand-alone PV system. According to Masheleni and Carelse (1997), charge controllers are required to improve the efficiency of the system and to protect the storage batteries. Huang et al. (2010) presented an article on system dynamic modelling and charging control of a lead-acid battery for a stand-alone solar PV system. According to Huang et al. (2010), the battery charging control is usually designed to stop charging after the overcharge point. Test results performed by Huang et al. (2010) indicated that the control system is able to increase the charged energy to 78%, as compared to the case when the charging stops after the overcharge point.

OTHER CONTROLLERS

Letting et al. (2012) presented the implementation of a particle swarm optimization (PSO) algorithm as a C-Mex S-function. The algorithm is used to optimize a 9-rule fuzzy logic controller (FLC) for MPPT in a grid-connected PV inverter. Putri and Rifa'i (2012) proposed a neural fuzzy controller for controlling the PV system output voltage by using a buck converter to operate at the maximum power point. According to Putri and Rifa'i (2012), their PV system can operate at the maximum power point even though the module temperature and sun irradiation are shifting the maximum power point.

Cirstea and Parera-Ruiz (2010) proposed a field-programmable gate array (FPGA) controller for a combined solar/wind power system. According to Cirstea and Parera-Ruiz (2010), this approach enables the design and fast hardware implementation of efficient controllers for distributed energy resource hybrid systems. Ellouze et al. (2010) proposed a sliding mode controller for a PV water pumping system. According to Ellouze et al. (2010), the use of the nonlinear sliding mode method provides a very good performance for motor operation and robustness of the control law despite the external/internal perturbation.

Energy storage

This section provides a review on the storage devices for a solar water pumping system. The performance and efficiency can be increased by choosing the appropriate storage device. The following types of energy storage are discussed: 1) water storage and 2) batteries and other storage.

Stand-alone PV systems have an option of backup batteries. The components for a PV system without backup batteries are less, but energy is only available when the sun is shining. The performance of a PV system is affected by external factors such as temperature, load variation and solar radiation. A system without backup batteries requires accurate design to accommodate these external factors. Most systems have backup batteries for energy storage when the PV system is unable to satisfy the load requirements. Batteries can also supply energy during the night. Storage batteries are however not widely used in solar water pumping systems.

WATER STORAGE

Almost all existing pumping systems use water storage. Some systems however make use of energy storage devices in order to circulate water during the night period (for special applications) and other systems use the battery to supply a constant current to the motor (normally applicable where the solar modules are under designed for the specific solar water pumping system in order to save installation cost). Therefore, irrespective of the amount of power supplied by the solar panels, the motor will maintain a constant rotational speed.

Bakelli et al. (2011) proposed a solution for optimal

Table 3. Flooded lead-acid batteries compared to valve regulated lead-acid batteries (Trojan, 2012).

Flooded lead-acid batteries	Valve regulated lead-acid batteries (Gel-cell)
High maintenance	Less maintenance
Occasional filling of water when electrolyte evaporates	Enclosed electrolyte so no water filling
Release of hydrogen	Longer life
Must be kept upright	More robust

sizing of a PV pumping system with a water storage tank by using the loss of power supply probability (LPSP) concept. This proposed solution makes use of two optimization criteria's, the LPSP concept for the reliability and the life cycle cost (LCC) for the economic evaluation. According to Bakelli et al. (2011), a case study designed to supply drinking water in remote and scattered small villages situated in Ghardaia, Algeria was conducted.

Qing (2007) proposed a MPPT controller for a PV pumping system (PVPS) and a novel scheme with double pumps to improve efficiency of PVPS. According to Qing (2007), the pump with higher head works when solar irradiation is weak, while the pump with lower head is automatically switched on to work when solar irradiation is powerful.

BATTERIES AND OTHER STORAGE

Batteries are used for special applications of solar water pumping systems, where pumping is required during the night. The use of batteries can lead to: 1) decrease in performance of the pumping system, 2) decrease in the reliability of pumping system especially in an arid environment and 3) increases in the cost of pumping system.

There are many different types of batteries available. For solar systems, the cycle life of a battery is very important. The cycle life of a battery is the number of times it can be charged and discharged. For solar systems, a battery that can handle only about 10 cycles (for example, most lead acid batteries) is not suitable. Solar systems require a high number of cycles (for example, deep cycle batteries), that can handle thousands of cycles (Trojan, 2012).

Lead-acid batteries are the most commonly used battery type for solar applications, because of the low cost and low maintenance (Trojan, 2012). There are different types of lead-acid batteries and in this section, we compare flooded lead-acid batteries to valve-regulated lead-acid batteries. For batteries to last longer, deep discharges must be avoided and must be kept charged for as long as possible. From Table 3, we can see that the gel-cell battery is the better option battery for solar systems, as it has less maintenance, more robust and has a longer lifetime.

