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MSc. ENERGY ENGINEERING

Thesis title:

TECHNO-ECONOMIC ANALYSIS FOR STAND ALONE SOLAR WATER PUMPING SYSTEM FOR FARM IRRIGATION; A CASE STUDY IN SUDAN

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DEDICATION

This Master thesis is dedicated to the Almighty Allah. And dedicated to my loving mother Ms. Mona M. Alobied.

ABSTRACT

One of the critical problems currently being faced by the Sudanese transitional government is ensuring a sustainable economic and Agriculture contribute to 27% to the GDP and employing about 80% of the workforce. That is why irrigation plays a crucial role in the country development. This study intends to provide techno-economic analysis of stand-alone solar water pumping system and compare its performance and environmental impact with Diesel water pumping systems. The HOMER optimization software is used to evaluate both the environmental and the economic viability of the proposed pumping systems by taking into account the variations of both the solar radiation and diesel price. Although this master thesis has used a farm in Al-Ailfun district as a case study, solar water pumping technology can be applied for agricultural irrigation purposes for the rest of the country and all over the world especially in rural areas where access to electricity and fuel is difficult. implementing this technology would lead to higher incomes and better living conditions for farmers while improving agriculture output. Results have shown that implementing Photovoltaic systems for agricultural irrigation is more profitable when compared to diesel systems. The costs of producing one unit of energy by the PV system are lower than the diesel system. The HOMER results, in Sudan show that levelized cost of energy (LCOE) for solar and Diesel systems are 0.249 and 0.364 $/kWh respectively.

Keywords: Photovoltaic system; irrigation; pumping system; economic analysis.

RÉSUMÉ

L'un des problèmes critiques auxquels est actuellement confronté le gouvernement de transition soudanais est d'assurer une économie durable et une agriculture qui contribue à 27% du PIB et emploie environ 80% de la population active. C'est pourquoi l'irrigation joue un rôle crucial dans le développement du pays. Cette étude vise à fournir une analyse technico-économique du système de pompage d'eau solaire autonome et à comparer ses performances et son impact environnemental avec les systèmes de pompage d'eau diesel. Le logiciel d'optimisation HOMER permet d'évaluer à la fois la viabilité environnementale et économique des systèmes de pompage proposés en tenant compte des variations à la fois du rayonnement solaire et du prix du diesel. Bien que cette thèse de maîtrise ait utilisé une ferme du district d'Al-Ailfun comme étude de cas, la technologie SWP peut être appliquée à des fins d'irrigation agricole pour le reste du pays et partout dans le monde, en particulier dans les zones rurales où l'accès à l'électricité et au carburant est difficile. . la mise en œuvre de cette technologie entraînerait des revenus plus élevés et de meilleures conditions de vie pour les agriculteurs tout en améliorant la production agricole. Les résultats ont montré que la mise en œuvre de systèmes PV pour l'irrigation agricole est plus rentable par rapport aux systèmes diesel. Les coûts de production d'une unité d'énergie par le système PV sont inférieurs à ceux du système diesel. Les résultats HOMER montrent que le LCOE pour les systèmes solaires et diesel est respectivement de 0,249 et 0,364 $ / kWh.

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LIST OF ABBREVIATIONS AND ACRONYMS

SDGs	Sustainable Development Goals
GDP	Gross domestic product
UNDP	United Nations Development Programme
KOICA	Korea International Cooperation Agency
AC	Alternate current
PV	Photovoltaic
CSP	Concentrated Solar Power
MENA	Middle East and North Africa
LCOE	Levelized costs of electricity
$	American Dollar
COE	Cost of energy ($/kWh)
USD	United States dollar
RE	Renewable Energy
COVID_19	Corona virus disease 2019
DC	Direct current
DWP	Diesel water pumping
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
IFAD	International Fund for Agricultural Development
G	Daily irradiance on the PV surface (kWh/m2/day)

GHG	Greenhouse gasses
GIS	Geographic Information System
WB	World Bank
Ha	Hectare
HOMER	Hybrid Optimization Model for Electric Renewables
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kWh	Kilowatt-hour (Unity of energy)
LCOE	Levelized Cost of Energy (($/kWh)
MPPT	Maximum power point tracker
NGOs	Non-Governmental Organizations xi
NPV	Net present value
NPC	Net present cost ($)
IRR	Internal Rate of Return
O&M	Operating and maintenance ($)
OC	Operation cost ($/year)
PBP	Payback period (year)
BOS	Balance of System
SWP	Solar water pump
H D	dynamic head.
Hf	friction losses in the piping system, this depends on the flowrate

IDP	internally displaced person
PVWP	Photovoltaic water pumping
TDH	Total dynamic head (m)
V	Volume of water (m3)
VAT	Value Added Tax

1. INTRODUCTION

1.1 Background

The world's population is expected to increase from 7.7 to 9.7 billion in 2050. Africa has the highest rate of population growth in the world, since more than half of the global population growth between now and 2050 is expected to occur in Africa [1]. The rapid increase in population would emphasize the issue of food security, especially in sub-Saharan countries. On the other hand, the agricultural sector is affected by climate change due to the variability of rainfall and drought which led to severe food insecurity in rural areas, where farmers depend on traditional agricultural methods. This is what mainly attributed to a low level of agricultural productivity characterized by persistent rural poverty among farmers and with the increasing population, the pressure has often resulted in a vicious circle of poverty and environmental degradation.

Simultaneously, the energy demand is grows at more rapid speed. Nowadays the primary sources of energy are coal, petroleum and gas which are widely utilized by the modern population of the planet. These resources are expected to run out sooner than they would have an opportunity to replenish themselves. In addition, these energy sources are able to have a substantial negative impact on the natural surroundings. Carbon dioxide (CO_2), which is generated from fossil fuels and biomass combustion, is considered among the most notable greenhouse gases. Moreover, CO_2 is to some extent accountable for a worldwide environmental instability such as temperature increase and extreme weather which is what widely known as global warming or climate change phenomena. That is why there is a constant search for substitutes, clean energy resources, in addition to the approaches that are aimed to lessen the environmental negative outcomes.

In the sub-Saharan Africa, approximately 78% of large- and small-scale irrigation schemes use surface water, while 20% make use of groundwater resources[2]. Farmers are very aware of the limitations posed by water access and view their water source as a critical factor in their choice of irrigation method.

Renewable energy technologies are the most promising substitute for conventional energy sources since renewable energy sources are naturally replenished on a human timescale and they are considered as sustainable energy sources[3]. We often call renewable energy technologies “clean” or “green” energy, because they produce few if any pollutants. They are derived principally from the power of the sun’s radiation. There are also non-solar renewables, namely tidal energy and geothermal energy. However, these technologies are not mature yet, regarding efficiency, intermittency and storage capabilities.

Agriculture is one of the sectors that can solve these issues regarding the increase in population and energy demands by providing enough food stock and bioenergy such as energy crops and biomass. As the prime connection between people and the planet, agriculture can help achieve multiple Sustainable Development Goals (SDGs) [4]. With sustainable agriculture we can fight poverty and hunger. Improving the irrigation system is a key strategy to enhance agricultural productivity and stimulate economic development to achieve agricultural sustainability [5]. By improving the irrigation, system especially in rural areas, we can improve land productivity, enhance food security, grantee higher and more stable incomes for farmers by allowing them to do multiple cropping and crop diversification instead of seasonal farming which is usually after floods or rainy season to all year round farming.

To improve the irrigation system we need to address the “food-energy-water nexus.” Hence water and energy are the main drivers of agriculture (including irrigation, livestock and aquaculture) development. Agriculture is by far the largest water consumer, accounting for 69% of water withdrawals annually in the world and accountable for 30% of energy consumption[6], that is why water management is a core process in sustainable agriculture to meet the future food and energy demands of a rapid growing of the human population.

In regions where available rainfall is not able to meet the water requirements of irrigation, water pumps are required to lift water to where it is needed [7]. In general, water pumping depends on conventional electricity or diesel-generated electricity. From an environmental perspective, agriculture is among the sectors mostly causing global warming due to the use of fossil fuels to power generators which produce greenhouse gas emissions which can participate in climate change. Solar PV water pumping system can be implemented to minimize the dependency on fossil-based electricity generation.

The uses of diesel water pumping systems require not only expensive fuels but also create noise and air pollution. According to a recent study, the overall upfront cost of operation, maintenance and replacement of a diesel pump can be higher than a solar PV pump, since the PVWP system costs have dropped by 2/3 while fuel prices rose >250% since 2000[8], not to mention that refilling of the fuel and frequently the diesel fuel is not easily obtainable in remote regions. Moreover, the solar PV water pumping system is environment friendly; require low maintenance with no fuel cost and the solar energy source can be found all over the world for free.

1.2 Solar Energy Potential In Sudan

Sudan is the third largest country in Africa with an area of 1,886,068 km² (718,723 sq mi) and a population of 40,533,000, 65.9% of them are in rural areas. Sudan is located between 9°N and 22°N in north-eastern Africa. In 2017, the GDP in Sudan was 2,379 USD/capita. 52% of the population are surviving on subsistence agriculture[9]. Figure(1.1) is showing Sudan position in Africa, major cities, regions and the main water sources in the country such as the river Nile and its tributaries blue and white Nile.

Sudan has different resources of energy, the main sources of primary energy are oil, biomass, and renewable energy, such as hydro. Solar energy applications are still limited. Sudan has neither uranium nor coal. The main transformation and conversion processes are electric power generation, oil refinery, and wood-to-charcoal conversion. Renewable Energy in Sudan is not very common, however the country is classified among the top countries in the world in term of renewable energy potential, especially Solar Energy with both types PV and Concentrated Solar Power CSP.

Figure (1. 1): country profile

Source: https://www.cia.gov/library/publications/the-world-factbook/geos/su.html

Sudan lies in the area of maximum solar radiation in Africa. Fig. (1.2) shows the distribution of solar radiation in North African countries. The average annual value of solar radiation in Sudan is $8.0X10^4$ TWh/year. Despite the huge potential solar energy in Sudan, the installed capacity is only 2 MW from Photovoltaic (PV) cells, and approximately half of this amount is dedicated to the telecommunication industries such as remote off-grid antennas and satellites[10]. The Sudan Photovoltaic Electricity Potential is shown in Figure (1. 3)

Recently, various areas which are classified as rural started adopting solar technology for residential use, for charging, lighting and low load activities.

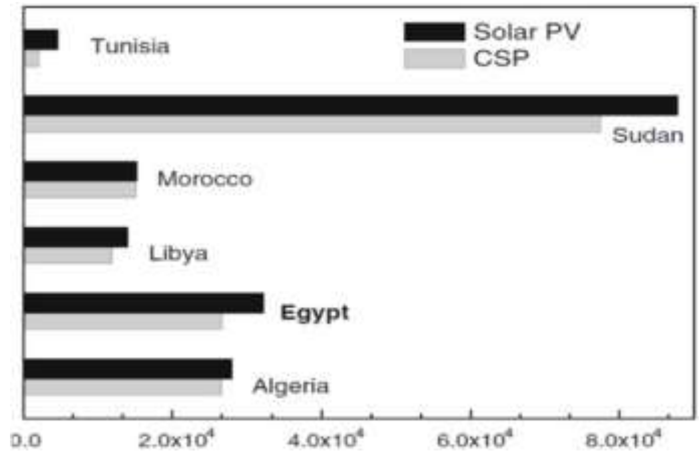


Figure (1. 2): Solar energy potential (TWh/year) for North Africa countries

Source: https://www.rcreee.org/

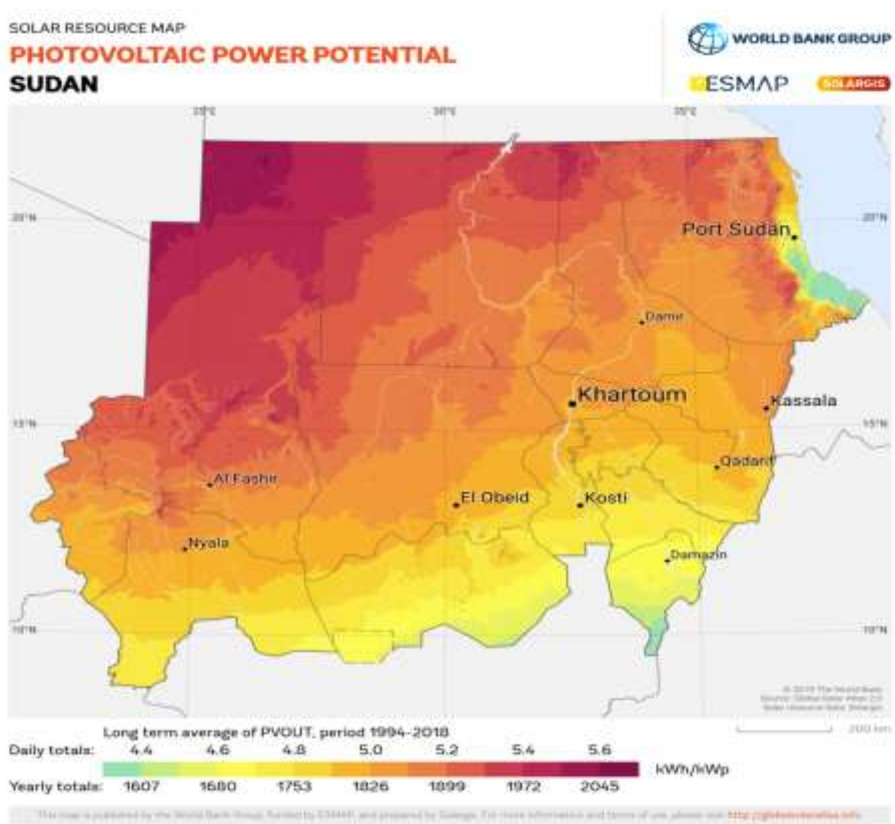


Figure (1. 3)Sudan Photovoltaic Electricity Potential

Source: Global Solar Atlas 2.0, Solar resource data: Solargis/ https://solargis.com/maps-and-gis-data/download/sudan

There is a remarkable spread of solar technologies in the west of the country at the refugees' camps. On April 4, 2019, the Sudan's the Ministry of Water Resources Irrigation and Electricity, and the United Nations Development Programme (UNDP) in Sudan signed an agreement with Korea International Cooperation Agency (KOICA) to implement a project on "Promotion of renewable energy and sustainable financial modality as the gateway to improve farmers' livelihoods and Green House Gas reduction". The program aimed at supporting sustainable agriculture for climate change affected communities in Sudan through the use of solar technology instead of diesel-based irrigation water pumps in farmlands.

