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DEPARTMENT OF ENVIRONMENTAL AND BIOSYSTEMS ENGINEERING

PERFORMANCE INVESTIGATION OF SOLAR PHOTO-VOLTAIC WATER PUMPING SYSTEMS; A CASE STUDY OF ABAKORE BOREHOLE WATER SUPPLY SYSTEM, WAJIR COUNTY KENYA

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LIST OF ACRONYMS AND ABBREVIATIONS

$	United States Dollars
AC	Alternating Current
DC	Direct Current
JMP	Join Monitoring Program
KNBS	Kenya National Bureau of Statistics
Ksh	Kenya Shillings
KWH	Kilowatt-hours
kWh/m^2	Kilowatts hours per meter square
$kWhm^2/day$	Kilowatts hours per meter square per day
LCC	Life-Cycle Cost
MDG	Millennium Development Goals
PSH	Peak Sun Hours
PV	Photovoltaic
TDH	Total Dynamic Head
TWh	Terrawatt hours
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations International Children's Fund
WHO	World Health Organisation

NOMENCLATURE

Solar radiation	The amount of solar energy that reaches the earth. The maximum amount of solar radiation that reaches the surface of the earth is approximately 1 Kw/m^2
Solar irradiance	The amount of solar energy received on a specific surface. Usually expressed in kW/m^2
Insolation	The amount of solar irradiance measured over a specific time period. Usually expressed in kWh/m^2
Peak Sun Hours	The average daily insolation expressed in $kWh/m^2/day$. It's most often expressed in the term peak sun hours. To achieve PSH, the total insolation is divided by $1kWh/m^2$

ABSTRACT

The performance of a directly-coupled solar photovoltaic water pumping system was investigated under field conditions. The objectives of the study were to establish the technical performance indicators of solar photovoltaic water pumping systems, then investigate the actual performance of the system operating under field conditions. The study set-up consisted of an 18.72 kW-capacity directly coupled solar PV water pumping system installed in a 150-meter-deep borehole in a remote village in Wajir northern Kenya. The system was studied over a 60-day period under varying solar irradiance. Data was collected using an in-built data logger and remote monitoring device integrated in the Pump Inverter/Controller assembly. The results showed that solar irradiance varied from 63 W/m^2 to a peak of 857 W/m^2, corresponding to a maximum power output of 11.75 kW. PV array efficiency of 12.1%, sub-system efficiency of 91.82% and overall efficiency of 5.14%. The results obtained were compared with manufacturer's recommendations and results reported elsewhere and it was observed that this system had a within range performance output. By obtaining an optimal load matching factor of 0.66, the results demonstrate that the system components at Abakore were averagely well matched, adequately configured and in close agreement with recommendations for load matching factor between the PV solar generator and the electro-mechanical system. The study concludes that solar PV driven systems when properly designed are more reliable and cost-effective in the long-run for water pumping applications. Since this study focused on analyzing one solar system, the findings are inadequate to make general conclusions on performance of installed solar pumping system. As such the study recommends further research to test and conduct performance evaluation of several solar pumping systems with different characteristic and at different locations over a longer period to compare influence of different characteristics and contexts.

CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 Energy for water infrastructure challenge

The United Nations Children Education Fund (UNICEF) and the World Health Organization (WHO) Joint Monitoring Program (JMP) 2016 report that 844 million people still lack access to basic drinking water globally (WHO & UNICEF, 2017). Out of these, 159 million collect drinking water directly from unsafe surface water sources and 58% of them lives in sub-Saharan Africa. In addition, the Global Risks 2015 reports that global water crisis ranging from recurrent droughts to the millions of people still without access to improved water sources is the number one threat facing the planet in the coming decade (World Economic Forum, 2015). In responding to this global water crisis, the United Nations has adopted a new set of seventeen Sustainable Development Goals (SDGs) with goal number six focusing on ensuring availability and sustainability of water and sanitation for all (United Nations, 2015).

Inadequate levels of investment in water harnessing and storage infrastructure remains a key factor perpetuating this crisis particularly in developing countries. Van Koppen (2003) highlights the ironic nature of this water crisis in that while majority developing countries are endowed with many lakes, rivers, large groundwater aquifers and high volumes of surface run-off during the rainy seasons, due to political, economic, financial and environmental challenges, the water is only marginally harnessed and processed to reach people where it is needed the most thus causing the chronic scarcity. One can then conclude that addressing water scarcity problem through increased investment in sustainable infrastructure to collect, treat and distribute water to the users is one of the most critical solutions to the global water crisis.

In the efforts to increase investments in water infrastructure, a problem of meeting the energy needs for water supply infrastructure arises. Pate et al., (2007) in underscoring the importance of energy for the water value chain shows that energy costs alone is over 75% of the total production costs municipalities in the United States of America incur in treating and distributing water to their clients. Similar observations are made by Copeland & Carter (2017) in the United States that as populations increase, the demand for electricity at water and wastewater plants is expected to grow by approximately 20%. UNESCO (2012), suggests that developing more water harnessing infrastructures as a solution to the global water scarcity crisis will result in an increased demand for energy especially for pumping applications since water infrastructure largely relies on energy throughout its value chain. It's also expected that groundwater will become increasingly energy intensive as water tables fall in several regions therefore making sustainable renewable energy supplies options such as wind and solar key components of water security debate (UNESCO, 2012). Recognizing that water pumping is a major energy consumer within the water value chain, The International Renewable Energy Agency (IRENA) (2015) asserts that solar-based water pumping solutions offer a cost-effective alternative to pumping sets that run on electricity or diesel especially for remote contexts where access to energy is limited or non-existence.

A wide range of equipment and techniques have been used to provide the energy required for water pumping applications. Presently the most common are manually operated hand pumps or foot pumps and diesel generator pumping sets. Hand pumps have been praised as low cost and easy to use but their limitation is that it can only be applied in shallow wells with low pumping heads thus not suitable for deep groundwater extraction. Even though diesel generator pumping systems are capable of very high output, their fuel consumption means very high operational costs too often beyond the ability of the users to pay for. This leads to their operation becoming intermittent thereby not delivering with reliability desired. My own experience of working in rural contexts in northern Kenya areas of Turkana, Isiolo, Wajir and Garissa for over 7 years with Non-Governmental Organizations (NGOs) where diesel systems are extensively applied is that the government or NGOs often provide fuel to subsidize the costs of operation, and spare parts. This has the negative effect of reinforcing a sense of dependency and fails to address the underlying economic and management issues thus making it unsustainable in the long term. Consequently, significant efforts have been made to develop several alternatives that attract lower service, maintenance cost and possess ease of operation advantages over hand pumps and diesel pumps. To address the limitations of diesel pumping sets and hand pumps, the use of solar power for water pumping applications is presented as an alternative approach.

1.1.2 The Kenyan context of the challenge

Kenya is increasingly facing the twin challenge of water scarcity and decreasing energy generation as the capacity of the traditionally used Hydro dams are rapidly dwindling due to climate change effects. As it is, Kenya's position lying along the equator endows it with significant amounts of renewable energy in the form of solar radiation that calls for deliberate efforts to integrate water and energy infrastructure planning to harness these resources within a nexus approach. Just recently in 2013, a UNESCO spearheaded exploration of groundwater resources in the drought stricken northern Kenya discovered huge reserves of groundwater aquifers estimated to yield a total renewable output of 3.442 billion cubic meters of water per year (Radar Technologies International (RTI), 2013). Stressing Kenya's vulnerability to climate change effects, water scarcity and low energy production, the Kenyan Ministry for Environment recognizes the need for more research and investment in groundwater exploration and renewable energy sources to identify, understand and sustainably exploit these groundwater aquifers (Nyandika, 2013).

Water stress is particularly felt in the semi-arid and arid regions of Kenya which face recurrent droughts. These regions interestingly have an abundant supply of sunlight which could be exploited as alternative energy for water pumping. Using solar PV for water pumping offers the unique advantage that there are significantly low operations and maintenance costs once the system is installed. This represents a huge cost savings that makes it affordable to offer increased access to water supply especially for vulnerable communities whose ability to pay is limited. Despite this huge potential and numerous advantages, the number of operational pumping systems based on photovoltaic energy in Kenya is still low with only an estimated 20% of the full potential harnessed (Pandey et al., 2016). The low economic viability in terms of capital expenditure of photovoltaic pumping systems vis-à-vis conventional options such as diesel sets has been widely cited as one of the main barriers against their large-scale adoption (Timmons, Harris, & Roach, 2014; Shim, 2017). On a more positive note for the proponents of solar water pumping systems, Maurya et al., (2015) observed that globally the cost of PV has come down while the cost of diesel has been regularly increasing. The World Bank reports that since 2009, the price of solar PV modules has dropped by 80% making the life-cycle cost of solar power several times cheaper than diesel (World Bank, 2015). In Kenya, Muok et al., (2015) observed that the prices of PV modules have fallen from US dollars 5 in 2000 to US dollars 0.5 in 2014.

1.2 Statement of Research Problem

The purpose of this research is to monitor and evaluate the technical performance of a directly coupled solar water pumping system installed in a remote village in northern Kenya. Maurya *et al*. (2015) concluded that even though there have been extensive studies measuring outdoor performance of PV modules as a single component of the pumping system, there is only a limited body of research on field conditions of the complete system consisting of the PV modules and the motor-pump sub-system and related auxiliaries. In the recent past, due to declining PV module prices as well as the increase in the number of players within the solar water pumping market offering competitive services and more choices for consumers, there has been a steady increase in the number of solar water pumping systems installed in Kenya. Despite this increasing adoption of the technology, only a limited number of studies has been undertaken to monitor and evaluate the performance of solar pumping systems installed in the field. As a result, McSoley observes that there is a common tendency to oversize PV generators and pumps using a "bigger is better" mentality which persists mostly within government District Water Offices (and the agencies who supply the equipment) in Kenya. A similar observation has been made by Wahab, Yassin, & Ahmed (2009) who stated that the private sector that provides the solution for pumping most often depend on some thumb rules and general information resulting in over or under-designed systems. This presents a need to monitor installed systems, evaluate and report on their performance to inform future design and system specifications. Kenna et al., (1995) observed that if there is limited quantitative measurement and analysis of the energy received (cumulative solar irradiation) and delivered (cumulative flow of water and pumped head) by the installations, then nothing is learned which will help to improve the technology.

1.3 Overall Objective

The overall objective of this study was to investigate the performance of directly coupled Photovoltaic water pumping system consisting of a PV array, a controller, a motor and a borehole pump under varying field operating conditions.