Other types like lithium and nickel metal hydride are popular with laptop computers, cell phone and other small electronic equipment, because they can come in smaller sizes. The downside is that they are expensive and therefore not suitable for use in large applications such as water pumping systems.

Ongaro et al. (2012) proposed a power management architecture that utilizes both super-capacitor cells and a lithium battery as energy storages for a PV-based wireless sensor network. According to Ongaro et al. (2012), by combining the two storages, it is possible to obtain a good compromise in terms of energy density. Glavin et al. (2008) proposed a stand-alone PV super-capacitor battery hybrid energy storage system. According to Glavin et al. (2008), the simulation results showed that the hybrid storage system can achieve higher specific power compared to the battery storage system.

Paska and Biczel (2005) proposed a concept hybrid solar wind power plant with a fuel cell, where energy is produced by a fuel cell when there is no solar energy. According to Paska and Biczel (2005), it is possible to build a hybrid solar and fuel cell power plant, which allows optimal utilization of the renewable uncontrolled primary energy carrier. Moghaddam and Hajizadeh (2010) proposed a hybrid power system based on a DC coupled hybrid PV/fuel cell/battery power system that supports the local grid. According to Moghaddam and Hajizadeh (2010), the main idea of the control strategy is to utilize the PV energy to the maximum by using MPPT; the rest of the power that cannot be met by the PV is supplied by the fuel cell.

Villela et al. (2010) proposed a small-scale compressed air energy storage (CAES) system that can work in conjunction with individual PV panels. According to Villela et al. (2010), the work represents an important step towards developing a low-power high efficiency CAES storage system that can work seamlessly with PV panels.

Converters/inverters

Power electronic converters are used in PV systems to convert the DC voltage to a higher or lower DC voltage and to convert DC to AC voltage (Rashid, 2001). This section provides a review on the DC-DC converter and the DC-AC inverter for a solar water pumping system. To optimize the performance and efficiency of the system, the correct inverter has to be selected for a chosen pump.

DC-DC BUCK/BOOST CONVERTER

DC-DC converters are used to adjust the DC output voltage to the required value. These converters are often incorporated into the MPPT controller to boost the voltage from the PV panels (Rashid, 2001). The buck converter is used to step down the DC voltage for applications that require a lower voltage than that being produced by the PV modules. The circuit of the buck converter consists of a power electronic switch, an inductor and a diode. To smooth the output of the converter, a capacitor is used (Mohan et al., 2003; Rashid, 2001). Mohan et al. (2003) specified that the output voltage across the inductor can be calculated by $V_o = [t_{on}/(t_{on} + t_{off})]V_s = D.V_s$, where t_{on} is the amount of time the switch is on and t_{off} is the amount of time when the switch is off. The output voltage is always lower or equal to the input voltage. The output voltage can be controlled by adjusting the duty ratio (D).

A boost converter is used to increase the voltage output of the PV modules. The boost converter consists of a power electronic switch, an inductor and a diode (Mohan et al., 2003; Rashid, 2001). The boost converter operates in continuous conduction mode and discontinuous mode depending on the energy storage capacity together with switching times. The diode is reversed biased when the switch is on and it isolates the output voltage; during this time, the inductor stores energy from the input voltage. When the switch is off the output voltage becomes the sum of the energy from the input voltage and the energy from the inductor. The output voltage can be calculated by $V_o = [1/1\text{-}D]V_d$, where V_d is the input voltage, V_o is the output voltage and D is the duty cycle. The output voltage (V_o) will always be higher or equal to the input voltage (V_d) and can be controlled by adjusting the duty cycle (Mohan et al., 2003).

DC-AC INVERTERS

The DC-AC inverter is used in PV systems that have AC loads. The loads can either be single-phase or three phase. Typical DC-AC inverters come in different forms such as full-bridge inverter (single or three phases), half-bridge diode clamp, and frequency-commutated current source inverter. The full bridge inverter is the most commonly used in PV systems (Kjaer et al., 2005).

A full bridge three-phase inverter consists of four switches that are controlled in such a way that the two switches on the same branch are never switched on at the same time. If any of the two switches is on, one branch is switched on at the same time the DC source is short-circuited. Modulation techniques used to control the switches include pulse width modulation (PWM) and square wave inverting. To avoid short-circuiting, the DC source the time interval between switching off one switch, and switching on another must be kept as short as possible. This particular time is referred to as the blanking time. Blanking time mostly depends on the switching device used.