1.3 Statement Of The Problem

Electricity sector in Sudan has been a victim to many challenges, starting with the increase of oil price after 2011, due to the separation of South Sudan, where two-third of the oil deposit is in the new country, South Sudan. The effect of oil scarcity is affecting the thermal power plants which generate up to 44% of the total installed electricity in the country. Sudan's electrical power sector has been subjected to poor infrastructure and maintenance which led to a frequent power cut off and many parts of the country have been experiencing frequent power outage on a daily bases. Electricity outage in the country is a major barrier to the economic development and prosperity since it cripples the development of the education, industrial and agriculture sectors.

In fact, the agricultural sector is the most affected sector even though it employs about 80% of the country's population and contributes to approximately 30% of Sudan's GDP [10]. The demand for food in Sudan is growing dramatically due to the increasing country population while cultivated land is decreasing. The irrigation system becomes expensive due to the lack of power for water pumping system. Generally, the irrigation technologies that are used in Sudan are traditional watering which is labour intensive and allow irrigation of only a small area (50 to 100 m^2). Diesel motorized technology which is expensive, is not available all the time not to mention air pollution. A little portion is grid connected (electrical irrigation) which is also struggling with power outage while solar technology is still behind. The adoption of renewable energy technologies has been identified as a priority in Sudan to reduce the dependency on fossil fuel. Currently the renewable energy share on the Country energy profile is application of solar PV has been limited in off-grid small scale project in rural areas, however it has been progressively contemplated in agricultural strategies and future plans of Sudan. Increasing of climate change and human population have increased the reduction of agricultural production due to droughts, the reduction of cultivated land and forced the farmers to find other alternative energy sources for water pumping system for irrigation. That's why this study is conducted to find a lower cost, environmentally friendly and sustainable technology among the existing technologies.

1.4 Research Objective

1.4.1 General objective

The main objective of this study is to analyze and examine the technical and economic aspects of a solar water pumping system compared to a diesel water pump for small-scale irrigation in Sudan.

1.4.2 Specifics objectives

In order to analyze economically and technically the cost of a solar water pumping system for small-scale agricultural irrigation in Sudan, it is necessary to take into account the following specific objectives:

1) To assess the potential of solar energy and water head within selected areas of Al-Ailafun, south-east of Khartoum, for irrigation purposes.
2) To estimate the everyday load and energy demand of the Case Study's irrigation system.
3) To Simulate and optimize the solar PV system using HOMER software.
4) To compare the Levelized costs of electricity (LCOE) of the solar PV water pumping system with the diesel system.

5) To identify the barriers and drivers of diffusion of solar water pumping system for irrigation purposes in Sudan.

1.5 Research Questions

1) Is the use of solar PV water pumping system sustainable (technical, social, and economic) and affordable compared to the use of non-renewable energy sources?
2) What is the lowest cost when comparing between solar and diesel water pumping system for agricultural irrigation in Sudan?
3) What are the barriers and drivers of diffusion of agricultural irrigation in Sudan?
4) What is the most efficient irrigation system to supply water to a cropped land?

1.6 Scope Of The Study

This study aims to analyze technically and economically the cost of solar PV water pumping system for agricultural irrigation. The case study is located in Al-Ailafun district, south-east of Khartoum. This district has been chosen because of its agricultural activity and lack of electricity from the national grid. The study was undertaken in Sudan (Al-Ailafun) from March up to July 2020 for collecting and analyzing data.

1.7 Significance Of The Study

This thesis would help the government to reinforce the policies needed to achieve the goals of economic development and poverty reduction strategies by improving the use of irrigation systems which lead to increase the agricultural production. This study will also help people to gain knowledge on how they can use renewable energy technologies especially solar water pumps for irrigation. The study will also help the future researchers to gain knowledge about the use of solar energy as power sources of water pumping system for irrigation. Finally this thesis would help researchers to address the solutions of droughts consequences for farmers.

1.8 Justification Of Case Study

There are three primary reasons why the location has been chosen;

- This area has a significant interest in irrigation due to the electricity deficit, abundant of water resources, intensive population growth and increased food demand.
- The farmers in this area have a significant interest in using solar energy for water pumping.
- The initial cost of the system in this area is one of the barriers. By showing that the system is economically attractive, the farmers, the government and the private sector will be encouraged to adopt the technology.

1.9 Difficulties Encountered During Data Collection

Data collection process had faced many obstacles, starting from the personal safety for the researcher herself, the hardship of the movement in the capital Khartoum at the early stages of COVID_19 and the early curfew.

The COVID_19 pandemic led to a global lockdown in internal and international movements which affected the whole thesis timeline and construction. Some modifications were made to adjust to COVID_19 pandemic effect on the economic sector, such as the case study location and the fuel prices.

1.10 Outline Of The Study

This thesis consists of the following chapters:

Chapter one is the introduction. It includes the background information, problem statement, objectives, significance of the study and thesis outline. Chapter 2 contains the literature review. Chapter 3 contains the methodology and description of models adopted for simulations, optimization, and technical and economic evaluation. Chapter 4 contains the results and discussions. Chapter 5 contains the conclusions and recommendations which highlight the main findings of the thesis and recommendations for the government and future researchers.

2. LITERATURE REVIEW

2.1 Introduction

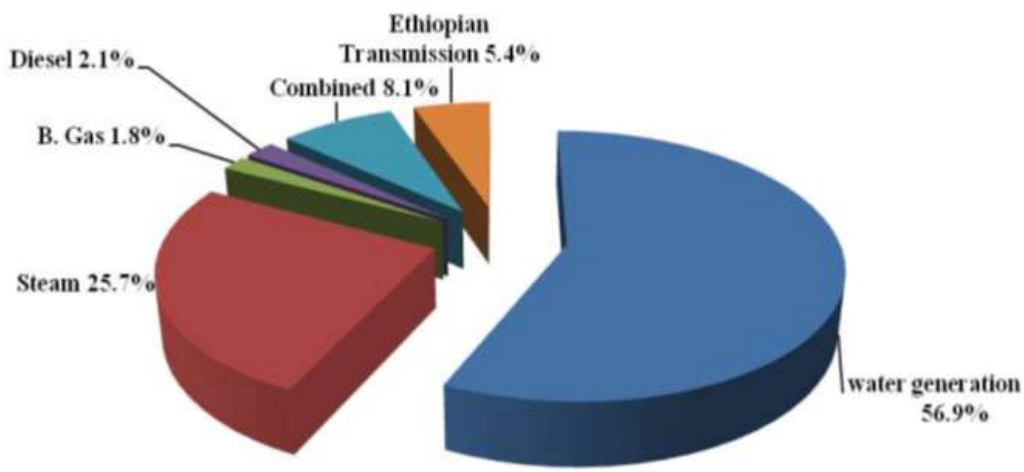
This chapter reviews the work done by other researchers in the field of renewable energy technologies, mainly solar energy and irrigation systems. The purpose of this literature review is fourfold:

The first part of this chapter deals with the country energy profile and overview of the agriculture sector for Sudan. The second part focuses on the water pumping systems for agricultural irrigation. The third part reviews the Solar PV pumping system operating principle, system components and Solar Pumps types. Other energy resources for irrigation system are also reviewed and compered with solar photovoltaic. The final part is focused how to size a solar PV water pumping system.

2.2 Country Energy Profile

Sudan is a rich country with a variety of energy resources. Yet many of these resources of the country have not been properly utilized due to the poor economic conditions, wars and lack of proper management. The main sources of energy are oil and renewable energy (hydropower, biomass and solar). Sudan has no nuclear power or coal. The main processes for transformation and conversion of energy are electric power generation, oil refinery, and wood-to-charcoal conversion.

The energy sources could be classified as conventional sources such as petroleum products, and non-conventional (renewable energy sources) such as Hydro, Solar and wind[11]. Renewable Energy technologies are not very common in Sudan except for Hydropower which participates by 56.9 % of the total electricity produced, as shown in Figure (2. 1) which explains the different sources of the total electric power generated in the year 2017.



Figure(2. 1): the contribution of electricity generation sources in total electric power generation, Source:[12]

Even though, the country is classified among the top countries in the world in term of renewable energy potential, especially solar energy. Wind energy in Sudan has a good potential as well. Three sites have been selected for the near future wind power program to increase the electrification rate in the country. The sites are located in the North-east in the Red Sea shore, the Western region, in Nyala and the Northern state, in Dongola. Table (2. 1) shows the production capacities per energy source in the country.

Table(2. 1): Production capacities per energy source

Energy source	total in Sudan
Fossil fuels	13.25 bn kWh
Nuclear power	0.00 kWh
Water power	15.36 bn kWh
Renewable energy	1.81 bn kWh
Total production capacity	30.11 bn kWh

Source: world data https://www.worlddata.info/africa/sudan/energy-consumption.php

According to the World Bank collection of development indicators in 2018, in Sudan, 59.78 % of the population have access to electricity specifically 83% of the urban population and 47% of the rural population have access to electricity[13].

2.3 Agriculture In Sudan

Agriculture is a main economic sector contributing 27% to the country's GDP. Nearly half of the national workforce is engaged in agriculture (i.e. crop, livestock, fisheries and forestry production) and agro-processing industries [12]. The potential opportunities of the Sudanese agriculture sector have remained unchanged for decades.

2.3.1 Agricultural resources

Sudan has the largest irrigated area in the sub-Saharan Africa and the second largest in all Africa, after Egypt. The total estimated area fully equipped for irrigation is 1,764,635 ha and an estimated cropped area of 1,148,665 ha, i.e. an estimated cropping intensity of 65%. The irrigated sub-sector contributes more than 50% of the total volume of the agricultural production although the irrigated area constitutes only about 11% of the total cultivated land. It has become more and more important over the past few decades as a result of drought and rainfall variability and uncertainty[14].

The main crops are sorghum, millet, wheat, maize, rice sesame, groundnuts, sunflower, cotton and tomato. The main cropping systems are irrigated farming schemes and rain-fed farming. Major agricultural exports are cotton, sesame, Arabic gum and livestock. Grain sorghum is the principal food crop, and wheat is grown for domestic consumption [15].

The main sectors of agriculture in Sudan are the irrigated sector, rain-fed mechanized, traditional rain-fed and livestock sectors. The irrigated agriculture sector area is about 2 million hectares out of about 74 million potentially arable hectares. About 93 per cent of the irrigated area is owned by the government and 7 per cent by the private sector. The area under rain-fed mechanized system covers about 6 million hectares in the state of Gedaref, Blue Nile, Upper Nile, Sinnar and Southern Kordofan. Mechanized farms are usually well over 420 hectares. In this sector land preparation, seeding, and most threshing are mechanized, whereas, weeding, harvesting, and some threshing are done manually by seasonal labour [16].

2.3.2 Agriculture and energy consumption

Sudan's farming systems are composed of three major categories, namely irrigated, mechanized and traditional rain-fed systems. The use of a diesel pump to pump water causes different problems on human life and environment, because it emits a large amount of CO_2. Various researches are being made with a focus to design solar photovoltaic water pumping systems which can provide electricity in an isolated area that can be used for crop irrigation and in different home activities.

The oil price increased by 400% due to the independence of South Sudan which left the country with only one-third of the oil reserves. Sudan mainly depends on imported oil, 47% from Saudi Arabia and 24% from United Arab Emirates, reaching a total of 05,095 M. T in 2017 [12]. On the other hand, the rapid reduction in the price of PV modules and higher solar insolation are the important factors which can accelerate the growth of solar power market and play a key role in studying the feasibility of harnessing solar energy technology especially in the agriculture sector of Sudan.

