TECHNICAL AND ECONOMICAL FEASIBILITY OF SOLAR PV PUMPING OF WATER IN SUDAN

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تعتمد كلية الدراسات العليا
هذه النسخة من الرسالة
التوقيع.........التاريخ.........

Dedication

To
My Mother
Brothers and Sisters
For their love and endless support

Acknowledgment

I would like to express my thanks and deep appreciation to my supervisor Professor Mahmoud Hammad for his continuous help and encouragement, for his patience and endless support.

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Nomenclature

Symbol	Description	Units
A	Ampere	A
A_{PV}	Area of PV array	m^2
C	Cost	$
d	Discount Factor	--
F_p	Pumping Factor	--
G_T	Solar Radiation	W/m^2
g	Acceleration Due to Gravity	m/s^2
h	Head	m
kWh/m^2	Kilowatt-Hours per Square Meter	
L	Liters	L
M	Maintenance Cost	$
m	Meter	m
N	Number of Module	--
n	Number of Years	--
O	Operation Cost	$
P	PV Array Power	W
P_e	Power Output	W
P_h	Hydraulic Power	W
P_i	Input Power	W
Q	Water Output	m^3/day or L/h
R	Replacement Cost	$
r	Correlation Coefficients	
T_r	Reference Temperature	C^o
V	Volt	V

Abbreviations

Abbreviations	Description
AC	Alternating Current
DC	Direct Current
E	East
LCC	Life Cycle Cost
N	North
NPV	Net Present Value
PV	Photovoltaic
SP	Submersible Pump
US$	United State Dollars
W	Watt
W_p	Watt-Peak

Greek Symbols

Symbol	Description	Units
η_s	Subsystem Efficiency	%
η_{PV}	PV Array Efficiency	%
η_o	Overall Efficiency	%
ρ	Density of Water	kg/m^3

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ABSTRACT

The technical and economical feasibility of solar photovoltaic PV pumping of water in Sudan was studied. Sudan has remotely isolated rural areas which pose problems to rural energy management and development because of poor road links with the urban centers, and remoteness from the national electrical transmission grid. For this purpose 9 sites were selected based on the available solar radiation data in Sudan. Photovoltaic water pumping systems are particularly suitable for water supply in remote areas where no electricity supply is available. Most PV pumping systems in Sudan consist of a PV array, an inverter, the motor–pump subsystem, and the water tank.

The Methodology of the study includes theoretical modeling of the system, where the mathematical relations of pump performance to the solar radiation levels during the year were applied to the all nine sites that were selected in this study. Experimental work and Life cycle cost (LCC) method applied to determine the economic life of the PV modules, and the diesel pumping in Sudan which was taken as 20 years.

The result of the computer simulation of the performance of a PV pump for the nine selected sites in Sudan illustrated clearly that it is possible to pump water using solar energy and that resembles a good technical practice. Water delivery by the pump depends on solar radiation intensity. The result of experimental work showed that the maximum water output of 1568 Liter per day in July where the solar radiation was high and the minimum water of 1355 Liter per day in May where the solar radiation was low. The results of LCC method showed the LCC of PV water pumping system is US$19224 less than the LCC of diesel pumping where it is about US$36572. The difference between the two values is US$ 17347 US$. Solar PV water pumping system has excellent performance in selected sites in Sudan, because Sudan has excellent sunshine and the solar radiation

reach 7.7kwh/m^2/day in one of the sites, so the technical feasibility is highly successful by using PV systems. These results indicate that PV solar water pumping in Sudan is more technically and economically feasible than diesel pumping system.

CHAPTER ONE

Introduction and Literature Review

CHAPTER ONE

1.0 Introduction and Literature Review

1. Introduction

One of the most available types of renewable energy is solar energy, which can be the main source or alternative energy source in power generation. The benefits of using renewable energy are that it is clean and friendly to the environment.

Photovoltaic (PV) systems convert sunlight directly to electricity, the use of photovoltaic (PV) as the power source for pumping water is considered as one of the most promising areas of PV application. Photovoltaic powered water pumping systems require only that there be adequate sunshine and a source of water. The use of photovoltaic power for water pumping is appropriate, as there is often a natural relationship between the availability of solar power and the water requirement. The water requirement increases during hot weather periods when the solar radiation intensity is high and the output of the solar array is at its maximum. On the other hand, the water requirement decreases when the weather is cold and the sunlight is less intense.

Development of renewable energy sources, therefore, has a high potential in Sudan. Solar energy, with excellent sunshine of over 3000 hours per year, is of paramount importance, the application of which is already quite significant and is growing at steady rate. Solar energy is suitable for small-scale water pumping in remote areas where the demand is regular, such as for drinking water, and it may also be used for irrigation.

Most areas in Sudan have climates suitable for solar pumping. The direct coupled photovoltaic water pumping system studied consists of the PV array, DC-AC Inverter, Submersible pump/Motor unit, a storage tank that serves a similar purpose to battery storage.

1.1 Problem of Water Pumping in Sudan

Sudan has remotely isolated rural areas which pose problems to rural energy management and development because of poor road links with the urban centers, and remoteness from the national electrical transmission grid, previous works found that solar water pumping is feasible in many countries except in Sudan, beside the increases in fuel price sharply increase the cost of pumping with diesel, relative to PV.

Traditional pumping and irrigation systems, employing diesel engines and electric grid powered motors, represent a partial solution for some water delivery needs. But the cost of fuel and electricity, spare parts and service, or the equivalent in time and labor of hand pumping systems, make water pumping technologies extremely expensive for many rural towns and villages, the populations that need them most.

There is a lot of interest in solar water pumping in Sudan, for obvious reasons, over the past 10 years approximately 250 PV water pumps were installed in the country (Omer, 2001). Photovoltaic water pumping was promoted successfully in Kordofan state, it shows favorable economics as compared to diesel pumps, and is free from the need to maintain a regular supply of fuel. These studies investigate the feasibility of solar water pumping in Sudan.

Photovoltaic water pumping systems are particularly suitable for water supply in remote areas where no electricity supply is available. Water can be pumped during the day and stored in tanks, making water available at night or when it is cloudy. The advantages of using water pumps powered by photovoltaic systems include low maintenance, ease of installation, reliability and the matching between the power generated and the water usage needs. In addition, water tanks can be used instead of batteries in photovoltaic pumping systems.

1.2 Photovoltaic Water pumping Application

Water pumping using photovoltaics may be the most common use of complete PV systems in both developed and developing areas. Water pumping applications include,

- Villages water supplies
- Domestic water
- Irrigation
- Livestock watering

The using of photovoltaic solar pumping systems could be one of the possible solutions to the growing energy demand in rural areas. Water pumping for domestic use and irrigation, which is one of the basic needs in the rural areas of Sudan.

1.3 Objectives

The overall objective of this research was to determine the feasibility of using photovoltaic (PV) modules to power a water pumping system in Sudan involving a complete photovoltaic water pumping system that falls within the potential application for sustainable agriculture. Available literature showed that the systems were relatively successful compared to small diesel generators except in Sudan. This study is proposed to verify the results of Omer (2001) and evaluate the potential of solar PV pumping in Sudan.

The economic feasibility of solar photovoltaic PV pumping system is the most likely conventional alternative system, diesel pumping system, to supply solar water pumping system to improve the living condition of the population in remote areas to develop techniques for utilization of solar energy in a tropical environment at condition and then educate people about clean and alternative energy.

Most PV pumping systems do not use batteries, thus avoiding costly and high maintenance component and greatly increase the reliability of the system.

In rural areas, there is a critical need for fresh underground water and a low maintenance PV powered water system can bring health and prosperity to remote villages, without the burdens of paying for maintenance and spare parts.

This research will concentrate on technical and economical feasibility of solar PV pumping water in Sudan compared with diesel water pumping system. In the study some selected remote sites in Sudan based on the availability of solar radiation data, underground water data and the depth of water which the PV pumping station is installed on. The economic life of the PV pumping and the diesel pumping are taken as 20 years, in life cycle cost (LCC) analysis, the net present value (NPV) of all the capital and recurring costs for the PV-powered pumps is compared to the NPV of all the costs of competitive projects.

2. Literature Review

Yahya et al (1995) studied design and installation of solar photovoltaic powered water pumping system at Usmanu Danfodiyo University, Sokoto. The design and installation of a PV powered water pumping system to replace the existing conventional a.c. powered system at Usmanu Danfodiyo University in Sokoto has been successfully carried out. The installed system was tested and the result showed satisfactory performance of the system.

Hammad (1999) studied experimentally characteristics of solar water pumping in Jordan. The study showed pumping factor (Fp) ranged from $39m^3.m/d.m^2$ in November up to $50.5\ m^3.m/d.m^2$ in July. This factor, along with the module average efficiency and the pump average efficiency, were used to design PV generator for different wells and to calculate monthly expected performance. The year-round monthly average efficiency of the module used in the experiments was 4%. The average pump efficiency was found to be around 20%.

Jafar (2000) studied a model for small- scale photovoltaic solar water pumping in Fiji. A simple method for modeling the output of a solar photovoltaic water pumping system was presented. He showed the equations for the best fit curves and the correlation coefficients (r^2). The equations gave a combined relationship for flow rate as a function of irradiance and head. The predicted flow rates were plotted against head. Superimposed on these were the actual measured values. The average deviation between the measured and the predicted values was less than 8% of the measured values. This deviation, although relatively small, was accounted for in terms of the fluctuating solar input and unsteady module temperatures during the measurement.

Omer (2001) attempted to explore the potentialities of solar energy with particular reference to application of solar PV water pumping in remote rural areas of Sudan. Solar radiation ranged from 5.5 to7.5 KW m^{-2}day^{-1} in the plan of the solar array. The peak pumping rate was 821 min at 820W m^{-2}. However, the average overall system efficiency was still low. He found that the cost of a PV pumping system was high and was roughly proportional to the size of the system. He concluded that the system was not yet competitive with diesel engine set.

The economic viability of a stand-alone solar photovoltaic PV system with the most likely conventional alternative system, i.e. a diesel-powered system, was analyzed by Kolhe et al (2002) for energy demand through sensitivity analysis using a life-cycle cost computation. The analysis showed that PV-powered systems were the lowest cost option at a daily energy demand of up to 15 kWh, even under unfavorable economic conditions. When the economic parameters are more favorable, PV-powered systems are competitive up to 68kWh/day. These comparisons are intended to give a first-order indication of when a stand-alone PV system should be considered for application. As the cost of PV systems decreases and diesel costs increase, the break-even points occur at higher energy demand.

Badescu (2002) analyzed a solar water pumping system consisting of four basic units: a PV array, a battery, a DC motor, and a centrifugal pump. The results showed that during the clear days, with a high value of solar irradiance and high cell temperature, the

PV cell had lower efficiency, while during cloudy days, when the temperature T_{cell} was smaller, the cell efficiency was larger. Winter months were associated with larger sun-to-user efficiency. The battery plays the role of a buffer, as the main part of the electricity supplied by the PV array was always used to drive the motor. The electric power used to drive the motor is rather constant during the year.

Hamidat et al (2003) studied small-scale irrigation with photovoltaic water pumping system in Sahara regions. His work shows that for low heads it is possible to use a photovoltaic water pumping system for small-scale irrigation of crops in Algerian Sahara regions.

Hrayshat (2004) studied the potential of solar energy development for water pumping in Jordan. For this purpose, 10 sites were selected based on the available solar radiation data. All the 10 selected sites had pumping head of 20 m. He divided the selected sites into three different categories: The first one, which includes Taffieleh, Queira, H-4, and H-5, were considered to be adequate for solar water pumping. Because the annual amount of water output obtained from the four sites in this category forms about 62% of all water pumped from all the 10 sites combined. The second category was considered to be promising. It includes Ras Muneef, Mafraq, and Hasa. Their water output adds up to about 29% of all water pumped from all sites.

The third, which includes Deir Alla, Baqura, and Wadi Yabis, was considered to be poor, because only about 9% of the water pumped from all sites combined can be obtained from these three locations. Some the selected sites were considered to be adequate. The latter is the best among all of the selected sites for solar water pumping.

Fiaschi Daniele (2004) studied the possibility of improving the performance of deep well solar pumping systems by using centrifugal pumps with variable rotational speed and modular number of working stages was investigated and compared with traditional systems equipped with pumps having a fixed number of stages.

The sensitivity to the PV arrays peak power W_p shows an optimal value for the 46-stage pump around 2800 W, which is explained by the large increase in pumping efficiency during the February –September period. Beside the economic analysis shows a certain degree of advantage of the DSP solution in terms of payback time if a correct matching of all plant data and design variables is performed.

Eker (2005) studied solar powered water pumping systems in Turkey, photovoltaic power is more cost-competitive when used to power a micro irrigation system as compared to an overhead sprinkler system. Photovoltaic power for irrigation is cost-competitive with traditional energy sources for small, remote applications, if the total system design and utilization timing is carefully considered and organized to use the solar energy as efficiently as possible.

Daud (2005) investigated experimentally solar powered induction motor- driven water pump operating on a desert well, in Jordan. 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 has been developed. The system was installed on a desert well in Jordan, where the average solar radiation amount to 5.5 kW h/m^2/day, to provide the Bedouins living in the well area with drinking water, a mathematical model to enable testing the system performance by computer simulation was developed. This model allows the representation of motor torque in function of speed (and slip) at different supply frequencies, as well as the flow rate and efficiency of the system in function of supply frequency and pumping head.

Prior to its installation on the desert well, the system performance, in accordance with frequency and head, was thoroughly tested in the laboratory. Simulation and laboratory testing results were well matched. At constant pumping head, the flow rate was proportional to the supply frequency of the motor. At constant flow rate, the pumping head was proportional to the supply frequency squared only in the range below the peak efficiency of the pump, higher system efficiency was achievable at higher frequency. It was advisable to operate the motor pump at the nominal frequency, flow rate and head corresponding to maximum efficiency.

Ghoneim (2006) presented design optimization of photovoltaic powered water pumping systems in the Kuwait climate. The direct coupled photovoltaic water pumping system studied consists of the PV array, DC motor, centrifugal pump and a storage tank.

The life cycle cost method was implemented to evaluate the economic feasibility of the optimized photovoltaic powered water pumping system. At the current prices of PV modules, the cost of the proposed photovoltaic powered water pumping system was found to be less expensive than the cost of the conventional fuel system.

Glasnovic (2006) conducted a study model for optimal sizing of photovoltaic irrigation water pumping systems on two locations in Croatia, the result of such approach was a new mathematical model for optimal sizing of the nominal electric power of the PV generator. Meah et al (2006) conducted a study solar photovoltaic water pumping for remote locations, the study showed the solar PV water pumping system had excellent performance in terms of productivity, reliability, and cost effectiveness. Drought affected areas like Wyoming, Montana, Idaho, Washington, Oregon, and part of Texas could use solar PV water pumping systems to improve the water supply to livestock in remote locations. They showed that solar PV was reliable for remote locations despite the failure of component. Among the all major components, the pump/motor is the most vulnerable part of the PV system.

Odeh et al (2006) analyzed economic viability of photovoltaic water pumping systems. PV water pumping systems have shown better economic viability than diesel water pumping systems for equivalent hydraulic energy capacities of up to 8000 m^4/day, 4100 m^4/day and 2600 m^4/day respectively. Considering pumping head of 50 m, for example, PV pumping systems hold a cost advantage for daily water volume capacity of 52m^3/day at interest rate of 20%, 82m^3/day at interest rate of 10% and 160 m^3/dayat interest rate of 0%. The average equivalent hydraulic energy costs of the five systems considered increases from US$ 3.1/1000 m^4 for PV and US$ 6.13/1000 m^4 for diesel at 0% interest rate to US$ 7.12/1000 m^4 for PV and US$ 6.65/1000 m^4 for diesel at 20% interest rate. This is equivalent to 130% increase on equivalent hydraulic energy unit cost of the PV pumping system and only 8.5% increase on the diesel case.

All systems studies showed relative successful results compared to small diesel generator except in Sudan which was carried out by Omer (2001). Therefore, this study isproposed to verify the results of Omer (2001) and evaluates the potential of solar PV pumping in Sudan.

CHAPTER TWO

Sudan Climate and System Description

CHAPTER TWO

2.0 Sudan Climate and System Description

2.1 Sudan Climate

Sudan is the largest country of the African nations with an area of 2.5 million square kilometres, extending between longitudes 21° 45 E and 39° E, and latitudes 3° N and 23° N and has a population of approximately 35 million. The growth rate is 2.5 % and population density is 10 person per square kilometre.

Sudan has a predominately continental climate which roughly divides into three climatologically regions (Omer, 2002): Region one is situated North of latitude 19 ° N. The summers are invariably hot (mean maximum 41 °C and mean minimum 25 °C with large decimal variation, low relative humidity averages 25%). Winters can be quite cold. Sunshine is very prevalent. Dust storms occur in summer. The climate is a typical desert climate where rain is infrequent and diurnal (annual rainfall of 75-300 mm). The annual variation in temperatures is large (maximum and minimum pattern corresponding to winter and summer). The fluctuations are due to the dry and rainy seasons.

Region two is situated South of latitude 19° N. The climate is a typical tropical continental climate.

Region three comprises the areas along the Red sea coast and eastern slopes of the Red sea hills. The climate is basically as in region 1, but it is affected by the maritime influence of the Red sea.

The two main air movements determine the general nature of the climate. Firstly, a very dry air movement from the north that prevails throughout the year, but lacks uniformity and secondly, a major flow of maritime origin that enters Sudan from the south carrying moisture and bringing rain.

2.2 Water Resources

The most prominent feature of Sudan's geography is the Nile river system (including the White and the Blue Nile) which bisects the country North to South illustrated in Sudan map in Figure (4.1) in chapter four. In northern Sudan, away from the Nile system and its few tributaries, the land is dry semi-desert to desert. The population density is highest along the Nile and its tributaries. The surface water of these rivers is utilized for village water supplies and irrigation. Near the river, the water table level normally remains high with large diameter hand dug wells in use for water supply and irrigation.

Groundwater sources include the vast Nubian and Um Rwaaba aquifers, the Gezira formation, several significial areas of basement complex and numerous smaller superficial deposits. The sedimentary deposits Nubian aquifer under lay's 28% of Sudan's area, largely in the North and West, North-West of Khartoum (Hodgkin, 1990).

This aquifer is divided into six major basins which cover much of the area of northern Sudan from the Red sea Hills west and from the middle of Central Region to the north (except for the basement complex areas of central Kordofan and the Jebel Marra plateau). The water level range from 5 to 120 meters and even flow to the surface at the oases El Natrun and Nukheila in the northwest part of Sudan, well yields tend to be good, often in the range of 25 m^3/ hour or more.

2.3 Solar Energy in Sudan

There are sixteen meteorological stations throughout the country which collect solar radiation data. The first of these began collecting data in 1967. The Meteorological Department is using Eppley pyranometers and Speedomax recorders to calculate hourly solar radiation totals. These data are used to determine the monthly average total radiation. These data in table 2.1 showed that Sudan enjoys a considerable solar energy with all areas north of 12 degrees except the eastern part of eastern region reporting annual average radiation levels above 5.6kWh/m^2/day on a horizontal surface. Half of the 16 stations report annual average figures above 6.1kWh/m^2/day (Hodgkin, 1990).

The monthly data shows that the lowest solar radiation levels occur in most locations during December when the day length is shortest and highest values occur during the spring (April to June). Data available concerning hours of bright sunshine (recorded by Campbell-Stokes instruments) indicate lower levels of sunshine during the late spring and summer months. This is caused by cloud cover and larger amounts of dust and particulate matter in the air during these periods. In Southern regions (which might normally be expected to exhibit higher solar radiation levels due to proximity to the equator) and along the Red sea coast the levels are actually lower than in the north. This is due to the much higher cloud cover experienced in these areas, especially during the rainy season (May to September). More northern areas experience much lower rainfall and much lower cloud cover resulting in higher average solar radiation levels. These data indicate that the northern Sudan has amore favourable solar energy regime than in the south and east. The country strives hard to make use of technologies related to renewable sources in rural areas where it is appropriate and applicable. Sudan already has well-established solar thermal applications. Some examples of the most promising solar thermal applications are industrial solar water heaters in the residential sector and in larger social institutions, such as nurseries, hospitals, and schools. Solar cookers, solar dryers for peanut crops, solar stills, solar driven cold stores to store fruits and vegetables, solar collectors, solar water desalination, solar ovens and solar commercial bakers. Solar photovoltaic systems PV are used for lighting, solar refrigeration to store vaccines for human and animal use, water pumping, battery chargers, communication network, microwave receiver stations, radio systems in airports, and educational solar TV posts in some villages, Omer (2002).

Table (2.1): Solar radiation at selected sites in Sudan in kWh/m^2/day

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abu Naama	5.7	6.3	6.7	6.8	6.7	6.2	5.8	6.2	6.5	5.3	6.1	5.4
Aroma	5.4	5.7	6.2	6.2	6.2	6.1	6.2	6.9	6.6	5.9	5.2	4.7
Babanousa	5.7	6.3	6.7	6.8	6.6	6.3	5.7	5.8	6	5.7	5.5	5.4
Dongola	5.6	6.4	7.1	7.5	7.7	7.6	7.2	7	6.7	6.4	5.8	5.3
El Fasher	5.4	6.4	6.9	7	7	6.6	6.3	6.3	6.2	6.3	5.7	5.4
Showak	5.6	6.5	7.1	7.3	7.1	7.5	6.2	6.2	6.4	6.1	5.8	5.4
G.Gawazat	5.7	6.2	6.5	6.6	6.3	6	5.7	5.7	6	6	5.9	5.7
Hodieba	5.4	6	6.8	7.1	6.8	6.4	6.3	6.5	6.3	6	5.6	5.3
Juba	5.4	5.4	5.4	5.8	5.7	5.4	5	4.9	5.9	5.6	5.4	5.3
Kadugali	6	6.4	6.6	6.7	6.4	5.8	5.2	5.1	5.2	2.8	6	5.9
Malakal	5.6	6	6.2	6.2	5.6	5	5	5.4	5.3	5.4	5.6	5.5
Port Sudan	4.2	5.2	6.3	4.2	7.1	6.6	6.3	6.3	6.2	5.7	4.6	4
Shambat	5.6	6.3	6.8	7.1	6.8	6.5	6.3	6.3	6.3	6	5.7	5.4
WadMedani	5.8	6.4	6.9	7	6.8	6.6	6.2	6.2	6.5	6.2	5.9	5.6
Tokar	4.7	3.8	4.7	6	6.1	5.4	4.8	4.7	4.9	4.6	6	4.6
Zalengi	6.1	6.6	7.1	7.1	7	5.8	5.8	5.9	6	6.3	6.3	6

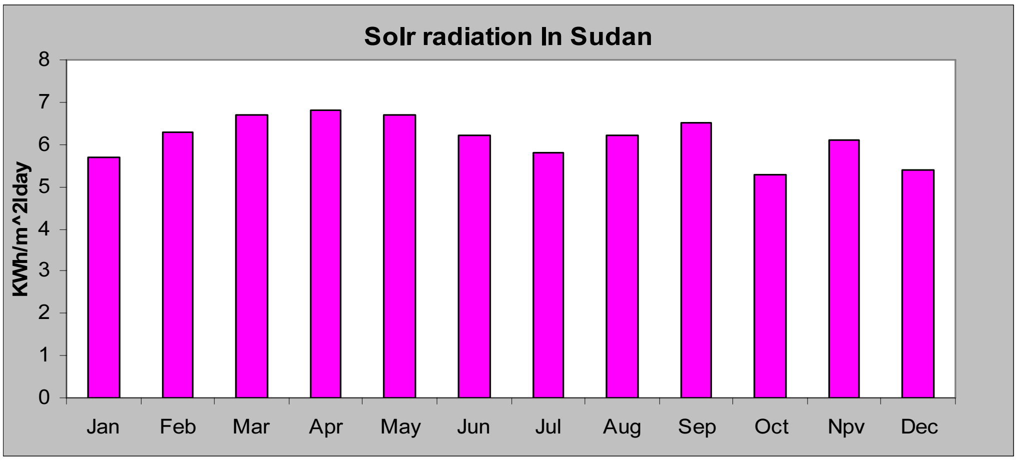

Figure (2.1) Monthly solar radiation in Sudan in kWh/m^2/day

2.4 Description of the System

2.4.1 Photovoltaic Pumps

The two most important factors in the operation of a PV pump are the availability of sufficient solar radiation to enable the pump to start (until the solar radiation reaches the threshold level), and works occur on a non-linear relationship between the pumping rate and solar radiation. The threshold level of a PV pump depends on the system components. Figure (2.4.1) illustrates a schematic diagram of typical PV pump components. It consists of a PV array, an inverter, the motor–pump subsystem, and the water tank.

PV pumping components have to be selected carefully for a proper matching of the system. Unlike conventional pumping systems, PV pumps have to be designed and installed properly to be competitive with other pumping technologies. Each component of a PV pump has intrinsic characteristics affecting the overall operating conditions. Therefore, it is desirable that the intercept of all respective component characteristics follows the maximum power line of the PV array generator. Depending on this internal matching, the efficiency of the overall system and related performances will meet an acceptable range. System design, particularly the PV array capacity, should be reviewed to ensure that sufficient energy is produced to start the motor as early in the day as possible.

In principle, modeling components individually and combining them into a single system can optimize PV pumps.

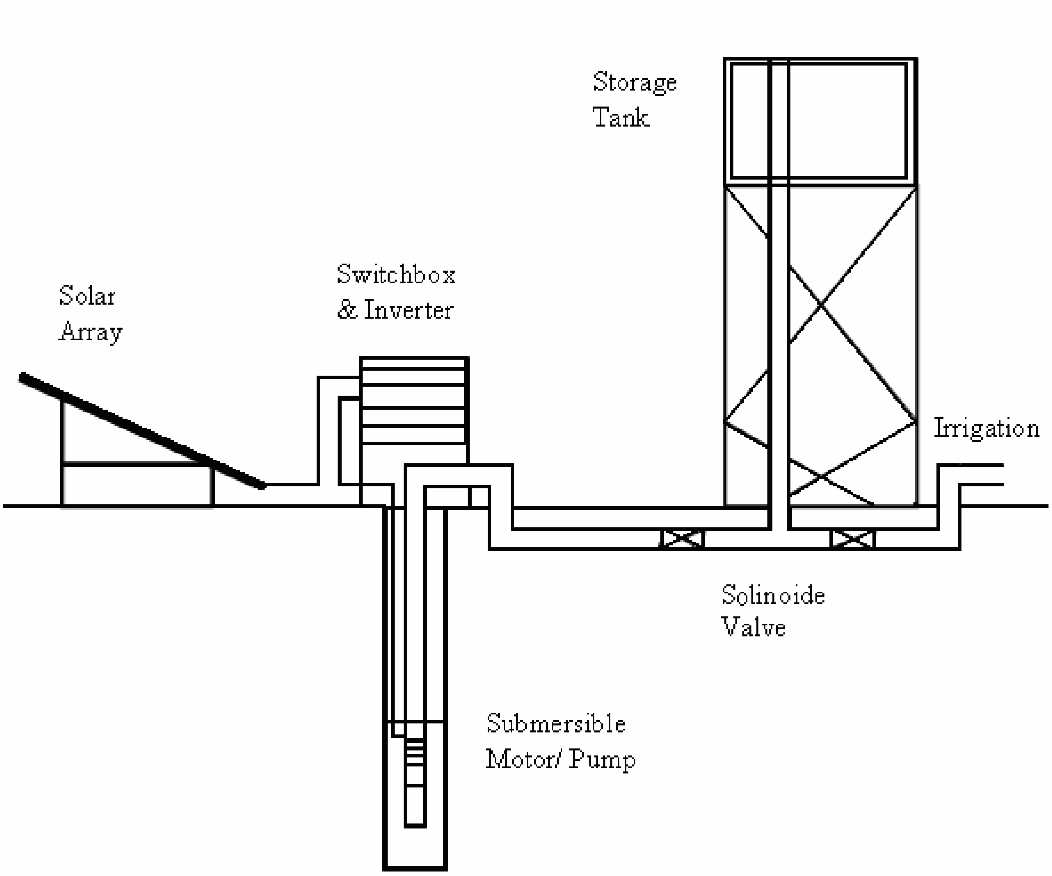

Figure (2.4.1) Components of the solar pumping system.

Solar pumping systems consist of a few simple units, which are connected to form a complete system. The elements of this system are:

1. Solar array:

The highly efficient solar modules are connected in series and in parallel to form a complete solar array with a nominal output voltage. The out put current varies with the irradiation on the array.

The DC output from the array is transmitted to the inverter through a main switch in the inverter.

2. DC-AC inverter:

The inverter converts the DC power from the solar array into three-phase AC power which is transmitted to the submersible motor.

3. Submersible pump/motor unit:

The submersible motor is direct coupled underneath the pump so that the motor and the pump form a complete unit.

As the AC power input to the motor changes according to the irradiation on the solar array, the water output will vary with the irradiation as well.

The submersible pump unit is installed in the bore hole, connected to the riser main and after electrical connection to the main switch box and connection of the solar array; the pump will deliver water through the riser pipe.

4. Batteries:

Batteries for storage of the electrical energy from the array are very expensive and have a relatively short life.

5. Storage tank:

All solar water pumping systems use some type of water storage. The idea is to store water rather than store electricity in batteries, thereby reducing the cost and complexity of the system.

Instead of storing the energy in batteries, it is much cheaper and more reliable to store the energy by storing the water in a water storage tank or reservoir.

Most PV pumping systems do not use batteries, thus avoiding costly and high maintenance component and increasing the reliability greatly.

CHPTER THREE

The Methodology of the Study

CHAPTER THREE

3.0 The Methodology of the Study

3.1 The Theoretical Modeling of the System.

A fairly accurate design method is to create a clear mathematical relationship between the solar radiation energy, the PV array power, and the required hydraulic energy to fulfill the water demand. This method can easily be used by field technicians or by end users (Flowers, 2004). The method is explained in chapter four.

The mathematical relationship between the PV array power and solar radiation energy is:

$$P = A_{PV} G_r \eta_r \tag{3.1}$$

Where P is the PV array power (in Watt-peak, W_P)

η_r is the efficiency of the PV array at reference temperature ($T_r = 25^oC$)

G_r is the solar radiation at reference temperature (Gr =1000 W/m^2).

A_{PV} is the effective area of the PV array in m^2(A_{pv}=$n_p n_s$A, where A is the area of a single module, and n_s is the number of the group of PV cells connected in series each containing n_p strings in parallel).

Equation (3.1) can be rewritten as:

$$P = 1000 A_{PV} \eta_r \tag{3.2}$$

The effective PV array area is calculated from the relationships of the daily power output P_e and the daily hydraulic power P_h (both in kWh):

$$P_e = A_{PV} G_T \eta_{PV} \tag{3.3}$$

And,

$$P_h = \eta_S P_e = \rho g h Q \tag{3.4}$$

Where

P_e the daily power output in kWh.

P_h the daily hydraulic power in kWh

η_{PV} is the efficiency of the PV array under operating conditions.

G_T is the daily solar radiation on the PV array surface kWh/m^2/day.

Q is the daily amount of water required m^3/day.

h is the total pumping head m.

η_s is the subsystem efficiency, the subsystem consists of the pump, the motor and the inverter.

ρ is the density of water.

g is the acceleration due to gravity.

Equating equations 3.3 and 3.4, gives the area of PV array:

$$A_{PV} = \frac{\rho g h Q}{G_T \eta_{PV} \eta_S} \qquad 3.5$$

Substituting Equation 3.5 into Equation 3.2, the PV array size in terms of hydraulic energy and solar radiation energy will be:

$$P = 1000 \frac{\rho g h Q \eta_r}{G_T \eta_{PV} \eta_S} \qquad 3.6$$

From Equation 3.6, it is possible to determine the required size of the PV array for a given pumping head and daily water demand, or conversely, to estimate the daily amount of water produced for the given array size and solar radiation energy.

The overall efficiency of a PV pumping system can be determined from the hydraulic power and from the solar radiation power input P_{in}. That is,

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} \tag{3.7}$$

3.2 The Experimental Work

To investigate year round performance of water pumping in Sudan it was decided to build a laboratory scale unit and run it throughout the year, one complete day each week and find a typical day long experiment that represent a monthly average performance. The experiment was expressed for three months (May, June and July) in laboratory of Jordan University.

The unit used consisted of:

1. Photovoltaic panel of monocrystalline (one module),
2. A control board with a functional block diagram of the system and properly positioned voltmeter and ammeter along with control switches.
3. A submersible pump powered by a DC motor 30/12 V maximum.
4. Two tanks: the over head tank of 4m height above the lower tank. The pump is installed in the lower tank.
5. The pyranometer which was used to measure solar intensity during the experiment was connected to a kipp and zonen solar integrator which displays the solar intensity in W.h/m^2.The pyranometer was directed and tilted at the same direction and tilt angle as the PV panel. The experimental work is explained in chapter six.

3.3 Life Cycle Cost (LCC)

The life cycle cost (LCC) method of comparison is a first-order indication when a system is considered for a particular application. LCC is also the most widely used evaluation method. In practice, when the pumping system is to supply drinking water, it is important to establish the comparative LCC of PV versus a diesel pump (Flowers, 2004). This is necessary because the economic benefits of supplying water are difficult to quantify.

LCC is the sum of all the costs associated with the pumping system over a given economic lifetime or over a selected period of analysis, expressed in the present value of money, that is the present worth (PW) of the costs system. All the future costs are discounted to the present-day value and added to the present-day investment costs, and the net present value is the LCC. This method was applied in the study to determine the cost of the PV modules, and the diesel pumping in Sudan which was taken as 20 years, this method will be explained in chapter seven.

In life cycle cost (LCC) analysis, the net present value (NPV) of all the capital and recurring costs for the PV powered pumps is compared to the NPV of all the costs of competitive projects. If the NPV of costs of PV-powered pumping is less than the costs of the alternatives, PV should feasible to use in Sudan.

CHPTER FOUR

Theoretical Modeling of the System and Results

CHAPTER FOUR

4.0 Theoretical Modeling of the System and Results

4.0.1 Solar Pumps Sites:-

In this study nine remote sites in Sudan were selected based on the available solar radiation data. The system consists of an array of modules, a DC-AC inverter and a submersible motor/ pump. The mathematical relations of pump performance to the solar radiation levels during the year from equation (3.1) to (3.7) were applied to the all nine sites that selected in this study to show the feasibility of solar water pumping in Sudan, the nine selected sites were illustrated in table (4.1) and Figurer (4.1).

Table (4.1): Water pumping characteristics of the sites.

No	Site	Pumping head, h, (m)	Daily water production Q, (m^3/day)
1	University of Gezira	21m	36
2	Hodieba	11m	44
3	Foja	38m	21
4	Mayo	22m	45
5	Nyala	40m	30
6	Aldoma	42.5m	30
7	South Kordofan	40m	27
8	South Kordofan	45m	24
9	Village near Dongula	15m	28

Figure (4.1): Water pumping sites selected in Sudan.

4.1 The First Site:-

The submersible pump (Grundfose) was installed in University of Gezira, the site is about one kilometre west of the Blue Nile north of Wad Medani. The total pumping head 21 meters, there is no storage tank at the site so the water is being delivered directly into irrigation channels. The daily solar radiation is 6.4 kilowatt- hours per square meter per day with water production of 36 cubic meters per day.

The mathematical relations of pump performance to the solar radiation levels during the year are:-

The daily hydraulic power, P_h (in kWh/day)

$$P_h = \rho g h Q = 2.06 kWh / day$$

The effective area of the PV array, A_{PV} (in m^2)

$$A_{PV} = \frac{\rho g h Q}{G_T \eta_{PV} \eta_S} = 6.13 m^2$$

The PV array Power, P (in Watt-Peak, Wp)

$$P = \frac{1000 A_{PV} \eta_r}{0.7} = 1313.8 W_P$$

The number of module N,

$$N = \frac{1313.8}{50} = 26.277 \approx 28$$

The number of module equal 28 must be 7 in series to meet the system voltage requirement and the 4 in parallel to meet the system current requirements.