Tirumala et al. (2002) proposed an efficient, low cost DC-AC inverter for PV systems with increased reliability. According to Tirumala et al. (2002), the proposed modular approach helps to increase the reliability of the system by introducing redundancy, while lowering the cost by having identical modules in parallel. Ribeiro et al. (2010) proposed a single-stage DC-AC converter for PV systems. According to Ribeiro et al. (2010), a DC-DC converter is merged with an inverter in a single-stage topology to be used as an interface converter between the PV systems and the AC utility grid.

Pumps/motors

Pumps come in different sizes and shapes. This section provides a review on the pumps for a solar water pumping system. The performance and efficiency of the system can be increased by choosing the appropriate pump. The following types of pumps are discussed: 1) DC borehole pumps and 2) AC swimming pool pumps.

DC BOREHOLE PUMPS

Motor-pump units are available in DC and AC for borehole pumps. DC motor pumps are however more commonly used in South Africa, since no conversion of energy is required. This section therefore only focus on DC borehole pumps.

Water pumps are selected depending on water needs; the higher the amount of water pumped, the higher the energy demand. In rural areas, the water consumption per person per day is 122 litres, whereas a typical urban household has a water consumption of 250 L/person/day (Keshavarzi et al., 2006). Table 4 provides the typical pump sizes for DC borehole pumps (Agriworld, 2012). To optimize the performance and efficiency of a solar water pumping system, the correct size motor need to be identified from the amount of litres required per day. Choosing a too large motor is inefficient if the whole system was not designed for that specific motor.

Figure 6 provides a solution that does not require a battery backup (Akihiro, 2005). The pump only works when the sun is shining and stores the water for future usage. The system pumps water from a well. The PV module in the system is a single BS SX 150S mono–crystalline PV module. Each module produces a maximum power of 150 W (Markvart and Castaner, 2003). The MPPT is constructed of a switch-mode DC-DC converter and a controller (Akihiro, 2005).

The DC-DC converter boost the DC voltage from the PV panels and the controller maximizes the output of the

Table 4. Typical pumps sizes for DC borehole pumps (Agriworld, 2012).

Motor size (W)	Litres/hour	Litres/day (5.5 h of sunshine)
550	1,000	5,500
750	3,100	17,000
1,100	4,800	26,000
3,000	6,000	33,000
9,000	35,000	192,500

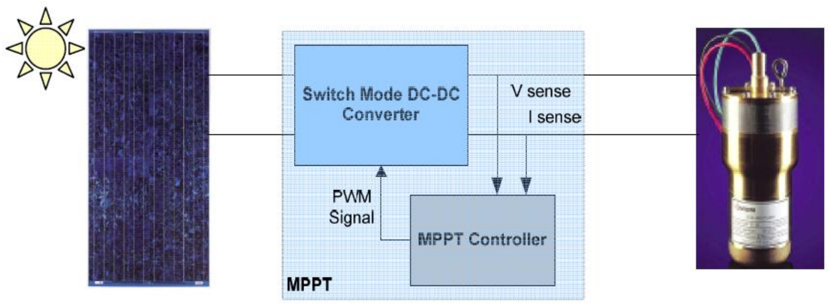

Figure 6. PV water pumping system (Akihiro, 2005).

Table 5. Recommended pool pump sizes (Delport and Marais, 1995).

Pool size (L)	Motor size (W)	Flow rate (L/min)
41,400	450	115
59,400	600	165
79,200	750	220
108,600	1,100	300

PV panel by making sure it always operates at its maximum power point. The water pump used in this system is a Kyocera SD 12 to 30 submersible solar pump, which has a rated maximum power usage of 150 W. This pump is a diaphragm-type positive displacement pump equipped with a brushed permanent magnet DC motor and designed for use in standalone water delivery systems (Akihiro, 2005). The system produce a daily output of up to 5000 L, flow rates of up to 17 L/min and heads of up to 30 m. The disadvantage of this solution is that it will not work during cloudy days. A battery bank should be incorporated in the design for applications requiring a constant supply of water (Kyocera, 2001; Sunpumps, 2012). Normally batteries are not preferred and storage is usually done in the form of a water storage tank.

AC SWIMMING POOL PUMPS

Pool pumps are used to circulate the water in swimming pools for filtering and have to operate between 5 to 12 h a day depending on the pool and pump size. Pool pumps installed in South Africa range from 0.45 to 1.1 kW, which on average translates to 0.6 GW of installed capacity, which can meet the energy demands of around 500,000 households (Ndlovu, 2008). Table 5 provides the suppliers recommended pool pump sizes (Delport and Marais, 1995). To optimize the performance and efficiency of a solar water pumping system, the correct size motor must be chosen for a specific size pool.