2.3.3 Climate change

Climate change is significantly impacting the agriculture sector by increasing water demand; limiting crop productivity while reducing water availability in the regions where irrigation is most needed. Considerable attention has been given to climate change and its impacts. Agriculture is considered to be one of the sectors most vulnerable to climate change.

The "environmental and climate change assessment"[18] undertaken by IFAD analysed historical temperature and rainfall patterns, modelled estimated future projections of precipitation and rainfall, as well as future runoff of the Nile, flows until 2050. The assessment indicates that climate change is already leading to more severe and chronic droughts and threatening all rainfed agricultural systems. Increased temperatures and declining rainfall have shifted the boundary between desert and semidesert zones southwards by between 50 and 200 km over the past 80 years. This trend is continuing and large areas of the remaining semi-desert and low rainfall savannah – key livestock production zones – are at risk of desertification. By 2050, vulnerability assessments show that temperatures are likely to rise by between 1.5 and 2.5°C throughout the country (1.6°C in Atbara; 2.1°C in Khartoum; 0.6°C in El Obied; 1.5°C in El Fasher and Gedaref; 2.0°C in Kassala; 0.8°C in Damazene; and 1.3°C in Malakal).

The average annual rainfall is expected to increase in most areas but with significant changes in its seasonality and more frequent droughts. The highest annual reductions are predicted for Gedaref and Kassala States; while the highest seasonal variability is predicted to be in Northern, North Darfur, River Nile and the Red Sea States. Increased temperatures and higher rates of evapotranspiration will increase water demand for agriculture significantly; and accordingly, the potential for moisture stress in crops and animals will increase. Rainfed cropping areas will shrink, and the impact of droughts will increase.

2.4 Irrigation Pumping Systems

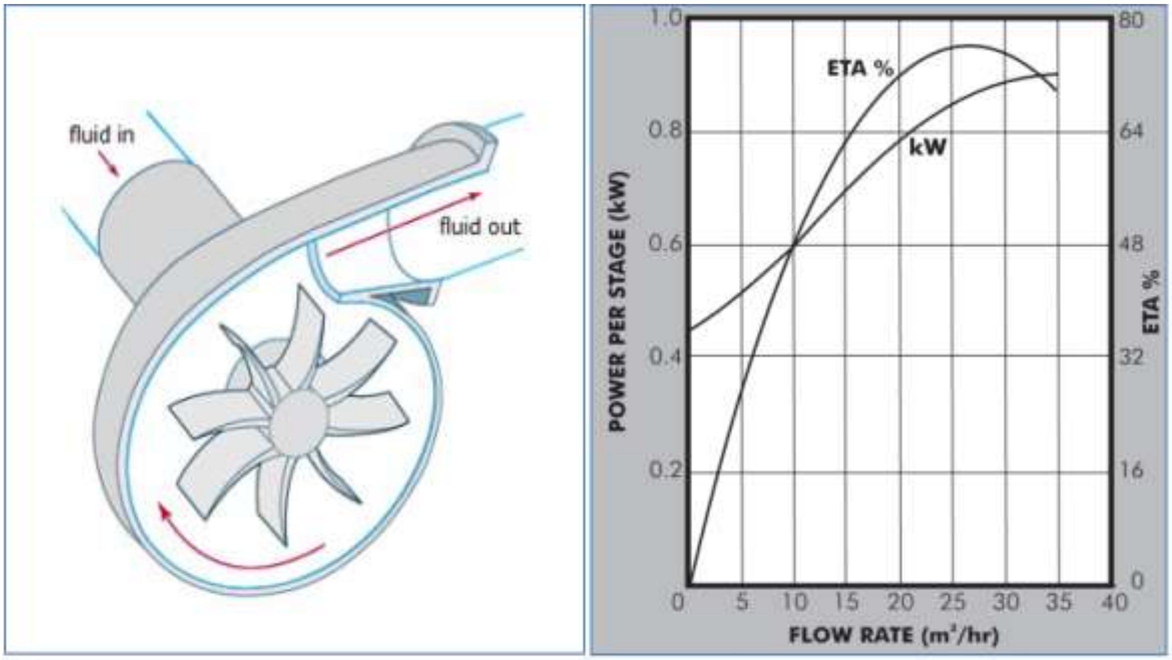
Water pumping systems play an essential role in providing energy to move the fluids "in this case water" from one point to another for agricultural purposes. The irrigation systems have the role of taking water from the water source, conveying it to individual fields within the farm and distribute it to each field in a controlled manner. Depending on the elevation and location of water resources, there are two methods used for irrigation. When the water surface is situated on a higher slope, the gravity flow method is used and no pumping is required. When the source of water is underground or at low slop, the pumping system which is also known as the pressurized irrigation system is required to conveyed water through some external pressure where pumps are an integral part of this system [17].

There are some considerations such as land slope, soil permeability and type, plot size and crops, water availability, required labour inputs and economic costs/benefit have to be analyzed before carrying out the irrigation process. Most Sudanese cropped areas are irrigated using surface water resources by the method of gravity, especially for areas near Dams. The Gezira Scheme is Sudan's oldest and largest gravity irrigation system, located between the Blue Nile and the White Nile. The scheme together with its extension of Managil scheme with a total equipped area of 846,772 ha is the largest single scheme in Sudan and one of the largest irrigation schemes in the world. The traditional irrigation is practiced on the floodplains of the main Nile downstream of Khartoum and substantial areas along with the Blue and White Nile, and the Atbara river as well as on the Gash and Tokar deltas[14]. There are several types of pumps with different subcategories (centrifugal pumps and positive displacement pumps are the most popular types), each of them is used in a specific field.

2.4.1 Centrifugal pumps

Centrifugal pumps are applied for a broad variety of flow and head demands. This category of pumping systems in general has a life span from 5 to 10 years with productivities in the 80 per cent range. They can be categorized as volute pumping systems, in which the impeller is walled by a spiral covering and turbine pumping systems, in which the impeller is walled by diffuser vanes that slightly bear a resemblance to the reaction turbines.

When the impeller rotates the fluid, it accelerates it in a radial direction outward to the surrounding volute casing which creates a centrifugal force in the fluid. The Principle of operation of a centrifugal pump may be explained as: The liquid is forced into the eye of the impeller by atmospheric pressure. Then vanes of the impeller pass kinetic energy to the fluid, thereby causing the fluid to rotate. The fluid leaves the impeller at high velocity. The impeller is surrounded by a volute casing which converts kinetic energy into pressure energy [19]. Figure (2. 2) shows a schematic diagram of a centrifugal pump and its power consumption graph.

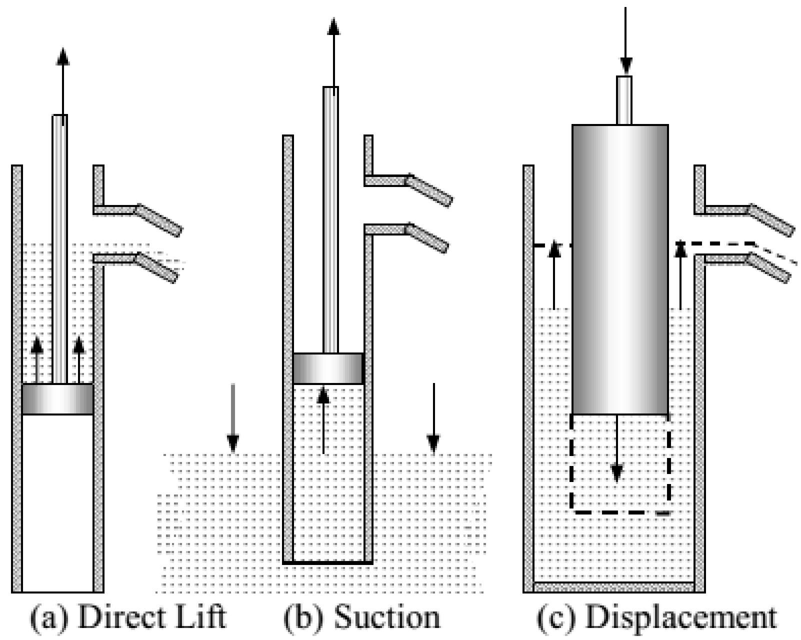


Figure(2. 2): schematic diagram centrifugal pump and power consumption graph

2.4.2 Positive displacement pumps

This system, Fig. 2.3, appears to be more effective at higher heads, and it is the most applicable for high-head low-flow use. Leaking fluids in the packing or in the valves of these pumps, on the other hand, will result in the rapid decrease of their output and productivity. Rotary pumping systems are utilized for low-lift use even though they are proven to achieve better productivity as they are pumping unclear water mixed with mud. These pumps are not advised for heads that exceed 20 meters[19].

The manual or animal driven pumping systems (for example, hand pumps, water-wheel pumps etc.) are, for the most part, utilized in various developing countries in order to extract water from boreholes and wells for future irrigation. On the other hand, the power that these pumps require is rather inadequate in comparison to other power sources, for instance, renewable sources of energy. Moreover, hand pumps and other manual pumping systems are nearly at all times afflicted by system failures that come as a result of the insufficient efforts, unproductive design, absence of spare fragments of the pumping systems for further maintenance, or exhaustion and for that reason are not trustworthy[5].



Figure(2. 3): Operating principles of positive displacement pumps

2.4.3 Energy resources for water pumping system

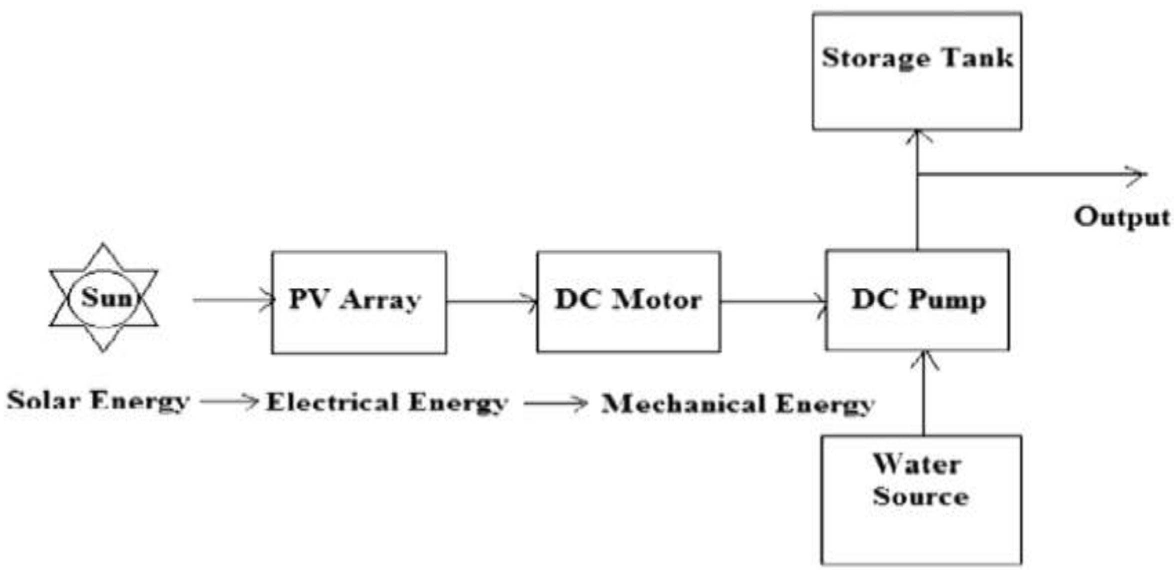
According to Prakhar M 2013 study, the energy sources are mainly selected based on their technical, environmental and the economic aspects. Although the reliability of the energy source is the main factor, the system’s affordability is another crucial selection factor, especially in rural areas of developing countries where income levels are considerably low. There are different sources of energy that are used to pump water, such as renewable energy (hydropower, wind, solar, biofuels etc.), human energy, and fossil fuels such as diesel for small generators[20]. Generally, the amount of energy required varies depending on the method of irrigation applied. For instance; the flood irrigation method is considered less energy consumptive when compared to pressurized irrigation method since pressurized method needs too much energy to lift water at a certain height. A comparison between Solar PV and Other energy sources in Water pumping systems is shown in Table (2.2) below.

Table(2. 2): Comparison of Solar and Other energy sources in Water pumping Systems [21]

Power Source	**Advantages**	**Disadvantages**
Generator (usually Diesel power systems)	• Moderate capital costs. • Can be portable. • Extensive experience available . • Easy to install .	• Needs maintenance and replacement • Maintenance often inadequate, reducing life • Fuel often expensive and supply intermittent • Noise, dirt and fume problem • Site visits necessary
Wind Turbine	• Potentially long-lasting. • No fuel required. • Clean.	• High maintenance and costly repair. • Difficult to find parts. • Seasonal disadvantages. • Need special tools for installation. • Labor intensive . • No wind, no power.
Solar Photovoltaic	• Low maintenance. • No fuel costs or spills. • Easy to install. • Simple and reliable. • Clean.	• Potentially high initial cost. • Lower output in cloudy weather. • Must have good sun exposure between 9 AM and 3 PM.