The daily power output P_e (in kWh/day)

$$P_e = A_{PV} G_T \eta_{PV} = 6.13 * 6.4 * 0.15 = 5.8848 kWh / day$$

The subsystem efficiency η_s

$$\eta_S = \frac{P_h}{P_e} = \frac{2.0601}{5.8848} = 0.35$$

The Overall efficiency of the PV pumping system, η_o

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} = \frac{2.0601}{6.13*6.4} = 0.0525$$

The result of the mathematical relation to the performance of a PV pump in the University of Gezira illustrated in table (4.1.1) and the Figure (4.1.1) showed the possible water pumping Q m^3/day versus the solar radiation kWh/m^2/day, the water delivery by the pump ranged from 31.5 to 39.3 m^3/day depending on solar radiation level, the solar radiation ranged from 5.6 kWh/m^2/day in December and January to 7 kWh/m^2/day in April in summer. Figures (4.1.2) showed the daily hydraulic power in kWh/day depending on water delivery by the pump it was increase when the water output increase.

Figures (4.1.3), (4.1.4) and (4.1.5) show the monthly solar radiation kWh/m^2/day, water output in m^3/day, power output in kWh/day and hydraulic power in kWh/day in University of Gezira.

Also, the monthly sub-system efficiency is 0.35, array efficiency is 0.15 and overall efficiency is 0.525, all efficiency were constant they were independent on both solar radiation and water output. Figure (4.1.6), (4.1.7) and (4.1.8) illustrated clearly the monthly bar solar radiation kWh/m^2/day, water output in m^3/day and power output in kWh/day and hydraulic power in kWh/day in University of Gezira.

Table (4.1.1): Performance of solar pumping system at depth of 21m in the University of Gezira site

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Radiation	5.8	6.4	6.9	7	6.8	6.6	6.2	6.2	6.5	6.2	5.9	5.6
Water Output m3/day	32.6	36	38.8	39.3	38.2	37.1	34.8	34.8	36.5	34.8	33.2	31.5
Hydraulic power (Ph in kWh/day)	1.87	2.06	2.2	2.3	2.19	2.12	1.99	1.99	2.09	1.99	1.89	1.8
power Out Put (Pe in kWh/day)	5.33	5.88	6.35	6.4	6.3	6.07	5.7	5.7	5.9	5.7	5.4	5.1
Sub-System Efficiency	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Overall Efficiency	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Array efficiency	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

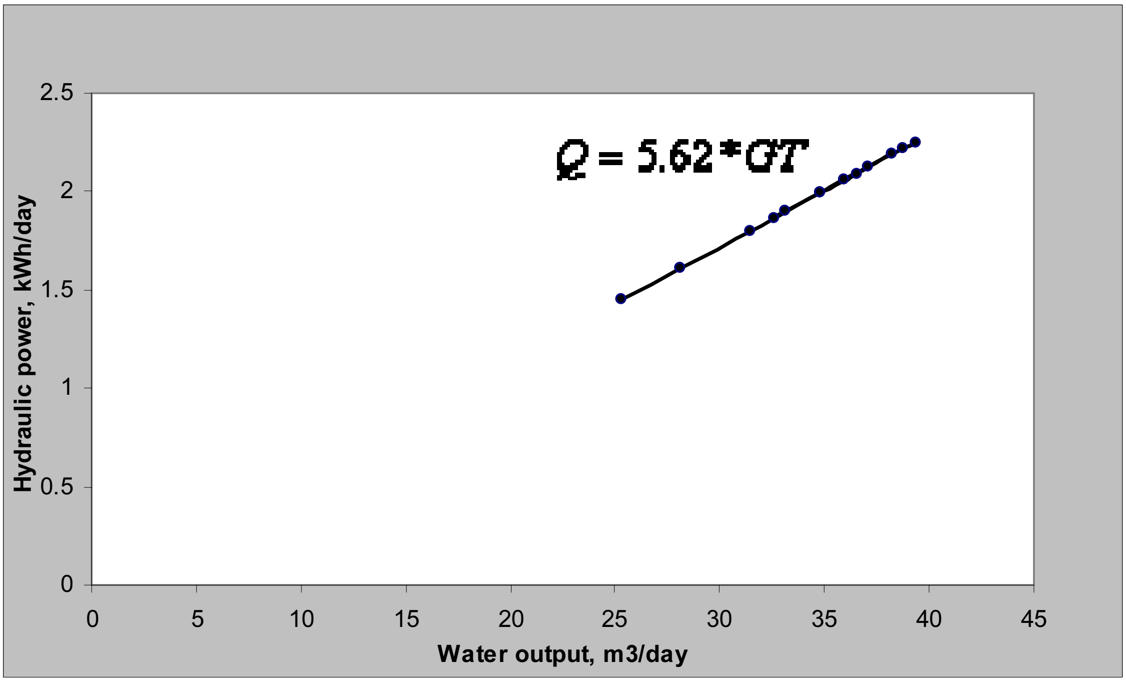

Figure (4.1.1) Possible water pumping at depth of 21m in University of Gezira site.

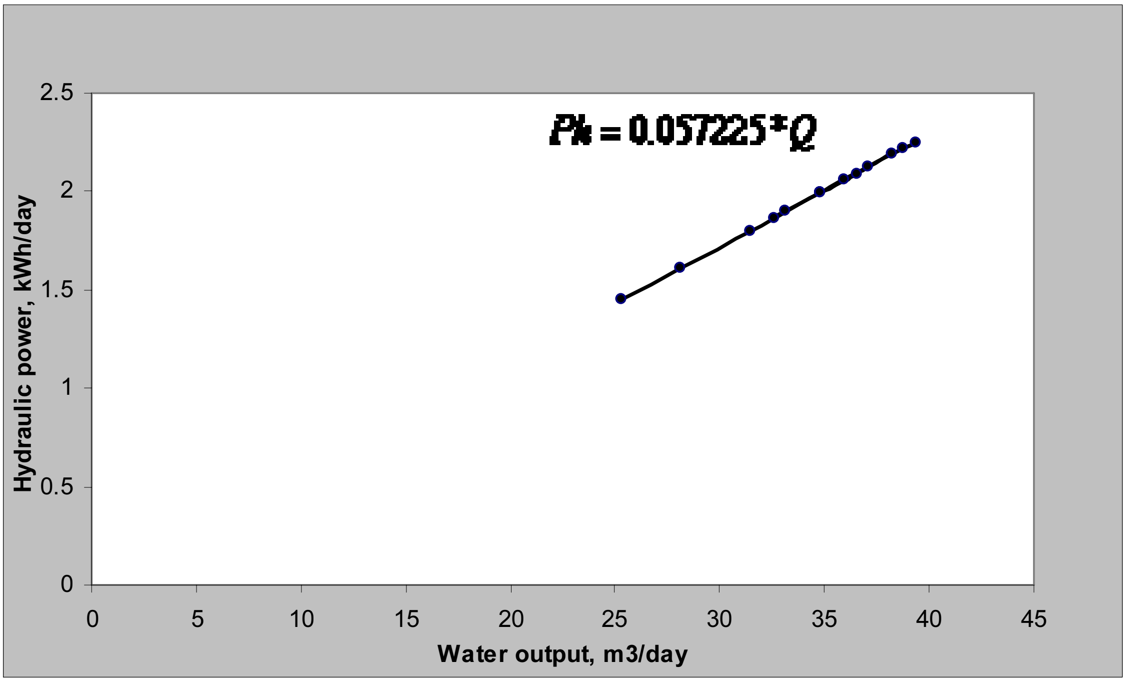

Figure (4.1.2) Hydraulic power in kWh/day against water out put in m^3/day.

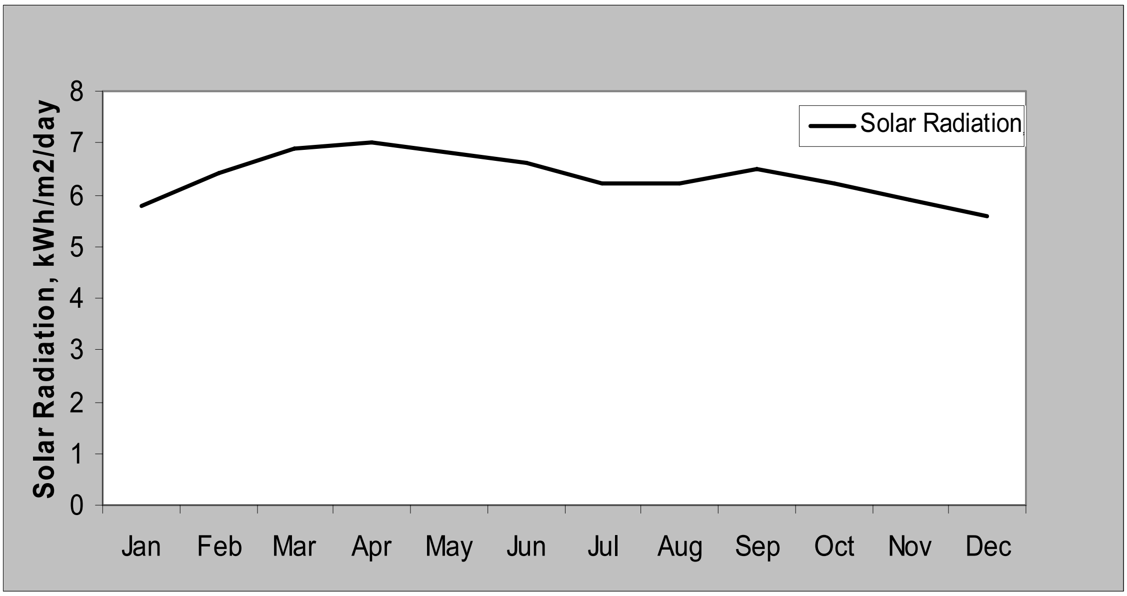

Figure (4.1.3) Monthly solar radiation in kWh/m^2/day in University of Gezira.

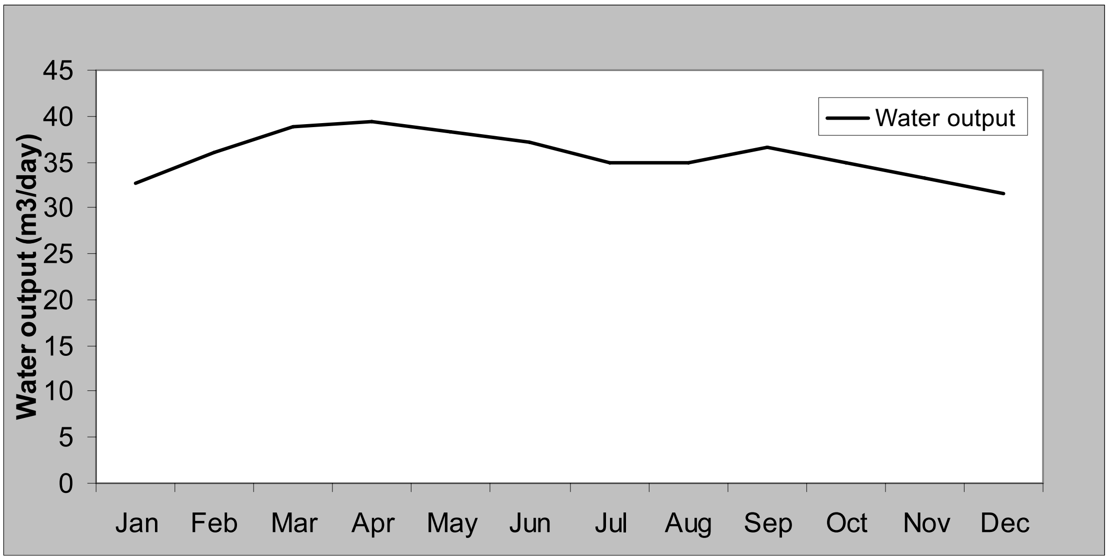

Figure (4.1.4) Monthly water output in m^3/day in University of Gezira.

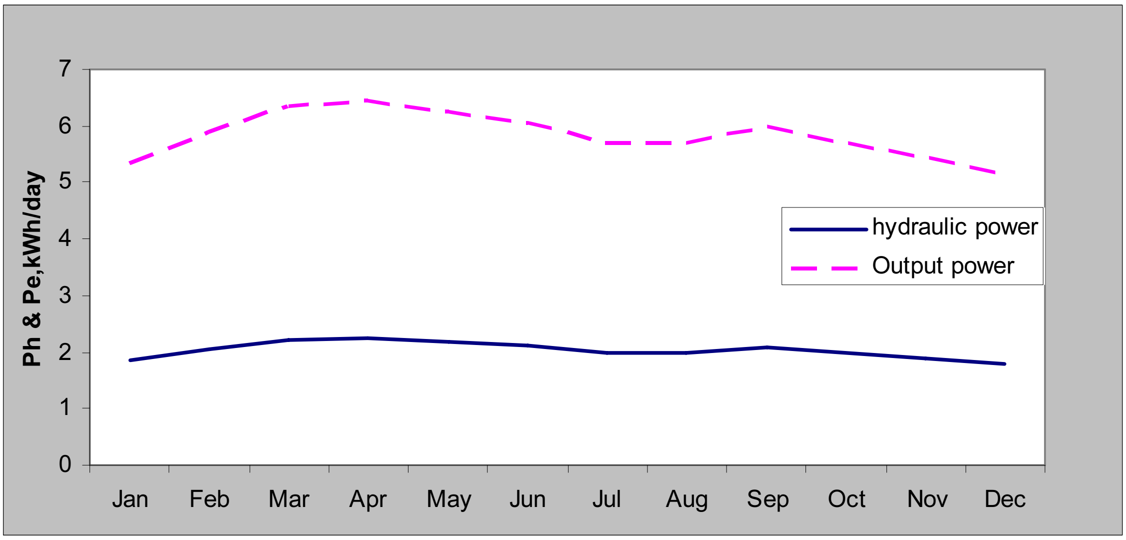

Figure (4.1.5) Monthly power output in kWh/day and hydraulic power in kWh/day in University of Gezira.

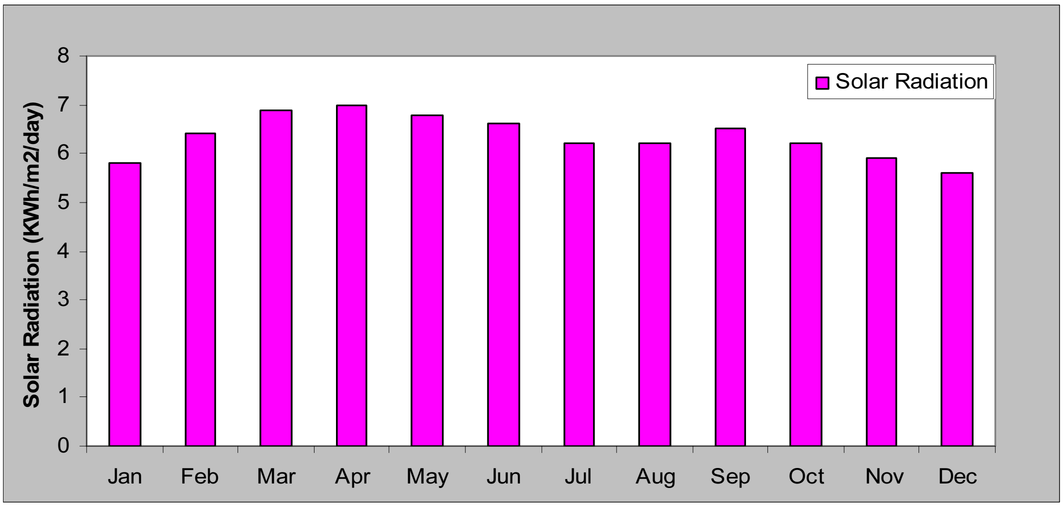

Figure (4.1.6) Monthly bar of solar radiation in kWh/m^2/day in University of Gezira.

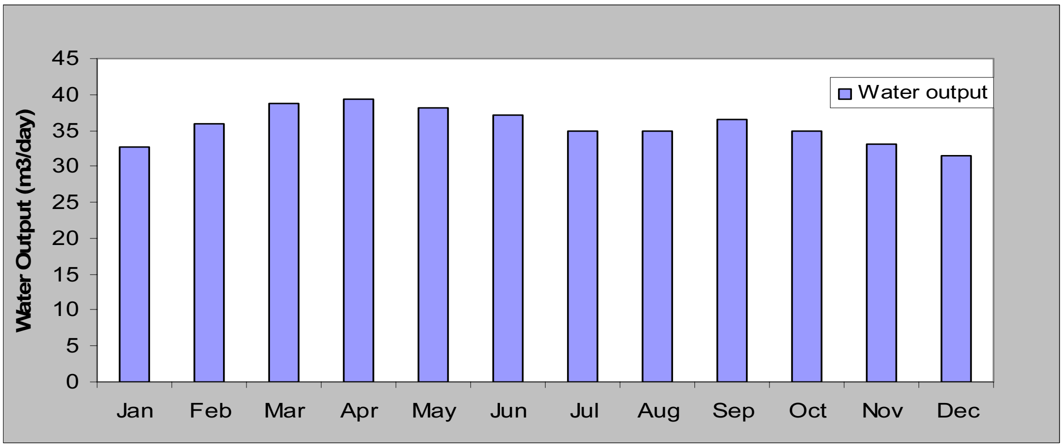

Figure (4.1.7) Monthly bar of water output in m^3/day in University of Gezira.

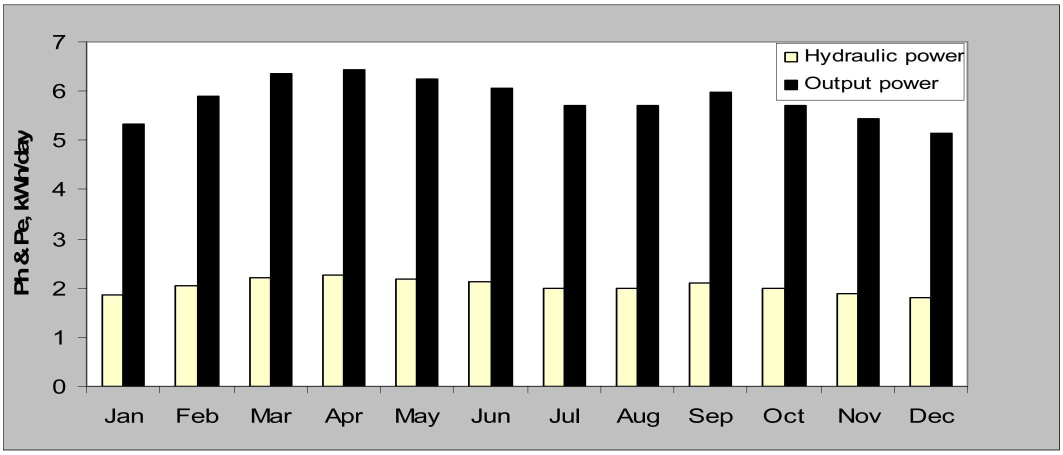

Figure (4.1.8) Monthly bar power output in kWh/day and hydraulic power in kWh/day in University of Gezira.

4.2 The Second Site:-

The pump (Grundfos SP-8) utilizing 21 Arco solar M-51 modules were installed at the Hodieba Agricultural Research Station Farm South of Ed Damer. The site is just east of the rail line about two kilometers east of the Nile.

The daily total solar radiation is 6.5 kilowatt-hours per square meter, water production of 44 cubic meters per day, and the total pumping head 11 meter.

The mathematical relationships between the solar radiation energy, the PV array power, and the required hydraulic power to fulfill the water demand. This method can be used by field technicians.

The daily hydraulic power, P_h in kWh/day

$$P_h = \rho g h Q = \frac{1000*9.81*11*44}{1000*3600} = 1.3189 kWh/day$$

The effective area of the PV array, A_{PV} in m^2

$$A_{PV} = \frac{\rho g h Q}{G_T \eta_{PV} \eta_S} = \frac{1000*9.81*11*44}{6.5*1000*3600*0.15*0.30} = 4.509 m^2$$

The PV array power, P (in Watt-Peak, Wp)

$$P = \frac{1000 A_{PV} \eta_r}{0.7} = \frac{1000*4.509*0.15}{0.7} = 966.2 W_P$$

The number of module, N

$$N = \frac{966.2}{50} = 19.3 \approx 21$$

The number of module connected each 7 modules in series to meet the system voltage requirement and the 3 modules in parallel to meet the system current requirements.

The daily power output, P_e in kWh/day

$$P_e = A_{PV} G_T \eta_{PV} = 4.509*6.5*0.15 = 4.396 kWh/day$$

The subsystem efficiency η_s

$$\eta_S = \frac{P_h}{P_e} = \frac{1.3189}{4.396} = 0.30$$

The Overall efficiency of the PV pumping system, η_o

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} = \frac{1.3189}{4.509 * 6.5} = 0.045$$

The result of the mathematical relation to the performance of a PV pump in the Hodieba illustrated in table (4.2.1) and the Figure (4.2.1) shows the possible water pumping versus the solar radiation, the water delivery by the pump ranged from35.9 to 48 m^3/day depending on solar radiation level, the solar radiation ranged from 5.3 kWh/m^2/day in December to 7.1 kWh/m^2/day in April in summer. Figures (4.2.2) shows the daily hydraulic power in kWh/day depending on water delivery by the pump it was increase when the water output increase. Figures (4.2.3), (4.2.4) and (4.2.5) show the monthly solar radiation kWh/m^2/day, water output in m^3/day, output power and hydraulic power in kWh/day in Hodieba.

Also, the monthly subsystem efficiency 0.35, array efficiency 0.15 and overall efficiency 0.053 in Hodieba all efficiency were constant they were independent on both solar radiation and water output. Figures (4.2.6), (4.2.7) and (4.2.8) illustrated the Monthly bar of the solar radiation kWh/m^2/day, water output in m^3/day, power output in kWh/day and hydraulic power in kWh/day in Hodieba.

Table (4.2.1): Performance of the system at depth of 21m in Hodieba site.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Radiation	5.4	6	6.8	7.1	6.8	6.4	6.3	6.5	6.3	6	5.6	5.3
Water Output m3/day	36.6	40.6	46	48	46	43	42.7	44	42.7	40.6	37.9	35.9
Hydraulic Power (P_h in kWh/day)	1.096	1.2	1.38	1.4	1.38	1.3	1.27	1.3	1.27	1.2	1.14	1.08
Power Out Put (Pe in kWh/day)	3.65	4.06	4.6	4.8	4.6	4.33	4.26	4.4	4.26	4.06	3.79	3.58
Sub- System Efficiency	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Overall Efficiency	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045
Array efficiency	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

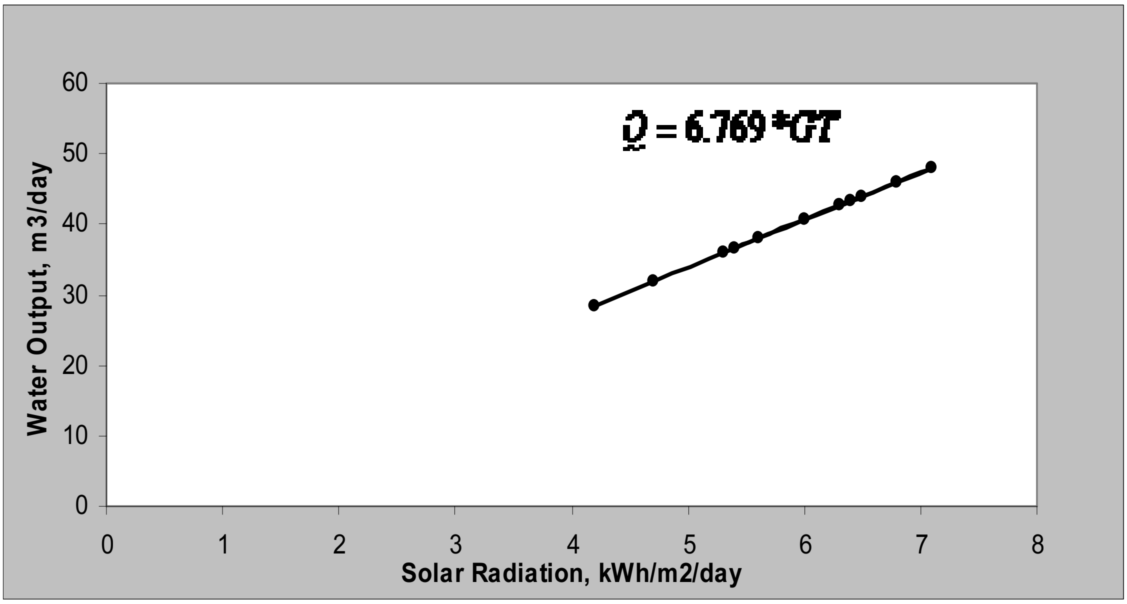

Figure (4.2.1) Possible water pumping at depth of 11m in Hodieba site.

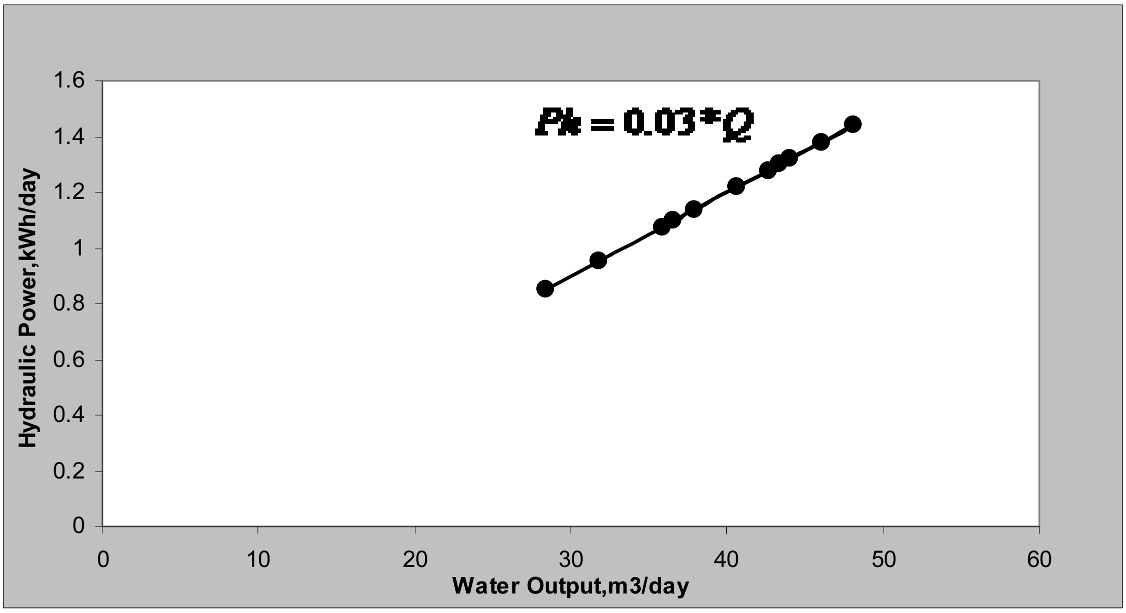

Figure (4.2.2) Hydraulic power kWh/day against the daily water output m^3/day.

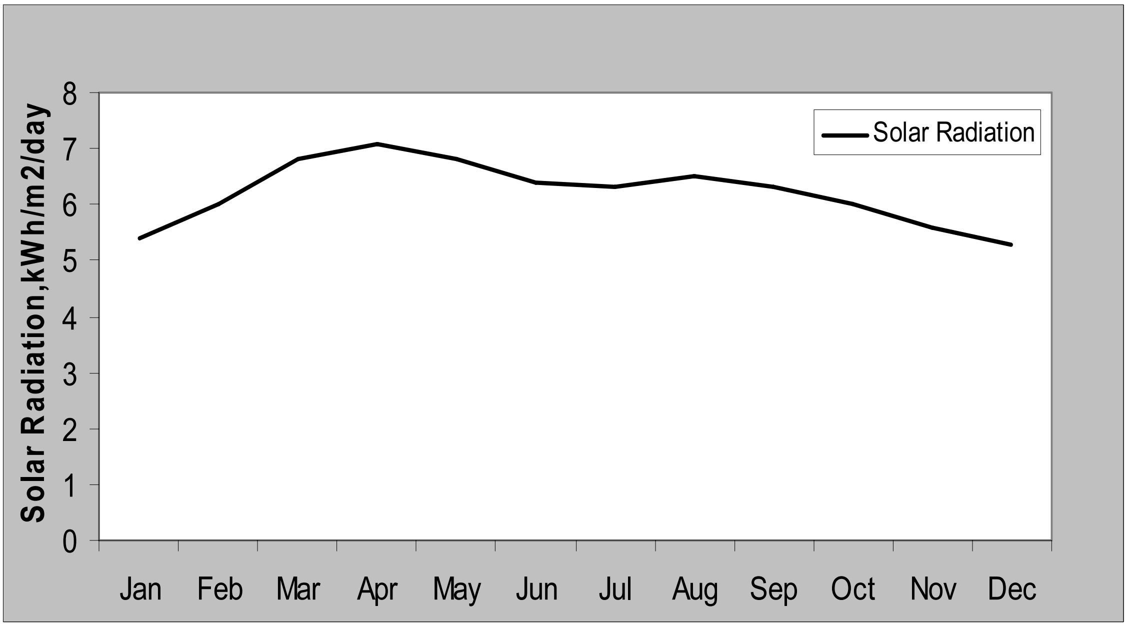

Figure (4.2.3) Monthly solar radiation kWh/m^2/day in Hodieba.

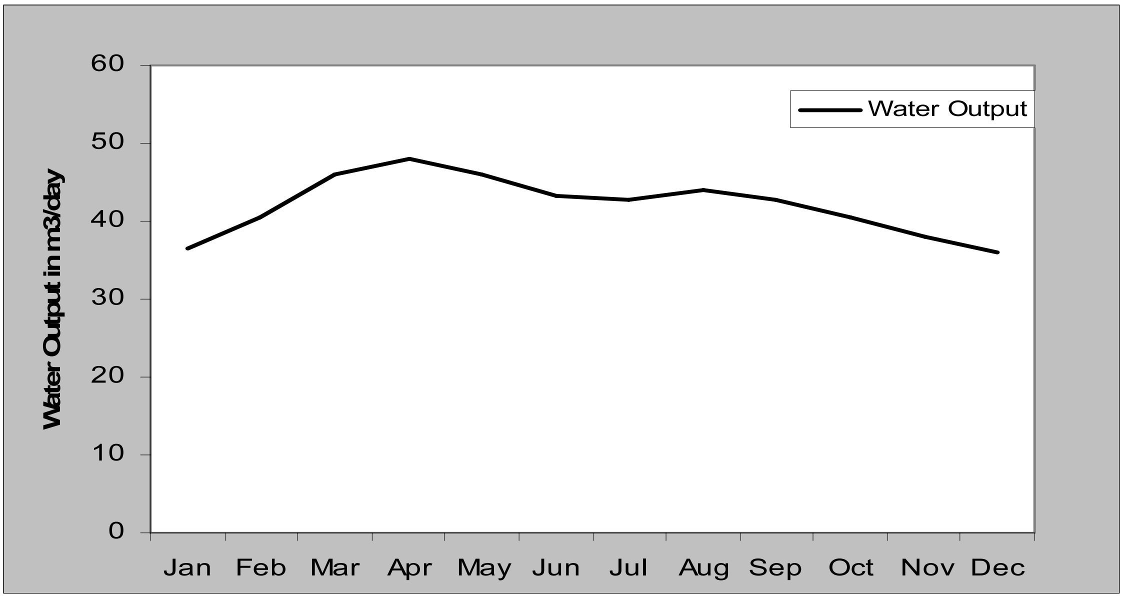

Figure (4.2.4) Monthly water output in m^3/day in Hodieba.

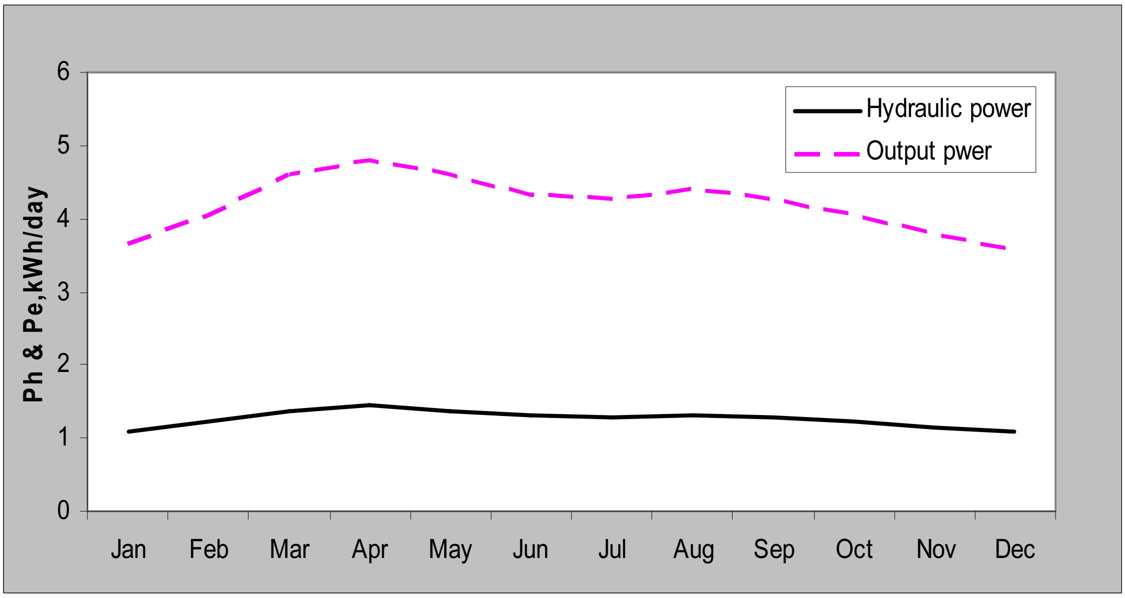

Figure (4.2.5) Monthly output power and hydraulic power in kWh/day in Hodieba.

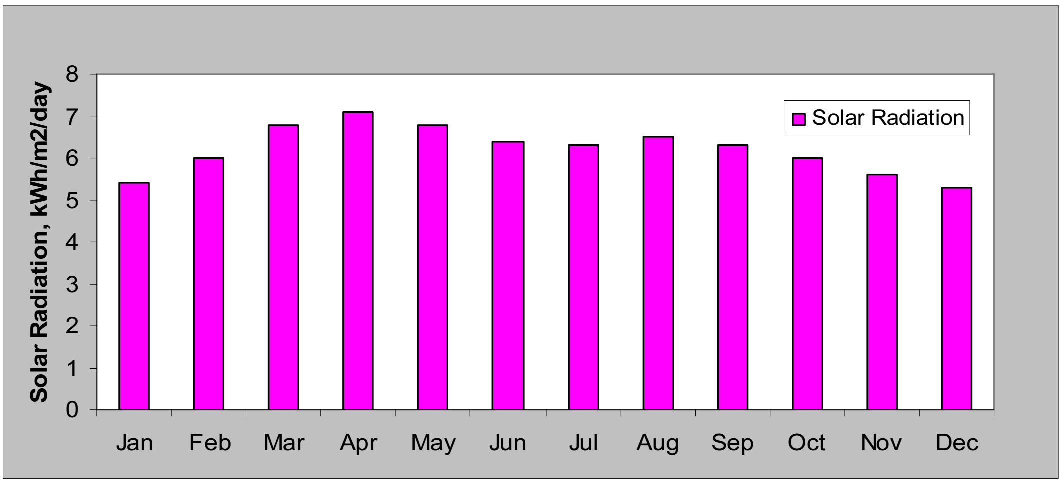

Figure (4.2.6) Monthly bar solar radiation kWh/m^2/day in Hodieba.

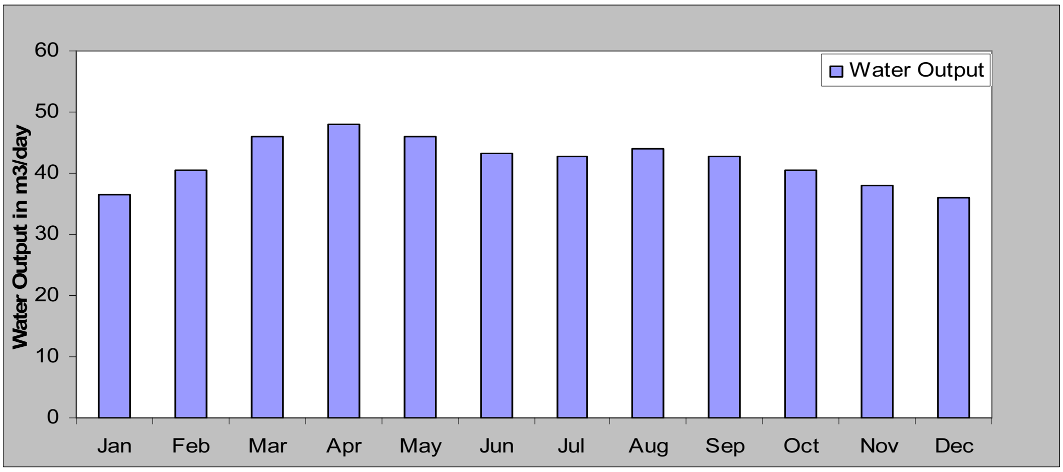

Figure (4.2.7) Monthly bar water output in m^3/day in Hodieba.