1.4 Specific Objectives

(1) Establish from literature, the parameters to be monitored to enable performance evaluation of solar photovoltaic water pumping systems.

(2) Evaluate the performance of an operational 18.72 kW photovoltaic water pumping system installed at Abakore borehole water supply system in Wajir, Kenya.

1.5 Scope of the study

The result of this study is expected to contribute to knowledge in the field by showing actual field performance data. This will enable designers of the next solar PV water pumping installations with similar or proportionally related requirements, to optimally select and better match to the end-user needs, and most significantly, it is expected to test and reinforce the claim that solar water pumping is an economically viable option thereby making it more appropriate for bottom of the pyramid end users in remote locations.

CHAPTER 2: LITERATURE REVIEW

2.1 The Water functionality crisis and solar pumping solution

Lockwood & Smits (2011) reviewed the status of rural water sustainability across different countries in Africa found and an average failure rate of 20-40% amongst rural water projects. Sutton (2004) similarly report that between 10% and 50% of communal water points may be out of service at any given time in sub-Saharan Africa because of frequent system breakdowns. Hand-pumps have been extensively used in remote rural areas beyond the reach of electricity grids to supply water for small village communities, however they are only limited to providing low volumes of flow per day. For large applications requiring high volumes of output beyond the capacity of handpumps, Meier (2012) recommends the use of motorized pumps such as diesel and gasoline engines or grid-connected electricity. Owing to high operations and maintenance costs required by conventional engine driven pumps and the limited reach of grid-electricity to most decentralized remote communities, the exploitation of solar energy for water pumping is increasingly becoming a popular viable option for the delivery of water.

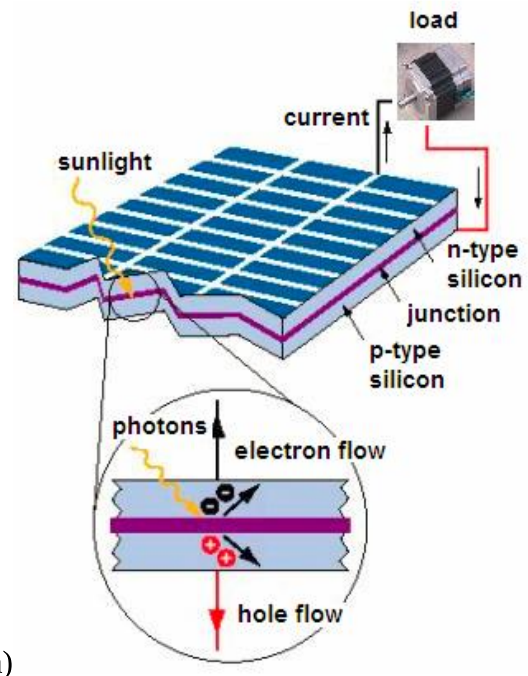
2.2 Theory of solar Photovoltaic technology

2.2.1 Photovoltaic Effect and solar cells

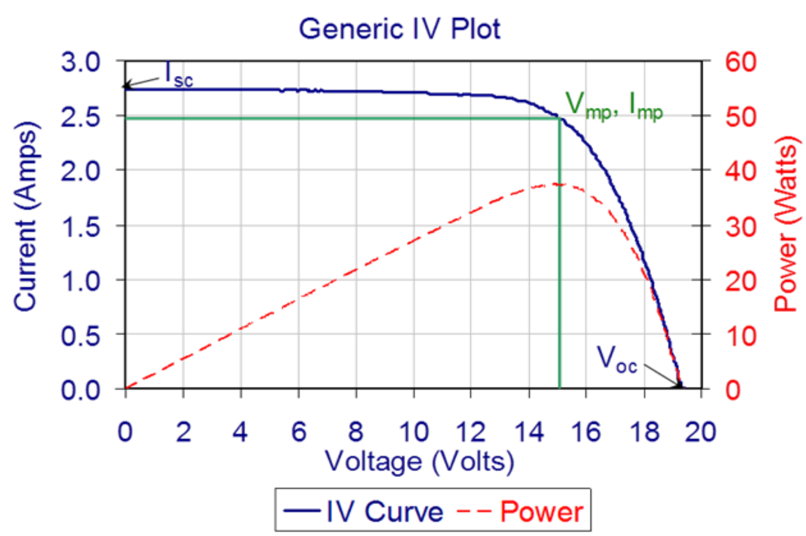
Solar photovoltaics belongs to the broad category of energy sources categorized as renewable since they are replenished by natural processes. Photovoltaics involve converting radiant energy emitted by the sun into useful electricity for various applications by a device called solar cell through a process called photovoltaic effect (Mertens & Roth, 2014).

Solar cells are made from Silicon, a type of semi-conductor material. Semiconductors are materials that conduct electricity at high temperatures supplied either through heat or light but act as electrical insulators at low temperatures (Dincer & Meral, 2010). Figure 2.1(a) shows the schematic layers of a typical PV cell. Because Silicon in its purest form does not conduct electricity, small amounts of either Phosphorous or Boron impurities are added to it to improve its conductivity through a process called doping (Komp, 2002). To create the n-type silicon, it's doped with Phosphorous thus leaving one free electron while a p-type silicon is created by doping using Boron which leaves one electron missing. In a solar cell, the n-type and p-type silicon are placed side by side. When excited by energy from sunlight, the free electron in the n-type side jumps over and fills the missing electron in the p-type silicon. Through this process, an electric field is created across the cell. The n-type and p-type sides of the solar cell are then connected to an external electric circuit and electrical current flows. Chikate & Sadawarte (2015) and Dincer & Meral (2010); highlighted cells temperature and solar irradiance as the two most important factors affecting the photovoltaic process. Irradiance is the amount of sunlight falling on a given surface and as such the higher the irradiance the more efficient the solar cells are in converting sunlight into electricity (Elminir, Benda, & Tousek, 2001;) while the warmer the solar cells are due to increasing temperature, the less efficient they become as voltage decreases (Solar Energy International, 2013; Dubey, Sarvaiya, & Seshadri, 2013).

The electrical performance of the photovoltaic solar cell is presented in form of a current-voltage curve normally referred to as the I-V cure ((Herman, Jankovec, & Topič, 2012). Figure 2.1 (b) shows a generic IV curve. Solmetric Corporation (2001) defines the I-V curve as a tool for describing the energy conversion of a solar module at the existing irradiance and temperature. The voltage and current where the cells produces the most power is referred to as the maximum power point (MPP) and V_{mp} and I_{mp} are the maximum power voltage and current respectively. The short circuit current which is the current when Voltage is zero, and open circuit voltage which is the Voltage when the current is zero are labelled as I_{sc} and V_{oc} respectively.



(a)



(b)

Figure 2.1 (a) Schematic of the layers of a typical PV cell and (b) the generic IV curve of a typical PV cell (Dincer & Meral, 2010)

To increase their utility, dozens of individual PV cells are interconnected together in a sealed, weatherproof package called a module which are again wired in series and parallel into a PV array to achieve the desired Voltage and current (Dunia, Mwinyiwiwa, & Kyaruzi, 2014). For modules in series the current in Amperes 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 Figure 2.2 is demonstrates the effect of series or parallel connection of modules.

There are three main types of photovoltaic modules widely available on the market - Monocrystalline (Mono-Si), Polycrystalline (Poly-Si) and Thin-film (TFPV) and the distinguishing parameter between the three types is in the purity of the silicon it's made of (Gaur & Tiwari, 2013). Mono-Si contains a higher purity silicone thus resulting in the highest efficiency ranging from 15-20% in comparison to Poly-Si panels' efficiency of 13-16% (Adam & Lehal, 2016). The United States manufacturer of solar panels, SunPower claims producing the most efficient Mono-Si panels with a recorded efficiency of 22.8% (SunPower, 2017). Mono-Si is easily recognizable by an external even coloring 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. 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.

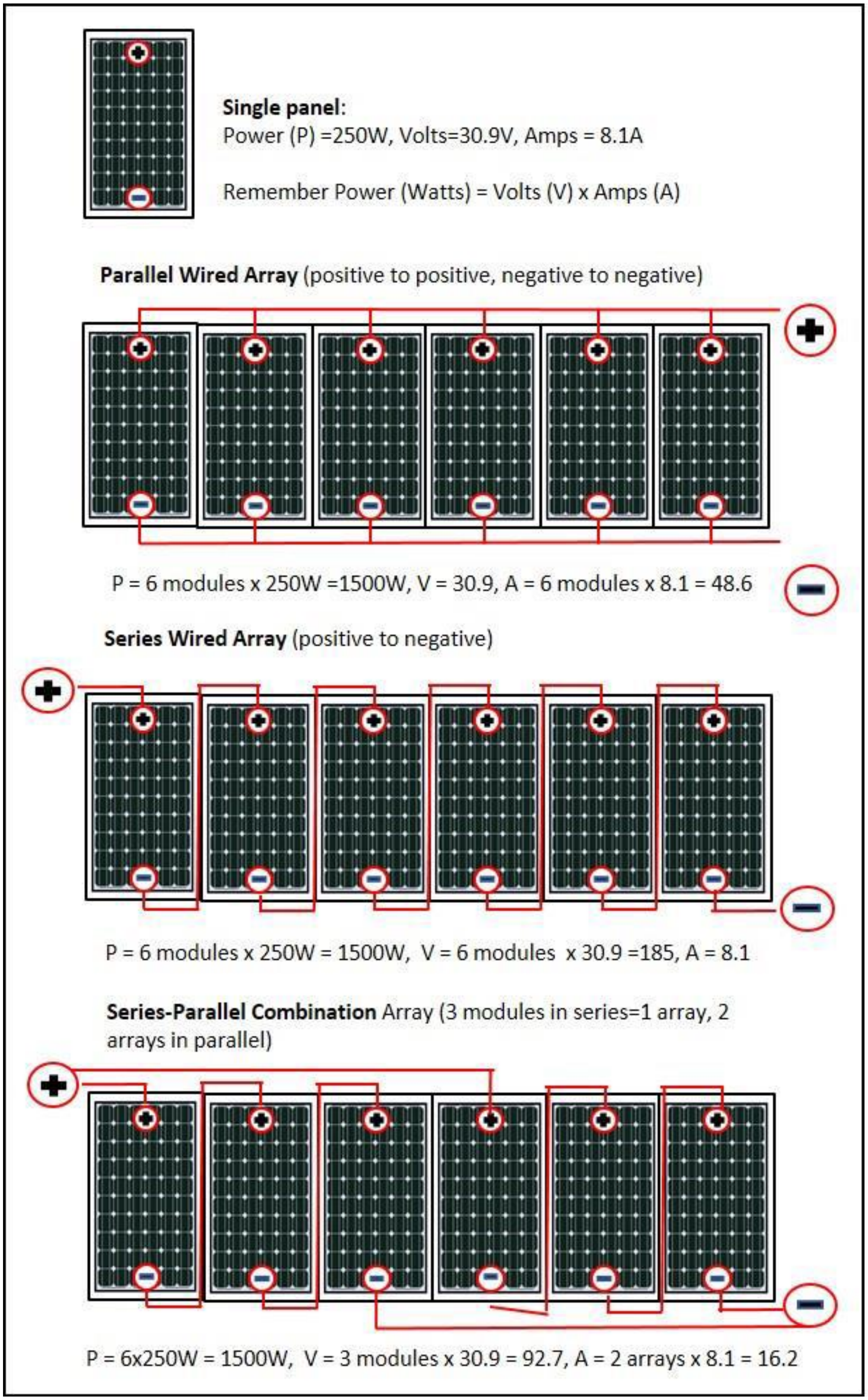


Figure 2.2 Different solar modules configurations

2.2.2 General application of Photovoltaics

The general application of photovoltaic systems can be broadly categorized as stand-alone systems or grid-connected systems. The energy produced by stand-alone systems can either be used directly as it is being produced or stored for later usage often using batteries. The stand-alone systems can also be integrated with another energy source such as diesel generator, fuel cells or wind turbines to create what is known as hybrid systems.