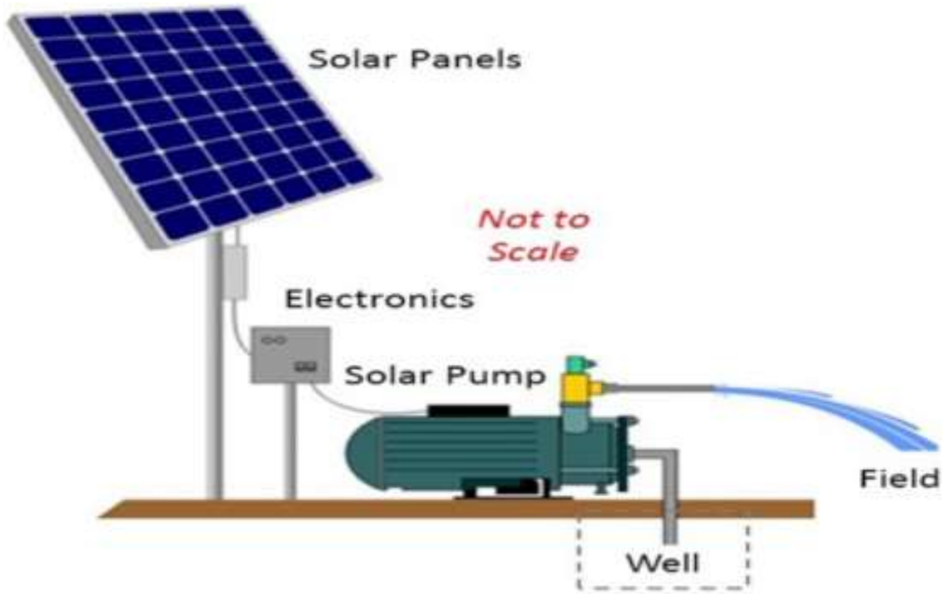
2.5 Solar Pumping System

The solar water pumping systems are based on solar PV technology which converts sunlight into electricity to pump water. The solar PV panels are connected to a motor (DC or AC) which transfer electrical energy supplied by the solar PV panel into mechanical energy which is converted to hydraulic energy by the water pump, Fig. 2.4 . The capacity of a solar pumping system to pump water is a function of three main variables: pressure, flow, and power to the pump. For design purposes, pressure can be considered as the work done by the pump to lift a certain amount of water to the field or storage tank. The elevation difference between the source of the water and the storage tank determines the work that the pump has to achieve. The water pump would draw a certain power which a PV array has to supply.[22]



Figure(2. 4): Block diagram of a direct coupled PV DC water pumping system. Source: [22]

Solar water pumping systems come in many forms for many different applications yet are mainly divided into three components: the solar panels, the electronics, and the pump itself. Figure (2.5) shows the basic design of the solar water pumping systems included in this thesis, which consists of solar panels, a pump controller, a DC pump, or an AC pump with an inverter.



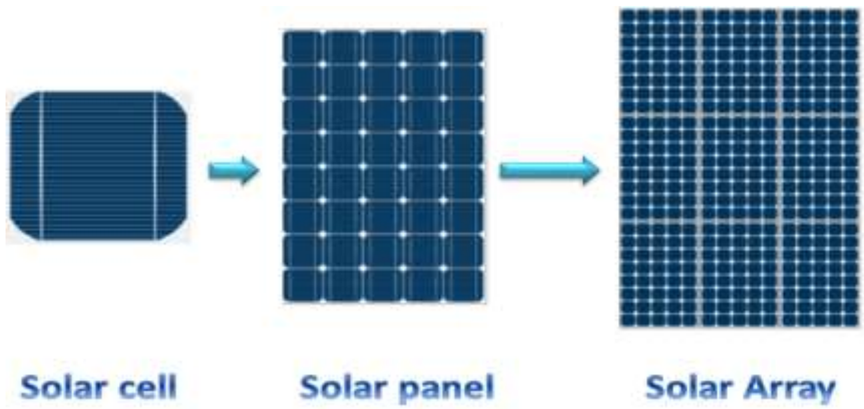
Figure(2. 5) : sketch of solar pump design

A typical solar-powered pumping system contains the following equipment: a solar array, which converts sunlight into electricity; system controllers, which control the Array and the pump; an electric motor, which drives the pump; and a water pump, which moves the water from a source to its delivery point.

2.5.1 The solar panels

Solar or photovoltaic (PV) cell is made of semiconducting materials that can convert sunlight directly into electricity. When sunlight strikes the cells, it dislodges and liberates electrons within the material which then move to produce a direct electrical current (DC). This process is achieved without any moving parts "nonmechanical device".

The most common type of solar cells in the world today are made of silicon. The solar cell is the basic unit of a photovoltaic module or panel. A single solar cell produces about a half a volt of electricity and up to about eight amps depending on the type of cell. The solar cell consists of a piece of silicon with contacts to electrodes that are put across the surface and on the back of the cell. A half a volt would not be able to do much. So, cells are connected in series to create what's called a series string. Thus, increasing the voltage, this is similar to how batteries are put together in electronics, front to back, so they add up to a higher voltage. The voltage of the series string is simply the sum of the half volt cells. When designing a photovoltaic system, photovoltaic modules, also known as panels, they put together in what is called a photovoltaic array. Just like when the series strings of cells are wired together to make the module, also the wired modules together in series to make an array in order to increase the voltage of the overall system.[21]



Figure(2. 6): Solar cell, PV solar panel, and PV panel array.

Solar panels are by far the most expensive component of the solar water pumping systems. The size of the array is dependent on the power needed for the pump, so even a small change in the pump horsepower can have an outsized impact on the overall cost of the system. Panels can be either fixed or have manual single-axis tracking to ensure that the highest levels of sunlight are hitting the panels during both morning and afternoon hours.

2.5.2 Solar pump

A typical solar pump draws water from the well or surface water source to storage tanks or users directly. Solar pump type is determined by the site conditions, flow required and the nature or type of water resource whether it’s a surface water source such as a pond and a river or it is an underground water source. Thus there are two major types of solar pumps depending on the location of water source; Submersible pump and Surface pump.[23]

The most commonly used submersible pumps are centrifugal pumps and positive displacement pumps [23];[21]. Both centrifugal pumps and positive displacement pumps are explained in the 2.4.1 and 2.4.2 of this chapter. As for surface pumps, they are commonly applicable in surface water sources such as ponds, shallow wells, and streams, the water to be pumped should not be more than 7 meters below ground level or pump inlet as suction lift. This suction lift needs to be maintained to a minimum limit so as to ensure the system reliability and pump efficiency.[23]

2.5.3 Electric motor

Each Solar pump is integrated with an electric motor which can be either AC or DC motor. The two types are explained in detail below:

2.5.3.1 DC motors

DC motors operate under direct current source, thus makes the motor more applicable where the direct coupling with PV panels is required. The DC motors are widely applied in small applications with a capacity not exceeding 3 kW. When opting DC motors it is necessary to consider a high efficient motor.[23] There are common types of DC motors such as:

- The Brush-Type: The traditional DC motor, in which small carbon blocks called "brushes" conduct current into the spinning portion of the motor. They are used in DC surface pumps and also in some DC submersible pumps. Brushes naturally wear down after years of use and may be easily replaced.[21]

- The Brushless type: It is a High-technology motor that used in centrifugal-type DC submersible pumps. The motor is filled with oil to keep the water out. An electronic system that used to precisely alternate the current, causing the spinning of the motor. There is a permanent magnet that exists in brushless DC motor which communicates with the stator electronically to lessen the requirement for brushes [21].

When the motor opted is DC motor type, there is no need to convert the DC from panels to AC by using DC/AC Converter [19]. The DC motors are considered expensive since they require regular maintenance of the brushes.

2.5.3.2 AC motors

These motors use alternating current to operate. They are widely used and commercially available at different ranges. According to [21] and other studies, induction motor and asynchronous motors are the fundamental two types of motors available. El-Shaikh et al. study described that AC motors could be further divided into single-phase motors and three-phase motors[24]. 1kW or fewer motors are not suitable for PV powered systems due to their tendencies of having low efficiencies. Additionally, to deliver the high starting current, power conditioning circuitry needs to be added [21]. There are about five starting methods of AC motors which are: DOL, Star-Delta, Auto Transformer, Soft Starter, and VFD. Connecting a DC motor directly from the PV system is considered as a least expensive method of pumping water by using solar energy[24], but as mentioned above this should be more applicable to a system with less than 3kW. Apart from the other comparisons, AC motors are reliable and cheaper compared to DC motors, thus to choose either to use AC or DC motors can be a complicated exercise. Girma identified five criteria that should be used for choosing a motor pump for a PV system, these criteria are; price, efficiency, reliability, availability, and the wattage[25].

2.5.4 System controllers

The pump controller is an electronic linear current booster that acts as an interface between the PV array and the water pump. It operates very much like an automatic transmission, providing optimum power to the pump despite wide variations in energy production from the sun.[21]

The two primary functions of water pump controller are; to monitor and modify the characteristics of the electricity produced by the photovoltaic solar panels that are the voltage and the current of the panels. The second function is to control or decide when the pump goes on and off whether electronically or non-electronically [25]. The basic components to be controlled and monitored are electricity from the PV panels, the water level in the well if it is a submersible pump, and the water level in the tank/storage if there is any. Controllers described in this part will include;

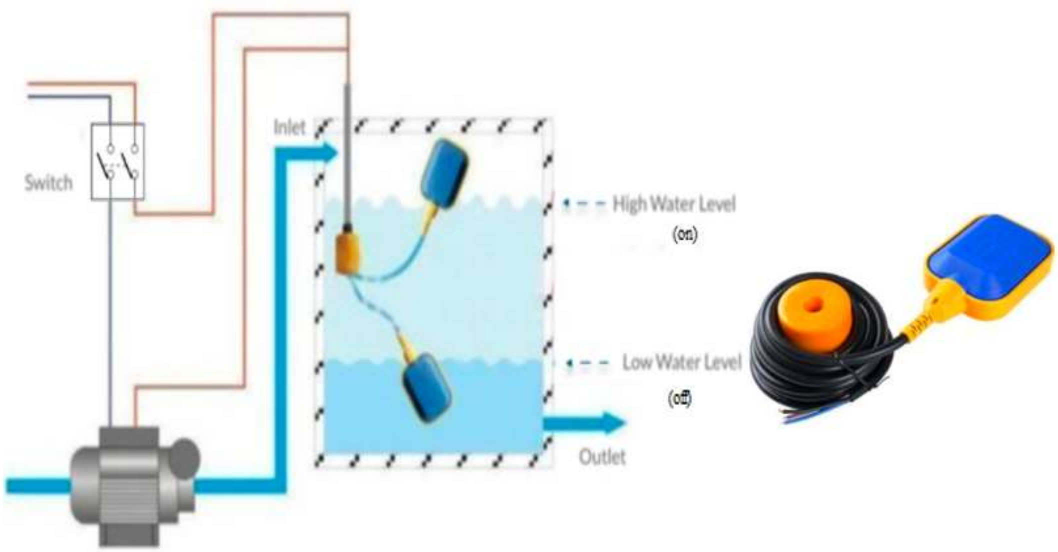
2.5.4.1 Electronic controller

The electronic controllers play a vital role in the water pumping system performance due to their ability to regulate the power production to match that produced by the panels to the power required by the pump. The electronic controller also plays a critical role in protecting the system by turning it off when the voltage is at an inappropriate level, meaning too low or too high compared to the operating voltage range of the water pump. This voltage protection role helps extend the lifetime of the water pump and reduce maintenance requirements [23]. One of the electronic pump sensors is a flow sensor. This sensor starts the pump when the flow is detected and stops when the flow stops.

The other sensor is dry run protection. In this sensor, the pump stop time should be modified in a range of running for instance between 10 to 180 seconds. The system is un-pressurized in no flow condition. Therefor it is rejecting pump cycling when there is no water. Motor maximum power determines the design of these electronics controllers [26].

2.5.4.2 Float switches

A float switch is installed inside the storage tank to control the pump according to water level, to turn the pump off when the storage tank is full. The float switch can be used to detect the water level in a borehole or water source that doesn't have stable water level, it encompasses of a float raising a rod that activates a microswitch when the water level shifts to required or unrequired level. Figure (2.7) shows the installed float switch in a system as well as the appearance of the float switch.[21]



Figure(2. 7): Float switch set up and its appearance on left side

2.6 System Designi And Sizing

Access to reliable, affordable and modern energy is an essential component for social and economic development for any country. The design and performance of a solar water pumping system require system sizing to grantee efficient performance. System sizing is a process that starts mainly with site assessment such as solar irradiance, flow rate, the ambient temperatures, hydraulic energy, total dynamic head, and water requirement.