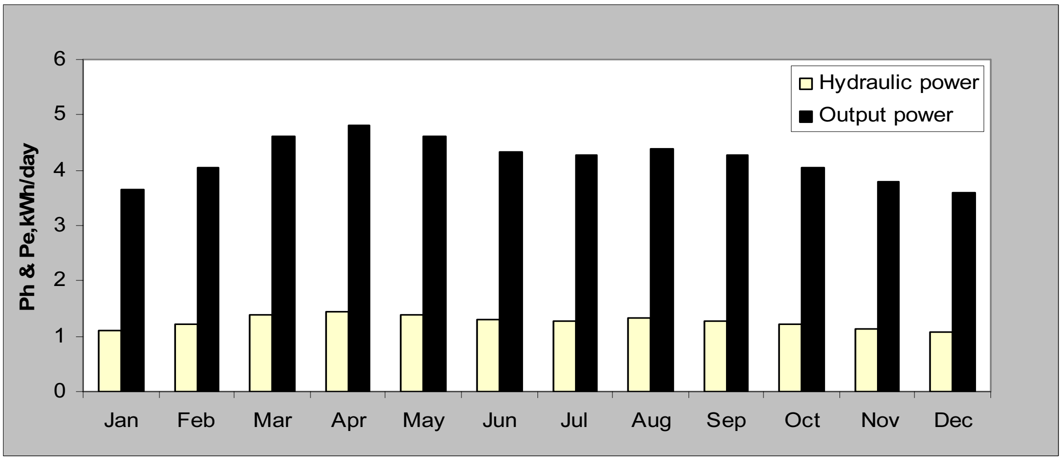

Figure (4.2.8) Monthly bar power output in kWh/day and hydraulic power in kWh/day in Hodieba.

4.3 The Third Site:-

The solar pump (Grundfos SP-8) utilizing twenty-one Arco Solar M-53 modules were installed in the village of Foja, northeast of Bara in Kordofan. The pumping head 38 m, the solar radiation about 6.5 kWh/m^2/day, the average water production of 21m^3/day.

Apply the method above and analysis in this site:

The daily hydraulic power, P_h in kWh/day

$$P_h = \rho g h Q = \frac{1000*9.81*38*21}{1000*3600} = 2.17455 kWh/day$$

The effective area of the PV array, A_{PV} in m^2

$$A_{PV} = \frac{\rho g h Q}{G_T \eta_{PV} \eta_S} = \frac{1000*9.81*38*21}{6.5*1000*3600*0.15*0.50} = 5.1775 m^2$$

The PV array power, P (in Watt-Peak, Wp)

$$P = \frac{1000 A_{PV} \eta_r}{0.7} = \frac{1000*5.1775*0.15}{0.7} = 1109.46 W_P$$

The number of module, N

$$N = \frac{1109.46}{50} = 22 \approx 21$$

The number of module connected each 7 in series to meet the system voltage requirement and the 3 in parallel to meet the system current requirements.

The daily power output, P_e in kWh/day

$$P_e = A_{PV} G_T \eta_{PV} = 5.1775*5.6*0.15 = 4.3491 kWh/day$$

The subsystem efficiency η_s

$$\eta_S = \frac{P_h}{P_e} = \frac{2.17455}{4.3491} = 0.50$$

The Overall efficiency of the PV pumping system, η_o

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} = \frac{2.17455}{5.1775 * 5.6} = 0.075$$

The result of the mathematical relation to the performance of a PV pump in the Foja illustrated in table (4.3.1) and the Figure (4.3.1) shows the possible pumping versus the solar radiation, the water production by the pump ranged from 19.13 to 27 m^3/day depending on solar radiation level, the solar radiation ranged from 5.1 kWh/m^2/day in August to 7.2 kWh/m^2/day in April in summer. Figures (4.3.2) shows the daily hydraulic power in kWh/day depending on water delivery by the pump it was increase when the water output increase. Figures (4.3.3), (4.3.4) and (4.3.5) shows the monthly solar radiation kWh/m^2/day, water output in m^3/day hydraulic power and power output in kWh/day in Foja. Also, the monthly sub-system efficiency 0.499, array efficiency 0.15 and overall efficiency 0.075 all efficiency were constant they were independent on both solar radiation and water output. Figure (4.3.6), (4.3.7) and (4.3.8) illustrated the Monthly bar of the solar radiation kWh/m^2/day, water output in m^3/day hydraulic power and output power in kWh/day in Foja.

Table (4.3.1): Performance of the water pumping system at depth of 38m in FOJA site.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Radiation	6	6.4	6.6	7.2	6.4	5.8	5.2	5.1	5.2	5.6	6	5.9
Water Out Put m3/day	22.5	24	24.75	27	24	21.75	19.5	19.13	19.5	21	22.5	22.13
Hydraulic Power (P_h in kWh/day)	2.33	2.49	2.57	2.8	2.49	2.25	2.02	1.98	2.02	2.17	2.33	2.29
Power Output (Pe in kWh/day)	4.66	4.97	5.13	5.59	4.97	4.5	4.04	3.96	4.04	4.35	4.66	4.58
Sub-System Efficiency	0.499	0.499	0.499	0.499	0.499	0.499	0.499	0.499	0.499	0.499	0.499	0.499
Overall Efficiency	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
Array Efficiency	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

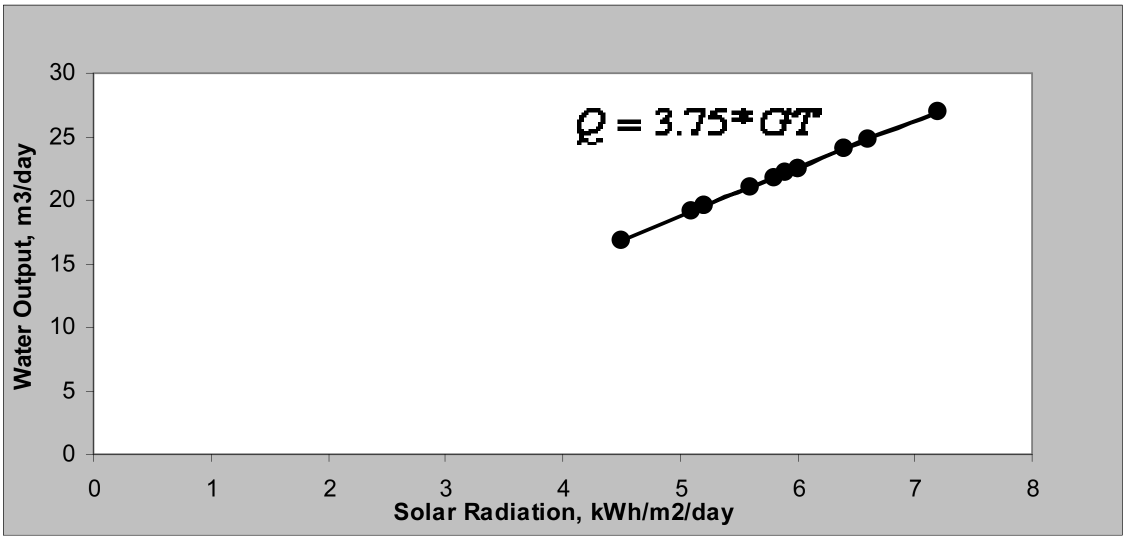

Figure (4.3.1) Possible water pumping at depth of 21m in Foja site.

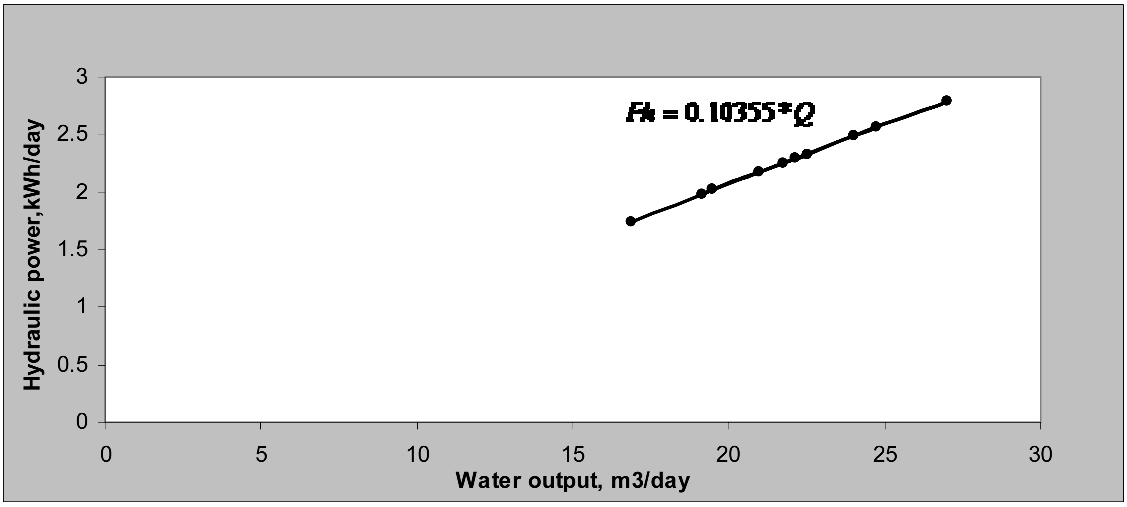

Figure (4.3.2) Hydraulic power in kWh/day against the daily water output in m^3/day.

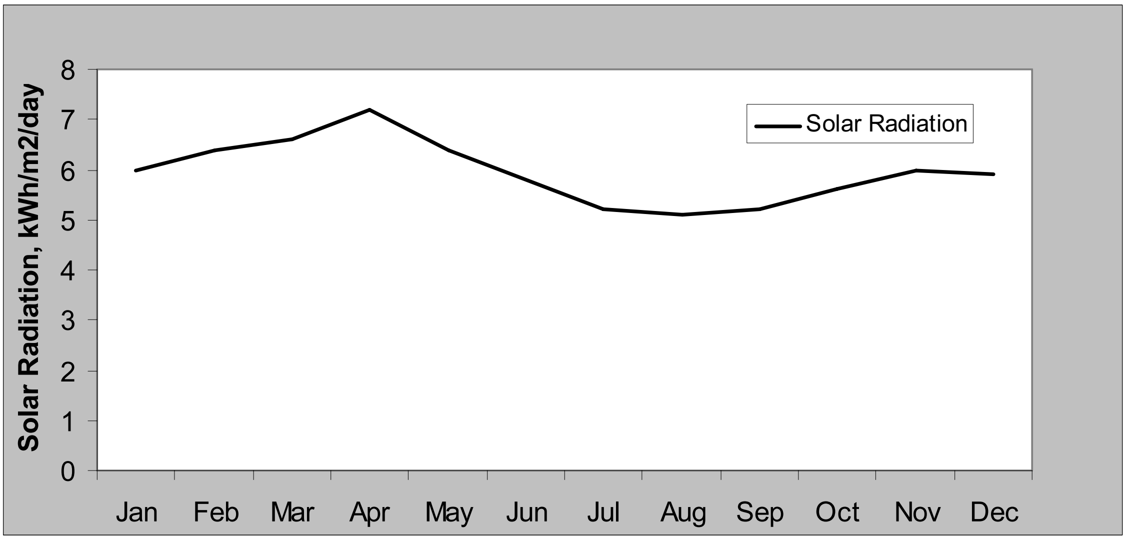

Figure (4.3.3) Monthly solar radiation in kWh/m^2/day in Foja.

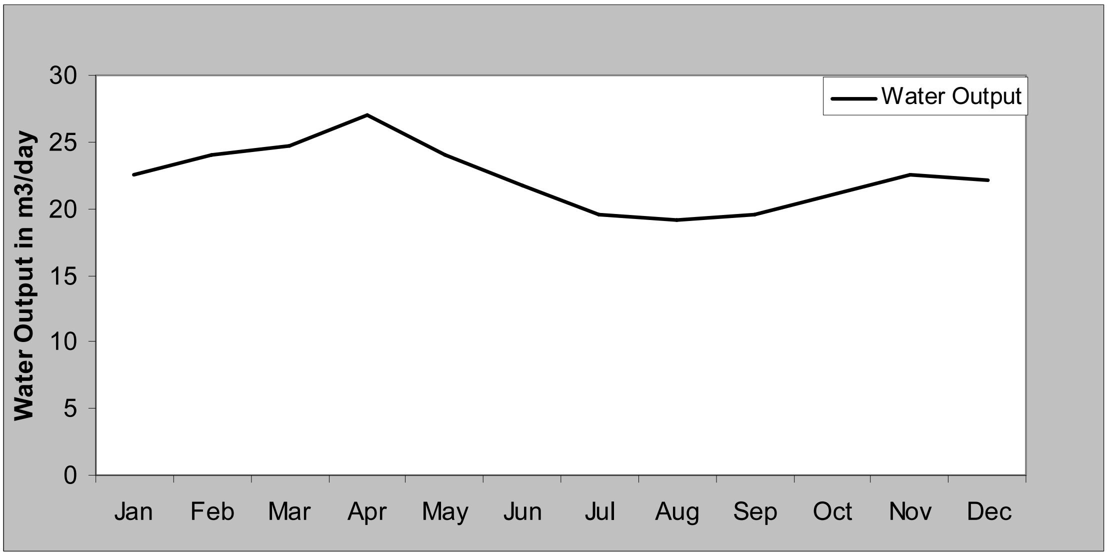

Figure (4.3.4) Monthly water output in m^3/day in Foja.

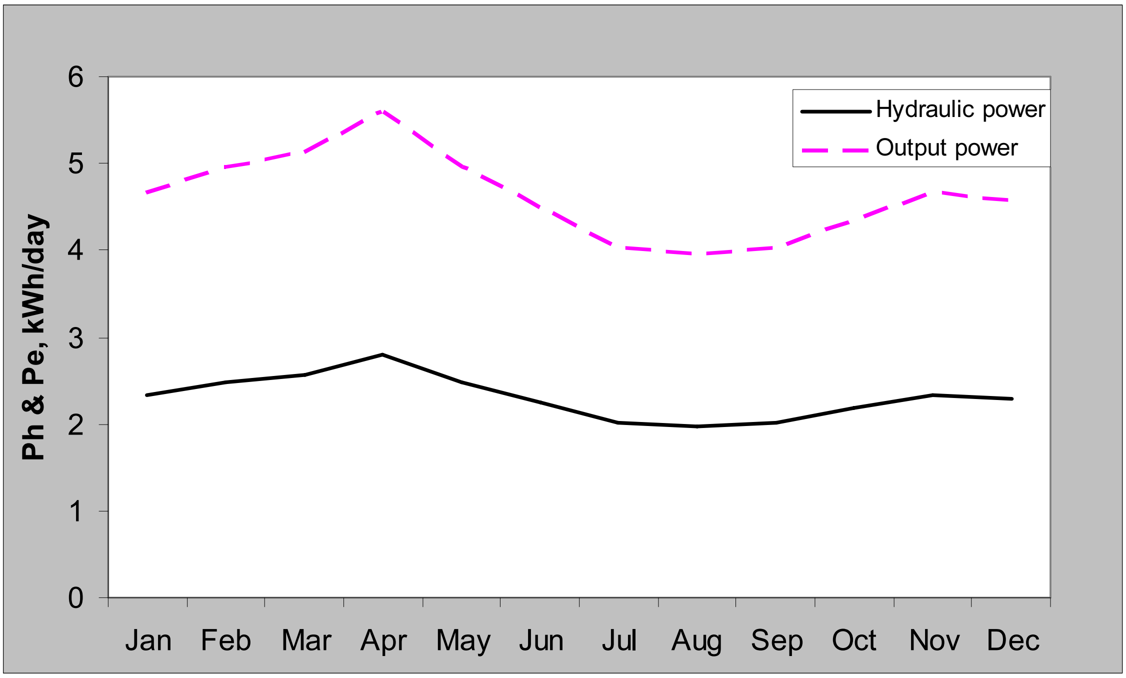

Figure (4.3.5) Monthly hydraulic power and power output in kWh/day in Foja.

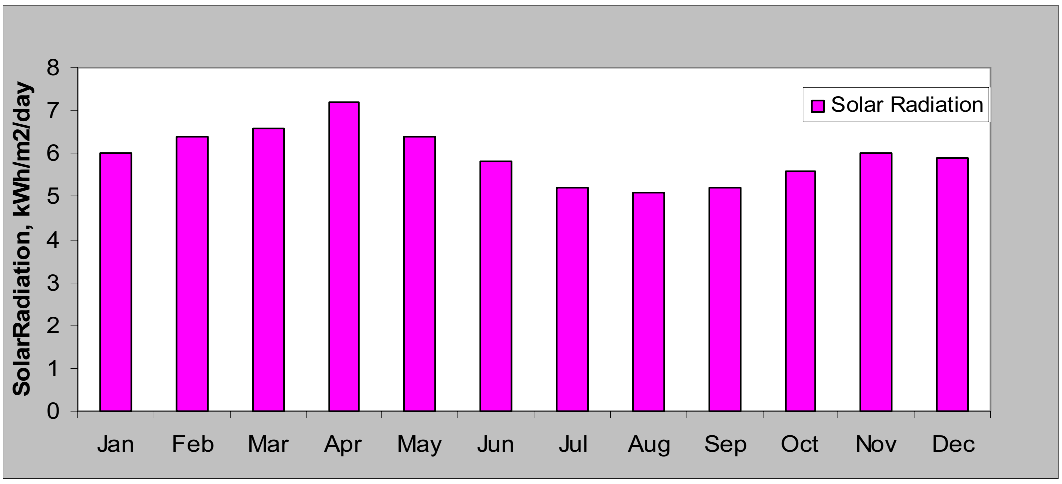

Figure (4.3.6) Monthly bar solar radiation kWh/m^2/day in Foja.

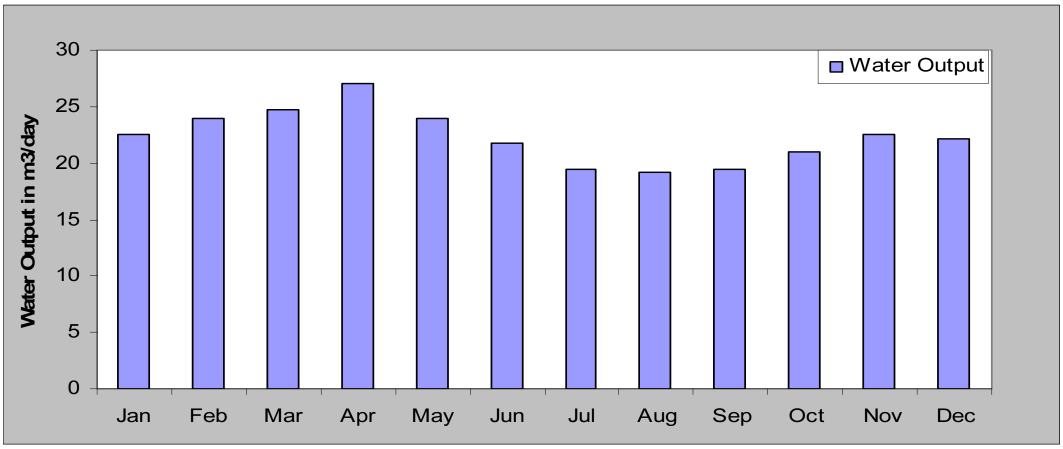

Figure (4.3.7) Monthly bar water output in m^3/day in Foja.

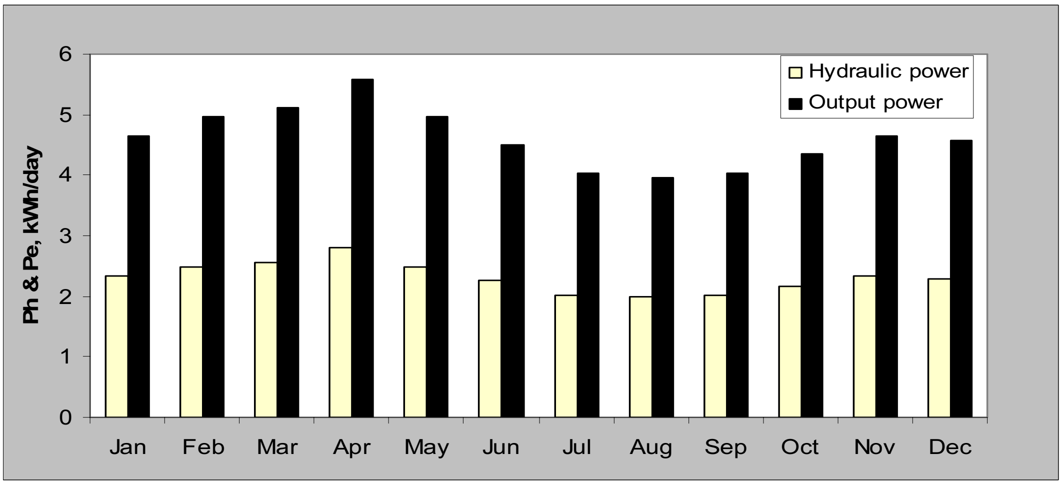

Figure (4.3.8) Monthly bar hydraulic power and output power in kWh/day in Foja.

4.4 The Fourth Site:-

The PV solar pumping system was installed at Mayo area in Khartoum. The system consists of three main parts:-

The solar generator

The invertor

The motor pump unit

The solar generator consists of 28 Siemens Solar modules type SM55, so the system 1.484 kW peak. The PV modules were connected each 7 in series to meet the system voltage requirement and the 4 in parallel to meet the system current requirements. The PV array was tilted 20° to give maximum yield and it was installed near the well to minimize the transmission loss and in such away to protect from damage by children and goats.

The pumping head 22 m, the water out put 45m^3/day and the solar radiation 5.7 kWh/m^2/day. For the purpose of the system characterization the following quantities were calculated:-

The daily hydraulic power, P_h in kWh/day

$$P_h = \rho g h Q = \frac{1000*9.81*22*45}{1000*3600} = 2.69775 kWh/day$$

The effective area of the PV array, A_{PV} in m^2

$$A_{PV} = \frac{\rho g h Q}{G_T \eta_{PV} \eta_S} = \frac{1000*9.81*22*45}{6.4*1000*3600*0.15*0.39} = 7.2055 m^2$$

The PV array power, P (in Watt-Peak, Wp)

$$P = \frac{1000 A_{PV} \eta_r}{0.7} = \frac{1000*7.2055*0.15}{0.7} = 1544 W_P$$

The number of module, N

$$N = \frac{1544}{55} = 28.07 \approx 28$$

The daily power output, P_e in kWh/day

$$P_e = A_{PV} G_T \eta_{PV} = 7.2055 * 6.4 * 0.15 = 6.9 kWh / day$$

The subsystem efficiency η_s

$$\eta_S = \frac{P_h}{P_e} = \frac{2.69775}{6.9} = 0.39$$

The Overall efficiency of the PV pumping system, η_o

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} = \frac{2.69775}{7.2055 * 6.4} = 0.058$$

The result of the mathematical relation to the performance of a PV pump in the Mayo illustrated in table (4.4.1) and the Figure (4.4.1) shows the possible water pumping versus the solar radiation, the water output by the pump ranged from 37.6 to 49.5 m^3/day depending on solar radiation level, the solar radiation ranged from 5.4 kWh/m^2/day in December to 7.1 hWh/m^2/day in April in summer. Figure (4.4.2) shows the daily hydraulic power in kWh/day depending on water delivery by the pump it was increase when the water output increase. Figures (4.4.3), (4.4.4) and (4.4.5) show the monthly solar radiation kWh/m^2/day, water output in m^3/day hydraulic power and output power in kWh/day in Mayo. Also, monthly sub-system efficiency 0.39, array efficiency 0.15 and overall efficiency 0.058 all efficiency were constant they were independent on both solar radiation and water output. Figures (4.4.6), (4.4.7) and (4.4.8) illustrated the Monthly bar of the solar radiation kWh/m^2/day, water output in m^3/day hydraulic power and output power in kWh/day in Mayo.

Table (4.4.1): Performance of the solar water pumping system at depth of 22m in Mayo site.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Radiation	5.6	6.4	6.8	7.1	6.8	6.5	6.3	6.3	6.3	6	5.7	5.4
Water Output m3/day	39.03	44.6	47.4	49.5	47.4	45.3	43.9	43.9	43.9	41.8	39.7	37.6
Hydraulic Power (P_h in kWh/day)	2.34	2.67	2.8	2.97	2.8	2.7	2.6	2.6	2.6	2.5	2.4	2.26
Power Output (Pe in kWh/day)	6.05	6.9	7.35	7.67	7.35	7.03	6.8	6.8	6.8	6.48	6.16	5.8
Sub-System Efficiency	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387	0.387
Overall Efficiency	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058
Array Efficiency	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

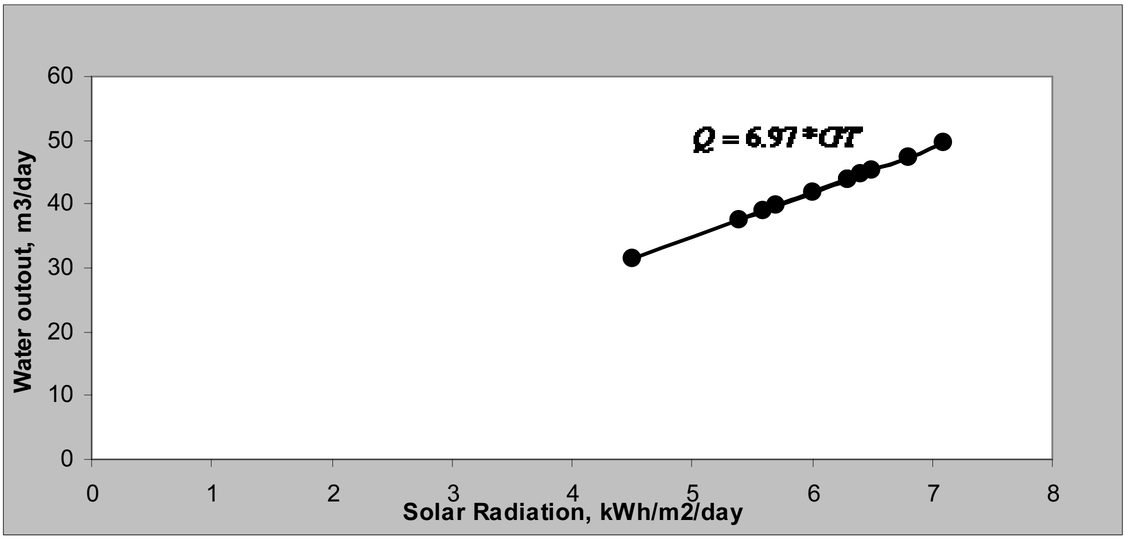

Figure (4.4.1) Possible water pumping at depth of 21 m in Mayo site.

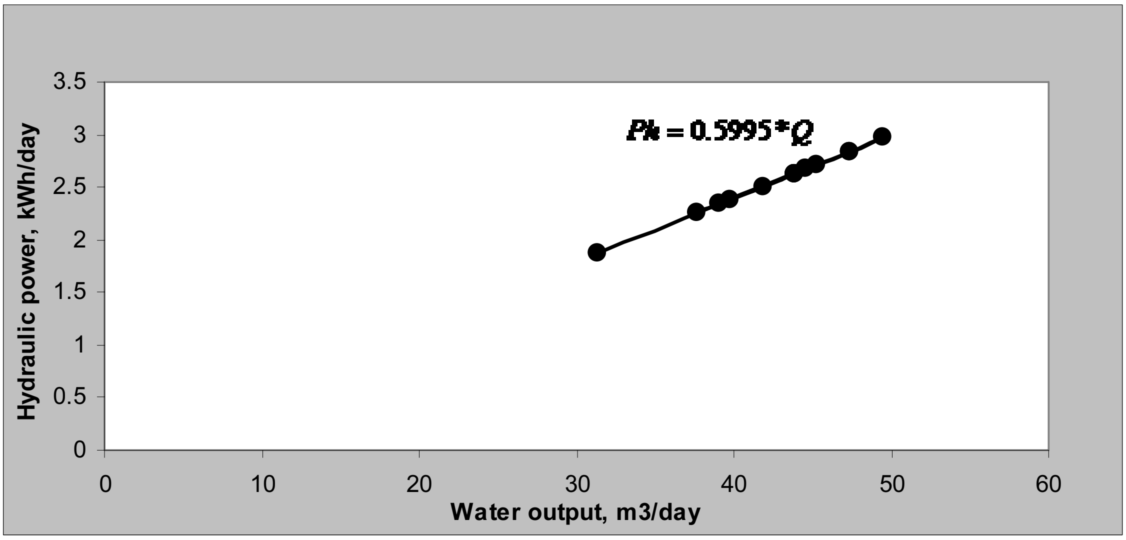

Figure (4.4.2) Hydraulic power in kWh/day against the daily water output in m^3/day.

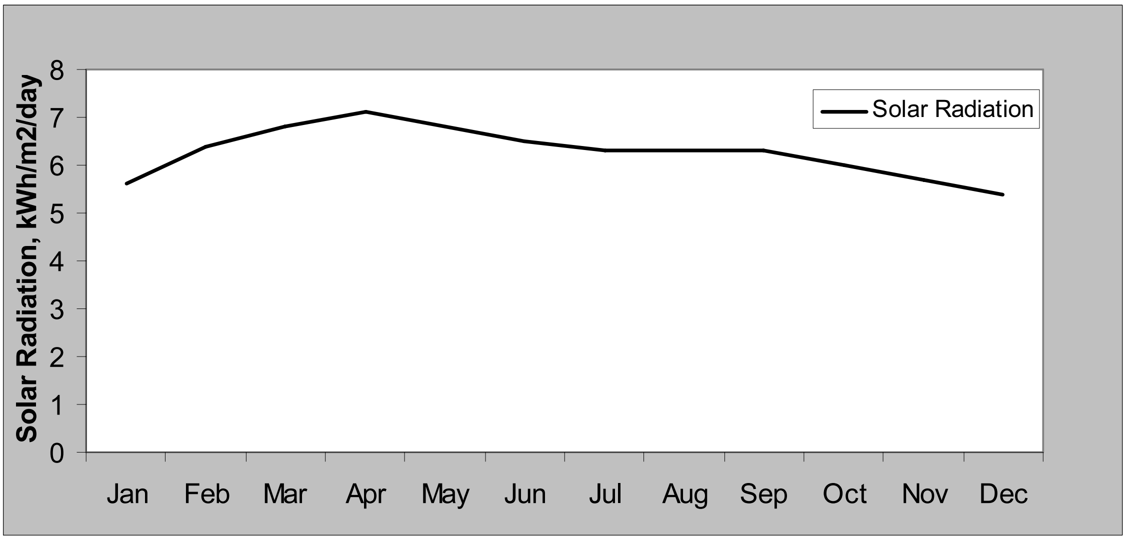

Figure (4.4.3) Monthly solar radiation kWh/m^2/day in Mayo.

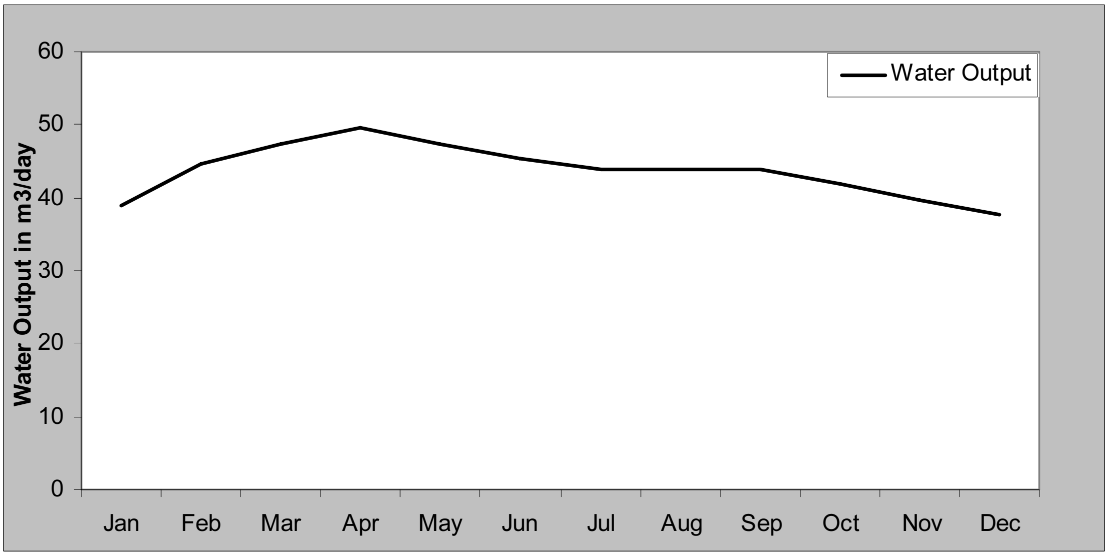

Figure (4.4.4) Monthly water output in m^3/day in Mayo.

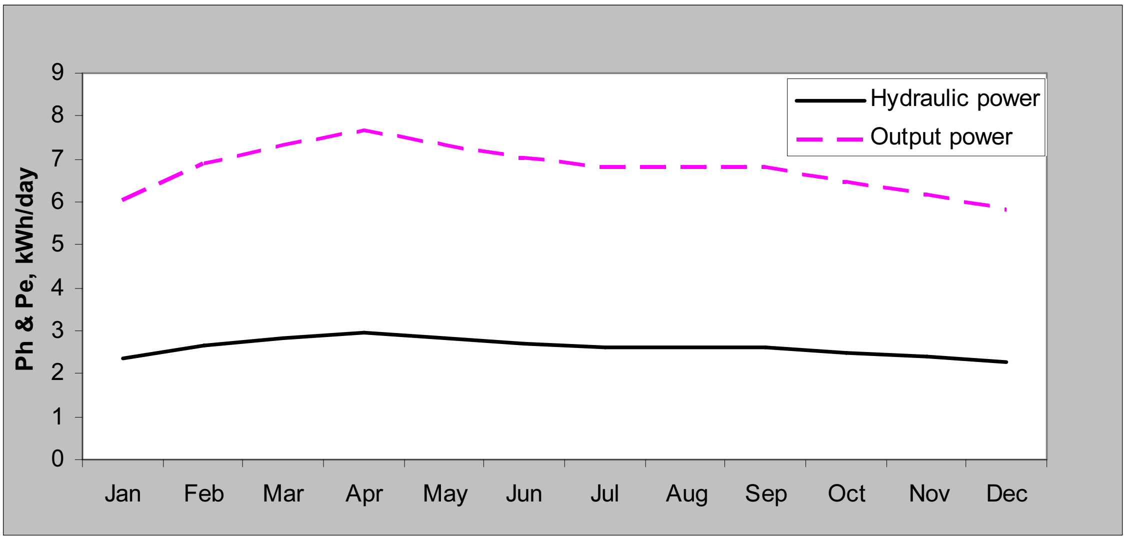

Figure (4.4.5) Monthly hydraulic power and output power in kWh/day in Mayo.

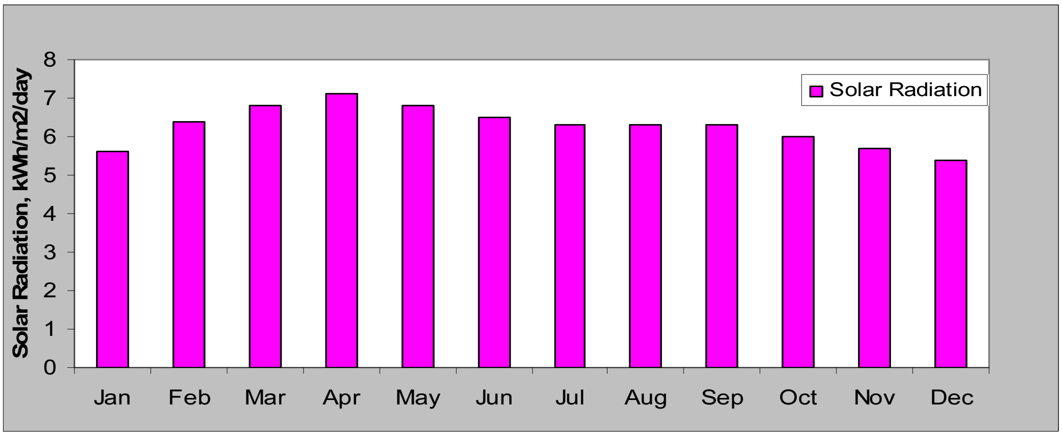

Figure (4.4.6) Monthly solar radiation kWh/m^2/day in Mayo.