The international solar energy society, German section provides the different photovoltaic system applications in a brief diagrammatic format shown in figure 2.3.

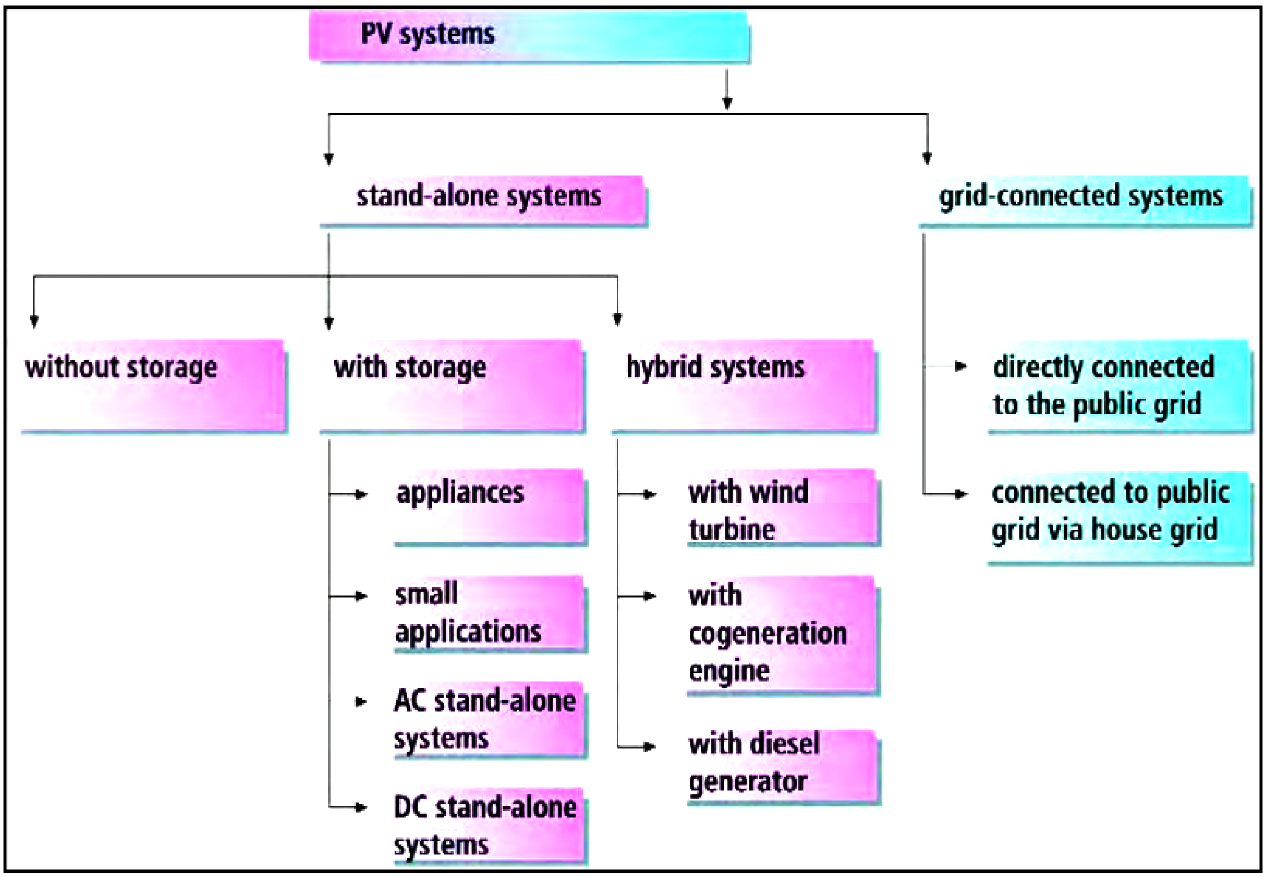


Figure 2.3 Different photovoltaic applications (International solar energy society, 2008)

2.3 Photovoltaics application for water pumping

A typical water pumping system using solar photovoltaic energy is shown in Figure 2.4 and consist of five basic parts:

(i) PV modules

(ii) Controller and/or inverter

(iii) Pump-motor assembly

(iv) Storage tank

(v) Electrical Wiring and piping.

The two common configurations for solar PV water pumping systems are directly coupled and indirectly coupled. The directly coupled configuration supplies electricity generated from the array directly to the pump motor while the indirectly coupled configuration supplied electricity either directly from the array to the motor or from a battery storage bank to the motor (Eker, 2005; Al-Ibrahim, 1997). A directly coupled solar PV water pumping configuration illustrated in Fig. 2.5 is composed of a PV generator (solar array), which converts solar energy into electrical energy, a motor which converts electric energy into a mechanical energy and a pump which converts the mechanical energy into hydraulic energy (Hamza & Taha, 1995). Solar powered water pumps can either be Helical Rotor (positive displacement) pumps which operate efficiently over a wide speed range and can pump water at low solar irradiation levels and as Centrifugal (rotor dynamic) pumps which are suitable for relatively lower heads and higher flow applications (Bossyns, 2013; Merlini, 2012; Argaw, 2001).

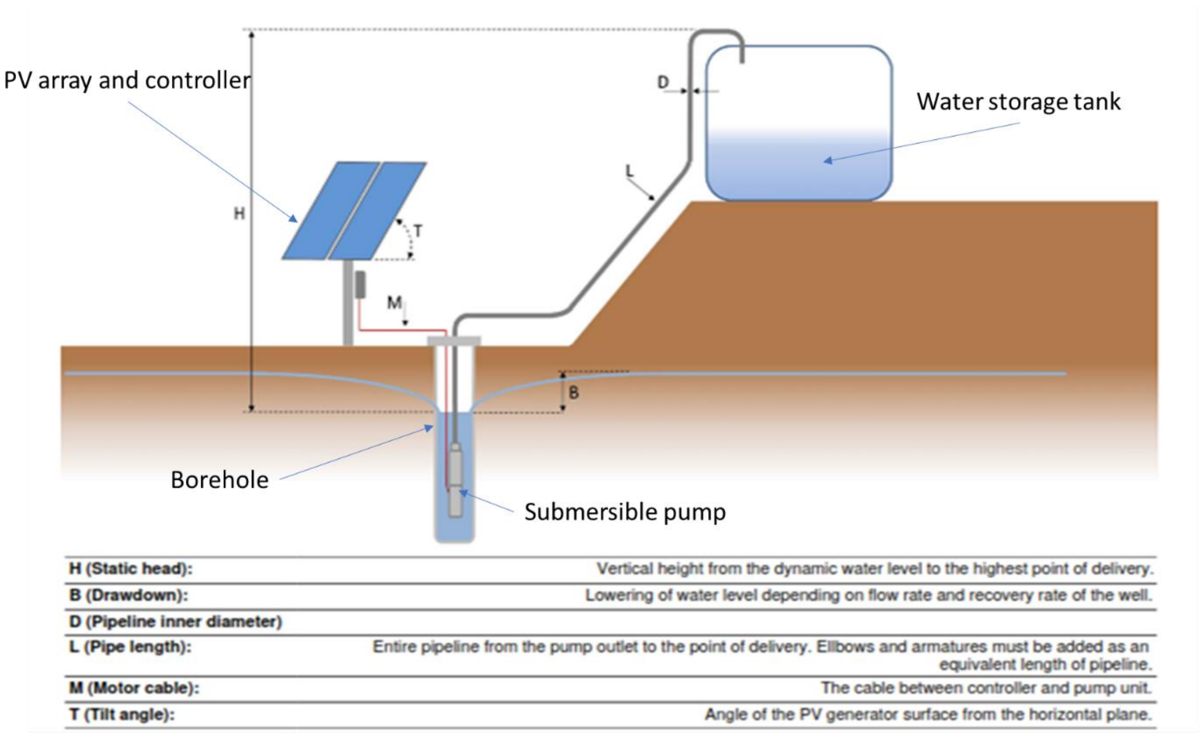


Figure 2.4: Typical layout of <u>directly-coupled</u> solar photovoltaic water pumping system. (Lorentz,2017)

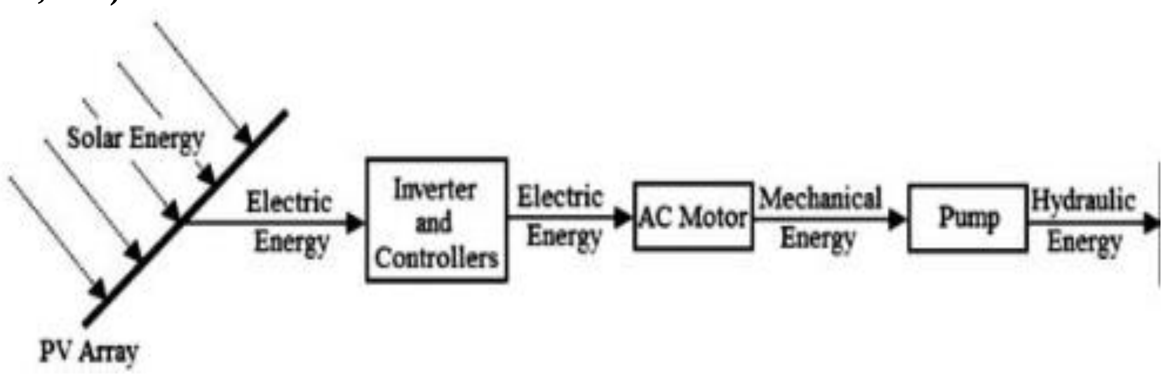


Figure 2.5: System flow of directly coupled photovoltaic pumping system (Hamza & Taha, 1995)

2.4 Theory of solar PV water pumping systems performance

The performances of the solar PV water pumping systems can be explained in terms of mathematical equations 2.1, 2.2, 2.3, 2.4, 2.5 described in Royer, Djiako, Schiller, & Sadasy (1998); Hsiao & Blevins (1984); Meinel & Meinel (1979); Abu-Aligah (2011); and Markvart (2009).