Table(2. 3) : Steps and their outputs in the sizing process of a solar pumping system

Assessment	Variables	Output
(1) Water source	(a) Water depth (b) Water level (c) Delivery capacity	- Pump type - Capacity of water available
(2) Water demand	(a) Consumption profile (b) Storage capacity	- Storage size
(3) Total head	(a) Static head (b) Dynamic head	- Pump size
(4) Solar resources	(a) Average annual daily PV potential	- PV size
(5) Flow rate		- Pump size

Sizing	Input Data
(6) Pump	(a) Flow rate (b) Total head

(7) Solar array	(a) Pump size

To develop a solar-powered water pump system it is necessary to determine the size of the system needed. This includes the PV panels size, the pump size, water storage tank size, pipe length, mounting structure, etc. The main steps for solar water pumping designing are:

2.6.1 Site assessment

Before implementing any renewable energy system it is necessary to conduct a site assessment to ensure the sustainability of the system. Taking into consideration that the solar panels need to be located in a place where there is sufficient solar radiation [23]. For solar water pumping system, site assessment includes identifying:

- The potential of the solar irradiation (kWh/m^2/day).
- Water demand: The amount of water needed for irrigation.
- The water source type (a stream, river, well or lake).
- When the water is needed (irrigation time).
- The total dynamic head "TDH" (m).
- The storage tank capacity "if there is storage tank" (m3).
- The ambient temperature.

2.6.2 Water source

The type of water source available on the site and its location, water quality and seasonal variations would influence the configuration of the solar water pumping system. These water sources can either be surface water sources such as rivers or subsurface source such as underground water. The depth of the well determines whether to use a surface pump or a submersible pump. In case of wells deeper than 7 meters below the ground level, it is demanded to use a submersible pump instead even though it would cost more [23].

2.6.3 Water demands

The water demand is considered a prime factor which influences the pump sizing. It could be calculated in a daily consumption rate and in some cases it is calculated as an hourly rate when the consumption pattern requires that. Several factors will affect water demand, for instance, the climate condition, soil type, characteristic of a crop, and variation in seasons. Table (2. 4) shows the average values used as international benchmarks for a daily consumption rate in various farming water applications such as livestock, and irrigation [27].

Table(2. 4): Daily consumption rate average values for different applications

Application	Unit	Daily consumption rate (Lit/day)
Livestock	Milking Cow	95
	Horse or Dry cow	76
	Sheep or Goat	7.6
	Chicken	1.5
Irrigation	Rice (1 ha)	100
	Cereals (1 ha)	45
	Vegetables (1 ha)	50
	Sugar cane (1 ha)	66

2.6.4 The total head

The total head is the distance between the storage delivery points to the submerged depth of the pump besides the head losses through the piping system due to friction. It is the summation of elevation head, major losses head, and minor losses head.

$$H\ Total = H\ Outlet + H\ S + H\ D + Hf \qquad \text{Equation(2. 1)}$$

Where:-

H Outlet = height of the outlet pipe above the ground level.

H S = static head due to the depth of the water level in absence of any pumping.

H D = dynamic head: It is the summation of a vertical distance from the water surface level to the water supply end (H S) and total friction losses (Hf)

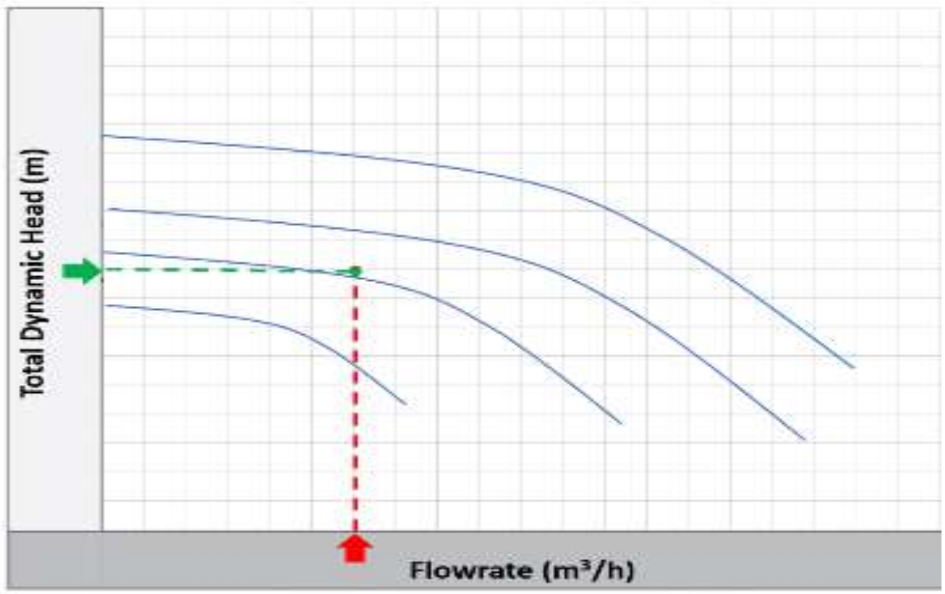
Hf = friction losses in the piping system, this depends on the flowrate.

The farm does not have a storage system currently, however, once the PV pumping system is installed a storage tank would be included.

The static head (H S) is the height between ground level and the storage volume. It should be kept to a minimum to reduce the lift requirements of the pump, but needs also to take into consideration the suitability of the storage location. Every meter of height accounts for one meter of dynamic head.

2.6.5 Pump selection

The pump power required can be computed by using the pump sizing graph provided by the pump manufacturer. This method requires two parameters only that are the total head (m) and the flowrate (m^3/hr). The flow rate and the total head are plotted on the sizing chart as shown in Figure (2. 8), below which is an illustration of the pump sizing graph provided by the pump manufacturing company, in red and green respectively, with the blue curves being pump performance curves. The point of intersection between flow and the total head is the point of reference [26].



Figure(2. 8): an example of the pump sizing chart

2.6.6 Solar array sizing

$$\text{PV power (Wp)} = \frac{\textbf{Pump Power (w)}}{(\textbf{Efficiency Factor} \times \textbf{Inverter Efficiency})} \qquad \text{Equation(2. 2)}$$

The final stage of the solar water pumping system sizing is the solar array sizing, which is deciding the array connections and how to make the interconnections in order to achieve the desired voltage and current. In case of series connection it would add up the voltages of the panels while keeping the current fixed. While parallel connections would add up the current while keeping the voltage fixed.

2.6.7 Inverter sizing

The sizing of the inverter depends on the overall capacity of the PV Array. With the assumption that the inverter losses are 4% during conversion processes to AC power and the efficiency is 97%. Then the DC power input from the solar array to the inverter will be calculated as follows;

$$\text{DC power input} = \frac{\textbf{inverter AC Power out put}}{(\mathbf{1-0.04}) \times (\mathbf{0.97})} \qquad \text{Equation(2. 3)}$$

The inverter AC power output is the product of AC voltage and AC current input to the pump (inverter output).The expected lifespan of the inverter is 10years on average; it means that this inverter must be replaced at least once during the project lifetime of 20 years. The replacement cost of the converter is assumed to be the same as the initial cost, while its operating and maintenance cost is zero.

2.7 Economic Aspects

Solar pumping makes more sense in applications not demanding very high water supply, so the solar-powered pump can operate slowly based on solar radiation availability. When compared to conventional diesel generator pumps, Since the system sizing always affects the cost of the PV system because the cost always varies directly with a power rating of the system, therefore all components should be designed efficiently to avoid the increase in the cost of the system. The economic evaluation of Solar water pumping system is done mainly to ensure whether the system is viable or not. There are various economic indicators calculated to grantee economic viability such as Life cycle cost analysis (LCCA), net present value (NPV), internal rate of return (IRR), and simple payback period (SPBP) are the five economic indicators that are mostly carried out. From the Energy Management and Conservation Handbook the following methods are explained;

2.7.1 Levelized cost of energy (LCOE) method

LCOE is a method used to compare renewable energy technologies adopted to produce electricity. The Levelized Cost of Energy defined as the cost in dollars of production of one kilowatt-hour (kWh) of electricity. LCOE indicates in term of money what it would cost the owner of the facility to produce one kWh of energy, including the total construction, central production costs of the power station during its economic lifetime. It takes into account investment cost, operation and maintenance costs, the quantity of energy produced by the project, taxes, selling price and other parameters. The LCOE can be either nominal, using current dollars, or real, using constant dollars and taking inflation into account. The Levelized Cost of Energy can be calculated by using the equation (2.4) below,

$$LCOE = \frac{TLCC}{\sum_{t=1}^{T} \frac{Ep}{(1+r)^t}}$$

Equation(2. 4)

Where; LCOE is the Levelized Cost of Energy, TLCC is the total life cycle cost, Ep is the electric energy produced throughout the lifetime of the project whereas t is the lifetime of the project and the r is the discount rate of the project.

2.7.2 Net present value (npv) method

The net present value is how much return, a power generating plant makes while taking into consideration the time value of money. When the result of NPV is positive, it shows that the power plant project will be profitable and if the NPV turns negative, it shows that it will not be a profitable investment. We can say that for a project to be “good investment” the NPV needs to be positive and it is a criterion for deciding whether to invest in a power plant project. Initial Investment Cost, I0 Present Value at the project lifetime,

$$NPV = -C_0 + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \ldots + \frac{C_T}{(1+r)^T}$$

Equation(2. 5)

Where; C0 =Initial Investment, C = Cash Flow, r = Discount Rate, T = Time.

2.7.3 Internal rate-of-return (IRR) method

The IRR method solves for the discount rate for which dollar savings are just equal to dollar costs over the analysis period; that is, the rate for which the NPV is zero. This discount rate is the rate of return on the investment. It is compared to the investor's minimum acceptable rate of return to determine whether the investment is desirable. Unlike the preceding three techniques, the IRR does not call for the inclusion of a prespecified discount rate in the computation, but rather, solves for a discount rate. The internal rate of return is typically calculated by a process of trial and error, by which various compound rates of interest are used to discount cash flows until a rate is found for which the NPV of the investment is zero. The approach is the following: compute NPV using Equation (2. 5), except substitute a trial interest rate for the discount rate, d, in the equation. A positive NPV means that the IRR is greater than the trial rate; a negative NPV means that the IRR is less than the trial rate. Based on the information, try another trial rate. By a series of iterations, find the rate at which NPV equals zero. Computer algorithms, graphical techniques, and—for simple cases—discount-factor tabular approaches are often used to facilitate IRR solutions.

2.7.4 Simple payback period (SPBP) method

Simple payback period is the period of time a project will take to recoup the cash outflow. It is the amount of time it takes to breakeven. This means the time it takes to recover all the investment cost of a power plant.

Equation(2.6) calculates the SPBP.

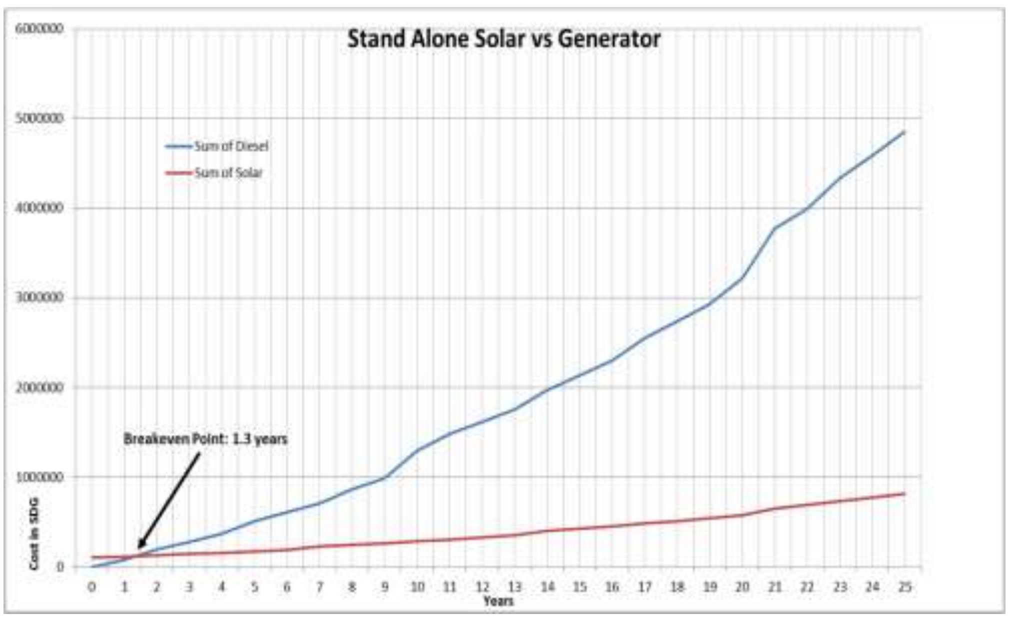
$$Payback\ Period = \frac{Cost\ of\ the\ Investment}{Annual\ net\ Cash\ flow}$$

Equation(2. 6)

If costs and savings are discounted. The technique is called Discounted Payback (DPB) Method.

The implementation of this methods is a necessity in evaluating energy systems which assists in decision making.