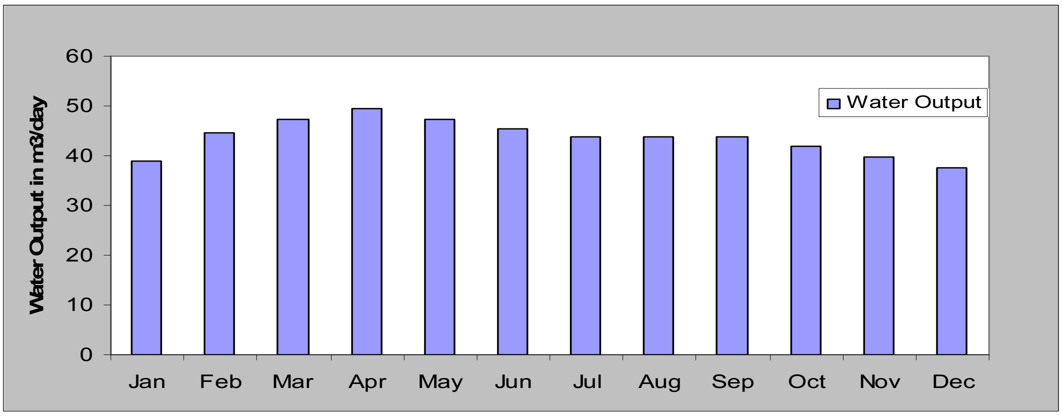

Figure (4.4.7) Monthly water output in m^3/day in Mayo.

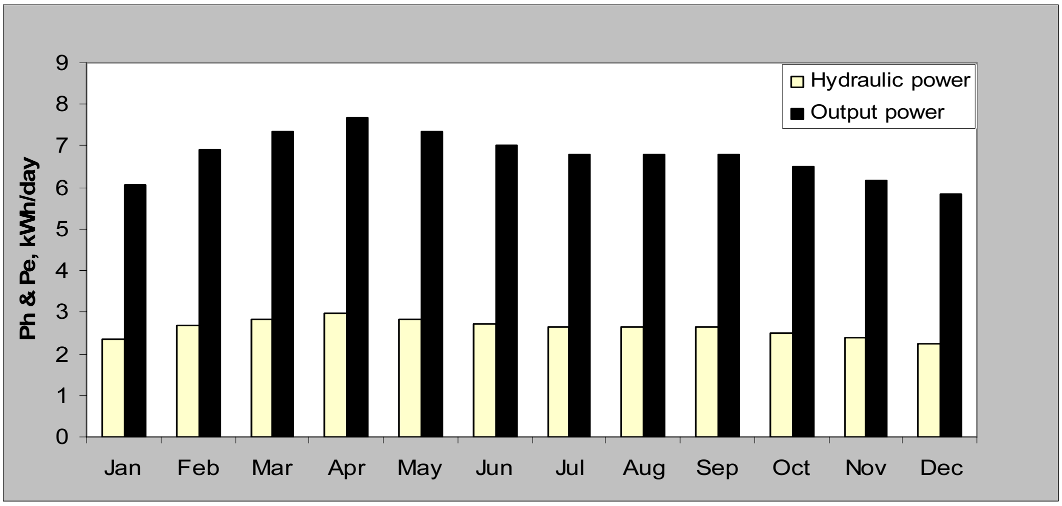

Figure (4.4.8) Monthly hydraulic power and output power in kWh/day in Mayo.

4.5 The Fifth Site:-

The PV solar pumping system was installed at Nyala city in South Darfour. The system consists of three main parts:-

1-The solar generator

2-The invertor

3. The motor pump unit

The PV modules were connected each 6 in series to meet the system voltage requirement and the 4 in parallel to meet the system current requirements.

The motor pump unit under investigation is Grundfos SP 5A-7.

The pumping head 30 m, the water out put $40m^3$/day and the solar radiation 6.4 kWh/m^2/day. For the purpose of the system characterization the following quantities were calculated:-

The daily hydraulic power, P_h in kWh/day

$$P_h = \rho ghQ = \frac{1000*9.81*30*40}{1000*3600} = 3.27 kWh/day$$

The effective area of the PV array, A_{PV} in m^2

$$A_{PV} = \frac{\rho ghQ}{G_T \eta_{PV} \eta_S} = \frac{1000*9.81*30*40}{6.4*1000*3600*0.15*0.65} = 5.24 m^2$$

The PV array power, P in Watt-Peak, Wp

$$P = \frac{1000 A_{PV} \eta_r}{0.7} = \frac{1000*5.24*0.15}{0.7} = 1122.9 W_P$$

The number of module, N

$$N = \frac{1122.9}{50} = 22.5 \approx 24$$

The number of module connected each 6 in series to meet the system voltage requirement and the 4 in parallel to meet the system current requirements.

The daily power output, P_e in kWh/day

$$P_e = A_{PV} G_T \eta_{PV} = 5.24 * 6.4 * 0.15 = 5.0304 kWh$$

The subsystem efficiency η_s

$$\eta_S = \frac{P_h}{P_e} = \frac{3.27}{5.0304} = 0.65$$

The Overall efficiency of the PV pumping system, η_o

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} = \frac{3.27}{5.24 * 6.4} = 0.0975$$

The result of the mathematical relation to the performance of a PV pump in the Nyala illustrated in table (4.5.1) and the Figure (4.5.1) shows the possible water pumping versus the solar radiation, the water output by the pump ranged from 36.25 to 44.37 m^3/day depending on solar radiation level, the solar radiation ranged from 5.8 kWh/m^2/day in December to 7.1 kWh/m^2/day in March and April in summer. Figure (4.5.2) shows the daily hydraulic power in kWh/day depending on water delivery by the pump it was increase when the water output increase. Figures (4.5.3), (4.5.4) and (4.5.5) show the monthly solar radiation in kWh/m^2/day, water output in m^3/day, hydraulic power kWh/day and power output in kWh/day. Also, monthly sub-system efficiency 0.65, array efficiency 0.15 and overall efficiency 0.0975 all efficiency were constant they were independent on both solar radiation and water output. Figure (4.5.6), (4.5.7) and (4.5.8) illustrated the monthly bar of solar radiation in kWh/m^2/day, water output in m^3/day and output power in kWh/day and hydraulic power kWh/day.

Table (4.5.1): Performance of the solar pumping system at depth of 30 in Nyala site.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Radiation	6.1	6.6	7.1	7.1	7	5.8	5.8	5.9	6	6.3	6.3	6
Water Output m3/day	38.12	41.25	44.37	44.37	43.75	36.25	36.25	36.87	37.5	39.37	39.37	37.5
Hydraulic Power (Ph in kWh/day)	3.12	3.37	3.63	3.63	3.78	2.96	2.96	3.02	3.07	3.22	3.22	3.07
Power Output (Pe in kWh/day)	4.79	5.19	5.58	5.58	5.5	4.56	4.56	4.64	4.7	4.95	4.95	4.7
Sub-System Efficiency	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Overall Efficiency	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097
Array Efficiency	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

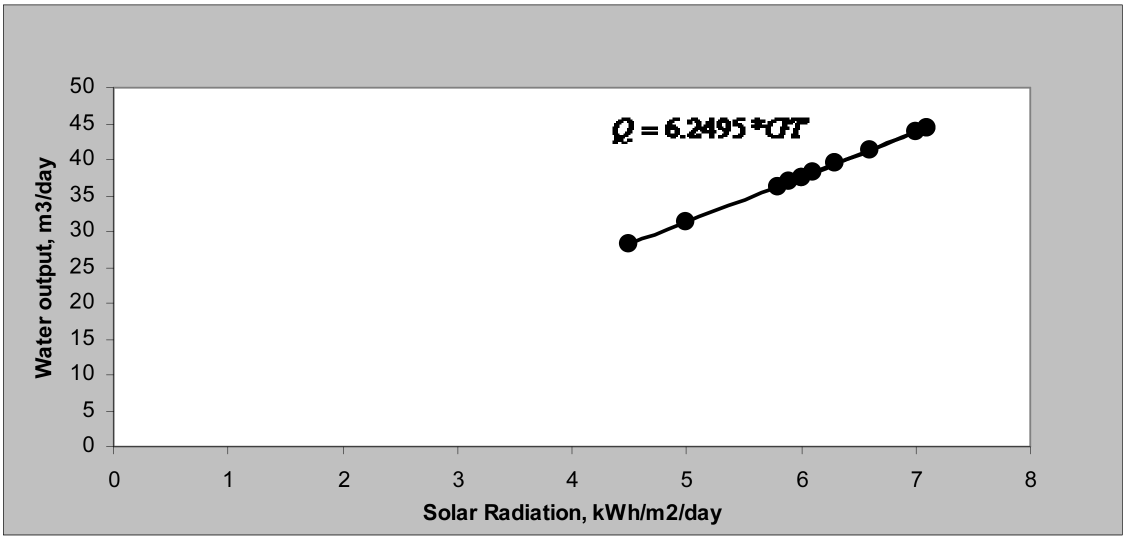

Figure (4.5.1) Possible water pumping at depth of 38 m in Nyala site.

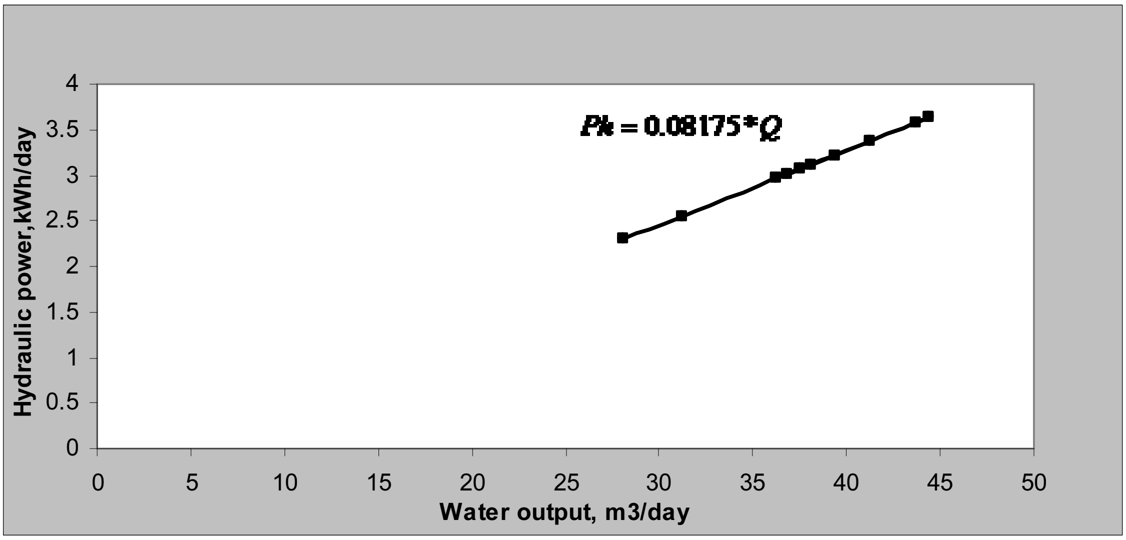

Figure (4.5.2) Hydraulic power in kWh/day against the daily water output in m^3/day.

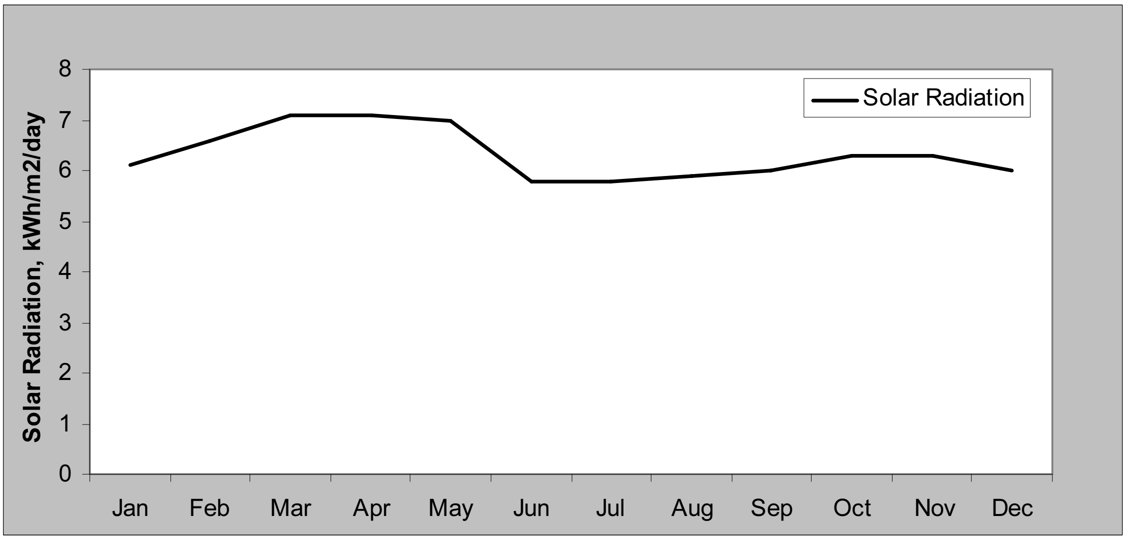

Figure (4.5.3) Monthly solar radiation in kWh/m^2/day in Nyala.

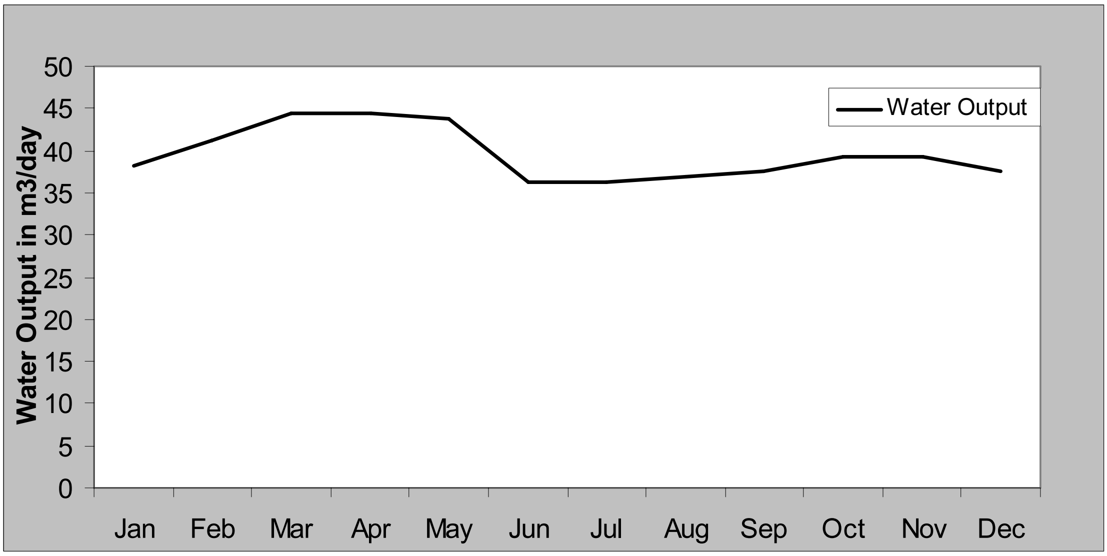

Figure (4.5.4) Monthly water output in m^3/day in Nyala.

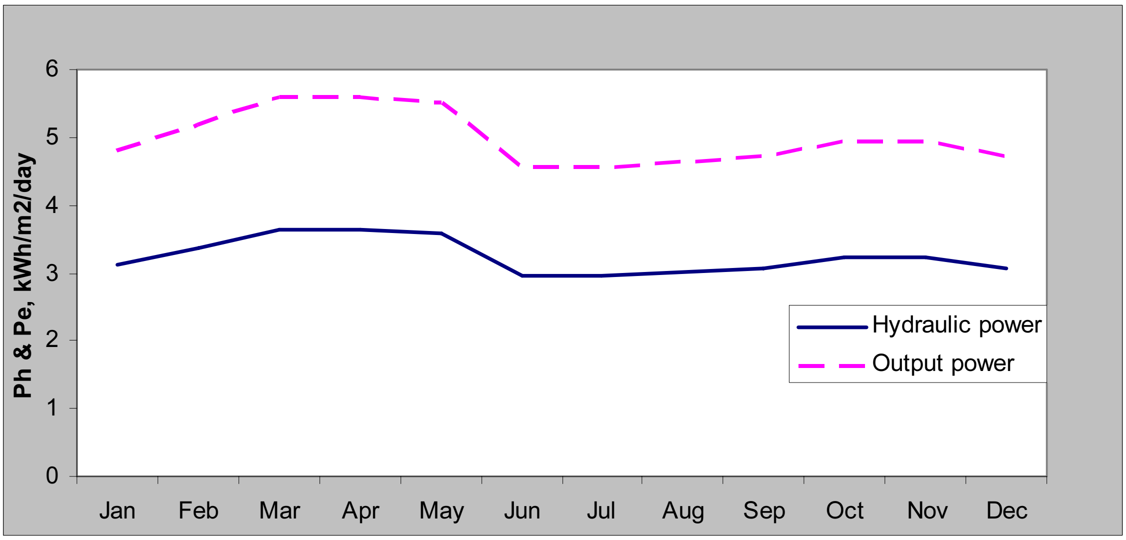

Figure (4.5.5) Monthly hydraulic power kWh/day and power output in kWh/day in Nyala.

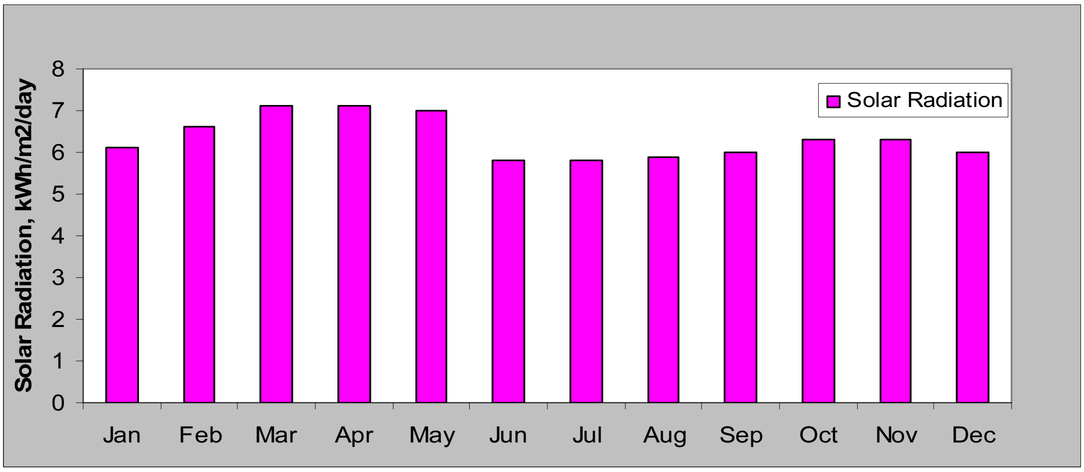

Figure (4.5.6) Monthly bar solar radiation in kWh/m^2/day in Nyala.

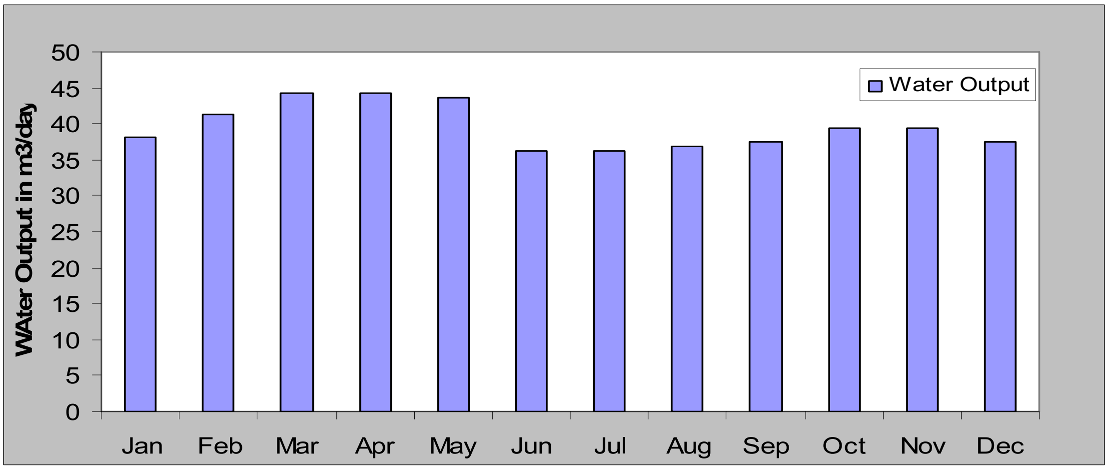

Figure (4.5.7) Monthly bar water output in m^3/day, in Nyala.

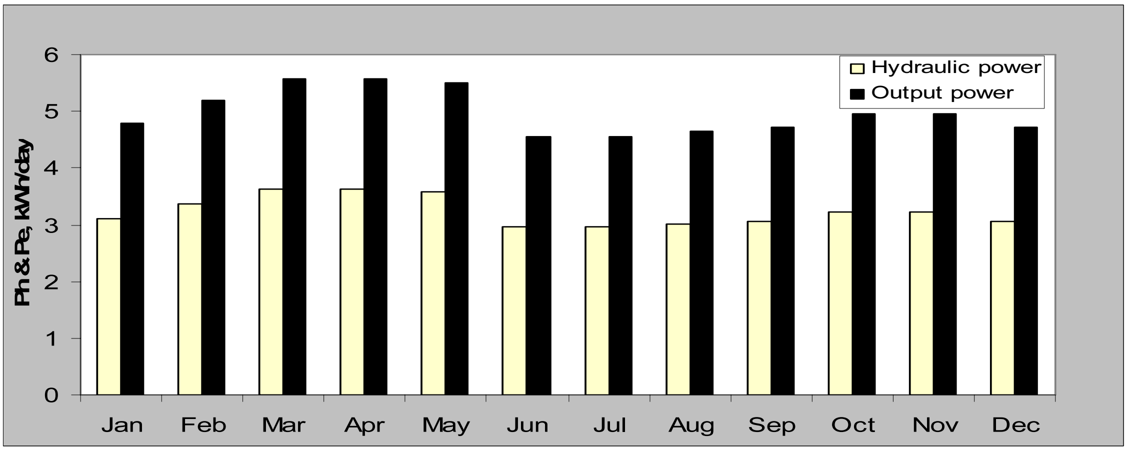

Figure (4.5.8) Monthly bar hydraulic power kWh/day power output in kWh/day in Nyala.

4.6 The Sixth Site:-

The solar pump (Grundfos SP 3A-10) was installed in the village of Aldoma in Kordofan. The total pumping head 42.5m and the solar radiation about 6.6 kWh/m^2/day with water production of 30 m^3/day.

Apply the method above and analysis in this site:

The daily hydraulic power, P$_h$ in kWh/day

$$P_h = \rho g h Q = \frac{1000*9.81*42.5*30}{1000*3600} = 3.474 kWh/day$$

The effective area of the PV array, A$_{PV}$ in m^2

$$A_{PV} = \frac{\rho g h Q}{G_T \eta_{PV} \eta_S} = \frac{1000*9.81*42.5*30}{6.6*1000*3600*0.15*0.49} = 7.162 m^2$$

The PV array power, P in Watt-Peak, Wp

$$P = \frac{1000 A_{PV} \eta_r}{0.7} = \frac{1000*7.162*0.15}{0.7} = 1534.7 W_P$$

The number of module, N

$$N = \frac{1534.7}{50} = 31 \approx 32$$

The number of module connected each 8 in series to meet the system voltage requirement and the 4 in parallel to meet the system current requirements.

The daily power out put, P$_e$ in kWh/day

$$P_e = A_{PV} G_T \eta_{PV} = 7.162*6.6*0.15 = 7.09 kWh/day$$

The subsystem efficiency η_s

$$\eta_S = \frac{P_h}{P_e} = \frac{3.474}{7.09} = 0.49$$

The Overall efficiency of the PV pumping system, η_o

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} = \frac{3.474}{7.162 * 6.6} = 0.074$$

The result of the mathematical relation to the performance of a PV pump in the Aldoma illustrated in table (4.6.1) and the Figure (4.6.1) shows the possible water pumping versus the solar radiation, the water output by the pump ranged from 24.7 to 31.1m^3/day depending on solar radiation level. The solar radiation ranged from 5.4kWh/m^2/day in December to 6.8kWh/m^2/day in April in summer. Figure (4.6.2) shows the daily hydraulic power in kWh/day depending on water delivery by the pump it was increase when the water output increase. Figures (4.6.3), (4.6.4) and (4.6.5) showed the monthly solar radiation in kWh/m^2/day, water output in m^3/day, power output in kWh/day and Hydraulic power in kWh/day. Also, monthly the sub-system efficiency is 0.49, array efficiency is 0.15 and overall efficiency is 0.074 all efficiency were constant they were independent on both solar radiation and water output. Figures (4.6.6), (4.6.7) and (4.6.8) illustrated the monthly bar of solar radiation in kWh/m^2/day, water output in m^3/day, power output in kWh/day and hydraulic power in kWh/day in Aldoma.

Table (4.6.1): Performance of the system at depth of 42.5 m in Aldoma site.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Radiation	5.7	6.3	6.7	6.8	6.6	6.3	5.7	5.8	6	5.7	5.5	5.4
Water Output m3/day	26.08	28.8	30.7	31.1	30	28.8	26.08	26.5	27.5	26.08	25.17	24.7
Hydraulic Power (Ph in kWh/day)	3.02	3.34	3.55	3.6	3.5	3.34	3.02	3.07	3.18	3.02	2.9	2.86
Power Output (Pe in kWh/day)	6.12	6.77	7.2	7.03	7.09	6.77	6.12	6.23	6.5	6.12	5.9	5.8
Sub-System Efficiency	0.493	0.493	0.493	0.493	0.493	0.493	0.493	0.493	0.493	0.493	0.493	0.493
Overall Efficiency	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074
Array efficiency	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

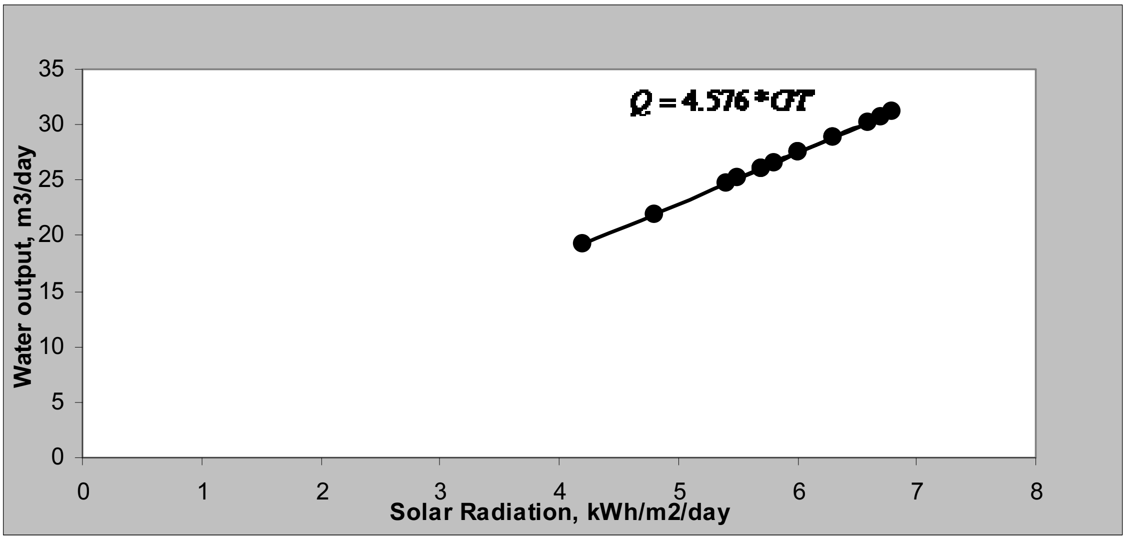

Figure (4.6.1) Possible water pumping at depth of 42.5m in Aldoma site.

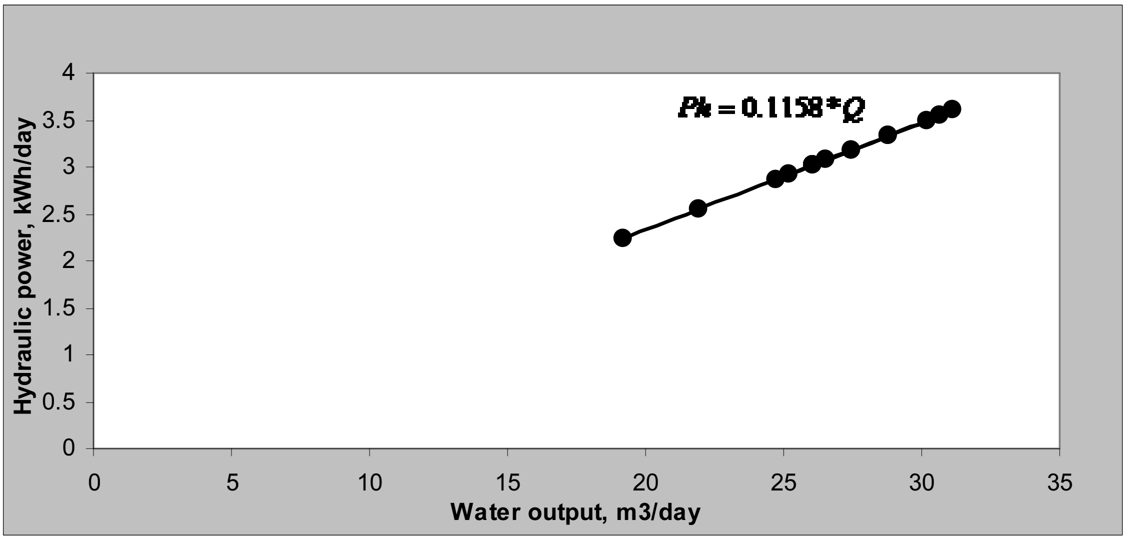

Figure (4.6.2) Hydraulic power output in kWh/day against the water output in m^3/day.

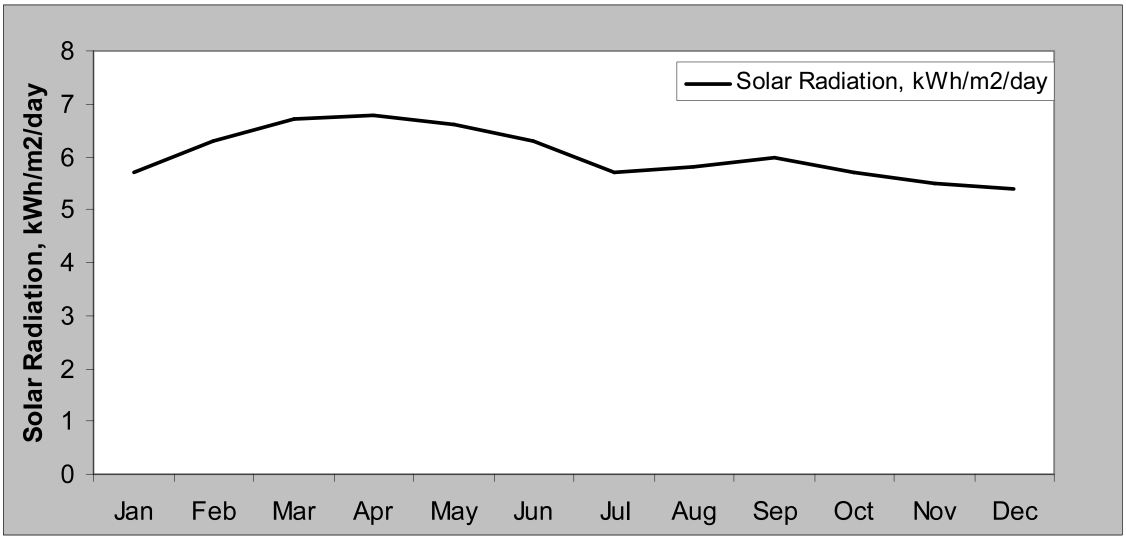

Figure (4.6.3) Monthly solar radiation in kWh/m^2/day in Aldoma.

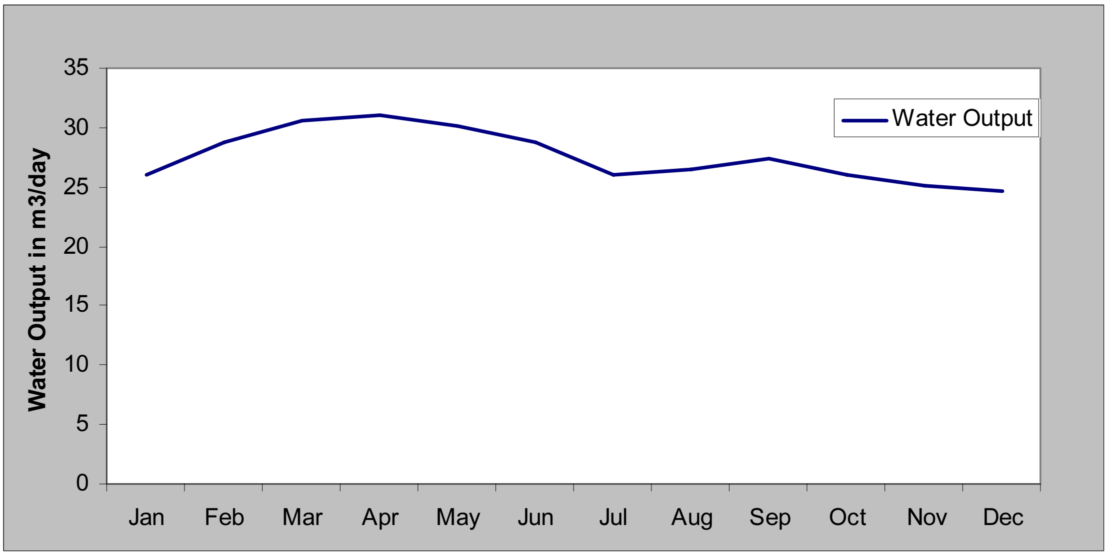

Figure (4.6.4) Monthly water output in m^3/day in Aldoma.

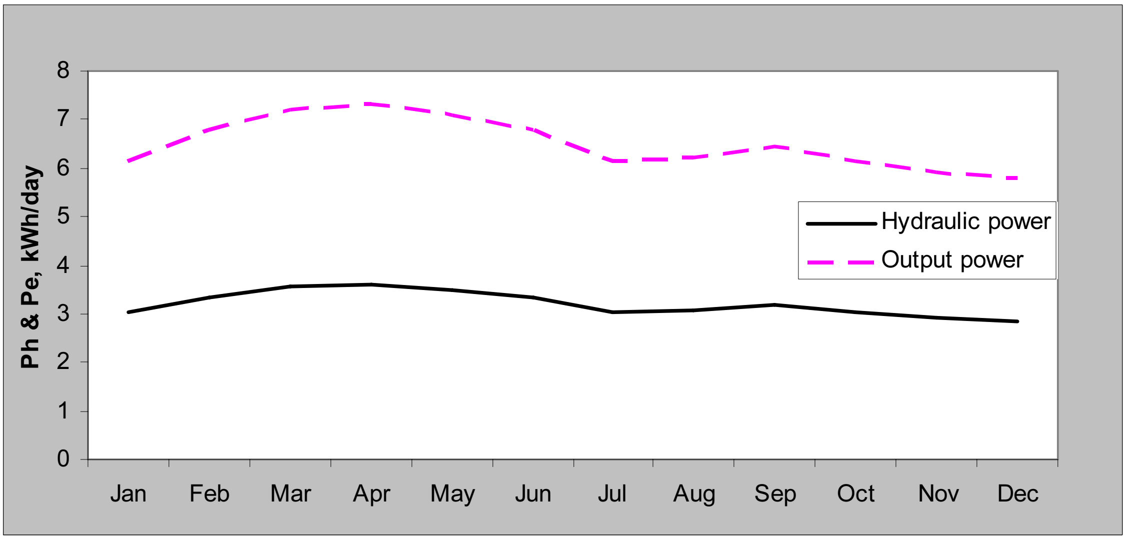

Figure (4.6.5) Monthly power output in kWh/day and hydraulic power in kWh/day in Aldoma.