1. P**hotovoltaic (PV) array efficiency** demonstrates how well the solar cells in the array convert solar energy contained in the sun's rays to usable electricity. It is the ratio of the electrical power output of the solar modules and the solar radiation input incident on the total surface area of the modules. This efficiency largely depends on the quality and kind of the material used to manufacture the solar cells.

   The power input on the PV array of area (m^2**)** during sunlight hours is obtained by integrating the solar radiation (W/m^2) over a certain period as obtained in equation 2.1

   $$\boldsymbol{E_{pv}(Wh) = A_{pv} \int_0^t G\, dt} \qquad \textbf{[2.1]}$$

   Where,

   A_{pv} (m^2) is the surface area of the PV array

   G, is the solar radiation received on the array plane (W/m^2)

   t, time period of sunlight

   $$\boldsymbol{PV\ Array\ Efficiency = \frac{Power\ Output\ of\ the\ Array(W)}{Array\ Power\ Input(W)}} \qquad \textbf{[2.2]}$$

2. S**ubsystem efficiency** is the ratio between the hydraulic power, which is the power required to lift a volume of water through a given head by the pump, and the output power generated by the solar array.

   The hydraulic output of the pump is given by;

   $$\boldsymbol{P_p = \rho g Q H} \qquad \textbf{[2.3]}$$

   Where,

   P_p, hydraulic power output of the pump in Wh

   H, the manometric head consisting of static head, friction losses and velocity head in meters (m)

   Q, Output flow rate of the pump in m^3/s

ρ, density of water (1000 kg/m^3)

G, gravitational acceleration (9.81 m/s^2)

$$\boldsymbol{SubSystem\ Efficiency} = \frac{\boldsymbol{Hydraulic\ Power\ output\ of\ the\ pump(Wh)}}{\boldsymbol{Array\ power\ Output(W)}} \qquad \textbf{[2.4]}$$

3. Total **(System) efficiency** indicates how well the overall system converts solar radiation into water delivery at a given head

$$\boldsymbol{System\ Efficiency} = \frac{\boldsymbol{Hydraulic\ power(W)}}{\boldsymbol{Array\ power\ Input}} \qquad \textbf{[2.5]}$$

In design practice, engineers have often selected a slightly larger pump as the actual hours of daily operation maybe less because of operational limitations (McSoley,2012). Chandel et al., (2015) observed that in solar PV water pumping systems, the pumps operate during peak sun hours so most pump designs are of a larger output capacity designed to supply water at maximum during periods of sufficient radiation. The electric power generated by the arrays varies with the solar irradiance received, and the efficiency of the motor is affected by the voltage and current produced by the array, which in turn is reflected in the water output pattern (Jäger et al., (2014); Kalogirou, 2014 and Sørensen, 2015). Kalogirou (2014) and Sørensen (2015) observed that the pump will start to pump when the solar irradiance rises above the system's threshold. The water output rate then increases as the irradiance continues to rise. As the motor-and-pump subsystem approaches its optimal operating point, the efficiency improves so that the water output increases more rapidly than does the irradiance. In the afternoon, when the array heats up, the efficiency of the photovoltaic process reduces, and thus the electric power output is also reduced. Later in the afternoon, as the array cools down, photovoltaic efficiency increases again, but then irradiance is falling off. When solar irradiance drops below the threshold, insufficient electric power is generated for the pumping system to produce water output and the pump stops

Sub-system efficiency determines how the motor-pump assembly converts the variably changing solar irradiance to water output useful to the users. It is the most critical parameter because it determines the size of array required for a desired water output, and the array is by far the largest cost item of photovoltaic pumping systems accounting for between 30-40% of the initial capital costs (Intermediate Technology Development Group, n.d).

The pump motor requires a certain power to overcome the starting torque. Most centrifugal pumps have low starting torque hence will readily start to rotate slowly even at low irradiance but at that point there is no water output until irradiance increases to a level of power sufficient to develop rotational speed required to pump water out. Modern manufactures of solar pumping systems incorporate an extra power conditioning device known as Maximum Power Point Tracker (MPPT) which essentially controls the release of power to the motor so that the power produced at low irradiance levels can be maximized to obtain the threshold power required to start the pump (Elgendy et al.,2010); Kalasathya & Khanna,2016); Aashoor,2015). The use of these additional powers conditioning equipment such as MPPT implies a power loss, typically 5%, additional costs and an additional potential failure mode (Makhomo, 2005). Hence to justify their use the increased costs must be compensated for by the extra volume of water output.

To optimize PV systems given the variability of irradiance throughout the day, Qing et al.,(2007) investigated the principle of PV pumping systems with double pumps. The study involved employment of the smaller pump to pump water in the morning and dusk and employ the larger pump when solar irradiation is powerful to improve efficiency thereby pumping more water out of the borehole. Using a similar concept, results by Mahmoud et al., (2013) showed an annual gain of 7.4% in water pumped using a programable control system. Obviously, these double pump systems even though pumps out more water have higher capital cost implications at a time when considerable efforts are being made to design an optimized system with the lowest possible capital costs.

2.5 Solar conversion efficiency and water pumping efficiency parameters

Best efficiency point is defined as the operating point of centrifugal pumps at which its efficiency is highest (Merkle, 2014; Forsthoffer, 2011). To reduce the need for frequent maintenance as well as minimize energy costs, it is necessary to operate water pumps at or near their best efficiency points (Kiplagat, 2012). Both Budris (2008), Inter-American Development Bank (2011) and Cardoso et al., (2017) concluded that to optimize a water pumping system, there is need to correctly select and match the pump to the load. Pump efficiency in a solar powered water pumping system can also be termed as the Subsystem efficiency which has been defined under section 2.4 as the ratio between the power required to lift a volume of water through a given head by the pump, and the input power received by the pump from the solar array generating electrical energy. Elrefai et al., (2016) carried out experiment and concluded that use of load matching devices such as maximum PowerPoint tracking can aid matching of solar PV array conversion efficiency with the water pumping efficiency.

2.6 Performance evaluation of solar photovoltaic pumping systems

2.6.1 Models of performance evaluation for solar pumping systems

At a basic level, the indicator of technical performance for any pump whether solar energy or fossil fuel energy powered is how much water it can deliver at a given total pumping head. For solar PV water pumping systems, the energy input to drive the pump element, solar irradiation, varies considerably over time in daily as well as monthly terms and is greatly season dependent. Argaw et al., (2003) carried out various sensitivity analyses and demonstrated that a slight change in solar irradiance changes the unit cost and the amount of water production. Thus, to accurately describe the technical performance of the system, it is imperative to measure the time-dependent energy input and corresponding water output. The concept of efficiency has been extensively used an indicator to describe pump performance (McGowan & Hodgkin, 1986). They defined efficiency as the measure of the losses involved in converting one type of energy to another. System efficiencies are normally normalized to array area thus allowing easy comparison of PV systems of different configurations and at different locations. Overall or system efficiency is often used to summarize how efficient the system under observation is. It is determined as the ratio of the useful hydraulic power which is a product of the pump flow rate and pumping head to the electrical power absorbed by the PV array generator. McGowan & Hodgkin (1986) stated that since all the different types of pumps have different definitions of efficiency, it is not particularly useful to compare efficiencies across the range of pumps. However, within a group of the same types of pumps, a higher efficiency implies lower unit cost at a given head.

Since PV water pumping systems consist of different components working together. Each component that makes the entire pumping system has intrinsic characteristics that affect the overall operating conditions. Two distinct sub-systems are identifiable; The PV array generator sub-system whose efficiency is defined by the PV array conversion efficiency and the motor-pump sub-system characterized by the motor-pump sub-system efficiency. The PV array efficiency, which is dependent on the solar cell materials, is determined as the ratio of the electrical energy output by the PV array to the solar energy incident on the array plane. Of the three types of solar cell materials in the market, Monocrystalline cells have the highest PV conversion efficiency and are the most expensive compared to polycrystalline cells and thin film cells with much lower efficiencies of 6-8%. According to Vick & Clark (2009) polycrystalline cells are mostly used for PV water pumping because 85% of the PV modules produced in the world are polycrystalline thus it is easier to find replacement modules, they obviously have the highest efficiency, they have longer lifetime of between 20-30 years and they have a slight decline in power output with time (about 1% per year) compared to Monocrystalline and thin film cells which experiences decreases of as high as 20% per year.

Sub-system efficiency or hydraulic efficiency is determined as the ratio of water volume pumped at a given head to the electrical energy input into the pump. The internal matching of these two systems is of critical design importance since it determines the best overall efficiency that can be obtained from the system in entirety. The best system optimization is obtained by modeling the individual components and then combining them into a single system.

Argaw, Foster, & Ellis (2003) defined the concept of Load Matching Factor as another important indicator to evaluate the technical performance of PV pumping systems. The Load Matching factor is the ratio of energy acquired by the hydraulic load to the maximum power extracted from the solar generator within a one day period. Koner (1995) concluded that the Load matching factor should be close to one for a well-matched PV pumping system. He defined the Load Matching factor obtainable from the solar radiation curve using equation 4.1.

$$\boldsymbol{Load\ Matching\ Factor} = \frac{\sum^{N}(\boldsymbol{G_r - G_c})}{\sum^{N}\boldsymbol{G_r}} \qquad \textbf{4.1}$$

Where N is the daily hour readings, G_C is the critical radiation threshold defined as the minimum radiation level required to start pumping and G_t as the solar radiation received on the PV array plane.