According to a study performed by Global Solar and Water Initiative for the IDP camps (internally displaced persons) in Darfur, Sudan, aiming at analyzing a number of existing solar pumping schemes, to evaluate the feasibility to use solar water pumps in a few selected IDP camps. There were over 200 solar pumping schemes installed in the country (mostly Darfur IDP camps and rural communities). The study results show that the stand-alone solar water pumping systems have in general shorter breakeven periods and a higher reduction costs when compared to equivalent diesel generators ones. The results of the assessment are shown in Figure (2.9), [28]. The study shows that the stand-alone solar systems should be prioritize as they are the most cost effective solutions and the payback period of the investment cost is shorter.



Figure(2. 9) : the cumulative cost over the life cycle of stand-alone solar and diesel generators

3. RESEARCH METHODOLOGY

3.1 Introduction

This chapter covers all the techniques and methods that used for conducting research. This section describes the methodology that followed in the study to answer the research questions and meet the research objectives. In this master's thesis, several commercial tools have been used to simulate the solar water pumping system such as Homer software and Excel Software. The information about the average monthly solar radiation on the selected site and the characteristics of PV system components were provided by Sudan Renewable Energy agency, the PVGIS (Photovoltaic Geographical Information System) for Africa, different internet websites, different books, scientific research papers and journals. The other part of this research included quantitative and qualitative interviews with various vital participants. These interviews and the survey comprised the practical portion of the study. The purpose of the survey is to identify the technical and social barriers for solar PV technology implementation in the irrigation sector.

The responses from the interviews and the results from the survey have been used to modify the preliminary system characteristics developed in the literature review. This chapter thus provides an overview of how to design, optimize, and assess the technical and the economic feasibility of proposed water pumping systems. The study has used both qualitative and quantitative approaches during sampling, data collection, and analysis. In data collection stage, qualitative approach used to collect ideas and opinions from the case study's farmer in an open-ended interview to the respondents where people provided their experiences in agriculture in general and irrigation system specifically, while the quantitative approach was used to collect responses from government institutions and non-government companies in a closed-ended interview and also a survey has been used to collect numerical data from farmers.

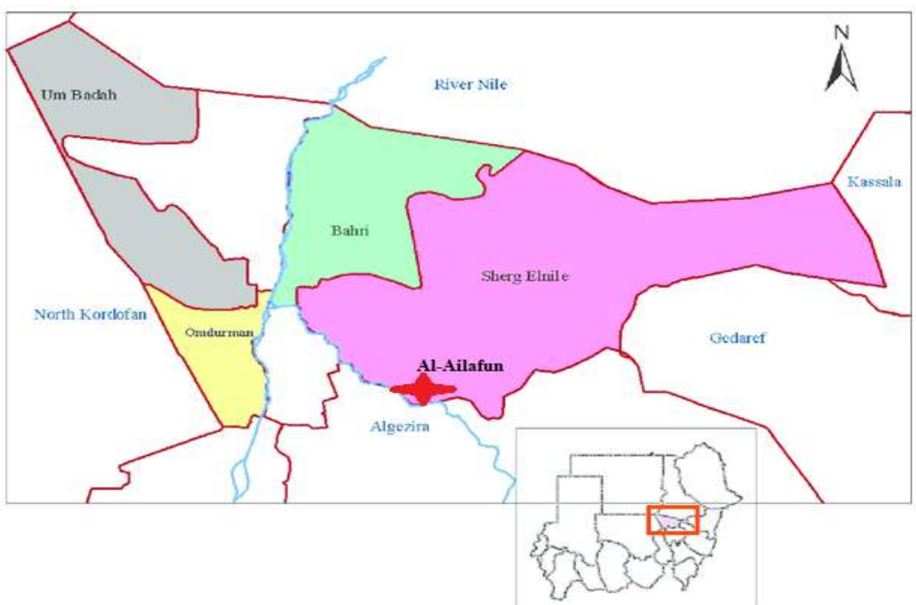
This thesis has been centered only on the development of a theoretical model which can be implemented practically in the proposed farm. It would improve the livelihood through economic (at a governmental and individual level) and environmental improvement. With the aim of achieving sustainable development by Addressing the Water-Energy-Food Nexus to facilitate the role of solar PV in agriculture as a way forward for Energy and food security.

3.2 Description Of The Case Study

In this study learning sites were obtained from different parts of Sudan through site visits and the review of appraisal reports, working papers, and articles. Among the states (Wilayah) which were included are Algizera, Dongola, northern Darfour and Khartoum state.

3.2.1 Khartoum case study

The case study in this thesis is a farm located near the national training camp for the Corps of Engineers on the shore of the Blue Nile southern area of Al-Ailafun city, which is located on the eastern bank of the Blue Nile in the direction of its estuary on an area of 12 square kilometers, and its position is at latitude 25,14 north and longitude 25,32 east at an altitude of 1302 feet above the sea. Al-Ailafun is southeast of Khartoum that located 30 km from the center of Khartoum. As shown in Figure(3.1).



Figure(3. 1): Map of Khartoum showing visited case study farm location “Al-Ailafun”

In Al-Ailafun a survey has been conducted in ten farms and the techno-economic analysis has been conducted in one of these farms. Even though there is electricity access in most of Al-Ailafun city there are some farms with no access to electricity. However, due to the high rate of electricity outage, approaching an average of 50 hours per week in summer, all ten farms have a diesel generator to meet the water demand during electricity outages.

3.2.2 Algizera case study

This part has been conducted in Algizera state. The reasons behind choosing this state are due to its high solar potential, enormous agricultural activities and abundant water resources. This study used sampling in order to obtain data from the respondents. Sampling has helped to simplify the work of the researcher, by concentrating on a few respondents instead of covering many respondents. In addition, sampling helped to make generalizations due to the limited time of the research.

In the selected study areas, 60 farmers have been taken from Somtubar and Deneigela sectors, by systematic random sampling technique. Generally, based on the multistage sampling process, a total of 66 participants were selected by systemic purposive and random sampling technique. The summary of the number of respondents selected from the study area are shown in Table (3.1). To carry out this study, both primary and secondary data sources were employed.

The primary data were collected by employing methods such as informant interview using a semi-structured checklist, expert and decision makers interview; focus group discussion, semi-structured farmer questionnaire and observation of events. Secondary data that could supplement the primary data were collected from published and unpublished documents obtained from different sources. These included country policy statements, strategies regulations, reports, papers and journal on irrigation practices. Items covered during the data collection aim to give a techno-economic situation of sampled farms, irrigation practices, opportunities and barriers of irrigation activities, crops grown, demographic features, irrigated land and the livelihood impact of irrigation activities. Discussions were also held with irrigation experts at the Sudan renewable energy agency and the ministry of electricity.

Table(3. 1): thesis samples and sampling techniques

Category of respondents	**Sample Size**	**Sampling techniques**
Farmers	60	Simple random sampling
Agronomists	2	Purposive sampling
Irrigation Experts	2	Purposive sampling
Administrative staff	2	purposive sampling
total	66	

3.3 Farm Case Study

This part covers the data collected from interviewing the farm owner to give a full description of the farm regarding its size, agricultural activities and the farm inhibitors, in order to calculate the water and energy demands. The farm is located near the national training camp for the Corps of Engineers, on the shore of the Blue Nile southern area of Al-Ailafun city. The farm size is three feddan (1.26 ha) which is equivalent to a 12600-meter square. However, due to the fuel scarcity, the implanted area has been reduced into two feddan during the last two years. The farm is considered a mixed farm which consists of both plants and animals, Fig(3.2).

Figure(3. 2): Image of the farm

3.3.1 Diesel water pumping (DWP) system

The current energy source for the irrigation system is a diesel generator which has a 16 horsepower (11.768 kW), since the owner had plans for expanding the farm. The Diesel water pumping system operates for ten to twelve hours a day every three days with an efficiency of 85% to meet the farm's water demand. Usually, the pump kicks in around seven in the morning with four inches pipe size. The fuel consumption is 36 liter per week (four gallon). The DWP system has three main components such as diesel engine, water pump and water head. To calculate the total cost of the Diesel water pumping system we must identify the fixed and running costs which are 63000 Sudanese pounds (1140 USD) as initial cost, the maintenance cost is around 1400 Sudanese pounds (25 USD) twice a year and fuel cost is around 1160 Sudanese pounds (21 USD) per week. It has been assumed that the pump is replaced every 10 to 12 years.

3.3.2 Water demand

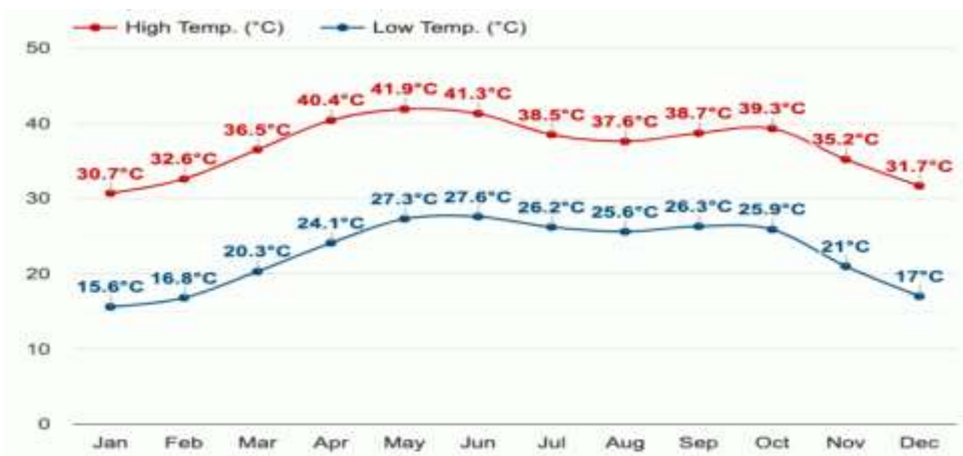
The farm has lemon and orange trees which require irrigation all year round. There is a seasonal vegetable farming. The seasonal implantation is not regular in most of small scale farmers due to fuel shortage that led to a national crisis especially for the agricultural sector. Farmers are complaining since they are not able any more to obtain sufficient quantities of diesel for their irrigation pumps and tractors, due to the fuel crisis and the skyrocketing prices at the black market. Under these conditions, the case study farmer would dismiss the seasonal agriculture to grantee enough fuel for the permanent trees.

The farm has a herd of animals their amount change through the year due to selling and breeding. Animals such as goats, sheep, gooses, chickens and rabbits. The animals depend on the farm agriculture residue also they do not consume much water for drinking compare to farm irrigation. The water source on the farm is the Blue Nile which the farm is facing. The farm has a surface diesel water pump. The pump Total Dynamic Head is almost 7.5 meter.

The water is pumped directly from the river to a canal system which is the major source of farm irrigation. Each canal has sub-canal spreading through the farm. The farm does not have storage tank currently.

3.3.3 Temperature

The farm is located in a region that experiences high-temperature conditions with temperature vary from 15.6 to 41 through the year. The hottest months being April, May, and June. Al-Ailafun, according to Sudan Meteorological Authority database, experiences the lowest temperature conditions from December to February as shown in Figure (3.3).



Figure(3. 3): Annual temperature of Al-Ailafun

Source: Sudan Meteorological Authority

3.3.4 Rainfall

The region has a rainy season with peak precipitation of 48.3mm experienced during August. The days of rain are varying from an average of one day in June to five days in August as the peak which is shown in Figure (3.4). The rainfall received during this period is essential for agriculture and also for cooling the high temperature to within a favourable range for both the currently installed diesel system, future PV system and even for the wellbeing of the people.

Figure(3. 4): Average rainfall Al-Ailafun, Sudan

Source: Sudan Meteorological Authority

3.4 Data Collection And Analysis Methods

The field visits are a necessity to define the irrigation systems performance in relation not only to its physical features but also its design and management. To study the technical and economic aspects, the researcher has used surveys, in-depth oral interview, Physical Observations and documentaries as the main methods of collecting data. The selection of these methods has been guided by the nature of the data collected, the time availability as well as by the objectives of the research. The study has used the physical survey method; this has included observations and personal interviews (See appendix), which involved carrying out an energy demand survey for the agriculture irrigation system rural areas in Algazera state and Khartoum suburb to identify the current irrigation situation and solar water pumping implementation berries. HOMER software and Excel were used to analyze the statistical data and prepare the graphs and charts for results representation. The following part describes in detail the methods used for this study under the field visits and the desk reviews data collection.

3.4.1 Site visit; in-field observation

The researcher has visited three locations, first, the case study's farm in Al-Ailafun, second and third sites were the Somtubar and Deneigela sectors in Algazera state were more than six field trips took place to collect data. Sites condition were observed to assess the environmental and technical situations as well as the Economic condition since the ranking of agricultural costs indicates that the highest cost of crops production goes to labour, followed by diesel as fuel for water irrigation, fertilizers, pesticides and land preparation.