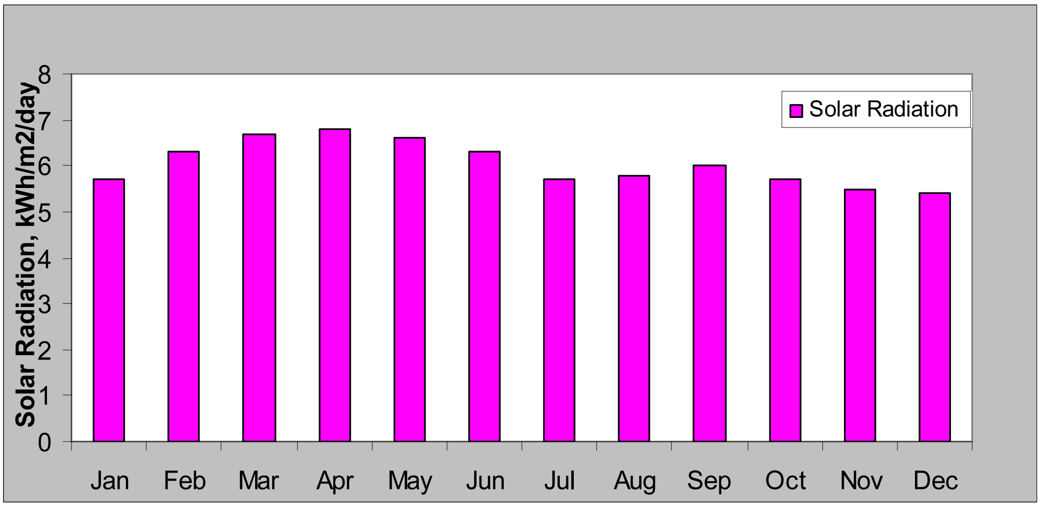

Figure (4.6.6) Monthly bar solar radiation in kWh/m^2/day in Aldoma.

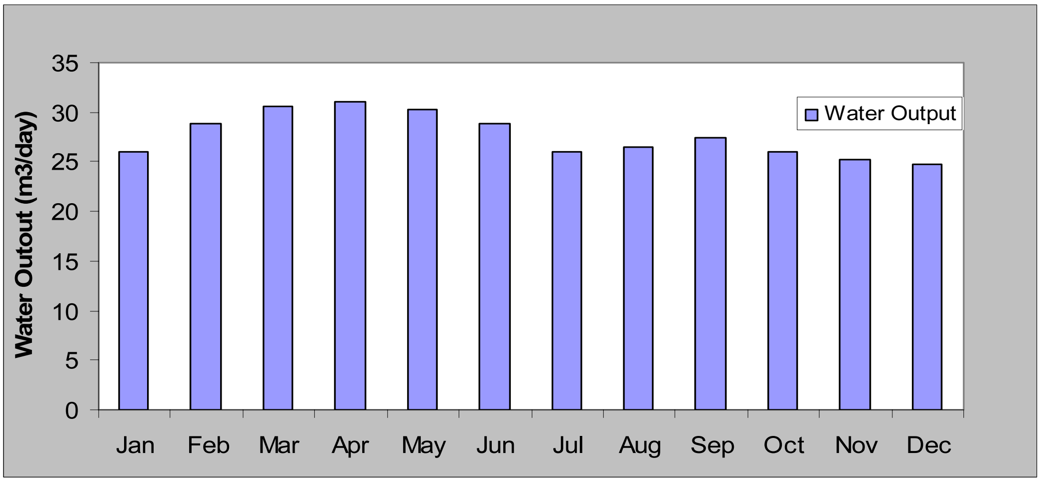

Figure (4.6.7) Monthly bar water output in m^3/day in Aldoma.

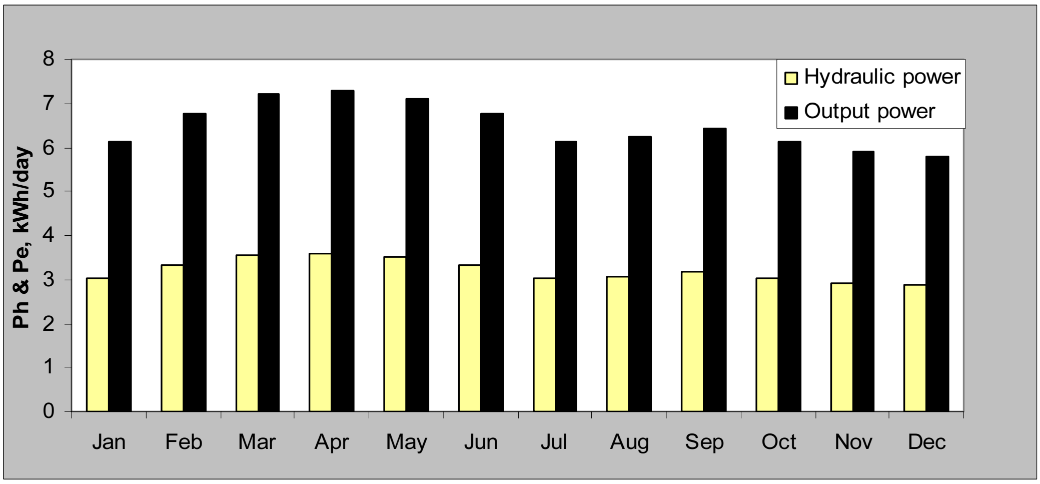

Figure (4.6.8) Monthly bar power output in kWh/day and hydraulic power in kWh/day in Aldoma.

4.7 The Seventh Site:-

The solar pump (Grundfos SP 5A-7) was installed in the village in South Kordofan. The pumping head 40 m, the solar radiation about 6.5kWh/m^2/day and the water production of 27 m^3/day.

Apply the method above and analysis in this site:

The daily hydraulic power, P_h in kWh/day

$$P_h = \rho g h Q = \frac{1000 * 9.81 * 40 * 27}{1000 * 3600} = 2.943 kWh/day$$

The effective area of the PV array, A_{PV} in m^2

$$A_{PV} = \frac{\rho g h Q}{G_T \eta_{PV} \eta_S} = \frac{1000 * 9.81 * 40 * 27}{6.0 * 1000 * 3600 * 0.15 * 0.45} = 7.27 m^2$$

The PV array power, P in Watt-Peak, Wp

$$P = \frac{1000 A_{PV} \eta_r}{0.7} = \frac{1000 * 7.27 * 0.15}{0.7} = 1557.14 W_P$$

The number of module, N

$$N = \frac{1557.14}{50} = 31.14 \approx 32$$

The number of module connected each 8 in series to meet the system voltage requirement and the 4 in parallel to meet the system current requirements.

The daily power out put, P_e in kWh/day

$$P_e = A_{PV} G_T \eta_{PV} = 7.27 * 6.0 * 0.15 = 6.543 kWh/day$$

The subsystem efficiency η_s

$$\eta_S = \frac{P_h}{P_e} = \frac{2.943}{6.543} = 0.45$$

The Overall efficiency of the PV pumping system, η_o

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} = \frac{2.943}{7.27 * 6.0} = 0.0675$$

The result of the mathematical relation to the performance of a PV pump in the village in South Kordofan illustrated in table (4.7.1) and the Figure (4.7.1) shows the possible water pumping versus the solar radiation, the water pumped by the pump ranged from 22.95 to 30 m^3/day depending on solar radiation level, The solar radiation ranged from 5.1 kWh/m^2/day in August to 6.7 kWh/m^2/day in April in summer. Figure (4.7.2) shows the daily hydraulic power in kWh/day depending on water delivery by the pump it was increase when the water output increase. Figures (4.7.3), (4.7.4) and (4.7.5) shows the monthly solar radiation in kWh/m^2/day, water output in m^3/day, output power in kWh/day and hydraulic power in kWh/day. Also, the monthly sub-system efficiency is 0.45, array efficiency is 0.15 and overall efficiency is 0.0675 all efficiency were constant they were independent on both solar radiation and water output. Figures (4.7.6), (4.7.7) and (4.7.8) illustrated the monthly solar radiation in kWh/m^2/day, water output in m^3/day, output power in kWh/day and hydraulic power in kWh/day.

Table (4.7.1): Performance of the solar water pumping system at depth of 21 in South Kordofan site.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Radiation	6	6.4	6.6	6.7	6.4	5.8	5.2	5.1	5.2	5.8	6	5.9
Water output m3/day	27	28.8	30.7	30	28.8	26	23.4	22.95	23.4	26.1	27	26.6
Hydraulic power (Ph in kWh/day)	2.9	3.14	3.24	3.29	3.14	2.8	2.55	2.5	2.55	2.8	2.9	2.89
Power output (Pe in kWh/day)	6.5	6.98	7.2	7.03	6.98	6.3	5.67	5.56	5.67	6.3	6.5	6.4
Sub-System Efficiency	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Overall Efficiency	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
Array efficiency	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

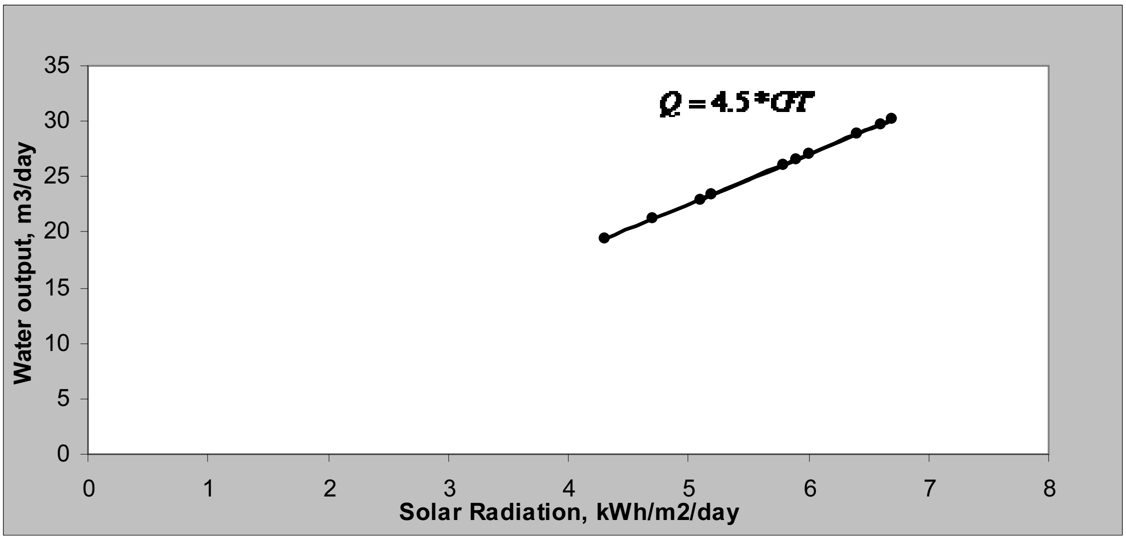

Figure (4.7.1) Possible water pumping at depth of 40m in South Kordofan site.

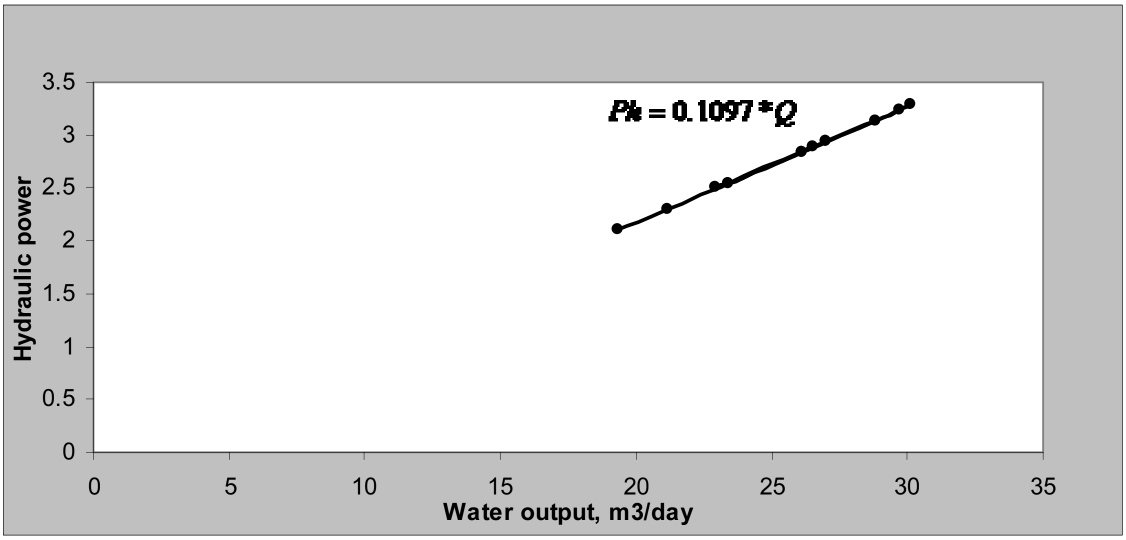

Figure (4.7.2) Hydraulic power output in kWh/day against the water output in m^3/day.

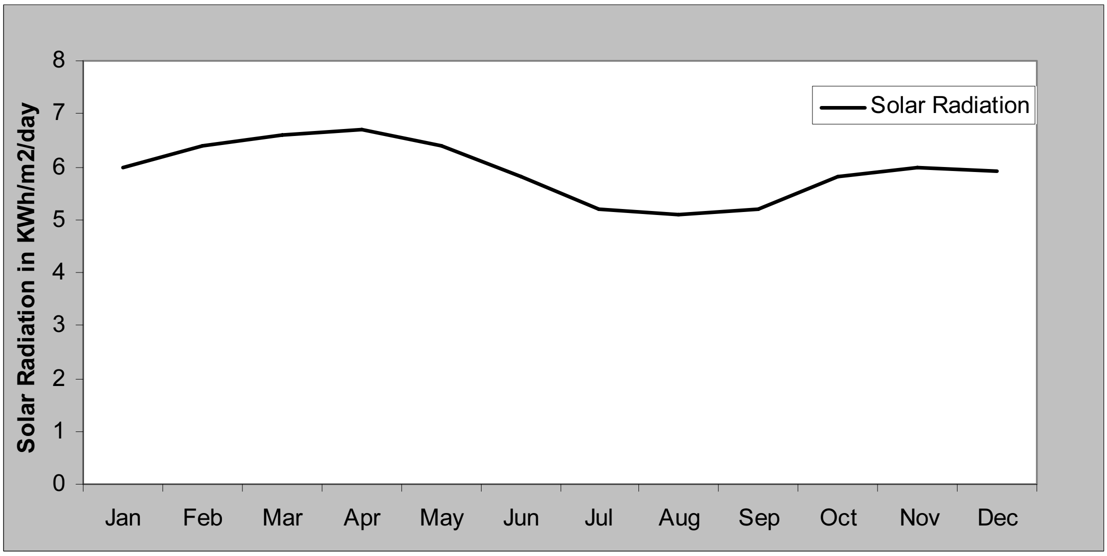

Figure (4.7.3) Monthly solar radiation in kWh/m^2/day in South Kordofan.

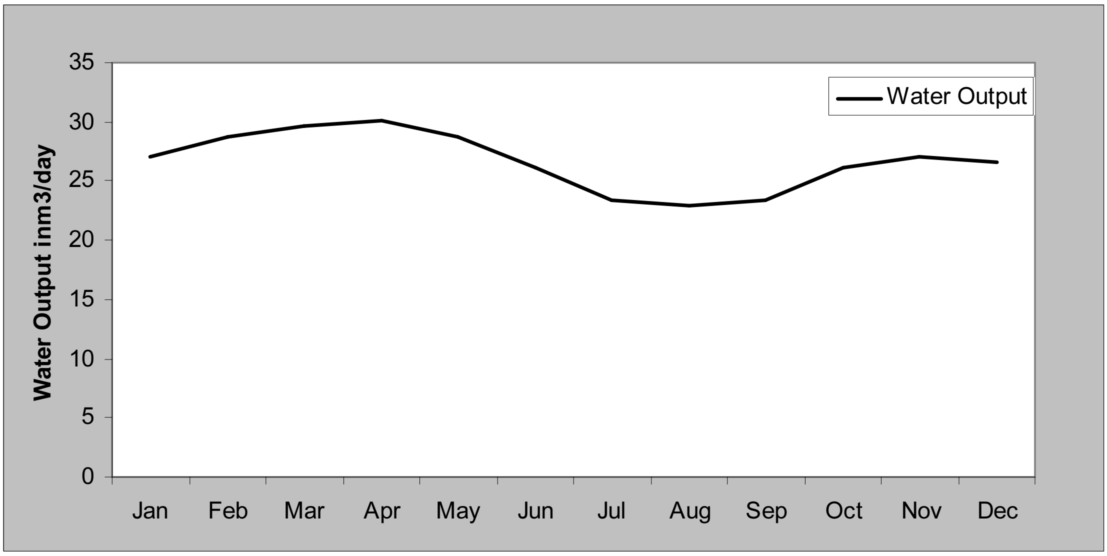

Figure (4.7.4) Monthly water output in m^3/day in South Kordofan.

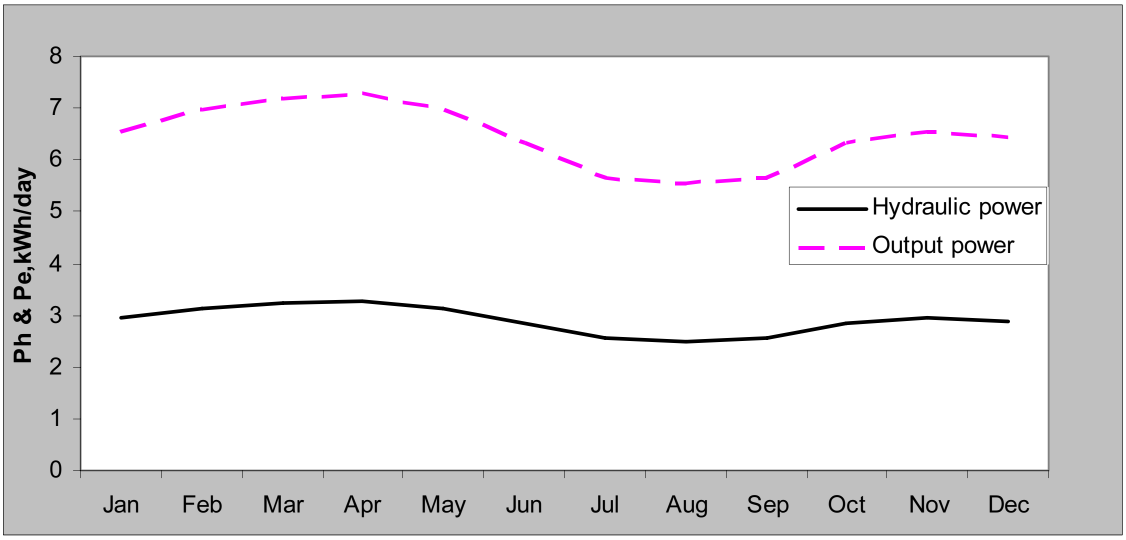

Figure (4.7.5) Monthly output power in kWh/day and hydraulic power in kWh/day in South Kordofan.

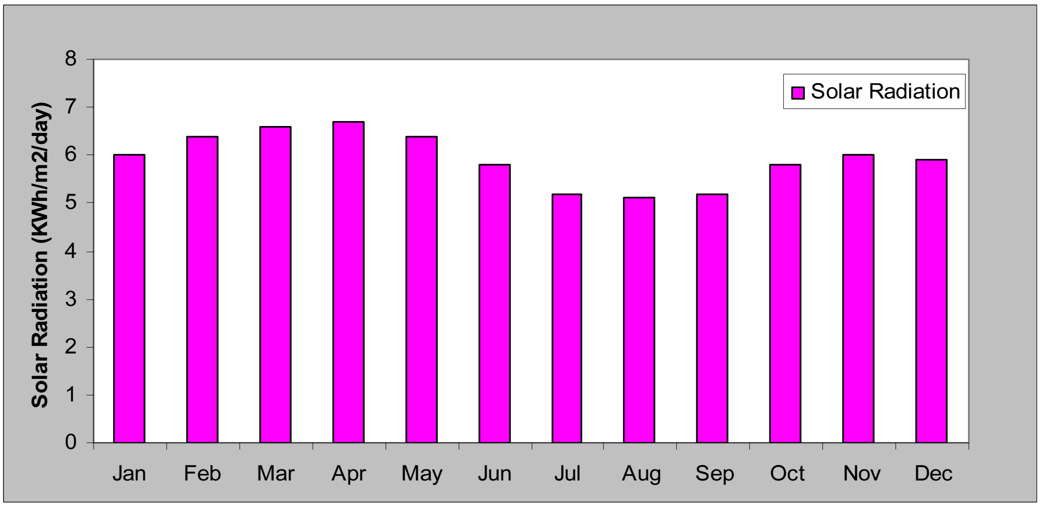

Figure (4.7.6) Monthly solar radiation in kWh/m^2/day in South Kordofan.

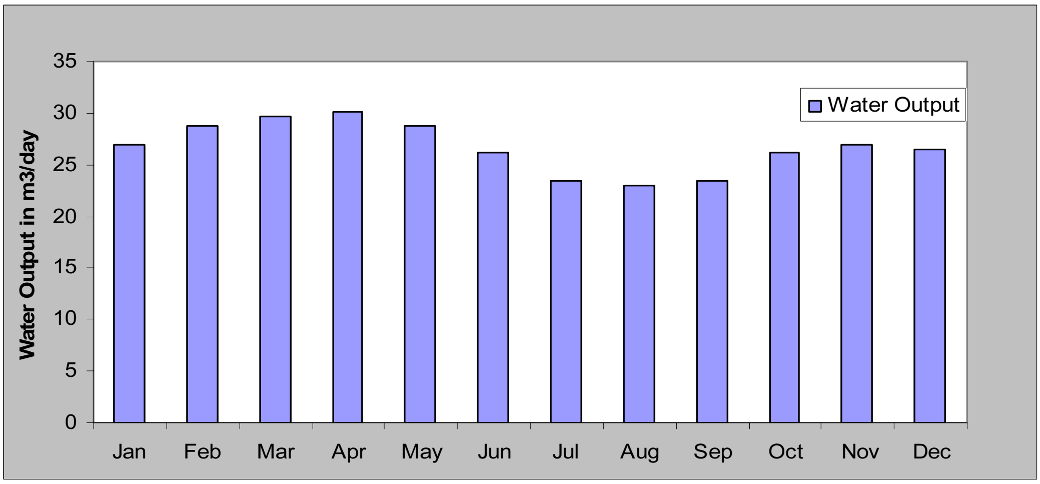

Figure (4.7.7) Monthly water output in m^3/day in South Kordofan.

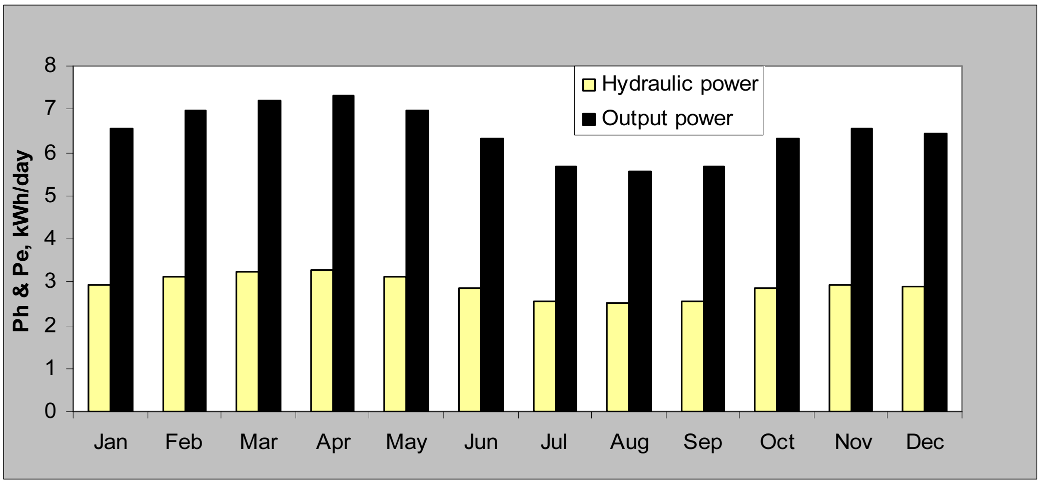

Figure (4.7.8) Monthly bar output power in kWh/day and hydraulic power in kWh/day in South Kordofan.

4.8 The Eighth Site:-

The solar pump (Grundfos SP 3A-10) was installed in the village near South Kordofan. The pumping head 45 meter, the solar radiation about 6.3 kWh/m^2/day and the average water production of 24 m^3/day.

Apply the method above and analysis in this site:

The daily hydraulic power, P_h in kWh/day

$$P_h = \rho g h Q = \frac{1000 * 9.81 * 45 * 24}{1000 * 3600} = 2.943 kWh / day$$

The effective area of the PV array, A_{PV} in m^2

$$A_{PV} = \frac{\rho g h Q}{G_T \eta_{PV} \eta_S} = \frac{1000 * 9.81 * 45 * 24}{6.3 * 1000 * 3600 * 0.15 * 0.49} = 6.3557 m^2$$

The PV array power, P in Watt-Peak, Wp

$$P = \frac{1000 A_{PV} \eta_r}{0.7} = \frac{1000 * 6.3557 * 0.15}{0.7} = 1361.93 W_P$$

The number of module, N

$$N = \frac{1361.93}{50} = 27.24 \cong 28$$

The number of module connected each 7 in series to meet the system voltage requirement and the 4 in parallel to meet the system current requirements.

The daily power out put, P_e in kWh/day

$$P_e = A_{PV} G_T \eta_{PV} = 6.3557 * 6.3 * 0.15 = 6.006 kWh / day$$

The subsystem efficiency η_s

$$\eta_S = \frac{P_h}{P_e} = \frac{2.943}{6.006} = 0.49$$

The Overall efficiency of the PV pumping system, η_o

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} = \frac{2.943}{6.3557 * 6.3} = 0.0735$$

The result of the mathematical relation to the performance of a PV pump in village in South Kordofan illustrated in table (4.8.1) and the Figure (4.8.1) shows the possible water pumping versus the solar radiation, the water pumping by the pump ranged from 20.6 to 25.9 m^3/day depending on solar radiation level, the solar radiation ranged from 5.4 kWh/m^2/day in December to 6.8 kWh/m^2/day in April in summer. Figure (4.8.2) shows the daily hydraulic energy in kWh/day depending on water delivery by the pump it was increase when the water output increase. Figures (4.8.3), (4.8.4) and (4.8.5) shows the monthly solar radiation in kWh/m^2/day, water output in m^3/day, power output in kWh/day and hydraulic power in kWh/day. Also, the monthly sub-system efficiency is 0.49, array efficiency is 0.15 and overall efficiency is 0.0735 all efficiency were constant they were independent on both solar radiation and water output. Figures (4.8.6), (4.8.7) and (4.8.8) illustrated the monthly bar solar radiation in kWh/m^2/day, water output in m^3/day, power output in kWh/day and hydraulic power in kWh/day in the village in South Kordofan.

Table (4.8.1): Performance of the solar water pumping system at depth of 21m in South Kordofan site.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Radiation	5.7	6.3	6.7	6.8	6.6	6.3	5.7	5.8	6	5.7	5.5	5.4
Water Output m3/day	21.7	24	25.5	25.9	25.1	24	21.7	22.1	22.9	21.7	21	20.6
Hydraulic power (Ph in kWh/day)	2.66	2.9	3.13	3.18	3.08	2.9	2.66	2.7	2.8	2.66	2.56	2.5
Power output (Pe in kWh/day)	5.4	6	6.4	6.5	6.3	6	5.4	5.5	5.7	5.4	5.2	5.1
Sub- System Efficiency	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Overall Efficiency	0.07	0.07	0.07	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.07	0.07
Array efficiency	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

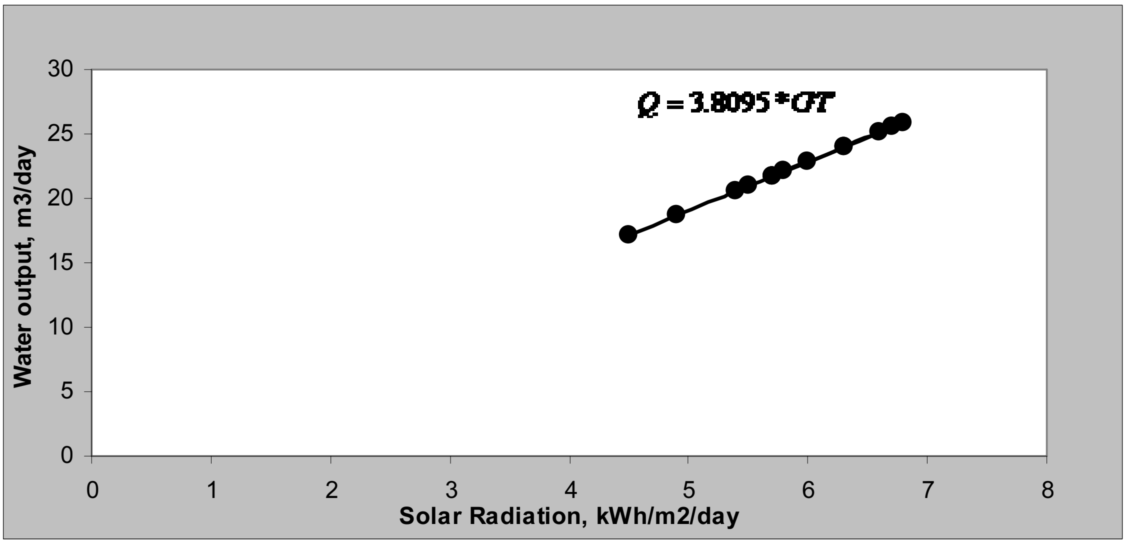

Figure (4.8.1) Possible water pumping in village in South Kordofan site with depth 45 meter.

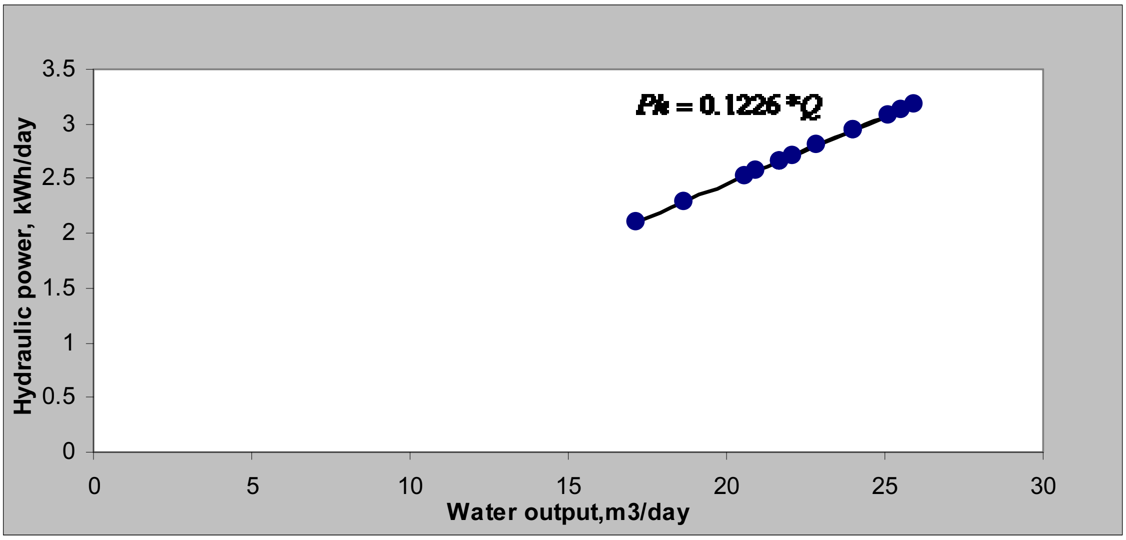

Figure (4.8.2) Hydraulic power output kWh/day against the water output m^3/day.

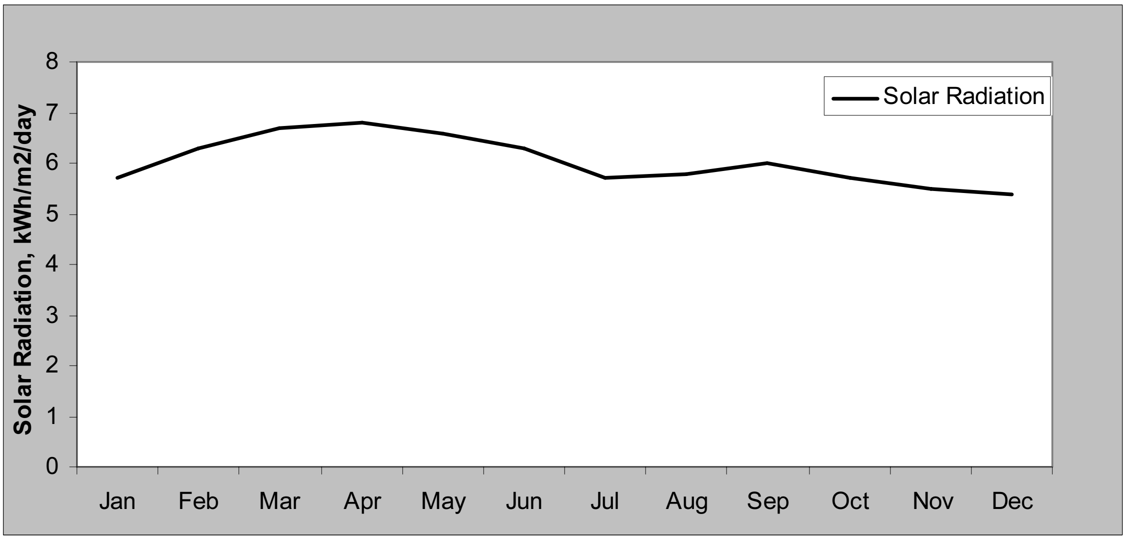

Figure (4.8.3) Monthly solar radiation in kWh/m^2/day in village in South Kordofan.

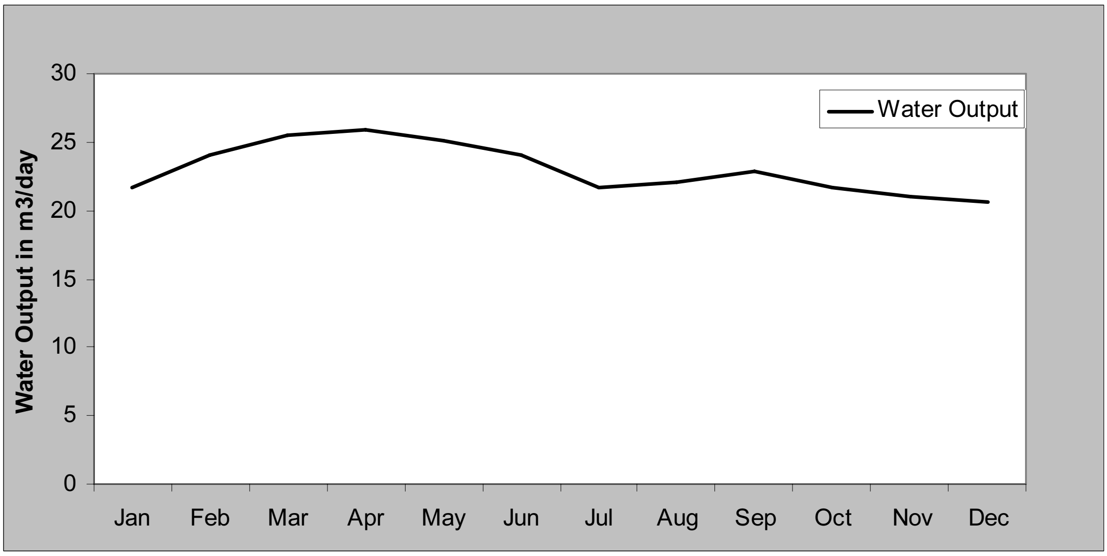

Figure (4.8.4) Monthly water output in m^3/day in village in South Kordofan.