Figure 7 provides a solution that also does not require a battery bank, because it uses a storage water tank for use when the PV panels are not generating electricity (Daud and Mahmoud, 2005). This system (Figure 7) is made up of four PV strings connected in parallel with each string made up of 14 PV modules. The PV generator can provide the DC-AC inverter with a maximum of 230 V_{DC} and the inverter can provide the motor with up to 127 V_{AC} (Daud and Mahmoud, 2005). An efficiency analysis of the pump is required, in order to operate the system as effectively as possible

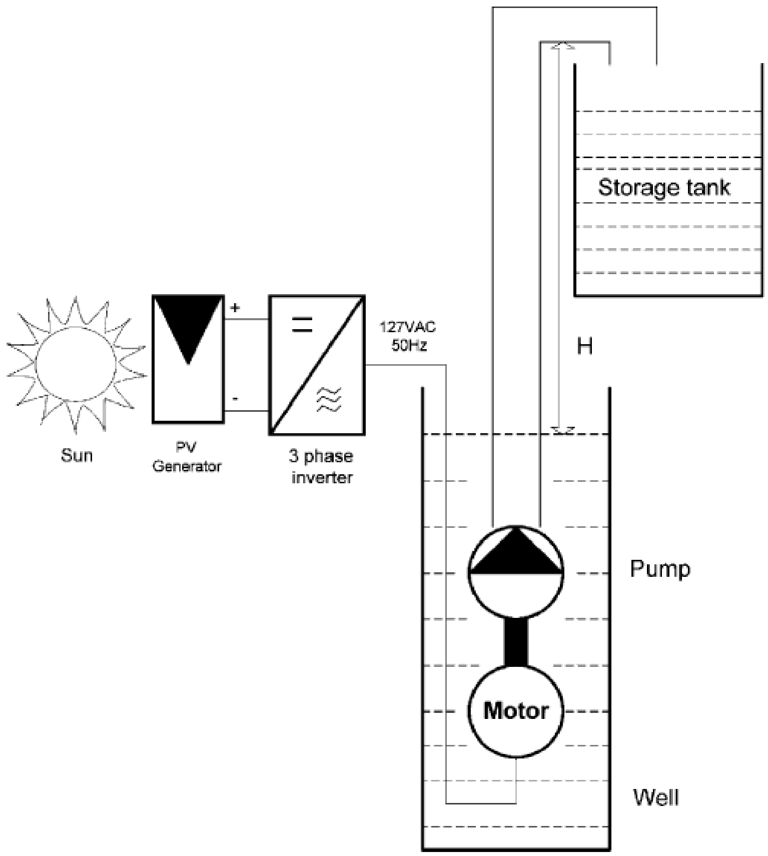

Figure 7. Schematic diagram of a PV power pumping system (Daud and Mahmoud, 2005).

(Gouws, 2012).

Conclusions

This paper provided a review on the factors that influence the performance and efficiency of a solar water pumping system. It is shown from literature that solar irradiation, meteorological data, air mass and diffuse radiation are important factors that influence the performance and efficiency of a solar water pumping system. The PV panel of the solar water pumping system is influenced by the type of PV material used, the tilt angle, azimuth and characteristics of the PV cell. Mono-crystalline silicon seems to be a good option for PV panels, since it has a high efficiency and an affordable price. The type of controller and storage medium used influences the performance and efficiency of the system. A good option for a controller is the MPPT controller, since it maximizes the efficiency of the PV panel. Other control like sliding mode control and FLC can also be used, but it is not commonly used in the industry.

The most popular storage for off-grid solar powered water pumping is a storage tank for the water. Other energy storages like super-capacitor, fuel cells and compressed air can also be used. The price, maintenance and reliability of these storages however, need to be taken into account. The user can decide on either a DC motor or an AC motor for the pump combination. AC induction motors are more energy efficient than DC motors, but the losses of the DC-AC inverter must be taken into account. Swimming pools normally have an asynchronous induction motor pump configuration, which the user would prefer to use. The size of this pump however might not be the best option in terms of performance and efficiency and need to be resized according to the specifications of the solar water pumping system.

To design a solar water pumping system to operate at maximum efficiency and performance, the needs, characteristics of the water source and the characteristics of the installation site (environmental conditions) have to be taken into account.

World Water and Solar Technologies, Inc. (WWST) has successfully completed solar-powered irrigation projects in California, New Jersey, USA and Egypt (Arab Water World, 2010). In 2004, World Water completed the world's largest solar-powered irrigation system at Seley

Ranches (Borrego Springs, California). This standalone system is capable of driving a 200 hp pump by using only the energy from the sun at 1000 gallons of water per minute from a depth of 300 feet (Arab Water World, 2010).

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