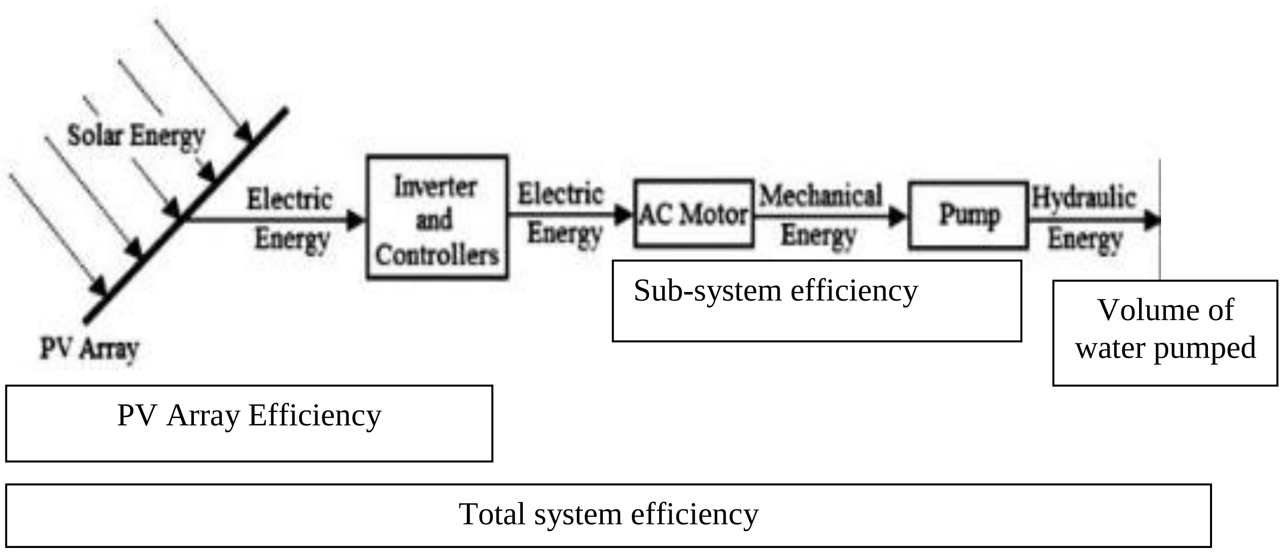


Figure 2.6: Technical performance indicators of solar PV water pumping systems

2.6.2 Data acquisition models for evaluating performance of solar pumping systems.

Data acquisition systems, both remote and on-site have been applied by different authors to collect data on installed solar PV-driven water pumping systems with the objective of investigating the system performance. Benghanem & Hadj Arab (2007) developed a micro-system data acquisition system structured around a microprocessor. The system composed of an analogue part acquiring meteorological parameters such as ambient temperature, daily solar irradiation received on PV array as well as the PV system parameters such as flow rate and total heat. It also had a numerical part transferred the data using an analogue to digital converter and transferred the data to personal computer using a bi-directional serial port. The data downloaded from the personal computer were then used to calculate performance parameters and loss of load probability of the system. Makhomo (2005) applied a remotely monitored datalogger called DATATAKER 605 collecting data from scanning sensors taking instantaneous measurements from a field operating solar PV water pumping system. Hadi (2003) applied external sensors, interface-card and transducers connected via a personal computer when evaluating the performance of a solar PV water pumping system set on a laboratory test bench. The data acquisition system collected parameters such as sun irradiation, system voltage and current output, flow rate and watt power of the inverter then calculated power output of the PV generator, water volume pumped, system and sub-system efficiency from the collected data. He displayed the measured and calculated data in graphical descriptions. Hegazi et al., (2010) connected separate components such as pyranometer LI-200 measuring solar irradiation, digital infra-red thermometer to measure cell temperature, voltage divider to measure PV array output voltage, current transducer for PV output current and a flow transducer to measure water flow rate to acquire data from a solar PV water pumping system. Mahjoubi et al., (2011) developed a GSM network based datalogger acquisition system connected to a test bench experimental set-up to collect data on solar PV parameters such as flow rate, global irradiation, cell temperature and PV array current and voltage output. The collected data was retrieved as short messages sent to a GSM phone as well as downloaded from GSM data bundles for analysis.

2.6.3 Successful applications of solar pumping systems performance evaluation.

Several studies have been conducted to evaluate both the technical performance and economic viability of photovoltaic pumping systems for water supply purposes, both for domestic and irrigation water. Makhomo (2005) monitored the field performance of a photovoltaic water pumping system over a period of two months in South Africa and achieved results showing a PV array conversion efficiency of 3.0%, a system efficiency of 32.0% and an overall system efficiency of 1.3%. Yatim et al., (1988) analyzed the performance of a 1.2 kW peak PV water pumping system which had been operating over a period of 3 years. Their analysis showed that the system performance does not deteriorate over this period. The system attained an overall 3.2% and the mean efficiency over the period was 1.9%. They also concluded that an increase in the temperature of the PV modules due to solar heating lowers the PV conversion efficiency at the rate of 0.06% per °C. In a similar study, Baskar, Annadurai et al., (2013) examined the performance of a 936 W photovoltaic water pumping system with water spray over the photovoltaic cells. The study found that spraying water over the cells increases the mean PV cell efficiency. He obtained PV array efficiency, subsystem efficiency and total efficiency of 3.26%, 1.40% and 1.35%, respectively, at 16 m total pumping head.

Daud & Mahmoud (2005) carried out long-term field testing of a photovoltaic-powered water pumping system employing an induction motor pump, capable of supplying a daily average of 50 m^3 at 37-m head. They obtained results showing that it is reliable and has an overall efficiency exceeding 3%. The system also obtained a PV efficiency of 8.93% and sub-system efficiency of 36.94%. Nwobi et al., (2014) concluded that even though solar-powered system has a higher initial cost of over 250% when compared to generator-powered system, it’s life-cycle benefits overshadows that initial cost and making it a more cost-efficient alternative to generator-powered systems. Mahmoud (1990) and Odeh et al., (2006) produced conflicting results on solar PV pumping systems performance. While Mahmoud (1990) concluded that up to a hydraulic energy equivalent of 6000 m^4/day, the cost of water pumped by PV is less than that for diesel system, Odeh et al., (2006) conclusions was that the competitiveness of PV pumping increased to 8000 m^4/day in comparison to diesel systems.

A study by Schumann & Amusha solar Namibia (2006) indicated that the cost of water increases more significantly with increasing head in the case of photovoltaic pumping systems compared to diesel pumps, which are relatively insensitive to head, it also concluded that the Unit water costs of photovoltaic systems at flow rates above 8m^3/day are similar at the same pumping head and range from around USD 0.13/m^3 for a 20m pumping head to USD 0.43/m^3 for an 80 m head system (Schumann & Amusha solar Namibia, 2006). Setiawan *et al.* (2015) carried out an economical comparison between Photovoltaic and diesel generator pumping systems using lifecycle cost calculation and HOMER simulation. Their analysis showed that the cost of energy value for photovoltaic usage is 0.312 $/kWh, and cost of energy value for diesel generator is 0.390 $/kWh. Zegeye et. Al., (2014) found the cost of water from a PV pumping system as 0.02$/$m^3$ and for that of diesel generator as 0.07$/$m^3$ in Ethiopia. They also concluded that the breakeven point between PV water pumping system and diesel pumping system is found to be less than four years using life cycle cost comparison. Farag et al., (2008) in evaluating the hydraulic performance of photovoltaic solar pumping system suitable for remote regions in Egypt had results showing that diesel engines system had the lowest value for unit water cost using life cycle cost analysis. Their results showed the water unit cost for pump operated by photovoltaic system is higher at 0.1$/$m^3$ and 0.03$/$m^3$ for diesel power systems respectively. They attributed this fact to a higher capital cost for solar photovoltaic pumping system and thus concluded that improving the solar photovoltaic system must focus on minimizing the unit water cost to use it in large scale.

2.7 Status of solar PV water pumping application in Kenya

The Solar and Wind Energy Resource Assessment (SWERA) project undertook a comprehensive study on the country-wide availability of wind and solar energy concluding that across Kenya, the total area capable of delivering direct nominal irradiance of 6 k Wh/m^2 per day is about 106,000 km^2 whose potential is 638,790 TWh (Theuri, 2008). A major solar market segment assessment carried out by Kenya Climate Innovation Centre (2016) reported that the Kenyan solar market is dominated by seven main applications; small Pico and solar charging systems, micro solar home systems such as Total D-light solar kits, solar home systems, stand-alone institutional PV systems mostly installed by the Rural Electrification Authority electrification programs to schools and hospitals, mini-grids ranging between 5kW to 1MW,telecomunications masts power source and grid connected systems driven by independent power producers. Most large-scale application of solar energy for water pumping in Kenya has been pioneered by NGOs since 2012 majorly for refugee camps in northern Kenya (Llario & Ndegwa, 2017). However, limited studies exist on the performance of large scale solar powered water pumping in Kenya. Kraehenbuehl et. Al., (2015) investigated the implementation of purely solar powered water pumping systems and hybrid systems consisting of diesel powered generators as well as solar photovoltaic in refugee camps in northern Kenya and South Sudan. Their study which was only limited to monitoring data on water production for both solar and diesel pumping system and fuel consumption for diesel generator sets showed fluctuations in water production caused by varying intensity of solar irradiation and showed the need for sufficient storage. Runo & Muema (2014) investigated high capacity solar powered water supply systems installed in South Central

Somalia and Daadab Refugee camps and concluded that $301,125 annual savings in water cost could be achieved if the borehole in Hagadera refugee camp was produced using solar photovoltaic system. This lack of documented performance experience on this technology proves further that such systems are still new to the market in Kenya and more studies are needed to encourage its widespread application.

2.8 Conclusion

The literature review indicates that even though the application of solar photovoltaic for high capacity water pumping has been introduced much earlier and much developed in other parts of the world; it remains a relatively new technology in Kenya. Having seen the evidence of its success in other parts of the world, PV application for water pumping is increasingly being applied piloted by donor funded NGOs especially in Northern Kenya areas such as Wajir to replace diesel pumping sets. There have not been a much studies done in Kenya to evaluate the technical performance of complete systems even though a few reports have been published for economic analysis mainly in comparison to diesel generator pumping sets. It is evident that limited field level performance evaluation of solar PV water pumping systems has been conducted in Kenya. This has led to a situation where design and purchase decisions are based on inadequate data thereby reducing the chances of well sized and cost effective pumping systems.

CHAPTER 3: MATERIALS AND METHODS

3.1 Study area

Abakore is a small village to the south of Wajir County located at latitude 0°37'41.98''N and longitude 39°42'26.47''E. The center has a population of approximately 500 households (3,000 people). Figure 3.1 shows the location of the study area.