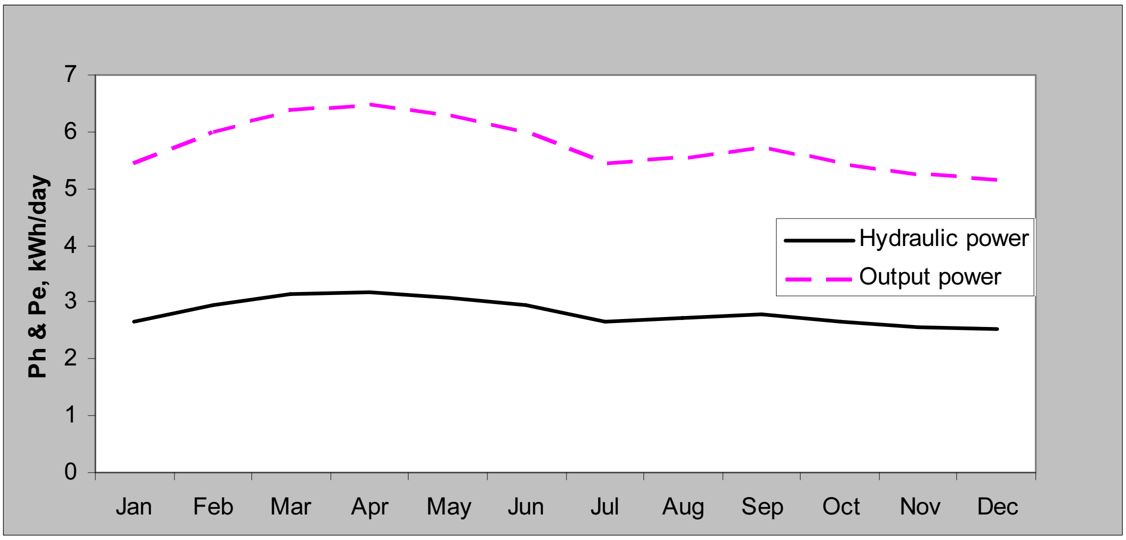

Figure (4.8.5) Monthly power output in kWh/day and hydraulic power in kWh/day in village in South Kordofan.

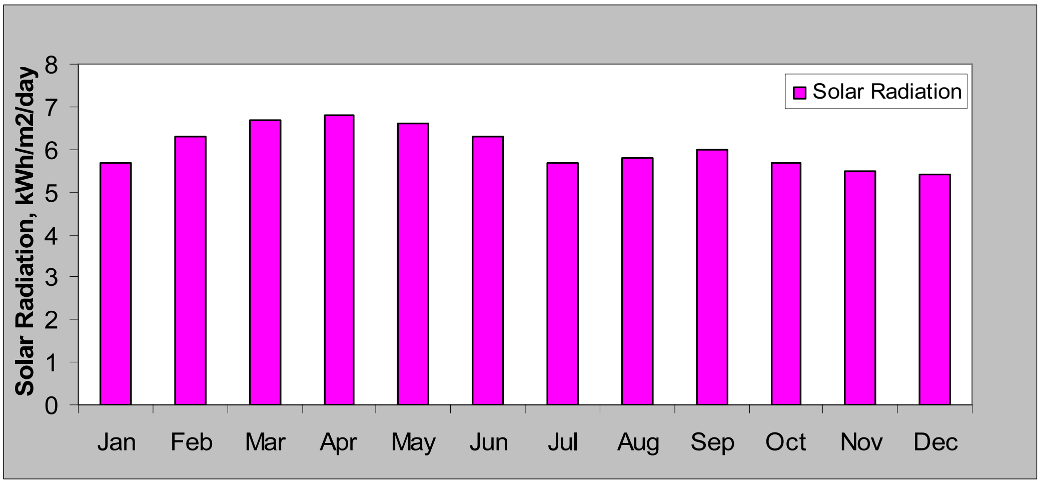

Figure (4.8.6) Monthly solar radiation in kWh/m^2/day in village in South Kordofan.

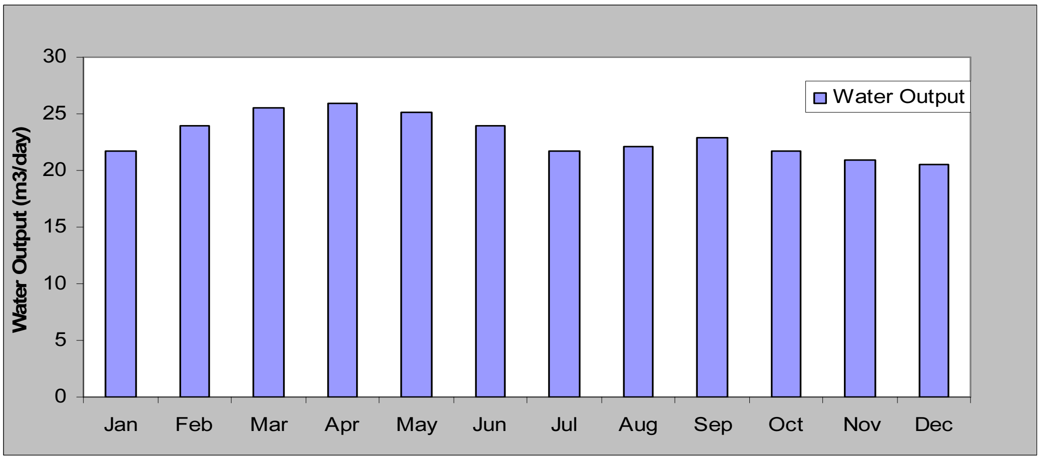

Figure (4.8.7) Monthly bar water output in m^3/day in village in South Kordofan.

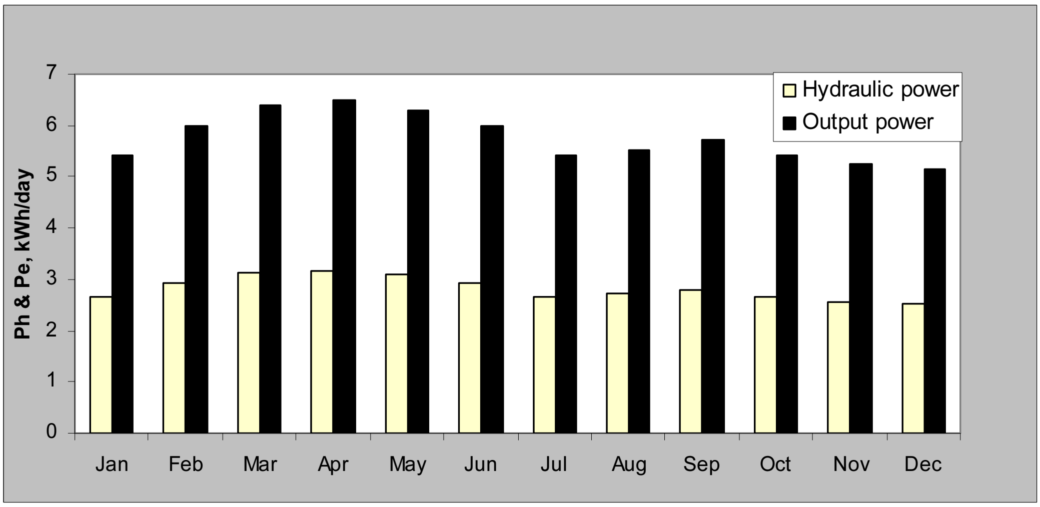

Figure (4.8.8) Monthly bar power output in kWh/day and hydraulic power in kWh/day in village in South Kordofan.

4.9 The Ninth Site:-

The solar pump (Grundfos SP 16-2) was installed in the village near Dongula. The pumping head 15 m, the solar radiation is 6.7 kWh/m^2/day, the average water production of 28 m^3/day.

Apply the method above and analysis in this site:

The daily hydraulic power, P_h in kWh/day

$$P_h = \rho g h Q = \frac{1000*9.81*15*28}{1000*3600} = 1.1445 kWh/day$$

The effective area of the PV array, A_{PV} in m^2

$$A_{PV} = \frac{\rho g h Q}{G_T \eta_{PV} \eta_S} = \frac{1000*9.81*15*28}{6.7*1000*3600*0.15*0.31} = 3.67 m^2$$

The PV array power, P in Watt-Peak, Wp

$$P = \frac{1000 A_{PV} \eta_r}{0.7} = \frac{1000*3.67*0.15}{0.7} = 787.17 W_P$$

The number of module, N

$$N = \frac{787.17}{50} = 15.74 \cong 16$$

The number of module connected each 4 in series to meet the system voltage requirement and the 4 in parallel to meet the system current requirements.

The daily power out put, P_e in kWh/day

$$P_e = A_{PV} G_T \eta_{PV} = 3.67*6.7*0.15 = 3.688 kWh/day$$

The subsystem efficiency η_s

$$\eta_S = \frac{P_h}{P_e} = \frac{1.1445}{3.688} = 0.31$$

The Overall efficiency of the PV pumping system, η_o

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} = \frac{1.1445}{3.67 * 6.7} = 0.0465$$

The result of the mathematical relation to the performance of a PV pump in the Dongula illustrated in table (4.9.1) and the Figure (4.9.1) shows the possible water pumping versus the solar radiation, the water output by the pump ranged from 22.1 to 32.2 m^3/day depending on solar radiation level, the solar radiation ranged from 5.3 kWh/m^2/day in December to 7.7 kWh/m^2/day in May in summer. Figure (4.9.2) shows the daily hydraulic power in kWh/day depending on water delivery by the pump it was increase when the water output increase. Figures (4.9.3), (4.9.4) and (4.9.5) shows the monthly solar radiation in kWh/m^2/day, water output in m^3/day, power output in kWh/day and hydraulic power in kWh/day. Also, the monthly sub-system efficiency is 0.31, array efficiency is 0.15 and overall efficiency is 0.047 all efficiency were constant they were independent on both solar radiation and water output. Figures (4.9.6), (4.9.7) and (4.9.8) illustrated the monthly bar solar radiation in kWh/m^2/day, water output in m^3/day, power output in kWh/day and hydraulic power in kWh/day in the Dongula.

Table (4.9.1): Performance of the water solar pumping system at depth 15m in Dongula site.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Radiation	5.6	6.4	7.1	7.5	7.7	7.6	7.2	7	6.7	6.4	5.8	5.3
Water output m3/day	23.38	26.7	29.6	31.3	32.2	31.7	30.1	29.2	27.97	26.7	24.2	22.1
Hydraulic power (Ph in kWh/day)	0.96	1.09	1.21	1.28	1.31	1.3	1.23	1.2	1.14	1.09	0.99	0.9
Power out Put (Pe In kWh/day)	3.08	3.5	3.9	4.13	4.24	4.18	3.96	3.85	3.69	3.5	3.19	2.9
Sub-System Efficiency	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Overall Efficiency	.047	.047	.047	.047	.047	.047	.047	.047	.047	.047	.047	.047
Array efficiency	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

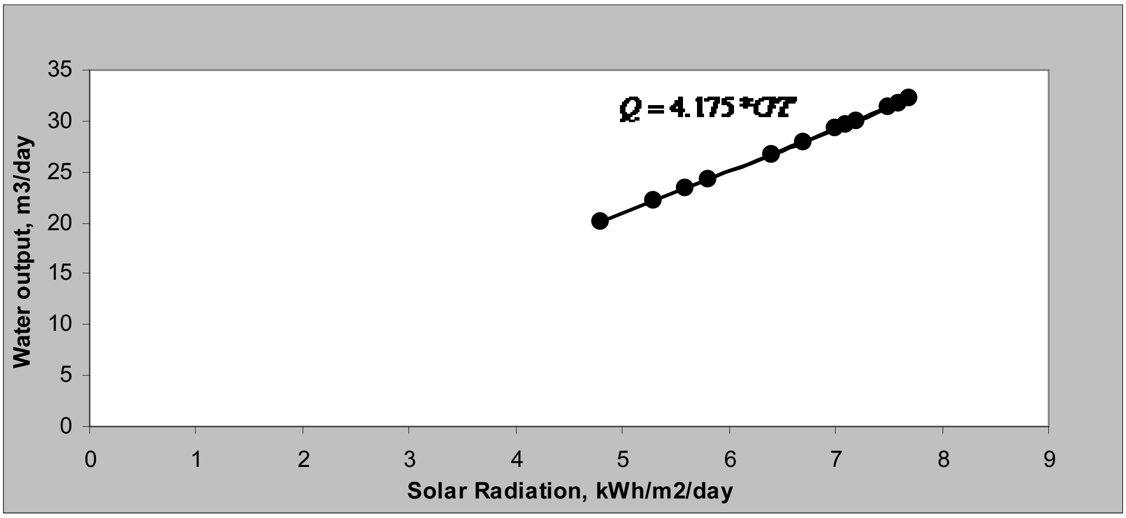

Figure (4.9.1) Possible water pumping at depth 14 m in Dongula site.

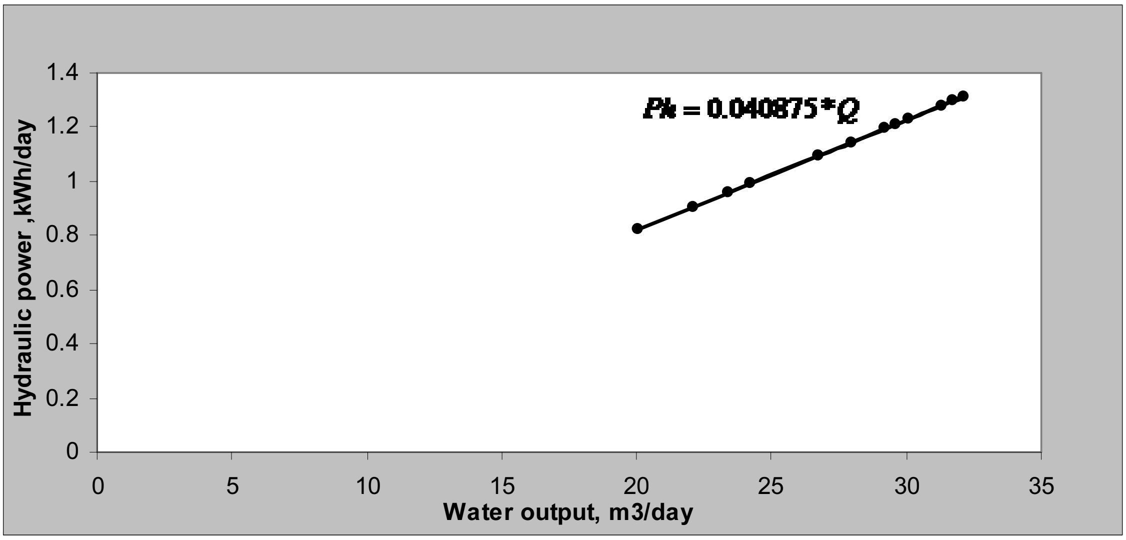

Figure (4.9.2) Hydraulic power output in kWh/day against the water output m^3/day.

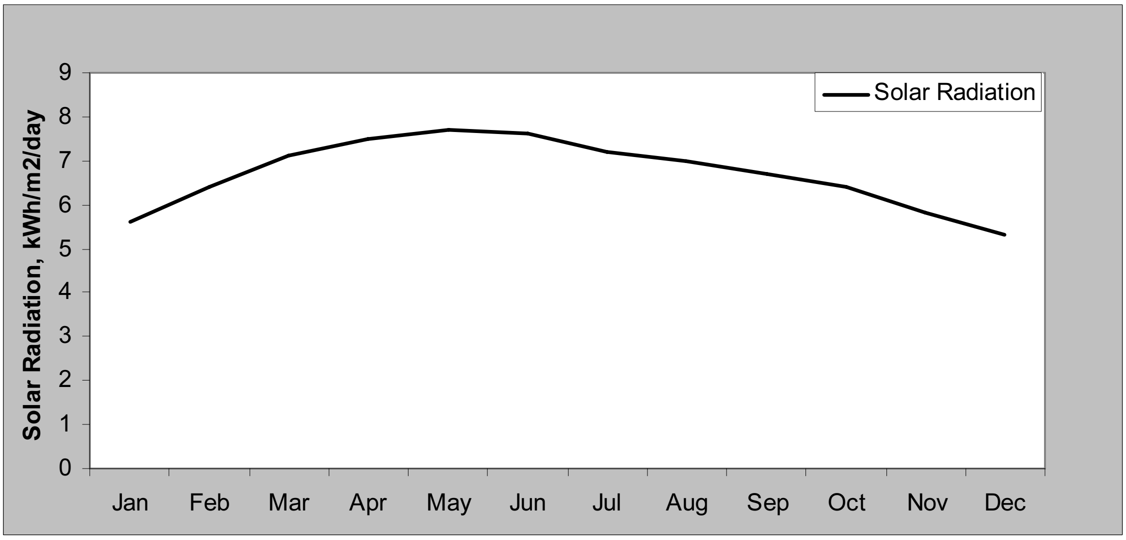

Figure (4.9.3) Monthly solar radiation in kWh/m^2/day in Dongula.

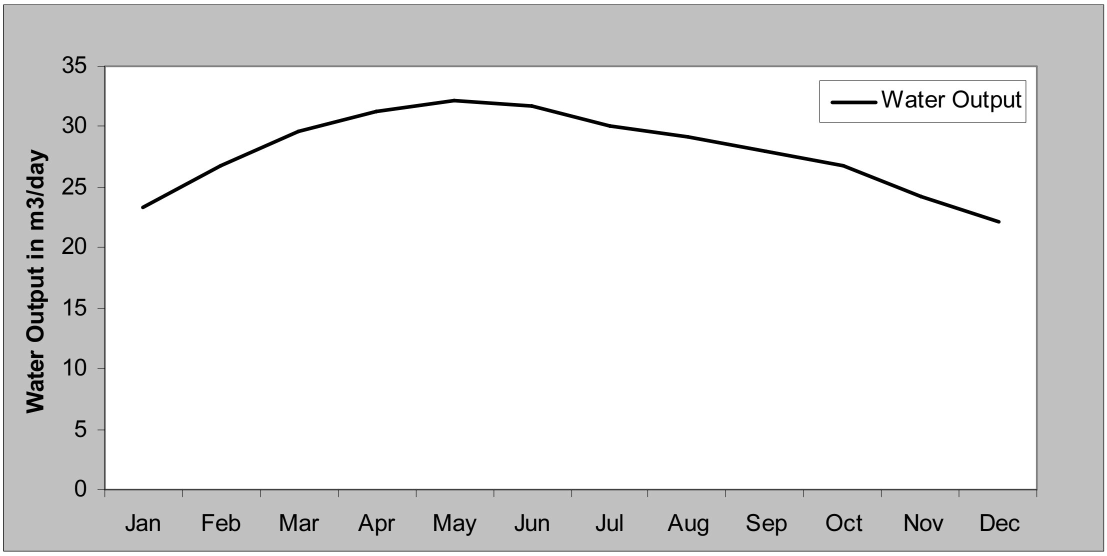

Figure (4.9.4) Monthly water output in m^3/day in Dongula.

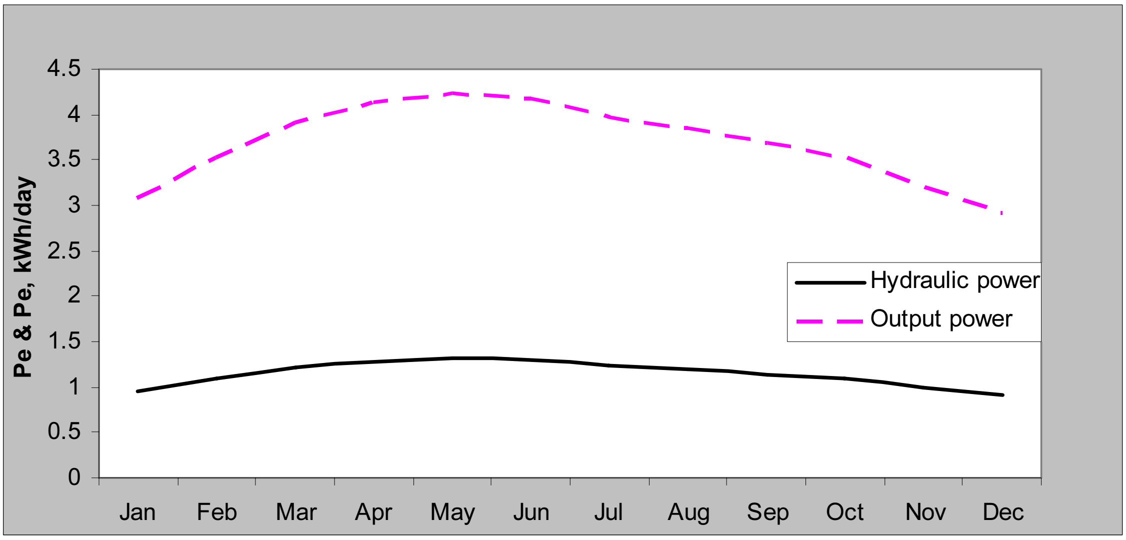

Figure (4.9.5) Monthly power output in kWh/day and hydraulic power in kWh/day in Dongula.

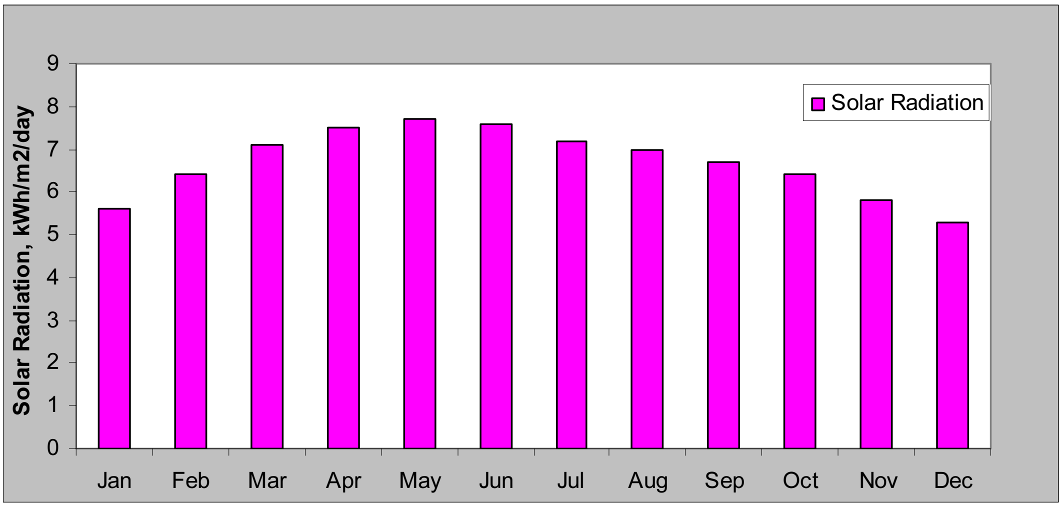

Figure (4.9.6) Monthly bar solar radiation in kWh/m^2/day in Dongula.

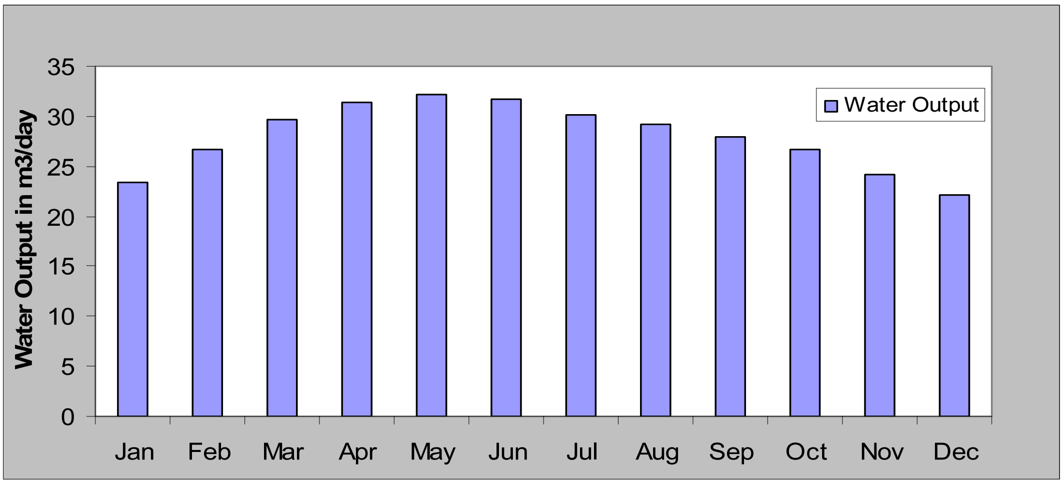

Figure (4.9.7) Monthly bar water output in m^3/day in Dongula.

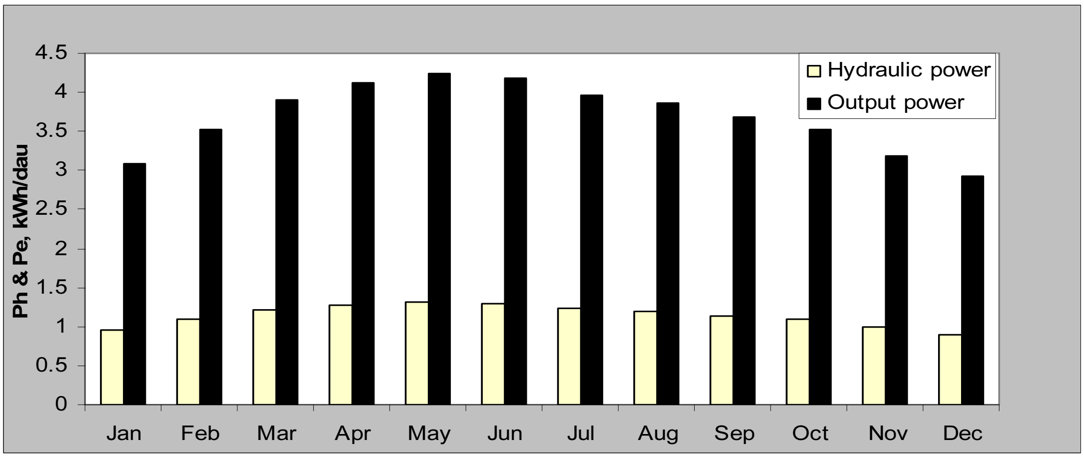

Figure (4.9.8) Monthly bar power output in kWh/day and hydraulic power in kWh/day in Dongula.

From the simulations result of the performance of PV pump for the all nine selected sites illustrated that it is possible to pump water using solar energy as a good technical practice. Figure (4.9.9) shows the Monthly solar radiation at selected sites with varies in the pumping head the maximum value in Dongula sites of 7.7kWh/m^2/day with pumping head 15m, and the minimum values in Foja sites of 5.1 kWh/m^2/day with pumping head 38m. Figure (4.9.10) shows the Monthly water output for selected sites, the maximum water output pumping with head 22m in Mayo reached around 49.5m^3/day, and the minimum water pumping with head 38m in Foja of around 19.13m^3/day.

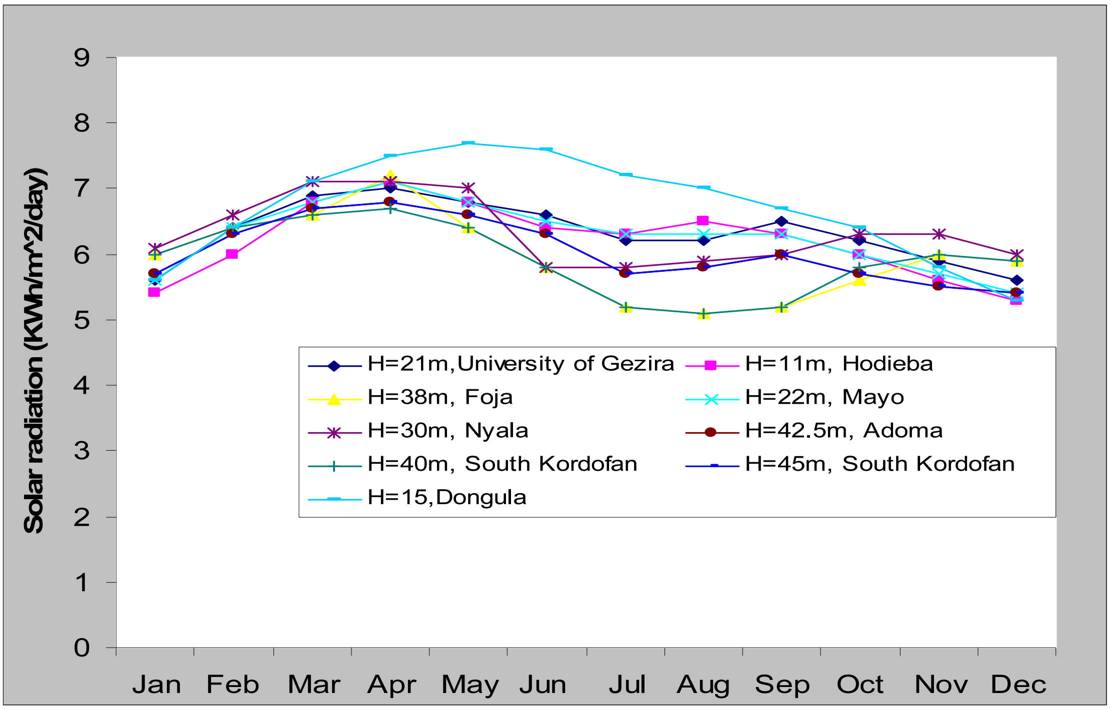

Figure (4.9.9) Monthly solar radiation at selected sites.

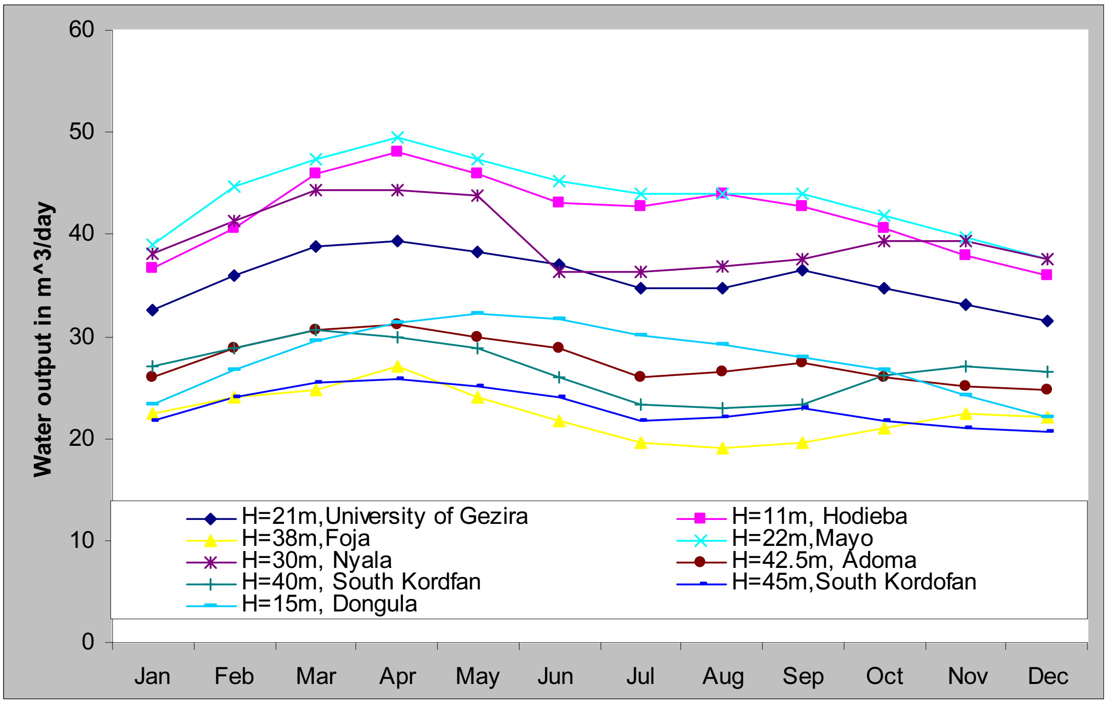

Figure (4.9.10) Monthly water output for selected sites.

CHAPTER FIVE

Experimental Work

CHAPTER FIVE

5.1 Experimental Work

To investigate year round performance of water pumping in Sudan it was decided to build a laboratory scale unit and run it throughout the year, one complete day each week and find a typical day long experiment that represent a monthly average performance. The experiment was performed for three months (May, June and July).

The unit used consisted of:

1- Monocrystalline Photovoltaic panel oriented towards South and tilted at 45^o from the horizontal and the panel area is $0.59 m^2$.

2- A control board with a functional block diagram of the system with a properly positioned voltmeter and ammeter along with control switches.

3-A submersible pump powered by a DC motor 30/12 V maximum.

4- Two tanks, the over head tank of 4m height above the lower tank in which the pump is immersed.

5- The pyranometer which was used to measure solar intensity during the experiment. The pyranometer was connected to a kipp and zonen solar integrator which displays the solar intensity in W/m^2 the pyranometer was tilted directed at the same direction and tilt angle as the PV panel the tilt angle 45^o.

The pumping head of the experiment was 4 m, solar radiation in W/m^2, flow rate in Litre per hour. The first experiment was in Monday 21/ May, the measured value of solar radiation, flow rate, voltage and current are showed in table (5.1.1). From the measured value the daily hydraulic power output, daily power output, subsystem efficiency, and overall efficiency were calculated, the results of the experimental work is shows in the Figure (5.1.1).

Table (5.1.1): Measured values of the first experimental in May (Monday 21/5/2007).

Time	Solar radiation G_T, W/m^2	Flow rate (Q) L/h	Volts (V)	Amperes (A)
7:00	549	96	15	1.03
8:00	668	117	15.7	1.05
9:00	746	132	16.6	1.06
10:00	832	144	17.3	1.07
11:00	914	152	17.7	1.078
12:00	948	155	18	1.08
13:00	913	151	17.8	1.076
14:00	862	146	17.4	1.07
15:00	783	138	16.7	1.06
16:00	692	124	15.4	1.05
Daily Value	7.907KW/m^2	1.355m^3/day		

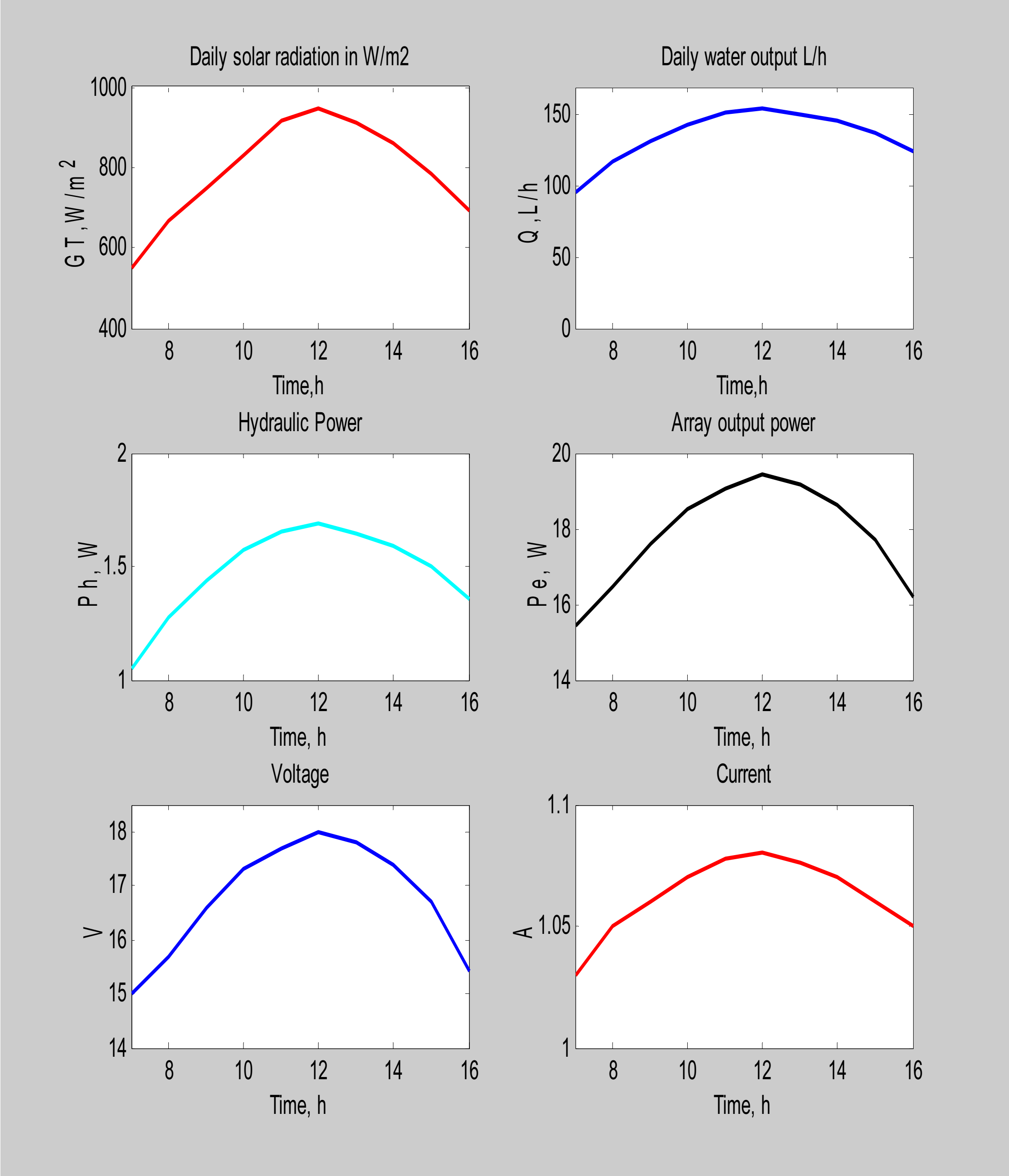

Figure (5.1.1) Result of the first experiment in May showing the daily solar radiation (W/m^2), daily water output (L/h), hydraulic power output (W), array output power (W), voltage and current.