3.4.2 Interviews

The interviews were used to collect primary data from the case study farm's owner, experts, decision-makers and administrative staff. It guided by questions that prepared before. The collected data from the case study farm's owner were general information that aimed to represent the social status, type of ownership, water and energy demands of the irrigation system. Technical information that aimed to provide the technical data such as the pump size, pump energy source, the operation time, yield, and the characteristics of the water source; economic, social and financial assessment as well as the operation, maintenance assessment. The interview questions are shown in (Appendix II). As for the decision-makers which they had their interview's questions (Appendix I) these questions were responded by the Renewable Energy Agency Director, Engineer and a consultant from the (Promoting The Use Of Electricity Powered Water Pumps System For Irrigation In The Northern State, Sudan) project and a private company engineers working in the solar energy.

3.4.3 Surveys

The primary data was obtained through questionnaires, which were conducted to sixty Farmers. A questionnaire of twenty-six short questions (Appendix III) with fifteen closed questions and five open questions were prepared to provide an Economic, Social and technical assessment. Questions were written in English and Arabic to help respondents to be able to provide the required information properly. The benefit of this methodology is that it permits a deeper level of communication allowing the researcher to access the interview participants' opinions. Among the sixty respondents, fifty of them were farmers in Algazera state; ten were from Al-Ailafun.

3.4.4 Documentary review

This method used to collect secondary data and was guided by Studies about previous work regarding the solar water pumping systems that was done. A review of research papers and funded projects in Sudan by the Ministry of Water Resources, Irrigation & Electricity and UN organizations was done in case studies. Those secondary data were collected from documents and reports from the mentioned organizations and other public and private companies related to solar energy and agriculture, published books and journals. The purpose of reviewing the secondary data is to enable verification of the primary data collected.

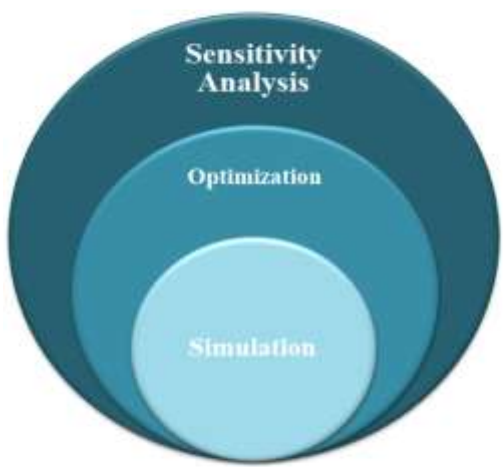
3.5 Data Processing And Analyzing

The collected data was analyzed quantitatively. The interviews and survey Answers/responses grouped and analyzed using HOMER software and Excel programs. Before data analysis process carried out, it is important to check the questions and answers to ensure the validity and authenticity of the answers given. All the information analyzed according to the research questions and the information available.

3.5.1 HOMER software

The HOMER software is an abbreviation of the Hybrid Optimization Model for Multiple Energy Resources, which is a hybrid system modelling software developed by the National Renewable Energy Laboratory. This software is a powerful tool for the optimal designing, sizing and planning of and hybrid renewable energy systems by carrying out a techno-economic analysis for off-grid and grid-connected power systems[29]. In this study, HOMER optimization software was used to evaluate, both the technical and economic viability of the proposed water pumping system by taking into account the variations of both the diesel prices and solar radiation, as experienced in most parts of Sudan.

The HOMER software is a powerful modelling method that could be used to simplify the design, analysis, and evaluation of both off-grid and grid-connected hybrid energy systems for distribution, generation, standalone and the remote applications[29]. HOMER performs three fundamental functions that include simulation, optimization, and sensitivity analysis.



Figure(3. 5): stages of solving problems with Homer

Source: [29]

The designed system uses data such as metrological data, load profile, economical, and technical data to find the optimum energy system for the chosen location. Introducing more data to HOMER would lead to a more accurate and efficient system. It is necessary to consider the highest discount and interest rates, the shortest system lifetime, and the lowest average daily solar radiation. Homer software would be used for modelling and simulation for the entire energy system. Therefore the inflation, interest, and fuel escalation rates must often be assumed. The performance evaluation of the water pumping system done by taking into consideration:

- The annual solar resources input and the initial load profiles are assumed to remain constant throughout the project lifetime.
- The average solar radiation for the case study's location is (5.6kWh/m2/day).
- The solar PV lifetime is estimated based on the guarantee of the PV panels that are assumed to be around 20 years.
- The inflation and discount rates are assumed to be 18 percent and 7.42 percent respectively. The price of a litre of diesel has been assumed to be 33 Sudanese pounds (SDG) which equivalent to 0.602 United States Dollar (USD).

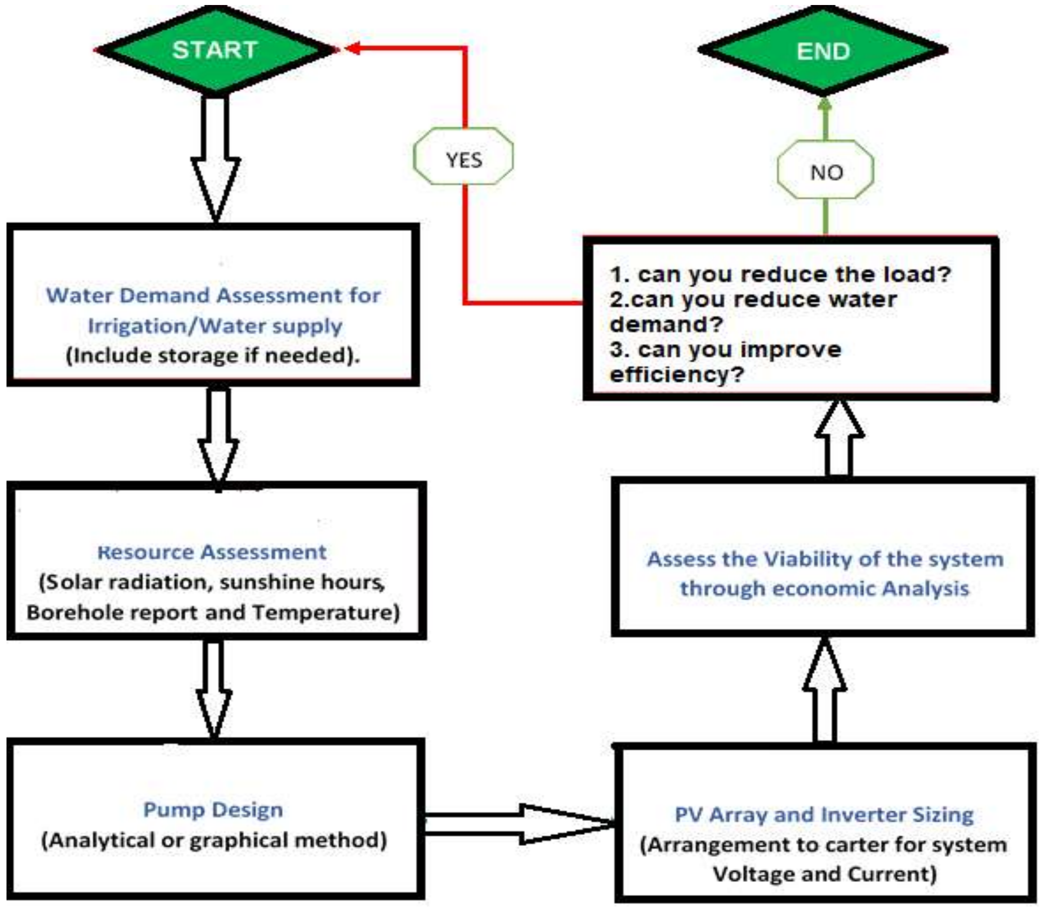
Solar water pumping system has a Deferrable load which is an electrical load that must be met within some time period, but not the exact time because these kinds of systems usually have some sort of storage such as water tank associated with them. This leads to some flexibility when the pump actually operates, provided the water to the tank.

3.5.2 EXCEL

Excel was used to analyze the statistical data and prepare graphs and charts for the representation of the data obtained from the survey and interviews.

3.6 Assessment Of The Optimal Solar Water Pumping System

The assessment of SWP is a complex process because it is affected by many factors; such as climatic parameters (solar radiation, temperature, and humidity), crop characteristics (type, variety, and development stage), and environmental conditions. The amount of water required for irrigation mainly depends on the type of crop and the size of the farm to be irrigated. Fig. (3.6) shows a diagram of design assessment with a feedback to grantee optimum design.

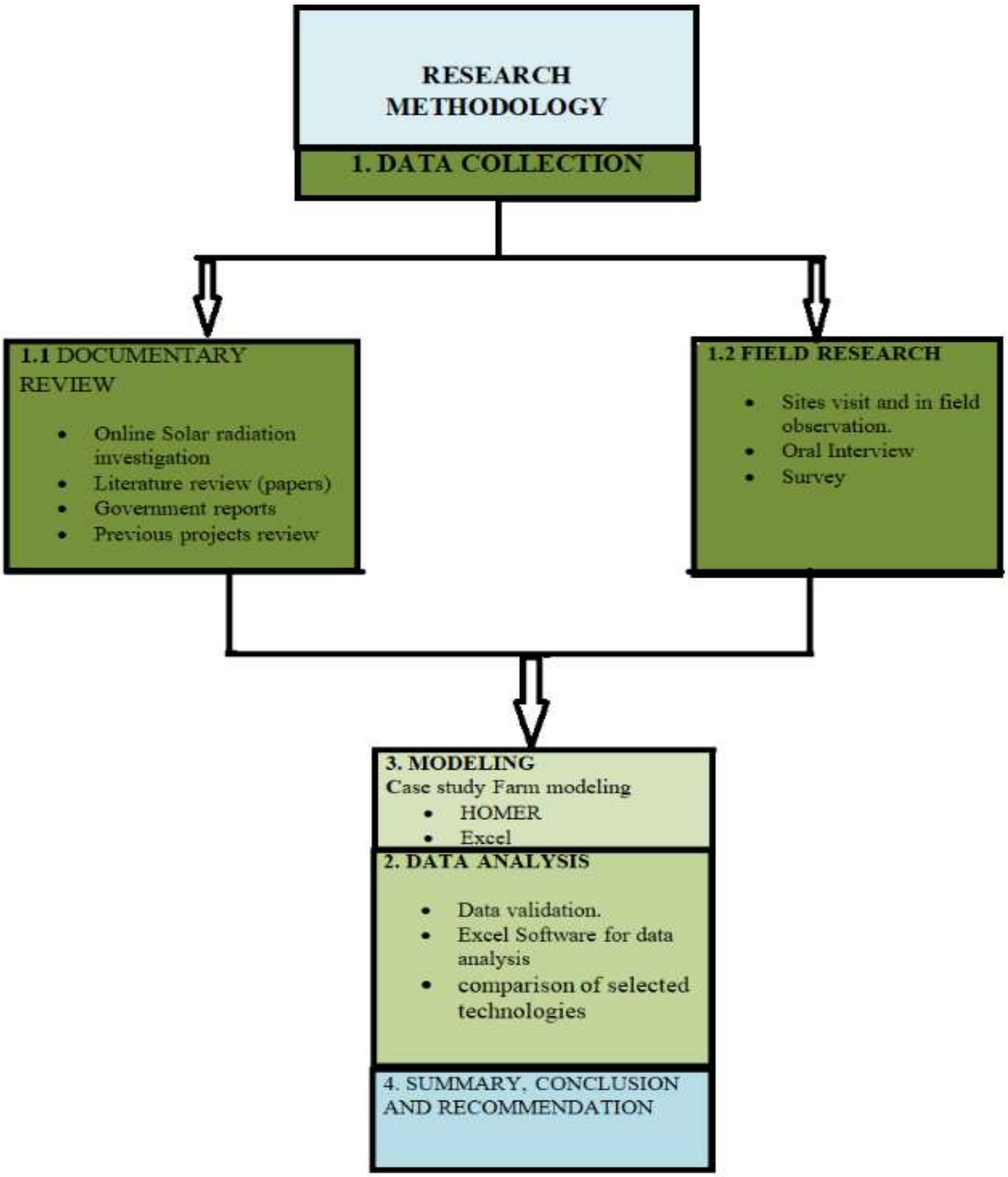


Figure(3. 6): Design Steps of Solar water Pumping system

It should be noted that from one step to another there are energy/water losses due to Energy conversion and equipment efficiency.

3.7 The Framework Of Research Methodologies

The methods used in this study are Data collection which is divided into two categories, first one is the literature review where all the information was obtained without directly going to the site. The second Category is when some of the information will be taken directly from the field through interviews and Questionnaire. The figure (3.7) below shows the research methods that were used in this study.



Figure(3. 7): The Framework of Research Methodologies

4. RESULTS AND DISCUSSIONS

This chapter presents the results and findings from the selected sites and case study's simulation results from HOMER software. These results included all environmental, technical and economic parameters which can express the performance of SWP irrigation system. The NPC, LCOE, OC and O&M of solar water pumping system are presented and discussed in this chapter. A presentation is given about the system configurations and assumptions taken during simulation in HOMER Pro.