Figure 3.1: Study area: Location of Wajir study area

The water supply system installed at Abakore comprises of a 6” diameter, 150-meter-deep borehole equipped with a 3-phase submersible centrifugal pump powered by an 18.7 kW directly coupled solar photovoltaic system. There is also a 30 KVA Lister Peter diesel engine water pump used as a back-up to the PV system in the event of PV pump failure or during extended hours after sunset. The water is stored in a 50,000 liters capacity masonry tank from where it is then distributed to livestock watering troughs and community public water points and institutions. The PV water pumping system at Abakore comprises three subsystems namely, a set of photovoltaic panels, a pump controller with an inbuilt DC to AC inverter and MPPT and a three-phase centrifugal pump.

Figure 3.2: Solar water pumping system installed at Abakore

3.2 Objective 1: Establish from literature, the parameters to be monitored to enable performance evaluation of solar photovoltaic water pumping systems.

To understand the performance of solar PV water pumping systems, a set of consistent and well defined performance indicators should be established. Global literature was analyzed focusing on electronic databases, relevant website and grey literature, textbooks, published and unpublished research papers with the objective of establishing pertinent system performance indicators.

3.3 Objective 2: Investigate the performance of an 18.72 kW photovoltaic water pumping system installed at Abakore borehole water supply system in Wajir, Kenya.

3.3.1 Study set-up

The experimental set-up consisted of a 150-meter-deep borehole installed and operational with directly coupled PV water pumping system comprised of;

1. Photovoltaic (PV) generator Array- 96 number 195 W_p Yingly JS 195 solar panels arranged in parallel columns of 24 modules connected in 4 series totaling to 18.72 kW

2. Motor-Pump assembly- a 3 phase submersible centrifugal pump, LORENTZ PS15k2 C-SJ17-18 pumping with a design Total Dynamic Head of 100m.

3. Water storage tank-one 50 m^3 masonry constructed tank.

The PV characteristics and pump specifications as given by the manufacturer's specifications are in Table 3.1

Table 3.1: Description of pumping system components

Solar panels	
Open circuit voltage, (Volts, V)	45.4
Voltage at MPP(V_{mpp}(V)	36.7
Short-circuit current, (Amperes, A)	5.65
Current at MPP(I_{mpp}(A)	5.32
Dimensions (Length, L/Width, W/Height, H)	1310 mm/990 mm/40 mm
Module efficiency (%)	14.7
Pump controller	Lorentz PS15K2 with integrated MPPT
Inverter power-input	15 kW
Pump-motor pump, kilowatts (kW)	11
Maximum power point voltage	850
Maximum Pump-motor current, A	24
Inverter/controller efficiency (%)	98
Maximum pumping head, meters(m)	140
Maximum pump flow rate (meters cube per hour,m^3/h)	25

3.3.2 Data Acquisition

The key limitation of data acquisition systems described under section 2.7.2 used to evaluate the performance of solar PV water pumping systems is that they require physical presence at the system throughout to connect various equipment to the solar PV water pumping system installed and download to a personal computer for further analysis. This characteristic makes it more suitable to collect laboratory set-up experiment as compared to a field-based installed system. To overcome this challenge, this study acquired a remote data collection in-built within the pump controller panel of the solar water pumping system at a cost of Ksh. 76,253 in January 2017 from LORENTZ, a German solar water pumping equipments manufacturer. The data logger called PS Data module is in-built on the pump controller to collect real-time system performance parameters such as PV array output voltage and current, input and output power, operating time and water flow rate. The data collected by the datalogger can either be retrieved using a specially developed application via Bluetooth within 10 meters of the installation or accessed remotely on a web-based platform called Pump Manager developed by the company. This system was selected for use in this study given its remote access capability and less physical interface with the installation.

Using this data logger and retrieval mechanisms, Performance of the system was monitored for 60 days continually from January 15th 2017 just after the system was newly installed. The 60-day period was chosen since that was the time available for the researcher to collect the field data. The operating hours of the system were limited to 12 hours per day. The following data relevant to operational parameters of solar PV water pumping installations were recorded every 30 minutes daily during the operating hours (1) Array in-plane Solar irradiation (W/m^2) ;(2) Water discharge rate, m^3/hr.;(3) Pump input voltage (V) and (4) Pump input current (A). The pumping system was designed to operate at a fixed Total Dynamic Head of 100m.

3.4 Data and Statistical Analysis

The field collected data was analyzed using descriptive statistical tools and the results presented graphically. The statistical analysis conducted included: Regression statistics to identify relationships between array in-plane solar irradiation, pump input voltage, pump input current and water discharge rate.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Performance evaluation of Abakore borehole photovoltaic water pumping system

The collected data from Abakore installation have been analyzed to evaluate the performance of the directly-coupled solar PV water pumping system. Figure 4.2 shows the observed solar irradiance in the plane of the PV array (W/m^2) and the power output of the PV array (kW). It was observed that the system generated a maximum power output of 11.72 kW from the panels against a solar irradiance input of 778.06 W/m^2 at about mid-day. Figures 4.3 shows that the pump discharge rate increased gradually as solar irradiance increased peaking at about 25 m^3/hr below falling as the strength of solar insolation reduced. The Pearson coefficient of correlation between solar irradiance and water flow rate was 0.925, and the significant difference by statistical significant test was meaningful with 1% of levels of significance. Figure 4.4 shows the diurnal variation in pump output.

The input variable measured was solar irradiance incident on the array plane. Figure 4.1 shows the variation of the incident solar irradiance monitored from morning until evening for a period of 60 days at Abakore.

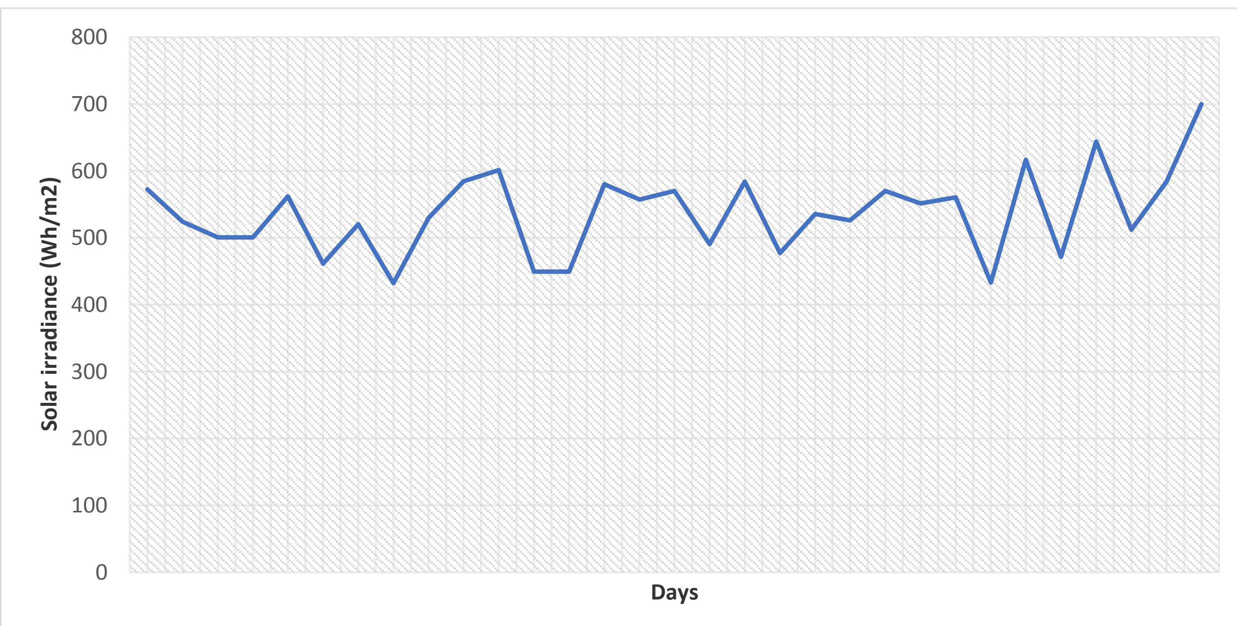


Figure 4.1: Diurnal variation of the solar irradiance incident on array plane.

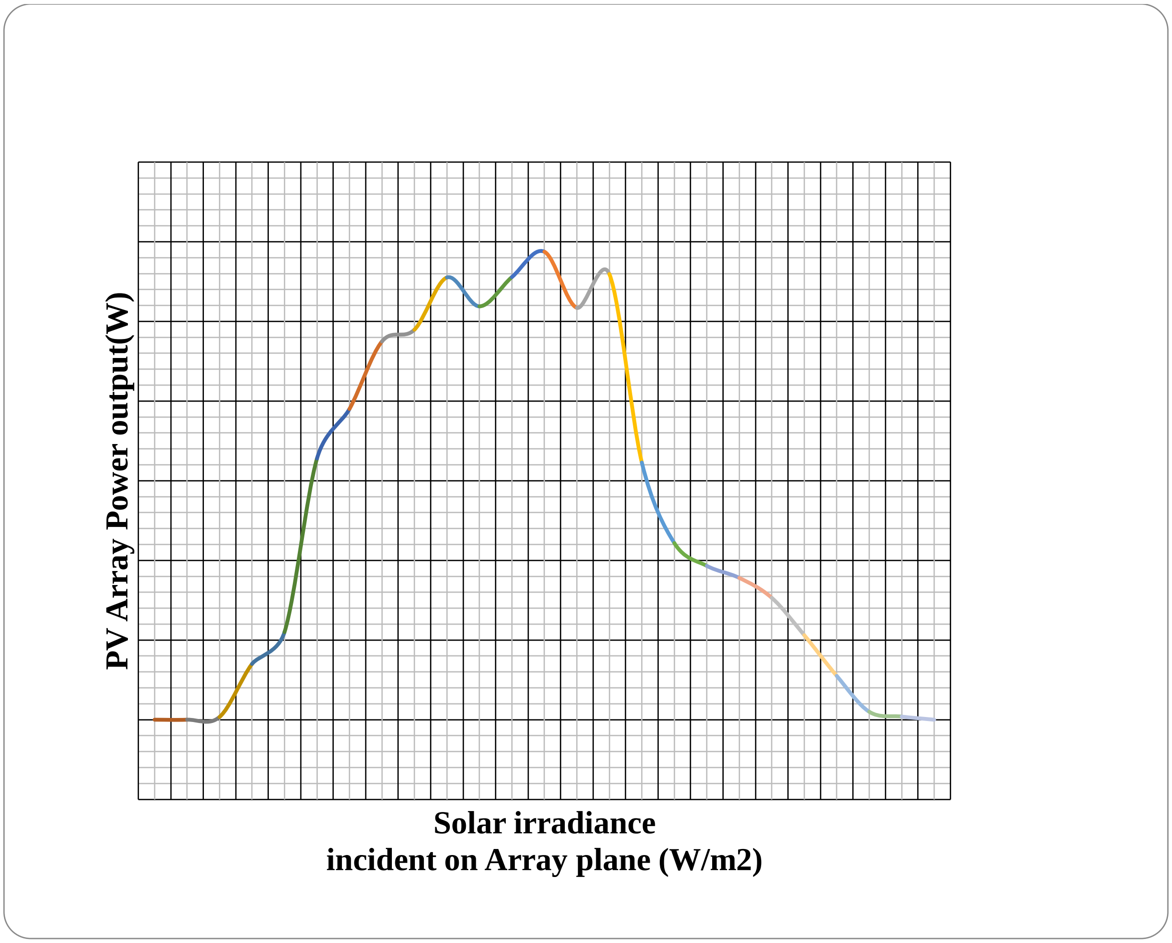


Figure 4.2: Variation of PV power output and the incident solar irradiance received on PV array plane