The second experiment in June (Sunday 24/6/2007), the measured value of solar radiation, flow rate, voltage and current were showed in the flowing table (5.1.2). From the measured value the daily hydraulic energy output, daily energy output, subsystem, and overall efficiency were calculated, the result of the experiment showed in the Figure (5.1.2).

Table (5.1.2): Measured values of the second experimental in June (Sunday 24/6/2007).

Time	Solar radiation W/m^2 (G_T)	Flow rate (Q) L/h	Volts (V)	Amperes (A)
7:00	556	102	19.1	1.04
8:00	694	124	19.2	1.045
9:00	812	140	19.27	1.054
10:00	894	151	19.33	1.06
11:00	964	156	19.38	1.067
12:00	992	158	19.4	1.07
13:00	966	155	19.37	1.068
14:00	898	150	19.32	1.06
15:00	830	142	19.26	1.051
16:00	703	128	19.2	1.04
Daily Value	8.309KW/m^2	1406 L/h		

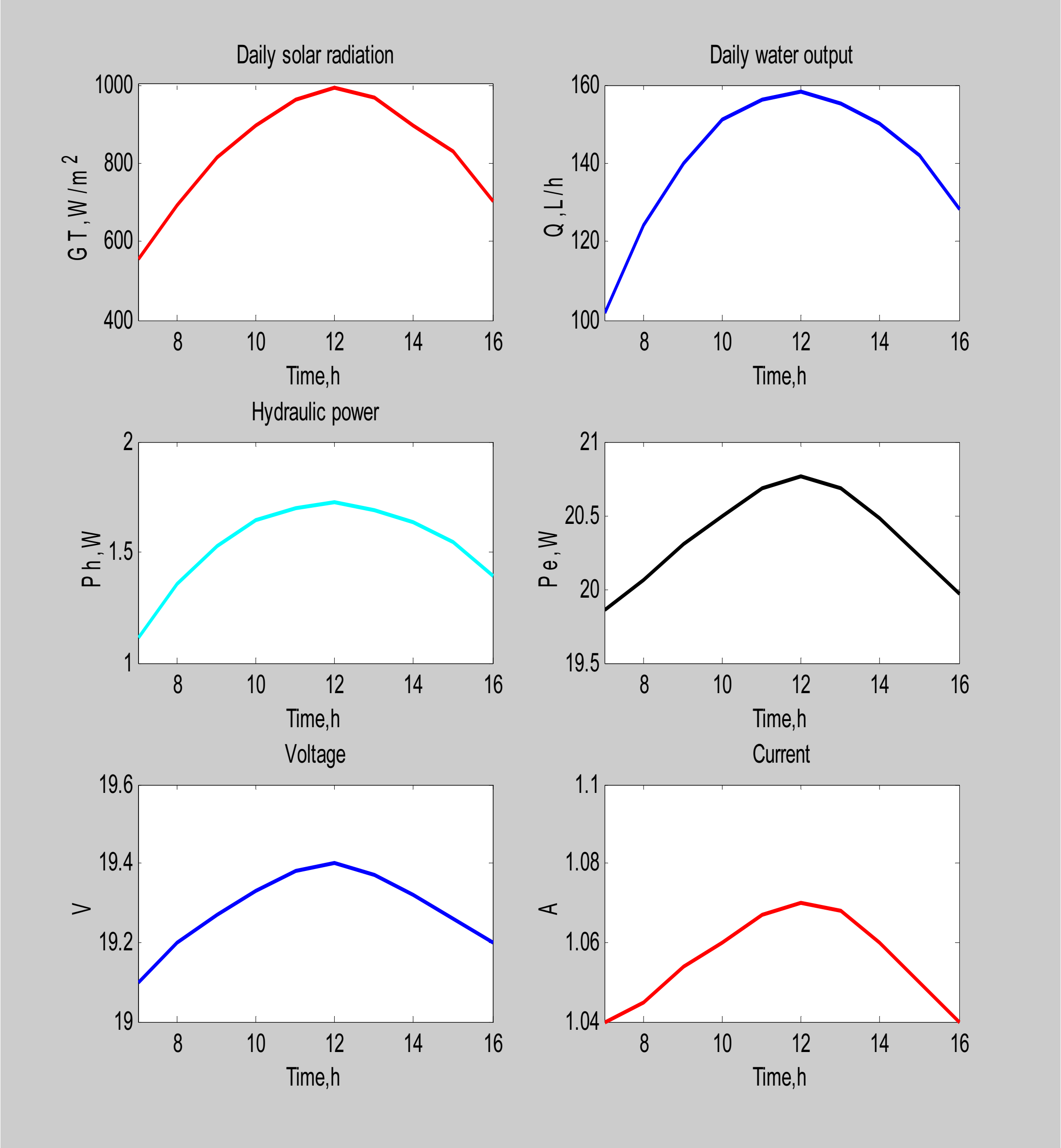

Figure (5.1.2) Result of the second experiment in July show the daily solar radiation (W/m^2), daily water output(L/h), hydraulic power output (W), array output power (W),voltage and current.

The third experiment in July (Monday 23/7/2007), the measured value of solar radiation, flow rate, voltage and current were showed in the flowing table (5.1.3). From the measured value the daily hydraulic energy output, daily energy output, subsystem, and overall efficiency were calculated, the result of the experimental showed in the Figure (5.1.3).

Table (5.1.3): Measured values of the third experimental in July (Monday 23/7/2007) with A_{PV} 0.59 m^2.

Time	Solar radiation (G_T) W/m^2	Flow rate (Q) L/h	Volts (V)	Amperes (A)
7:00	606	122	19.4	1.04
8:00	776	144	19.5	1.05
9:00	868	156	19.6	1.06
10:00	939	165	19.7	1.07
11:00	988	171	19.76	1.078
12:00	1011	174	19.8	1.08
13:00	988	171	19.78	1.075
14:00	939	165	19.7	1.07
15:00	868	156	19.6	1.06
16:00	776	144	19.5	1.05
Daily Value	8.759 KW/m^2	1568 L/h		

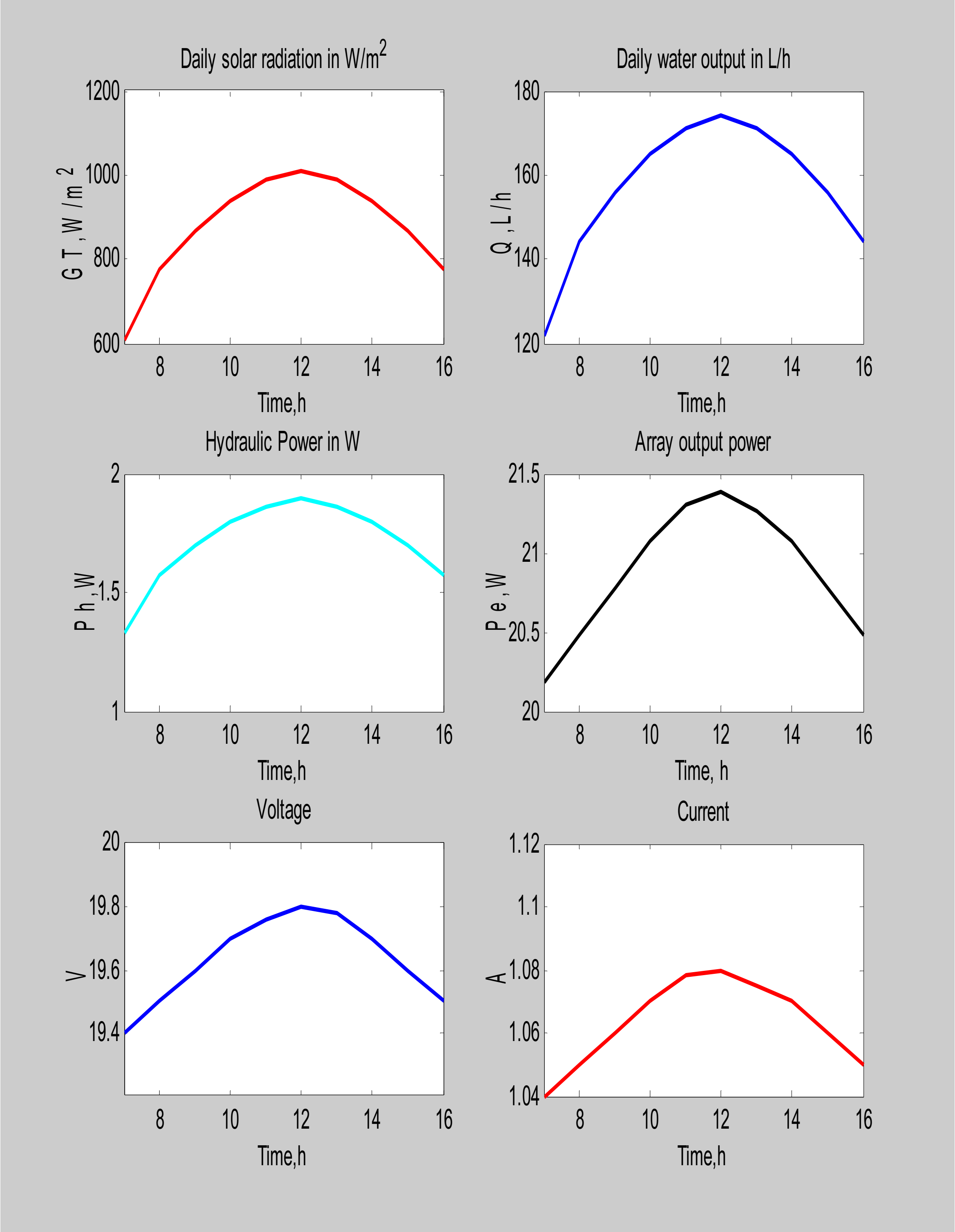

Figure (5.1.3) Result of the third experiment in July show the daily solar radiation (W/m^2), daily water output(L/h), hydraulic power output (W), array output power (W),voltage (V) and current(A).

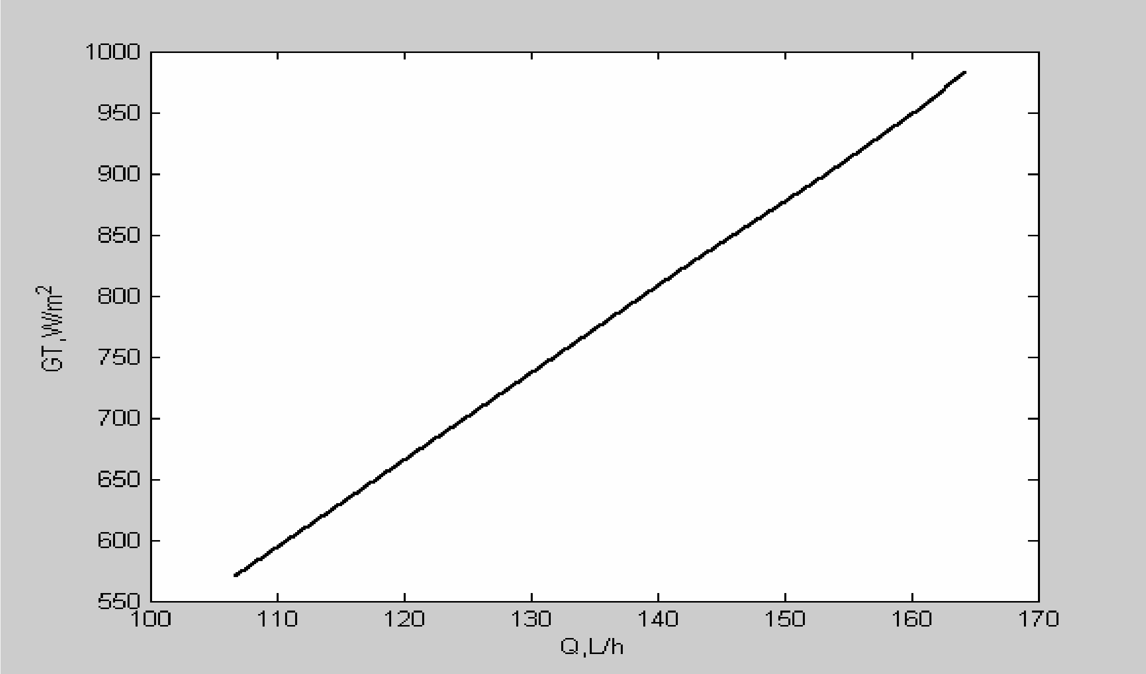

Figure (5.1.4) Water output Q (L/h) verse solar radiation (W/m^2) in experiments for 4m head.

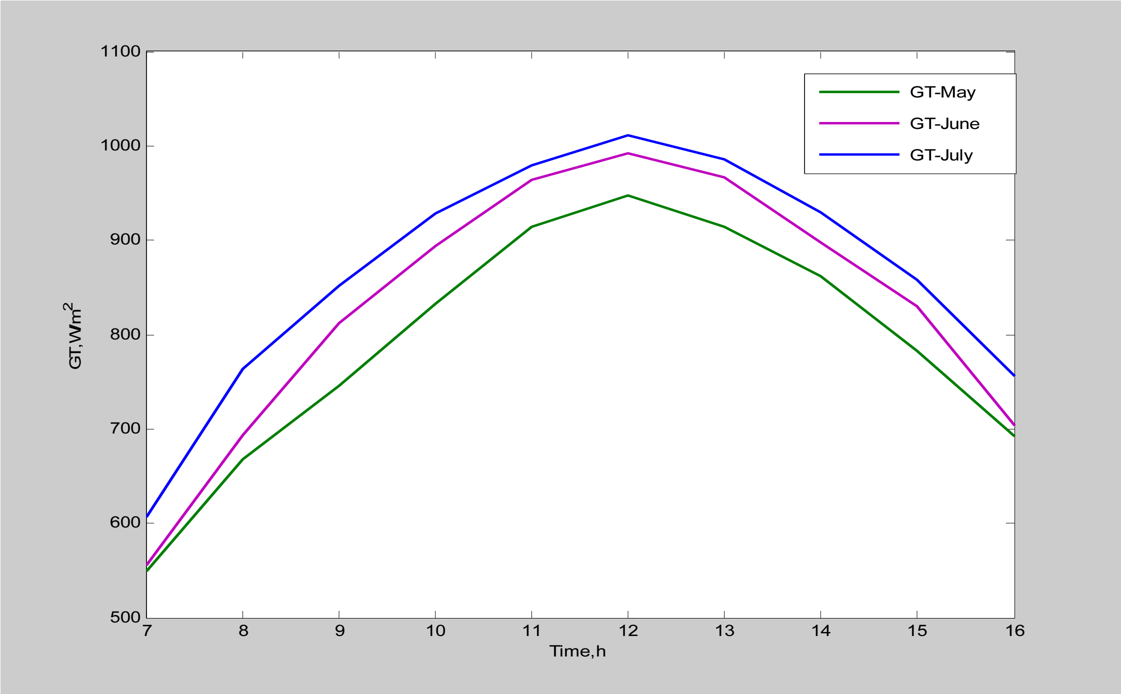

Figure (5.1.5) Solar radiation G_T (W/m^2) in three experiments in May, June and July.

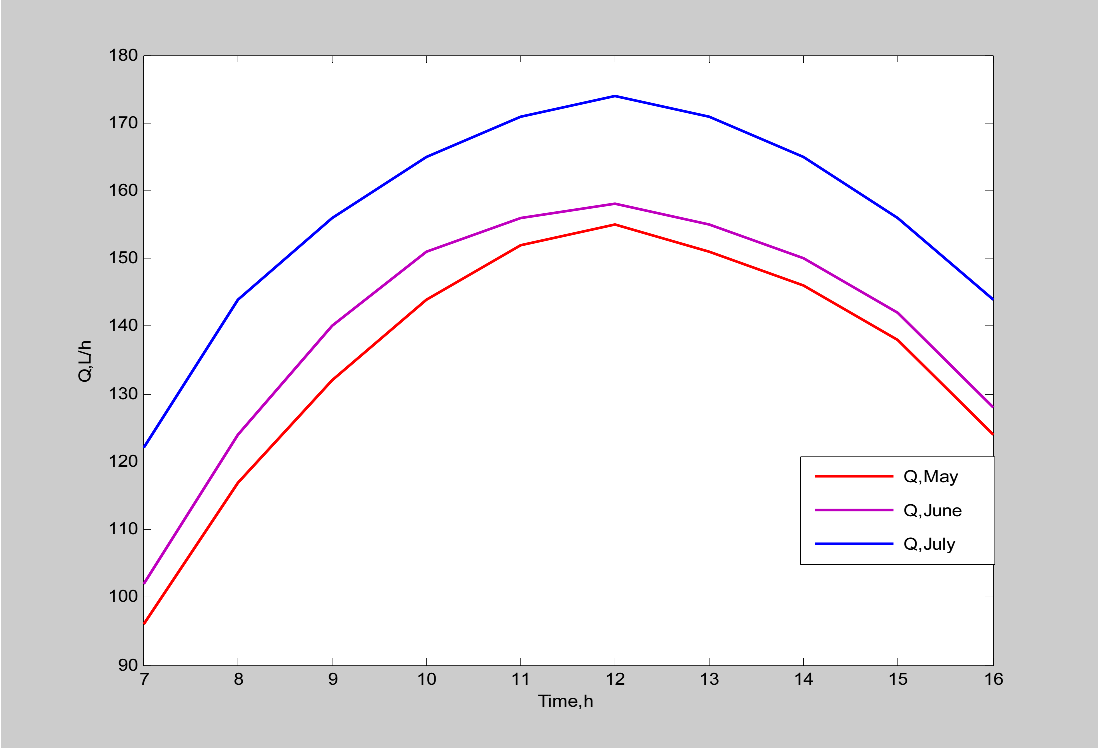

Figure (5.1.6) Water output Q (L/h) in three experiments in May, June and July.

The results obtained the experimental procedure and the calculation methods described in chapter three will be presented and the parameters governing the PV pump performance will announced.

The experimental procedure measured during the day solar radiation (GT), water output (Q) ,voltage (V) and current (A), these were substituted in the equations (3.3),(3.4) and (3.7) to obtain Ph, Pe, η_s,η_o,η_{PV}.

The above results of the three experimental which the daily solar radiation (W/m^2), daily water output (L/h), hydraulic power output (W), array output power (W), voltage (V) and current (A) during the day were presented in Figure (5.1.1) in May, Figures (5.1.2) and in June and Figure (5.1.3) in July.

Also, Figure (5.1.4) illustrate water output Q (L/h) verse solar radiation (W/m^2) in experiments for 4m head the relation between the variables is liner.

The difference between the performances of PV pump in the three experiments illustrated in Figures (5.1.5) and (5.1.6), showed the variations of water output as parameter to solar intensity. Figures showed as solar intensity increases the output water increases.

The solar radiation changes throughout the day, it was affected by the weather, and changes from season to season.

The maximum water output of 1568 Litter per day in July where the solar radiation was high and the minimum water of 1355 Litter per day in May where the solar radiation was low.

5.2 Error Analysis

One rule of thumb that could be used is that the error in the result is equal to the maximum error in any parameter used to calculate the result.

To estimate the uncertainty in the calculated result on the basis of uncertainties in the primary measurements (Holman, 2001). The result R is a given function of the independent variables $x_1,x_2,x_3,\ldots\ldots\ldots,x_n$. Thus,

$$R= (x_1,x_2,x_3,\ldots\ldots\ldots\ldots\ldots\ldots,x_n) \qquad (5.1)$$

Let w_R be the uncertainty in the result and $w_1,w_2,\ldots\ldots\ldots,w_n$ be the uncertainties in the independent variables. Then the uncertainty given as

$$\omega_R = \left[\left(\frac{\partial R}{\partial x_1}\omega_1\right)^2 + \left(\frac{\partial R}{\partial x_2}\omega_2\right)^2 + \ldots\ldots\ldots\ldots\ldots\ldots\left(\frac{\partial R}{\partial x_n}\omega_n\right)^2\right]^{\frac{1}{2}} \qquad (5.2)$$

From the result the output power

Pe= I*V

Where:
$$V = 19.8 \pm 1\%$$
$$I = 1.08 \pm 1\%$$

$$\omega_V = 19.8 * 0.01 = 0.198$$
$$\omega_I = 1.08 * 0.01 = 0.0108$$

From equations (5.1) and (5.2),

$$\omega_{Pe} = \left[\left(\frac{\partial Pe}{\partial V}\omega_V\right)^2 + \left(\frac{\partial Pe}{\partial I}\omega_I\right)^2\right]^{\frac{1}{2}}$$

$$\frac{\partial Pe}{\partial V} = I \quad , \quad \frac{\partial Pe}{\partial I} = V$$

Dividing by Pe

$$\frac{\omega_{Pe}}{Pe}=\left[\left(\frac{\omega_V}{V}\right)^2+\left(\frac{\omega_I}{I}\right)^2\right]^{\frac{1}{2}}$$

$$\frac{\omega_{Pe}}{Pe}=\left[\left(\frac{0.198}{19.8}\right)^2+\left(\frac{0.0108}{1.08}\right)^2\right]^{\frac{1}{2}}=0.0141=1.41\%$$

The uncertainty in the output power is 1.41% maximum.

The uncertainty in the hydraulic power

Ph= 0.0109*Q

Q = 122L/h ±0.25L/h

$$\frac{\partial Ph}{\partial Q}=0.0109$$

$$\omega_{Ph}=\left[\left(\frac{\partial Ph}{\partial Q}\omega_Q\right)^2\right]^{\frac{1}{2}}$$

Dividing by Ph

$$\frac{\omega_{Ph}}{Ph}=\left[\left(\frac{\omega_Q}{Q}\omega\right)^2\right]^{\frac{1}{2}}=\left[\left(\frac{0.25}{122}\right)^2\right]^{\frac{1}{2}}=0.2\%$$

The uncertainty in the output power is 0.2% Maximum.

The uncertainty in the solar radiation

G_T= 606W/m^2 ±0.5W/m^2

$$\frac{\omega_{GT}}{G_T}=\left[\left(\frac{0.5}{606}\right)^2\right]^{\frac{1}{2}}=0.08\%\text{ Maximum.}$$

5.3 The simulation in Amman

The mathematical relationships between the solar intensity energy, the PV array power, and the required hydraulic power to fulfill the water demand. This method can be used by field technicians.

The hourly solar intensity is 1011 W/m^2, water production of 174 L/h, and the total pumping head 4 meter.

The daily hydraulic power, P_h in W

$$P_h = \rho g h Q = \frac{1000*9.81*4*174}{1000*3600} = 1.8966W$$

The effective area of the PV array, A_{PV} in m^2

A_{PV}= (0.52*1.14= 0.59m^2)

The PV array Power, P (in Watt-Peak, Wp)

$$P = \frac{1000 A_{PV} \eta_r}{0.7} = \frac{1000*0.59*0.036}{0.7} = 30.34W_P$$

The number of module, N

$$N = \frac{30.34}{50} = 0.6 \approx 1$$

The daily power output, P_e in W

$$P_e = A_{PV} G_T \eta_{PV} = 0.59*1011*0.036 = 21.5W$$

The subsystem efficiency η_s

$$\eta_S = \frac{P_h}{P_e} = \frac{1.8966}{21.5} = 0.088$$

The PV array efficiency η_{PV}

$$\eta_{PV} = \frac{P_e}{A_{PV} G_T} = \frac{21.5}{0.59*1011} = 0.36$$

The Overall efficiency of the PV pumping system, η_o

Time	7	8	9	10	11	12	13	14	15	16
G_T, W/m^2	606	776	868	939	988	1011	988	939	868	776
Q, L/h	122	144	156	165	171	174	171	165	156	144
Ph, W	1.33	1.57	1.7	1.8	1.86	1.9	1.86	1.8	1.7	1.57
Pe, W	20.18	20.48	20.78	21.08	21.3	21.4	21.3	21.08	20.78	20.48

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h Q}{A_{PV} G_T} = \frac{1.8966}{0.59*1011} = 0.0032$$

Table (5.3.1): Results of simulation in Amman.

The experimental results were treated by the computer simulation of water solar pumping in Sudan and it gave results for the Amman data coincide with that of Sudan results.

The results of simulation in Amman shows in table (5.3.1) to compare these results with results of experiments, approximately there is no large different between them, so the two results are equivalent. The results of simulation in Amman illustrate in following figures (5.3.1), (5.3.2), (5.3.3), and (5.3.4).

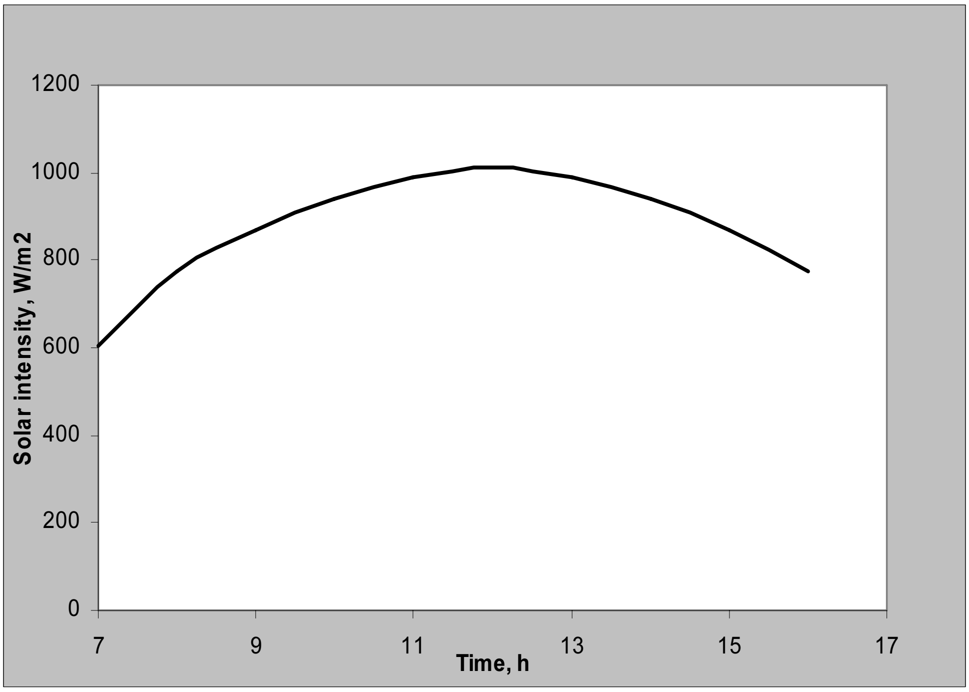

Figure (5.3.1) Solar radiation in W/m^2 against time in hour.

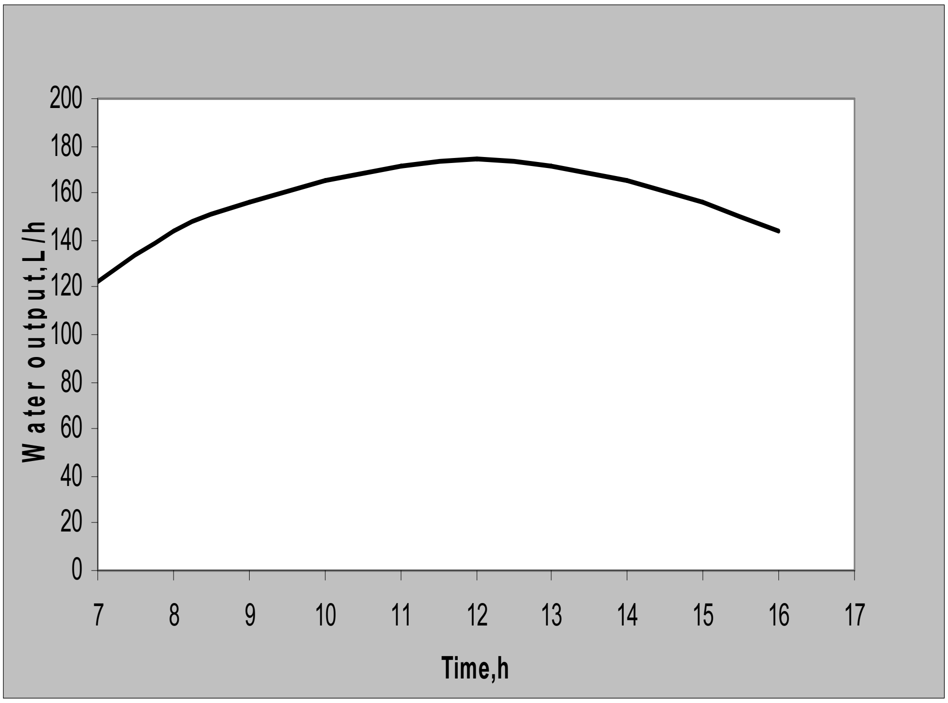

Figure (5.3.2) Possible water pumping at depth of 4m in Amman.

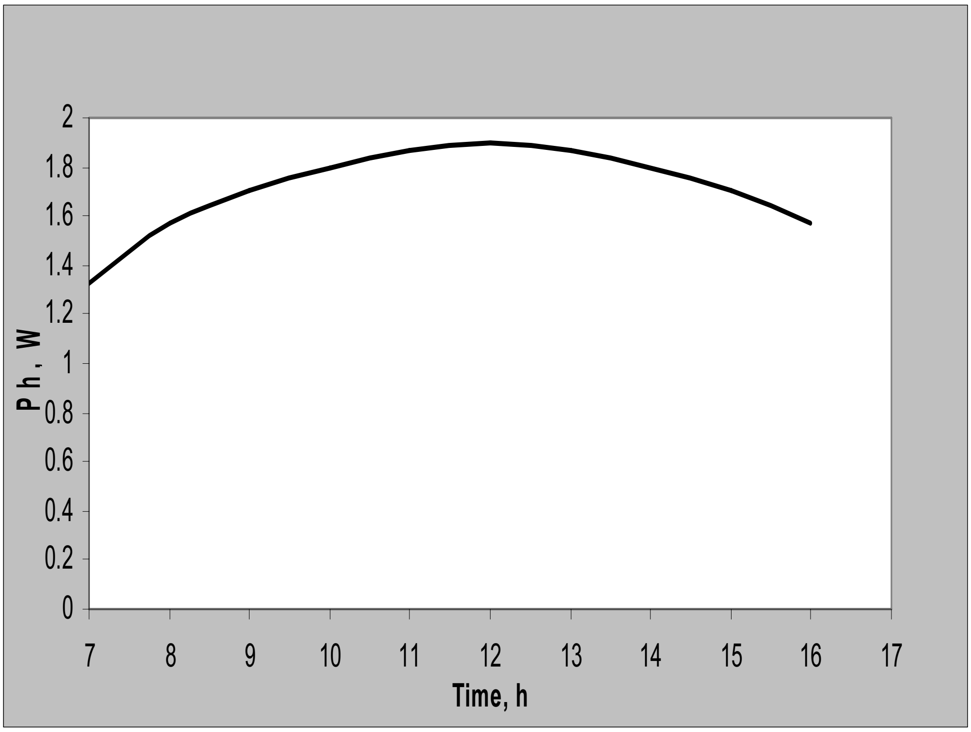

Figure (4.3.3) Hydraulic power in W against time, h.

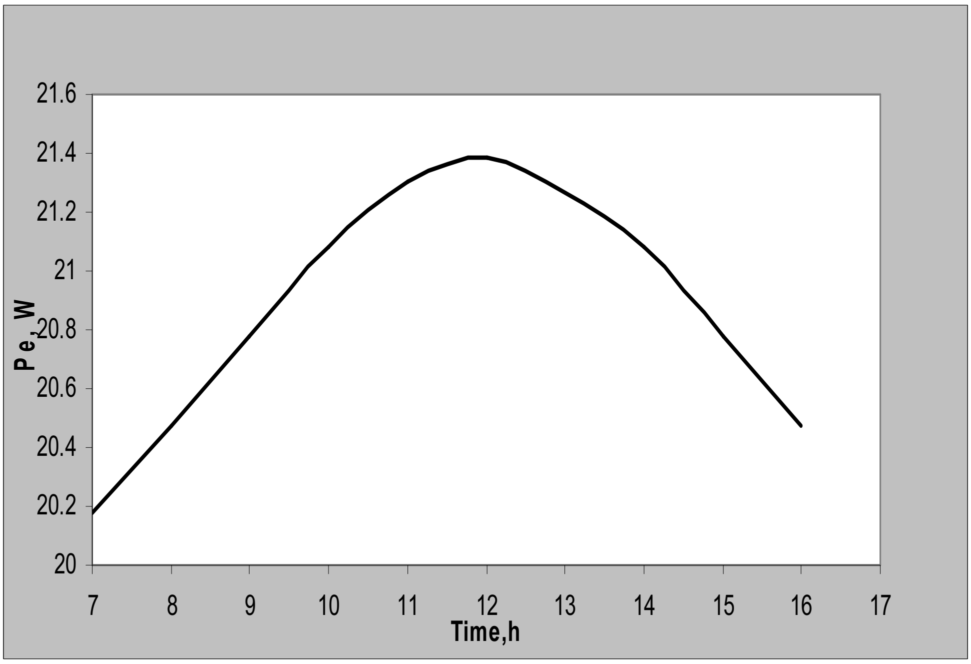

Figure (4.3.4) Output power in W during day.

CHAPTER SIX

Cost Study

CHAPTER SIX

6.0 Cost Study

Life Cycle Cost (LCC) is the most widely used evaluation method. LCC is the sum of all the costs associated with the pumping system over a given economic lifetime or over a selected period of analysis, expressed in the present value of money, which is the present worth of the costs of the system. All the future costs are discounted to the present-day value and added to the present-day investment costs, and the net present value is the LCC. The economic life of the PV pumping and the diesel pumping are taken as 20 years.

In LCC analysis, the net present value (NPV) of all the capital and recurring costs for the PV-powered pumps is compared to the NPV of all the costs of competitive projects. If the NPV of costs of PV-powered pumping is less than the costs of the alternatives, PV should feasible to use in Sudan.

In order to reasonable compare several pumping technologies it is important that they operate under similar conditions. This means that they must pump the same quantity of water through the same pumping head.

6.1 Cost Comparison

In this study cost comparison for solar PV and diesel water pumps was conducted over a pumping heads 40m and a daily flow rates 27m^3/day. The life cycle costs (LCC) were calculated over a 20 year period taking into account:

●the initial capital cost.

●the operation costs.

●maintenance costs.

- replacement costs.

6.2 Cost Analysis

In order to compare different systems offering the same service output the life cycle costing approach is used. This approach allows systems to be compared on an equal basis by reducing all future costs, which occur at different intervals of the systems life, to one value, referred to as the Life Cycle Cost (LCC) of a system study.

In order to calculate all costs in today's US dollar, the future costs are reduced to the present value using a discount rate. The discount rate is equivalent to a bank investment rate.

The costing of a pumping system that has a life expectancy of a number of years is comprised of the capital cost and the future costs, which include operating cost, maintenance cost and replacement cost.

A PV pumping system will operate for a period of time before it needs replacement. For example, the PV panels may be replaced after 20–30 years, whereas the pump may be replaced after 5–10 years. The life cycle costs of a PV pumping system are the initial cost of the complete system in the event of installation plus the annual operation, repair and maintenance expenses.

The capital cost(C) of a system includes the initial capital expenses for equipments, the system design and the system installation. This cost is always considered as a single payment occurring in the initial year of the system installation. Maintenance (M) is the sum of all yearly scheduled operation and maintenance costs. Replacement cost (R) is the sum of all repair and equipment replacement costs anticipated over the life of the system, and normally, the replacement costs occur only in specific years. Several factors should be considered when the period for an LCC analysis is chosen. For example, PV modules are usually assumed to operate for 20 years or more without failure, so 20 years is the normal period chosen to evaluate the economic feasibility of PV systems. However, the pump and motor may not last 20 years, so replacement costs for this case must be considered in the calculation if a comparison is to be made with alternative water pumping systems.

The life of the system is the life of the component with the longest replacement interval. The LCC are the initial cost of the complete, installed system in year 0, plus a replacement pump (with installation) in year 10, plus annual operation, repair and maintenance expenses.

The costs of well, storage tank, cable and distribution system are negligible in both capital costs of systems because these units existed in both systems and the cost of them is equivalent.

6.2.1Cost of PV Pumping System in Sudan

Capital and Installation Costs of PV pumping system in Sudan under the condition of 40m head and 27m^3/day water output include cost of the modules 32X50 about required reached $12000,while the value of subsystem pump/motor and inverter reached about $3000. The cost of Support structures was about $500, the Installation fees was about $1250 and the Transportation cost of the system was about $500. This cost is always considered as a single payment occurring in the initial year of the system installation which is showed in table (6.1).

Operations and Maintenance (O&M) Costs showed in table (6.1). The operating costs of a PV pump are nil. The cost of maintaining the pump is difficult to estimate because of variations in local repair capabilities, it is about$25 per year.

Replacement Costs, showed in table (6.1) the pump and motor subsystem is likely to need replacement after about 10 years, perhaps earlier in a difficult rural environment. For pump replacement costs, use the information for initial capital and installation costs given earlier about $4500.

Table (6.1): Initial capital, operation, maintenance and replacement cost of PV pumping system in Sudan.

A\ Solar pump	Capital Cost($)	Operation & Maintenance Cost ($)	Replacement Cost ($)
No of modules (32m-50Wp)	12000	25	
Inverter(A 1500)	2000		2000
The pump and motor unit	1000		1000
Support structures	500		
Installation fees	1250		1000
Transportation	500		500
Total	17250	25	4500
Grand Total			21775

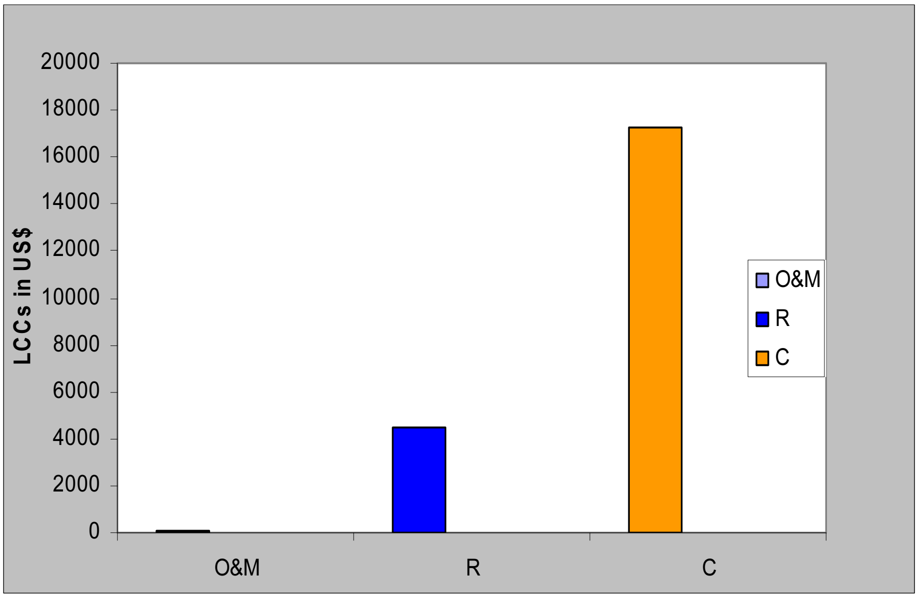

Figure (6.1) Annual initial capital cost (C), operation (O), maintenance (M) and replacement cost (R) of PV pumping in Sudan.

6.2.2 Cost of Diesel Pumping System in Sudan:-

The initial capital cost of diesel pumping systems is about $4200 including the pump, diesel engine, installation and transportation cost. The next step is to calculate the replacement cost. The life of the engine and pump in the difficult operating conditions typical for rural installations is 5 to 10 years, depending on operating hours and the quality of maintenance. In this study, an average life of 7 years is assumed, after which time the complete system must be replaced at the original capital cost, so the replacement cost equivalence to the capital cost $4200.

The operating costs are nil. Maintenance costs for a diesel pumping system varies widely. Sometimes this can be estimated on the basis of running hours or as a proportion of capital cost. However, typical maintenance costs are $900 per year.

To calculate the annual fuel cost, the total number of running hours is required.

The average fuel consumption under typical operating conditions depends principally on engine size, but other factors include the quality of maintenance, the ambient temperature, and the actual hydraulic load. The average fuel consumption is 8 liter per day the fuel costs \$.67 per liter, the annual fuel cost is \$2160.table(6.2) showed all costs of diesel pump installed with head 40m and water output 27m^3/day.

Table (6.2): Initial capital, operation, maintenance, replacement and fuel costs of diesel pump in Sudan.

B/Diesel Pump	Capital Cost($)	Operation & Maintenance Cost($)	Replacement Cost ($)	Fuel Cost($)
The Pump	1200		1200	
Diesel engine	1500	900	1500	2160
Installation fees	1000		1000	
Transportation	500		500	
Total	4200	900	4200	2160
Grand Total				11460

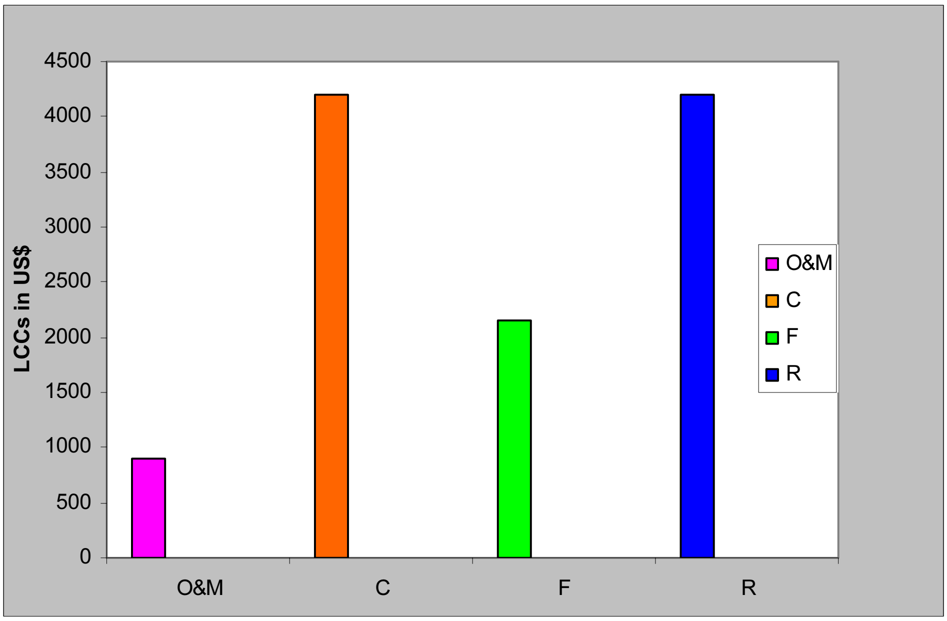

Figure (6.2) Annual initial capital cost(C), operation (O), maintenance (M), fuel (F) and replacement cost (R) of diesel pumping in Sudan.

The results of the analysis under the conditions of comparison showed the initial cost of the first year of the diesel pumping is less costly than the initial cost of PV pumping system, this result illustrated in tables (6.1) and (6.2) the initial cost of diesel pumping system is US$7260 it is very less, but the initial cost of PV pumping system is about US$17275it is very expensive. The annual initial capital cost, operation, maintenance, fuel and replacement cost of PV solar and diesel pumping in Sudan illustrated in Figures (6.1) and (6.2).

6.2.3 LCC of PV Pumping System and Diesel Pumping System in Sudan

In the following analysis long run leveled water pumping cost are compared for the two technology alternatives solar and diesel

LCC described in table (6.3) and (6.4) lists these costs over a 20 year system life.

PV modules are usually assumed to operate for 20 years or more without failure, so 20 years is the normal period chosen to evaluate the economic feasibility of PV systems in Sudan. However, the pump and motor may not last 20 years, so replacement costs for this case must be considered in the calculation if a comparison is to be made with alternative water pumping systems.

Table (6.3) and (6.4) uses a 10% discount rate and, for simplicity, assumes zero differential inflation. The discount factor D is obtained by

$$D = 1 / (1\ .1)^{n} \qquad 6.1$$

Where n = year.

NPV is found by taking the sum of capital, replacement, and O&M costs multiplied by the discount factor for the same year.

$$NPV = (C+O+M+R)*D \qquad 6.2$$

Where C is capital cost, O is operation cost, M is maintenance cost, and R is replacement cost.

NPV is the sum of capital, replacement, O&M, and fuel costs multiplied by the discount factor.

Table (6.3): LCC for PV pumping system in Sudan

Year	Capital Cost($)	Replacement Cost ($)	Operation & Maintenance Cost ($)	Discount Factor	NPV($)
0	17250		25.00	1.00	17275
1			25.00	0.909	22.725
2			25.00	0.826	20.65
3			25.00	0.751	18.775
4			25.00	0.683	17.075
5			25.00	0.621	15.525
6			25.00	0.564	14.1
7			25.00	0.513	12.825
8			25.00	0.467	11.675
9			25.00	0.424	10.6
10		4500	25.00	0.386	1746.65
11			25.00	0.350	8.75
12			25.00	0.319	7.975
13			25.00	0.290	7.25
14			25.00	0.263	6.575
15			25.00	0.239	5.975
16			25.00	0.218	5.45
17			25.00	0.198	4.95
18			25.00	0.180	4.5
19			25.00	0.164	4.1
20			25.00	0.149	3.725
			Total NPV		19224.85

Table (6.4): LCC for diesel pumping system in Sudan

Year	Capital &Replacement Cost($)	Operation & Maintenance Cost ($)	Fuel Cost($)	Discount Factor	NPV($)
0	4,200	900	2160	1.00	7260
1		900	2160	0.909	2781.54
2		900	2160	0.826	2527.56
3		900	2160	0.751	2298.06
4		900	2160	0.683	2089.98
5		900	2160	0.621	1900.26
6		900	2160	0.564	1725.84
7	4,200	900	2160	0.513	3724.38
8		900	2160	0.467	1429.02
9		900	2160	0.424	1297.44
10		900	2160	0.386	1181.16
11		900	2160	0.350	1071
12		900	2160	0.319	976.14
13		900	2160	0.290	887.4
14	4,200	900	2160	0.263	1909.38
15		900	2160	0.239	731.34
16		900	2160	0.218	667.128
17		900	2160	0.198	605.88
18		900	2160	0.180	550.8
19		900	2160	0.164	501.84
20		900	2160	0.149	455.94
			Total NPV		36572.09

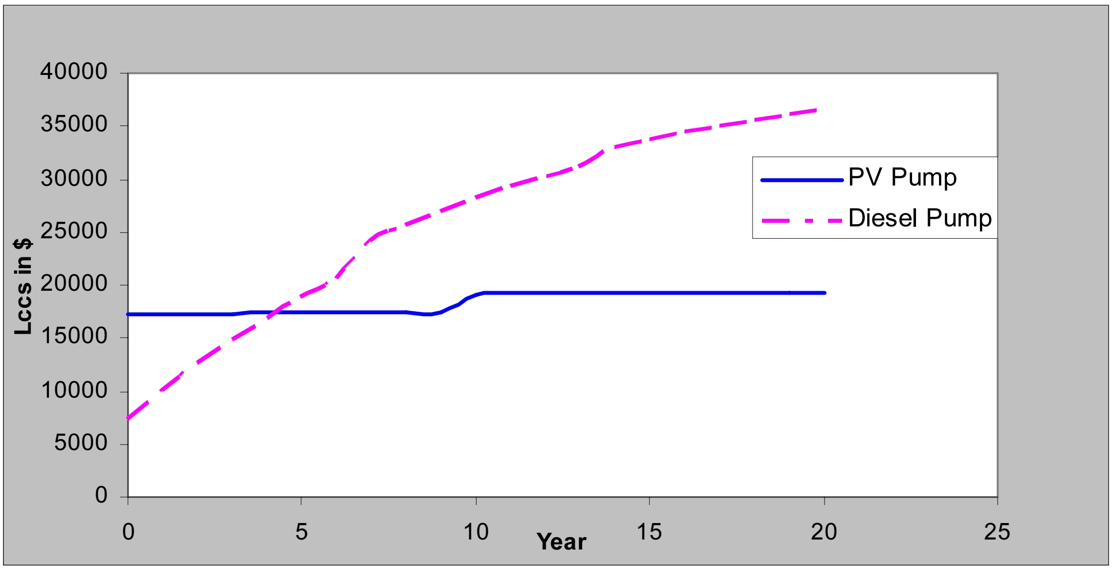

Figure (6.3) Life Cycle Costing of PV and diesel pump in 40 m head and 27m^3/day water output in South Kordofan in Sudan.

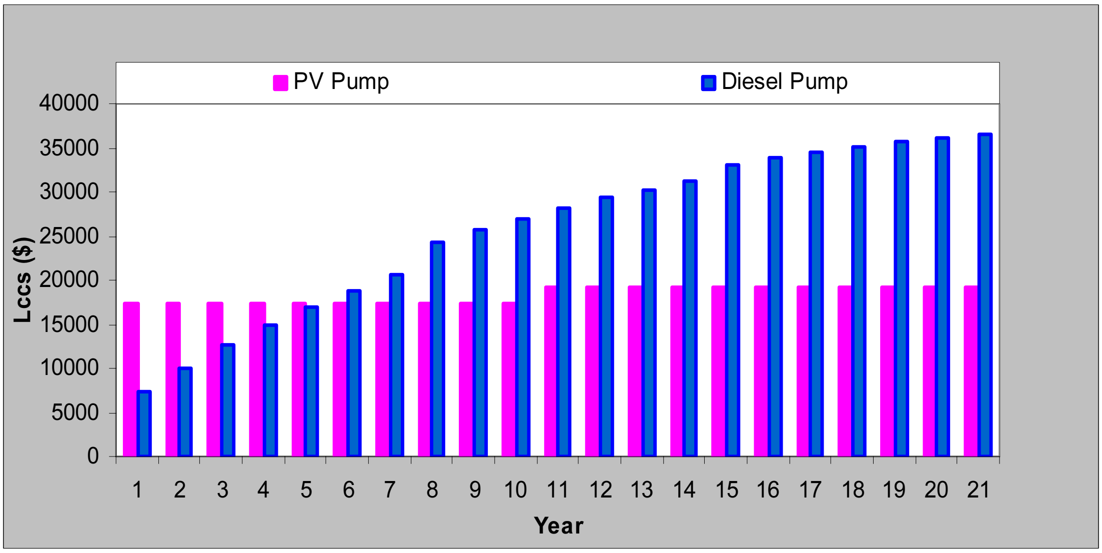

Figure (6.4) Life cycle cost comparison of PV and diesel pump, and the economical feasibility of PV pump in South Kordofan in Sudan.

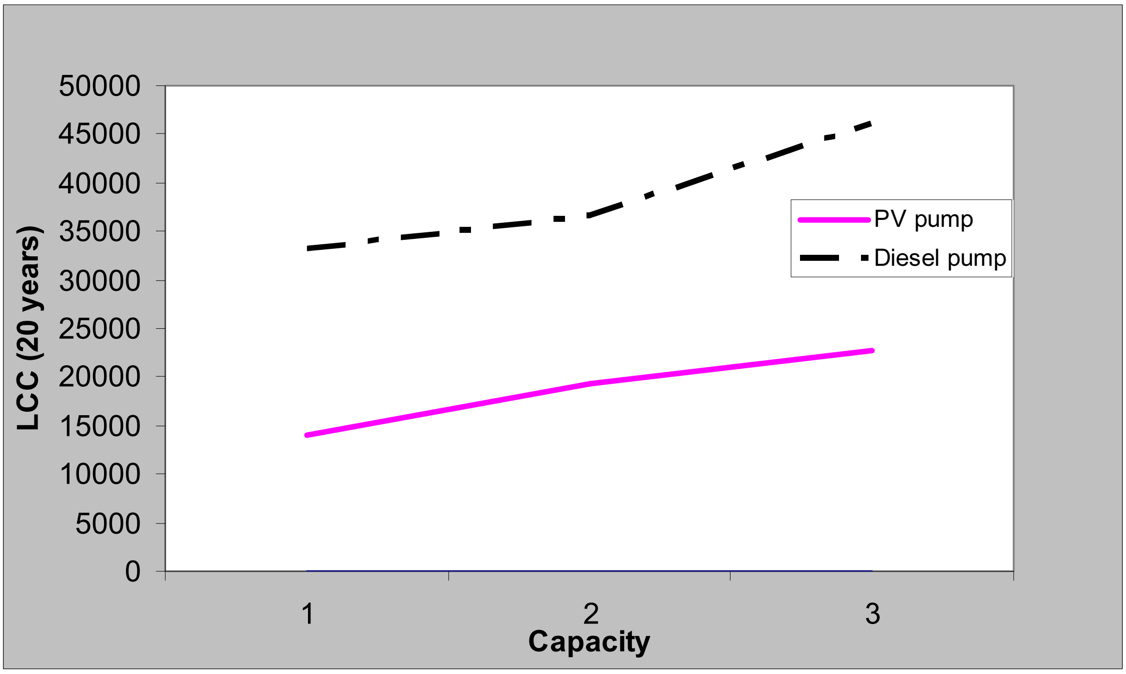

Figure (6.5) Life cycle cost (20 years) verse capacity in KW for PV pumping systems and diesel pumping systems in Sudan.

The results of the comparison between PV and diesel pumping systems will be influenced by changes in any of the key assumptions used. Increases in fuel price sharply increase the cost of pumping with diesel, relative to PV. The use of a higher discount rate improves the relative cost of the diesel, because most of the cost of the PV system occurs in the first year and is not sensitive to the discount factor.

For the same reason that recurrent costs of PV are low, PV-pumping systems are affected by rising future prices, where a cost of diesel pumping may be strongly affected.

The LCC of PV water pumping system is US$19224.85 less than LCC of diesel pumping show table (6.3), where it is about US$ 36572.09 it is two high show table (6.4). The difference between the two values is US$17347.24 these results indicate that PV solar water pumping is most economical feasibility application than diesel pumping system in

Sudan. PV solar pumping system is most effective pumping choice under the conditions in Sudan, Figure (6.3) illustrate good result of life cycle costs for two systems, the initial cost of PV system in the first year \$17275 this value approximately fixed during the first ten year after tens years the subsystem will replacement then replacement cost will added to capital cost, this change showed in curve of PV pump in Figure (6.3) and Figure (6.4). also the initial cost of diesel pumping system in the first year \$7260 very less, the increasing in the cost vary from year to other along the period of LCC, it is depend on the annual initial capital cost, operation, maintenance, fuel and replacement cost of diesel pumping. Figure (6.5) Life cycle cost (20 years) verse capacity in KW for PV pumping systems and diesel pumping systems in Sudan.

The yearly increase in cost of diesel system showed in Figure (6.3) and (6.4), the economical failure of diesel pumping system with economical feasibility of PV pumping system in Sudan determined in this study.

CHAPTER SEVEN

Discussions, Conclusion and Recommendations

CHAPTER SEVEN

7. 0 Discussions, Conclusion and Recommendations

7.1 Discussions

The result of the Computer simulations of the performance of a PV pump for the nine selected sites in Sudan illustrated clearly that it is possible to pump water to using solar energy as a good technical practice. Water delivery by the pump depends on solar radiation intensity. Figure (4.9.11) shows the Monthly solar radiation intensity at the selected sites, the maximum value of solar intensity is in Dongula sites with pumping head of 15m about 7.7kWh/m^2/day solar daily energy with 32.2 m^3/day water output required in May in summer and the minimum values in Foja of about 5.1 kWh/m^2/day with pumping head of 38m the water output required is 19.15m^3/day in August. The maximum water required demand is in Mayo site of about 49.5 m^3/day with head of 22m and solar radiation of 7.1kWh/m^2/day in April in summer and the minimum water pumping with head 38m in Foja 19.5m^3/day. The solar radiation changes throughout the day, it was affected by the weather, and changes from season to season.

The daily hydraulic power in kWh/day depending on water delivery by the pump it increases when the water output increases. System that were able to deliver water in proportion to solar intensity , they produce less water when the solar intensity was low and produce more when the solar intensity is high see Figures (4.1.1) and (4.2.1).

Also, sub-system efficiency, array efficiency and overall efficiency all efficiency were constant they were independent on both solar radiation and water output see Figures (4.1.6), (4.2.6) and (4.3.6).

From the above we can say that the PV pump system studied was seen to perform within acceptable range to that specified by the manufacturer.

The three experiments were carried out in University of Jordan laboratory. The results obtained from the three experiments for May, June and July, parameters of the daily solar radiation (W/m^2), daily water output (L/h), hydraulic power output (W), array output power (W), voltage (V) and current (A) were listed in tables (5.1.1), (5.1.2) and (5.1.3) . The maximum water output about of 1568 Litre per day obtained in July where the solar radiation was high and the minimum water output of 1355 Litre per day obtained in May where the solar radiation was low. The relation between water output and solar radiation was linear in the PV system as shown in Figure (5.1.4).

The difference between the results obtained from the experimental Work and the results of the mathematical model for to the performance of a PV pump in the nine selected sites in Sudan. Some parameters like solar radiation, pumping head and water required are different, so there are variations in some values calculated, for example: the maximum value of solar radiation in Sudan 7.7KWh/m^2/day, but during the experiment in Jordan 3.3KWh/m^2/day.

In life cycle cost (LCC) analysis, the net present value (NPV) of all the capital and recurring costs for the PV powered pumps is compared to the NPV of all the costs of competitive projects. If the NPV of costs of PV-powered pumping is less than the costs of the alternatives, PV should feasible to use in Sudan.

From the results of the analysis under the conditions of comparison showed the initial cost of the first year of the diesel pumping is less costly than the initial cost of PV pumping system, this result illustrated in tables (6.1) and (6.2) the initial cost of diesel pumping system is US$7260 it is very less, but the initial cost of PV pumping system is about US$17275it is very expensive. The annual initial capital cost, operation, maintenance, fuel and replacement cost of PV solar and diesel pumping in Sudan illustrated clearly in Figures (6.1) and (6.2).But the LCC of PV water pumping system is US$ 19224.85 less than the LCC of diesel pumping show table (6.3), where it is about US$ 36572.09 as shown table (6.4). The difference between the two values is US$.17347.24. These results indicate that PV solar water pumping is most economical feasibility application than diesel pumping system in Sudan. PV solar pumping system is most suitable pumping choice under the conditions in Sudan, Figure (6.3) illustrate good result of life cycle costs for two systems, the initial cost of PV system in the first year US$ 17275this value approximately fixed during the first ten year after tens years the subsystem will replacement then replacement cost will added to capital cost, this change showed in curve of PV pump in Figure (6.3) and Figure (6.4). Also the initial cost of diesel pumping system in the first year 7260 US$. The increasing in the cost vary from year to other along the period of LCC, it is depend on the annual initial capital cost, operation, maintenance, fuel and replacement cost of diesel pumping. The economical failure of diesel pumping system with economical feasibility of PV pumping system in Sudan determined in this study.

The results of the comparison between PV and diesel pumping systems will be influenced by changes in any of the key assumptions used. Increase in fuel price sharply increases the cost of pumping with diesel, relative to PV. The use of a higher discount rate improves the relative cost of the diesel, because most of the cost of the PV system occurs in the first year and is not sensitive to the discount factor.

The water head plays an important role in evaluating the economic feasibility of photovoltaic powered water pumping systems.

Costs of PV equipment and water pumps are expected to decrease more and more over the next few years as the production for PV systems goes up worldwide. These factors will make PV pumping systems more economic in the near future in Sudan. The results of the present work should encourage governments for wide installation of solar energy systems to keep the environment healthy and clean.

Solar water pumping has several advantages over traditional systems, for example, diesel engines require not only expensive fuels, and they also create noise and air pollution in many remote pristine areas. Solar systems are environment friendly, low maintenance, and have no fuel cost.

Water storage in metal or plastic tanks is used instead of power storage in a battery. This reduces costs and makes the system simpler. A float switch turns the pump off when the tank is full.

From the all results of this research the advantages and disadvantages of the solar PV pumping systems and diesel pumping systems illustrated in table (7.1).

Table (7.1): Advantages and disadvantages of PV solar and diesel pumping system

Types	Advantages	Disadvantages
Solar pumping	• No fuel required. • Low maintenance. • Module life is 20-30 years. • Cost effective for small power demand. • Environmentally sound.	• High initial capital cost. • Uses unfamiliar technology • Parts may be hard to obtain. • water storage is required for cloudy periods
Diesel pumping	• Low initial capital cost. • Familiar technology • quick and easy to install • widely used • can be portable	• Requires regular maintenance and fuel brought to site. • Requires dependable operator and service support. • Environmentally harmful. • Expensive when considering life cycle cost.

7.2 Conclusion

Solar photovoltaics pumping system is a cost effective and environmental way to pump water in remote areas in Sudan.

Solar photovoltaics pumping system was more feasible in remote areas in Sudan. Solar PV water pumping system has excellent performance in selected sites in Sudan, because Sudan has excellent sunshine and the solar radiation reach 7.7kWh/m^2/day in one of the selected sites, so the technical feasibility is highly successful by using PV systems. In spite of the literature (Omer 2001) which reports that solar PV is not feasible in Sudan.

The water head plays an important role in evaluating the economic feasibility of photovoltaic powered water pumping systems.

In this work, it was found out that the PV water pumping systems are more economical than diesel pumping systems. The LCC of PV water pumping system for one of the Sudan sites is US$ 19224 less than LCC of diesel pumping, where the diesel pumping LCC is about US$ 36572.

In addition, the expected reduction in the prices of photovoltaic modules in the near future is expected to make photovoltaic powered water pumping systems more feasible.

7.3 Recommendations

For better improvements or modification of solar PV pumping system, the following are recommended

1. Solar pumping system in remote areas was alternative to diesel pumping and it is more attractive in Sudan.
2. More solar pump must be installed in rural villages, because the results shows PV pumping is feasible and more economical in rural areas. In addition to it is solving the problem of water pumping in the rural villages.
3. The results of this study should encourage governments for wide installation of solar PV systems to keep our environment healthy and clean.
4. The economic feasibility is based on certain assumptions, and the results of the comparison between PV pumping systems and conventional pumping systems will be influenced by changes in any of the key assumptions used, like period of analysis and reliability of the equipment for that period.
5. The expensive prices of PV modules must be reduced by neglecting the tax and reducing the cost of transportation and installations fees to let the PV pumping more economical.

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APPENDICES

Appendix A

Comparison of pumping techniques

There are other options for pumping water in remote applications. These and their Advantages and disadvantages are listed in Table (A.1).

Table (A.1) Comparison of pumping techniques

Pump Type	Advantages	Disadvantages
Diesel and gasoline pumps	●quick and easy to install ●low capital costs ●widely used ●can be portable	●fuel supplies erratic and expensive ●high maintenance costs ●short life expectancy ●noise and fume pollution
Solar PV	●No fuel required. ●Low maintenance. ●Module life is 20-30 years ●Cost effective for small power demand. ●Environmentally sound.	●High initial capital cost ●Uses unfamiliar technology ●Parts may be hard to obtain. ●water storage is required for cloudy periods
Wind pumps	●unattended operation ●easy maintenance ●long life ●suited to local ●manufacture ●no fuel requirements	●water storage is required for low wind periods ●high system design and project planning needs ●not easy to install

Hydraulic pumps (e.g. rams)	●unattended operation ●easy to maintain ●low cost ●long life ●high reliability	●require specific site condition ●low output
achievable Animal driven pumps	●more powerful than humans ●lower wages than human power ●dung may be used for cooking fuel	●animals require feeding all year round ●often diverted to other activities at crucial irrigation periods
Hand pumps	●local manufacture is possible ●easy to maintain ●low capital cost ●no fuel costs	●loss of human productivity ●often an inefficient use of boreholes ●only low flow rates are Achievable

Appendix (B): Photos of experiments

Figure (B.1) The upper two tanks in head 4m.

Figure (B.2) Submersible Pump inside the lower tank.

Figure (B.3) Photovoltaic panel of monocrystalline (four modules).

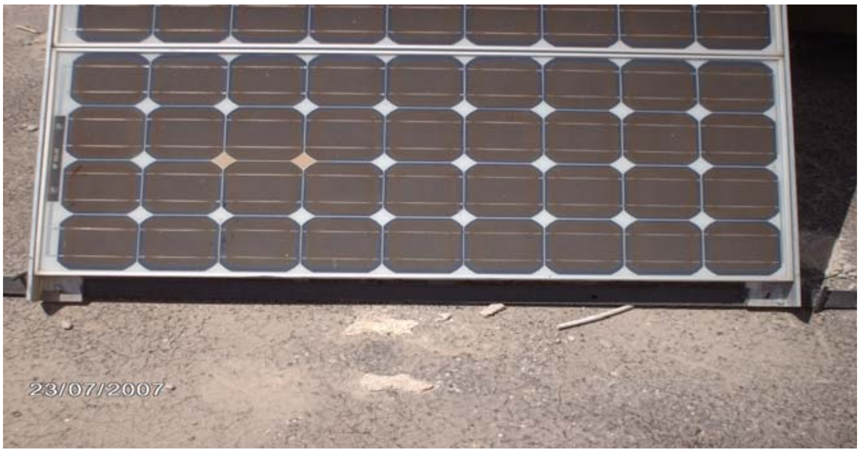

Figure (B.4) Photovoltaic panel of monocrystalline (one module).

Figure (B.5) Measuring devices pyranometer and Avometer which were used in experiments.

Figure (B.6) The integrator which was used to measure solar intensity during the experiment

Appendix (C): Measured and Result Values of Experiments

Table (C.1): Measured and result values of the first experimental in May (Monday 21/5/2007).

Time	$G_T W/m^2$	Q,L/h	P_h, W	P_e, W	V, v	I,A
7	549	96	1.0464	15.45	15	1.03
8	668	117	1.2753	16.49	15.7	1.05
9	746	132	1.4388	17.596	16.6	1.06
10	832	144	1.5696	18.511	17.3	1.07
11	914	152	1.6568	19.081	17.7	1.078
12	948	155	1.6895	19.44	18	1.08
13	913	151	1.6459	19.188	17.8	1.076
14	862	146	1.5914	18.618	17.4	1.07
15	783	138	1.5042	17.7	16.7	1.06
16	692	124	1.3516	16.275	15.4	1.05

Table (C.2): Measured and result values of the second experimental In June (Sunday 24/6/2007)

Time	G_T,W/m^2	Q,L/h	P_h, W	P_e, W	V, v	I, A
7	556	102	1.112	19.86	19.1	1.04
8	694	124	1.35	20.064	19.2	1.045
9	812	140	1.53	20.3	19.27	1.054
10	894	151	1.65	20.5	19.33	1.06
11	964	156	1.7	20.7	19.38	1.067
12	992	158	1.72	20.8	19.4	1.07
13	966	155	1.69	20.7	19.37	1.068
14	898	150	1.635	20.5	19.32	1.06
15	830	142	1.55	20.2	19.26	1.051
16	703	128	1.4	20.2	19.2	1.04

Table (C.3): Measured and result values of the third experimental in July (Monday 23/7/2007) with A_{PV} 0.59 m^2.

Time	G_T,W/m^2	Q	P_h, W	P_e, W	V, v	I, A
7	606	122	1.3298	20.176	19.4	1.04
8	776	144	1.5696	20.475	19.5	1.05
9	868	156	1.7004	20.776	19.6	1.06
10	939	165	1.7985	21.079	19.7	1.07
11	988	171	1.8639	21.3013	19.76	1.078
12	1011	174	1.8966	21.384	19.8	1.08
13	988	171	1.8639	21.2635	19.78	1.075
14	939	165	1.7985	21.079	19.7	1.07
15	868	156	1.7004	20.776	19.6	1.06
16	776	144	1.5696	20.475	19.5	1.05

الجدوى الفنية والاقتصادية لضخ المياه بالطاقة الشمسية الكهربائية في السودان

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ملخص

لقد تم دراسة الجدوى الفنية والاقتصادية لضخ المياه بالطاقة الشمسية الكهربائية في السودان، نجد أن المناطق الريفية البعيدة تثير مشاكل لإدارة تطوير الطاقة الريفية بسبب الطرق السيئة التي تربطها بالمراكز الحضرية وبعدها من الشبكة القومية لإرسال الكهرباء،لهذا الغرض تم اختيار تسعة مواقع مستندة على بيانات الإشعاع الشمسي المتوفرة في السودان.وضخ المياه بالطاقة الكهربائية الشمسية مناسب جداً لإمداد المناطق البعيدة بالمياه حيث لا يتوفر بها إمداد كهربائي، معظم أنظمة الضخ الفوطفولطية في السودان تتكون من: الخلايا الشمسية، المحول، موتور/طلمبة وخزان للمياه. منهجية البحث تتضمن العرض النظري للنظام حيث العلاقات الرياضية لاداء المضخة إلى مستويات الاشعاع الشمسي خلال السنة تم تطبيقها في كل تسعة المواقع التي اختيرت في هذه الدراسة ثم عمل تجارب ثم تطبيق طريقة (LCC) تكلفة دورة الحياة لمعرفة العمر الاقتصادي لضخ المياه بالطاقة الشمسية و الضخ بالديزل خلال 20 سنة.

نتيجة المحاكاة بالحاسب لأداء المضخة الشمسية في المواقع المختارة التسعة في السودان اثبتت إنه من الممكن استعمال الضخ بالطاقة الشمسية وهي ممارسة تقنية جيدة.كمية الماء الذي يضخ بالمضخة يعتمد على كثافة الإشعاع الشمسي والنظام يكون قادر علي ضخ المياه بالنسبة لكثافة الاشعاع الشمسي. إي يكون الضخ ضعيف إذا كانت كثافة الاشعاع منخفضة ويكون مرتفع إذا كانت كثافة الاشعاع عالية.وضحت نتيجة العمل التجريبي أن أقصى إنتاجية مياه 1568 لتر في اليوم في شهر يوليو حيث كان الاشعاع الشمسي مرتفع وأقل إنتاجية مياه 1355 لتر في اليوم في شهر مايو حيث كان الاشعاع الشمسي منخفض. نتيجة طريقة (LCC) وضحت تكلفة دورة حياة نظام الضخ

بالطاقة الشمسية 19224.85 دولار أمريكي أقل من تكلفة دورة حياة نظام الديزل حوالي 36572.09 دولار أمريكي، والفرق بين القيمتين حوالي 17347.24 دولار أمريكي. من خلال الدراسة وجد أن نظام الضخ بالطاقة الكهربائية الشمسية يمتاز بأداء جيد في المواقع المختارة في السودان، وذلك لان السودان يمتاز بشمسه الساطعة ويصل الاشعاع الشمسي إلى 7.7 كيلوواط ساعة على المتر المربع في اليوم، لذا فالعملية التقنية للضخ بالطاقة الكهربائية الشمسية ناجحة جداً. هذه النتائج تشير إلى أن نظام ضخ المياه بالطاقة الشمسية قد أثبت جدواه الفنية والاقتصادية من نظام الضخ بالديزل في السودان.