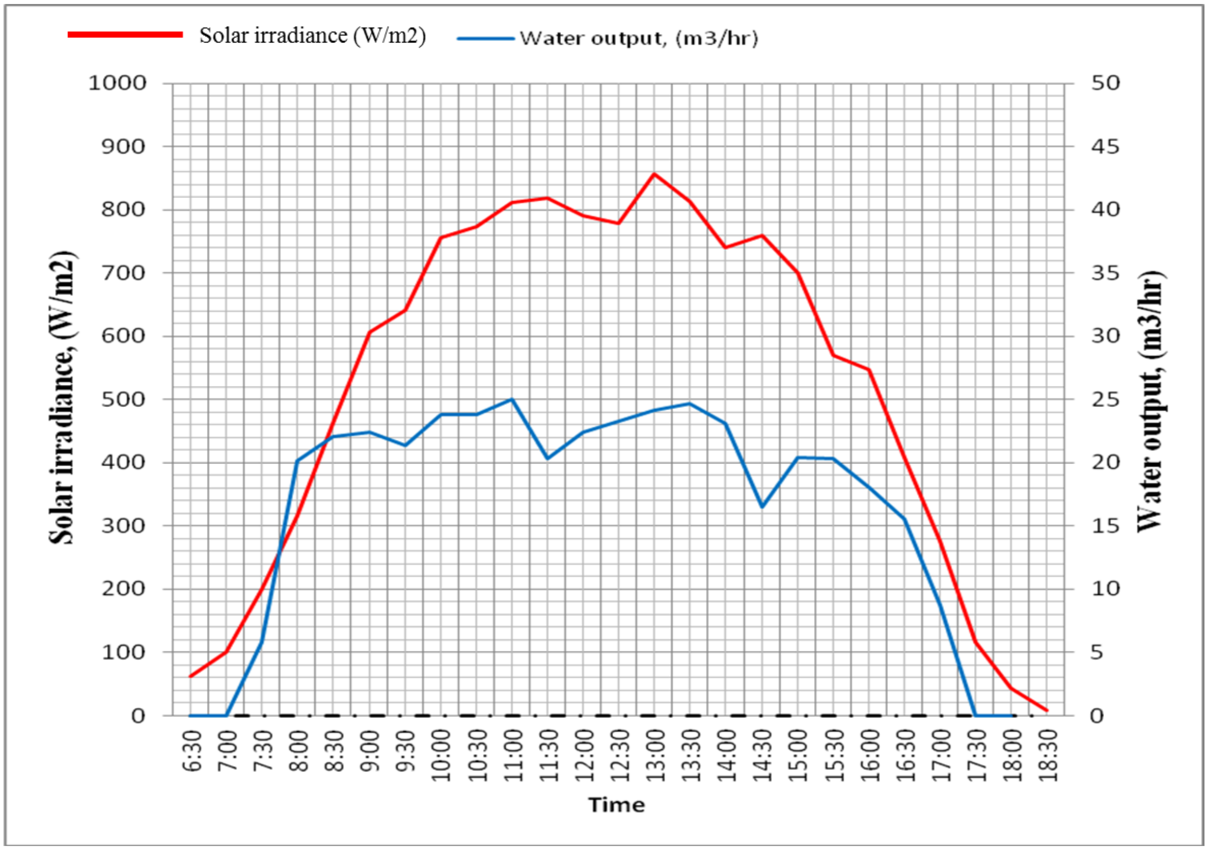


Figure 4.3: Relation between incident solar irradiance and water output

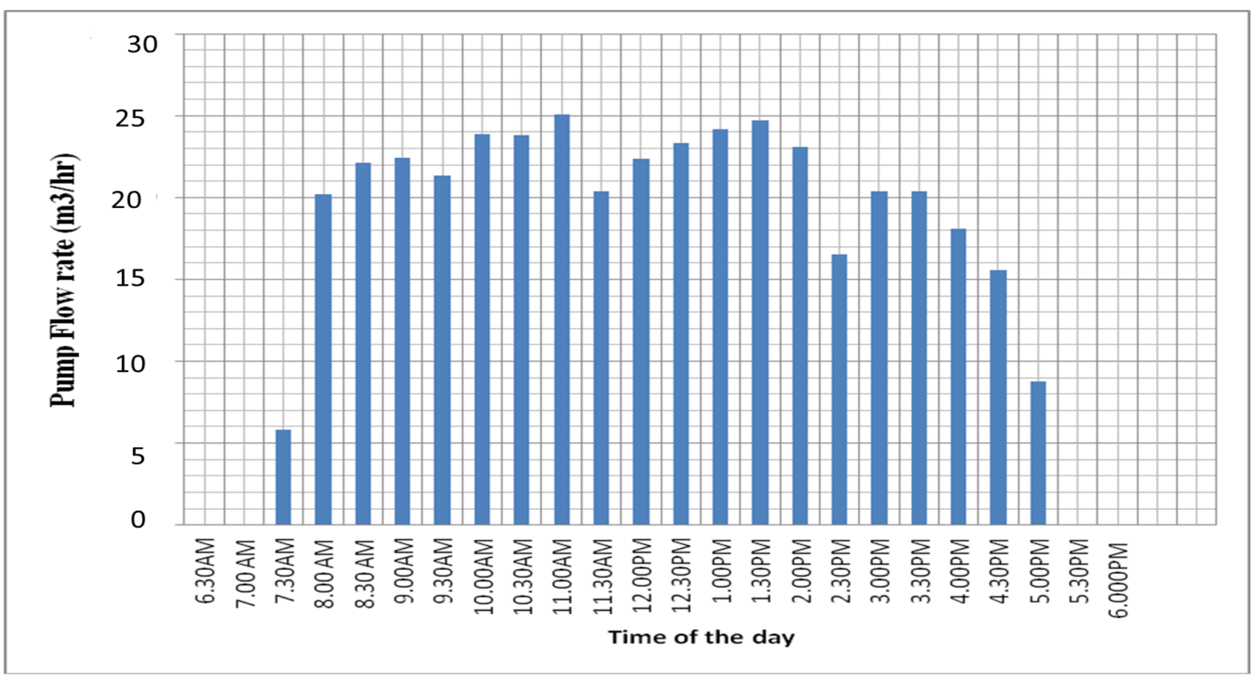


Figure 4.4: Diurnal variation of flow rate of the pumping system.

The results indicate an average of discharge of 156m^3/day. Figure 457 shows the relationship between nominal power output of the PV Array, the PV array actual power output at field conditions and the hydraulic power generated by the pump. The nominal power is determined as the irradiation received on the array plane multiplied by the standard test conditions efficiency provided by the manufacturer as 14.7%. It is the ideal power the PV array generator should generate as determined by the manufacturer at those standard test conditions. The results showed that the power generated by the PV array is below the ideal power at Standard Test Conditions. Figures 4.6 shows a comparison of the array, sub-system and overall system efficiencies obtained.

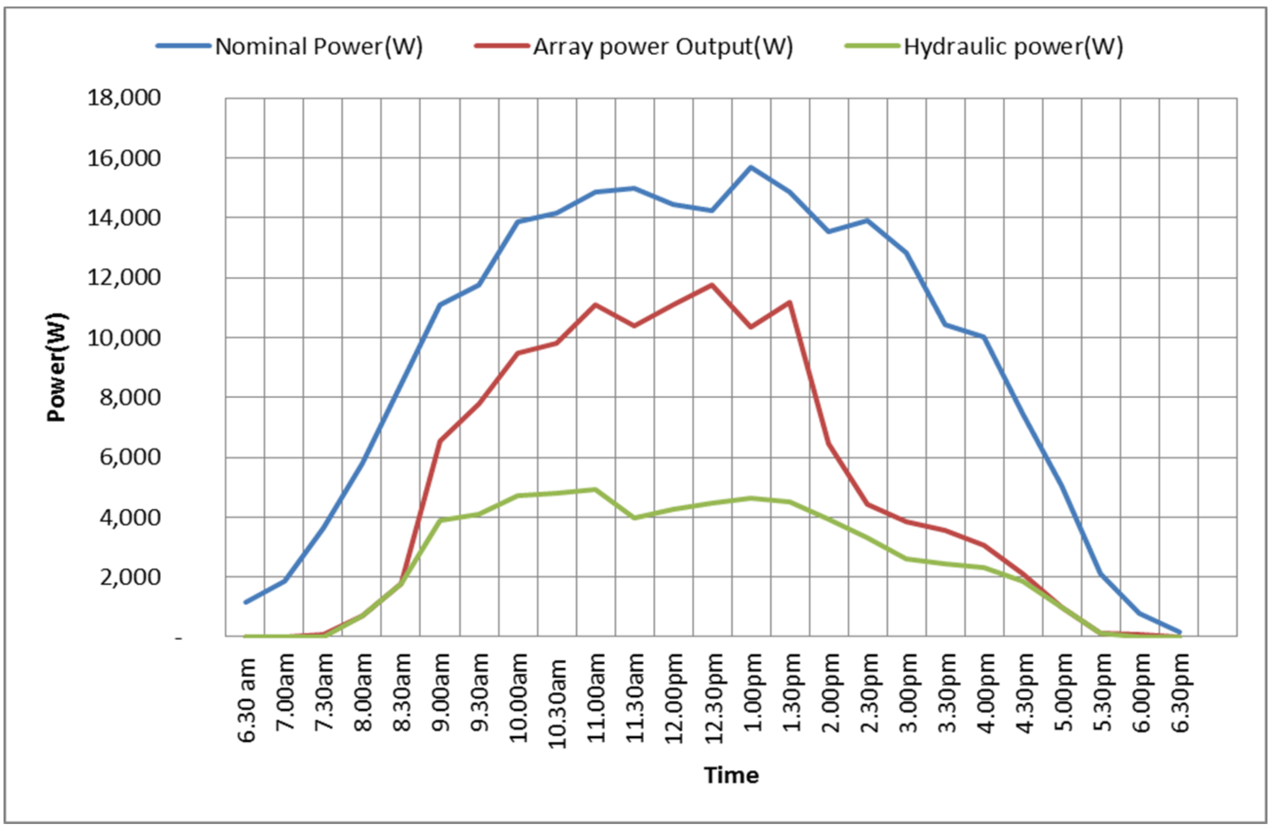


Figure 4.5: Relationship Nominal Power, PV Array Output Power, and the Hydraulic Power generated by the pump

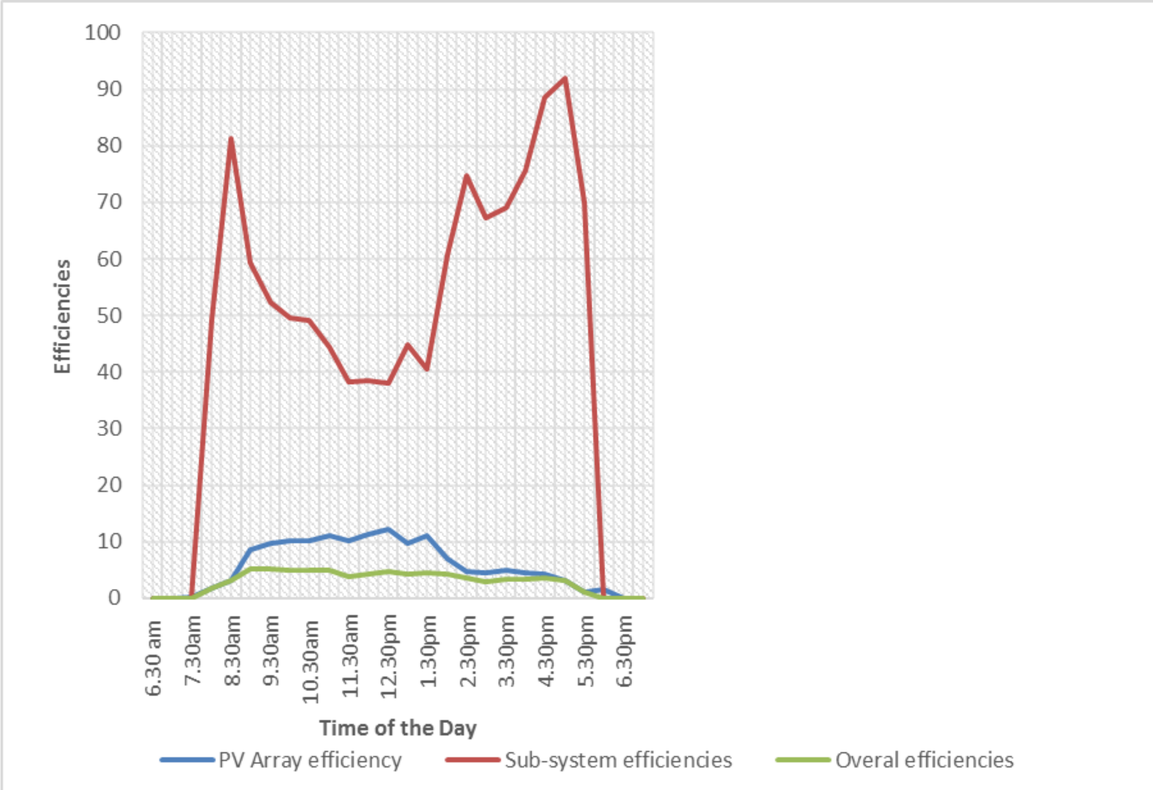


Figure 4.6: Comparison of Array, sub-system and overall system efficiencies

The system obtained a highest PV array conversion efficiency of 12.1%. This is slightly less than the manufacturer provided efficiency of Yingly J195 solar modules of 14.7%. This array efficiency compares well with reported achievable efficiency of monocrystalline solar panels cited elsewhere to range about 9 % - 15.1 % operating under variable field conditions (Makrides et al., 2012; Topi et al., 2006). This slightly lower efficiency observed at Abakore can be attributed to variations in cell temperature from the standard test conditions. This study did not analysis the effects of temperature variation on PV output but other researchers have shown that the efficiency decreases with increasing temperature (Dubey, Sarvaiya, & Seshadri, 2013). Other parameters that led to this lower efficiency include changes in the quantity of solar irradiance received on the array plane and incidence angle which varied through the day. Losses in wirings of PV modules into PV arrays and inverter losses are also attributable to the lower PV conversion efficiency.

The Sub-system efficiency and overall system efficiency exhibited a three-phase changing pattern throughout the day as shown in figure 8. Phase 1 occurs between 6 am to 9 am, phase 2 from 9 am to 4.30 pm, and phase 3 from 4.30 pm to 6:3 pm. During phase 1, the sub-system and overall system efficiency starts from zero and increases to a relatively high value, the efficiency remains relatively constant during phase 2 varying from a range of 5.14% to 3.7% for the overall system efficiency. The subsystem efficiency attains the highest value of 81.36% during phase 1 in the early morning and 91.82% at the end of phase 2 in the late hours of the day. This can be attributed to the fact that as the flow rate increases at higher irradiation conditions; the efficiency goes down due to the decrease in the pump efficiency. Even though the efficiencies of inverter and motor normally increase by higher flow rates (higher frequencies) this cannot compensate the decrease of the pump efficiency. These findings are similar to those reported by Hossain, Hassan, Mottalib, & Ahmmed (2015) who observed that the discharge increased with increase of solar radiation peaking in the noon and then decreased gradually as solar radiation decreased. The most important consideration in system design is the match between the motor-pump sub-system and the PV array. The sub-system efficiency is an indicator of the match between the motor-pump sub-system and the PV array. It's obtained as the ration between hydraulic power and the electrical power of the sub-system. The range of 49% to 91% sub-system efficiencies obtained at Abakore shows a good match between the motor-pump and the PV array. The optimum Load matching factor for the Abakore PV water pumping system was obtained as an average of 0.66. This value was obtained from the radiation threshold of $200W/m^2$ and from the daily average, hourly solar irradiance curve. This value is comparatively average and compares well to Koner's (1995) recommendation of 1.0 and Argaw (1995) who reported that a best load matching factor of 0.72 and at least 0.55 can be achieved. These results demonstrated that the system components of the Abakore system were averagely well matched and adequately configured.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This chapter draws conclusions to the study. It presents significance of the current study and its usefulness as a research work. In addition to that, it presents the key findings and contributions to this particular area of research and offer suggestions for possible future area of research.

From the results and discussion of the evaluation of the system under Abakore field conditions, useful conclusions can be drawn as follows:

5.1.1 Performance evaluation of Abakore borehole photovoltaic water supply system

1) The significance of this study lies in its objective of presenting performance results of system operating under real variable field conditions and not in a controlled laboratory environment. While the pump manufacture's data are quite useful for design estimation, they are often typically generated under ideal operating laboratory environments. Analysis performance of system operating in real variable environmental and climatic conditions is crucial in optimum sizing and design of the system thereby contributing to savings on huge investment capitals often associated with solar PV water pumping.

2) The 18 kW Abakore solar water pumping installation delivering a high average output of 25 m^3/hr at a pumping head of 100m. This presents a positive comparison with the 1980s when solar PV systems were considered not viable option for heads greater than 50 meters and water demands of 20 m^3/day.

3) With reference to the solar pumping system installed at Abakore, the average efficiency of the PV array generator was lower than manufacturer's specifications at standard test conditions. This can be attributed to significant high solar radiation intensities received on array plane that caused an increase in the temperature of the solar cells thus lowering the PV conversion efficiency in addition to dust accumulation on array plane. However, the array efficiency and overall system efficiency obtained compares well with most previous studies conducted and is within acceptable and expected ranges.

4) The power generated by the PV array was below the nominal power, which is the ideal power the PV array generator should generate as determined by the manufacturer at standard test conditions. This can be attributed to a deviation under real filed operation at from the Standard Test Conditions which the manufacturer used to determine the nominal power.

5) The overall system efficiency obtained for the Abakore installation was 5.14%. This shows a good result in comparison to current practice where PV-pumping system efficiency has considerably improved from 1-3 % in 1980s to 3.5-5% in 2015.

6) While the installed capacity was 18.72 kW and the maximum power generated by the PV array at prevailing climatic conditions was 11.1 kW, the maximum discharged obtained was 25.05 m^3/hr at a power input of 9 kW which is half of the installed capacity and almost at the prevailing climatic conditions power output. This demonstrates that while improvements in photovoltaic module manufacturing techniques are continuously researched, there remains a clear need for development towards both improved reliability, efficiency values and components matching of solar pumping sub-systems in order to extract the maximum power capability of the solar generator at all times.

5.2 Recommendations

The recommendations are aimed at improving the up-take and adoption of solar PV water pumping systems for larger duties up of 2,000m^4/day in addition to specifying how differently this study should be conducted in the future. Based on the findings of this study, it is suggested that the following considerations be duly considered in further research on solar PV water pumping systems applications.

1. This study collected performance data for only 60-days period. To provide longer term performance and sufficient time to identify and correct all potential defects in the system, a longer period of data collection ranging from 2 to 3 years, in a single location is recommended. This will provide key performance variations for different seasons of the year and how that can affect the system output.

2. Further in-depth analysis on the cost justification for using power storage batteries in the system rather than having it directly coupled. When the solar generator produce more than the maximum power required by the load, the excess energy would recharge the batteries so that when power from the PV panels falls as the day progresses, the power from the batteries can top up the input and keep the pumping going at an efficient rate until late in the evening. Finally, as the batteries deplete, the dying rays of the evening can be used to start to recharge the batteries, completing the charge the following morning when the rays are just coming up. Certainly, this will pump more water than not using any batteries, since the design captures unused energy, and when both designs would be pumping the battery one will be pumping at higher flow rates and higher efficiencies. The key question for such a study would be: what is the optimal battery size to make the system most cost effective? Will the additional water pumped as a result of introducing batteries in the system pay for the battery and its regular replacement knowing too well the conventional lack of preference for adding batteries to solar PV water pumping systems due to additional capital and maintenance costs?

3. Further research should conduct performance evaluation of several solar pumping systems with different characteristic and at different locations over a longer period to compare influence of different characteristics and contexts so as to enable generalization of findings. This study focused on one installed system which is insufficient for generalization on solar water pumping systems performance.

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