4.1 Lessons Learned From The SWP Project In Northern State

The project was launched in the year 2016 it is a five years project. The project aims at promoting the use of solar water pumps for irrigation in Sudan, by targeting 1468 solar pumps which are still an ongoing project and expected to be concluded in the year 2021. Initially, 29 solar pump systems with different sizes that vary from 3 KW to 29.6 kW results of 257.40 kW of solar energy powering 29 farms across seven localities to irrigate a total area of approximately 446 feddan (187.32 ha) in the Northern state. The Northern state has a considerable high solar radiation with low precipitation in comparison to the rest of the country as shown in figure (4.1). The installed operating pumps have proven to improve the farm's productivity as well as reduce dependence on fossil fuels such as diesel. Studies provided by the project anticipates that up to 268,000 tons of diesel could be saved and as much as 860,100 tons of CO_2 emissions could be avoided [30].

Figure(4. 1): irradiation and rainfall potential in the Northern state, Source:[31]

Another survey conducted by the United Nations Development Programme (UNDP) on the farmers using solar water pumps. The survey has shown high crop productivity with a total annual increase within the surveyed area shifting from an average of 161 to 237 tons after the adoption of solar water pumps. Moreover, the summer cultivated fields within the area of study increased up to 87% due to the stabilized energy source for irrigation. The project was financed by The Global Environment Facility (GEF), supported by the United Nations Development Programme (UNDP) and the executing agency was the Ministry of Energy and Mining, Sudan. Targeted farms were monitored and evaluated for four seasons throughout two years [32]. Figure (4.2) shows an image of a Farm benefited by the SWP project in Dongola, Northern state of Sudan.

Figure(4. 2): Farm using SWP in Dongola , Source: [32]

4.1.1 Techno-economic analysis of the SWP project in northern state

The Project will be implemented in two phases. The first phase is the pilot phase in which the UNDP/GEF has provided a fund to purchase the solar pumps and distribute them to the 28 selected small pump farmers in the State. The pumps vary in size and type depending on the water source, type of the planted crops and the size of the farms. The first phase is expected to prove and build trust among farmers that solar pumping is an attractive alternative to diesel pumping. The Initial Fund will provide a financing mechanism associated with a subsidy that reduces the high capital cost of the pump, reduce risks and increase the capacity of the farmers for purchasing the pumps.

The second phase would follow after the completion of the pilot phase, which took one year, covering the installation of the 28 demonstration small pumps for irrigating from River Nile, Mattara and groundwater sources in the seven localities of the State. The second phase is planned to be funded by a consortium of Banks. The consortium has to provide a fund for lending an additional 1440 pumps to the small farmers in the three types of an irrigation pump system in the seven localities. The solar pumps are both surface pumps and submersible pumps depending on the type of the water source. Photovoltaic modules installed are expected to have the life expectancy of 20 years, while the capacity of the pump varies between three to 29.6 kW. The Prices and Values of the Pumps are shown in table(4.1)**.**

Table(4. 1): The Prices and Values of the PV Solar Pumps in USD, source: [33]

Pump	Price (USD/pump)	Number	Value (USD)
Mattara (3.12 kw)	7880	479	3774520
Nile (5.12 kw)	11013	722	7951386
Borehole (29.6 kw)	13480	239	3221720
Total		1440	14947626

4.2 The Case Study Farm Analysis

The following part will cover the technical and the economic analysis of the case study farm located on the shore of the Blue Nile southern area of Al-Ailafun city. This part would include the solar water pumping system sizing, HOMER modelling results and comparison between the base case (diesel water pump) and the proposed case (solar water pump).

4.2.1 Water demand and total head

The first step in designing the solar water pump is to identify the farm's water source, its water demand and total head (as indicated in eq.2). Based on the information obtained from the farmer's interview the following data were obtained:

a) Daily water requirement: 84 m^3/day

Since the farm contains citrus trees (Orange and Lemon specifically) and vegetables, the farmer irrigates the trees once a week through the year and reduce it to twice a month during the fruiting season. As for vegetable, the farmer irrigates it once every three days. For the sake of this study, the weekly and monthly water demand was determined to calculate the daily water demand for the farm. In the sizing storage tank which might not be necessary in this case, any pumped water exceeds the determined daily water demand would be considered stored in the storage tank even if it goes to irrigate the farm directly. This means the size of the storage tank does not have to be as big as it should in the regular daily irrigation process since there is no need to store any water more than the animals drinking water.

Currently, the diesel pump works twice a week to produce an average of 588 m3 of water for farm irrigation and livestock drinking. However, the proposed solar water pump would meet the demand and filling the storage tank by working several hours per day.

B) The static head (HS) = 7 m

C) Dynamic head (HD) = 2m

D) Height of the outlet pipe above the ground level and the storage (H Outlet) = 3m

After estimating the friction losses (Hf); for a perfectly horizontal path, only 5% of the covered distance is accounted for [23], meaning that if the pipe runs for 100 meters in the horizontal direction with no inclination, 5 meters are added to the dynamic head. In the case of inclination, the height difference should be accounted for in the storage height value. For the farm case study, the pipe runs 20 meters which means 1 meter is added to the dynamic head. Then, by using Equation (4.1)**,** the total head (H total) of the water pumping system will be:

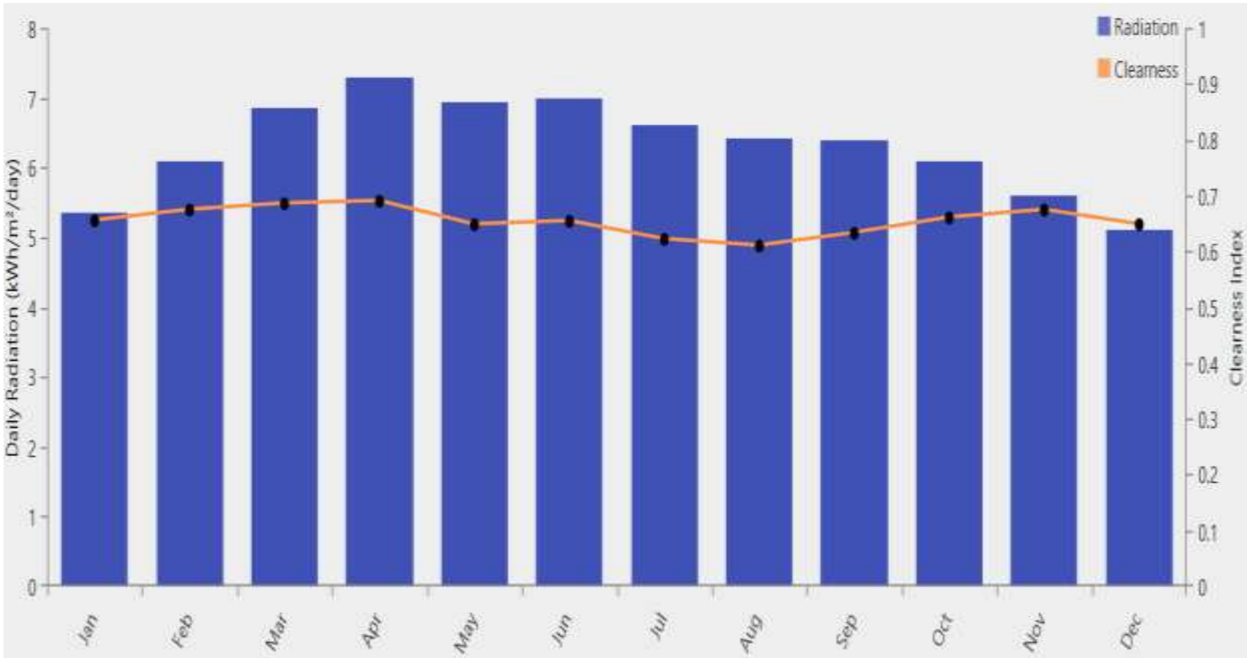
$$H\ Total = H\ Outlet + H\ S + H\ D + Hf \qquad \text{Equation (4. 1)}$$

$$= 3 + 7 + 2 + 1 = 13\ m$$

∴ the total head of the system is 13 meters.

4.2.2 Solar resources

The farm location is Latitud**e** 15°16 North, Longitude: 32 ° 59.21 East. **I**n this region the annual average solar radiation of 6.31kW/m^2/day. Irradiance reaches highest levels during the months of March, April, May, and June peaking in April at more than 7.29 kWh/m^2 per day as shown in figure (4.3) below.



Figure(4. 3): Average solar radiation and clearness index over 22 years period

It is necessary to take into consideration all the losses factors is necessary to take into consideration all the losses factors such as variation in temperature, radiation, soiling and dust, ageing in order to achieve the optimum design.

4.2.3 Pump sizing selection

The process of selecting the size of the solar pump requires using the pump manufacturer graph which needs only two variables the total head (H total) and the flow rate of the pumped water. It is possible to calculate the flow rate using Equation (4.1), this equation depends on the water demand and operating hours per day. However, since the solar water pump works based on the amount of solar radiation that is quite affected by many factors such as clouds, temperature etc. which makes it difficult to estimate the actual flow with the minimum knowledge of losses. Taking the maximum operating hours will downsizing the system that is why it is better to choose less than that to grantee meeting the water demands, in this case, the minimum operating hours is taken as four hours

Flow rate (m^3/h) = water demand (m^3/day) ÷ minimum operating hours (h/day) Equation (4. 2)

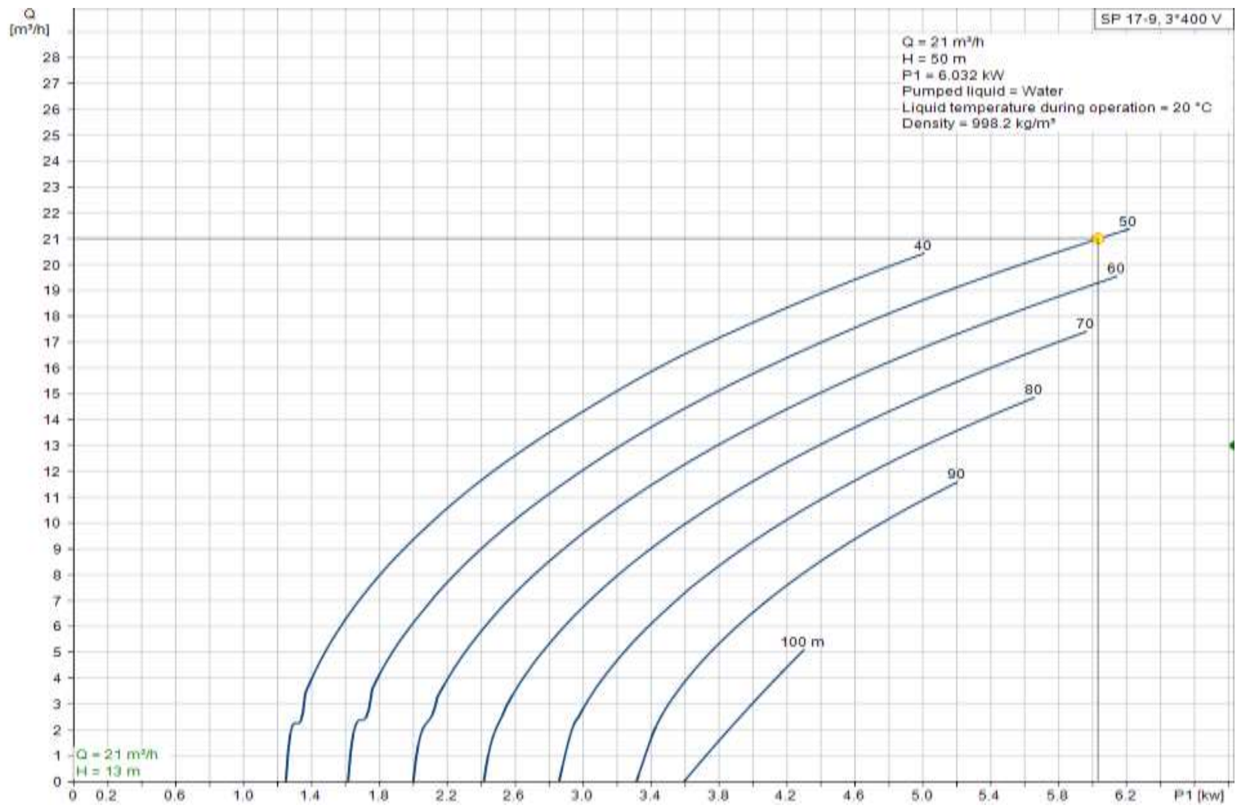
∴ the flow rate = 84 (m^3/day) ÷ 4 (h/day) = 21 (m^3/h)

From the Grundfos pump SP 17-9 manufacture graph Figure (4.4), this pump that capable of working within the head up to 50 m were selected. The parameters used in selecting the pump are 21 m^3/hr and 13 m which are the flow rate and total head respectively. The optimized number of peak suns hours is 4hrs based on the site location and solar radiation condition. The electrical data of this pump are shown in table (4.2)

Table(4. 2): The electrical data of SP 17-9 pump

Rated power	5.5 kW
Rated voltage	3 x 380-400-415 V
Rated current	5.50-5.50-5.70 A
Rated speed	2850-2860-2870 rpm

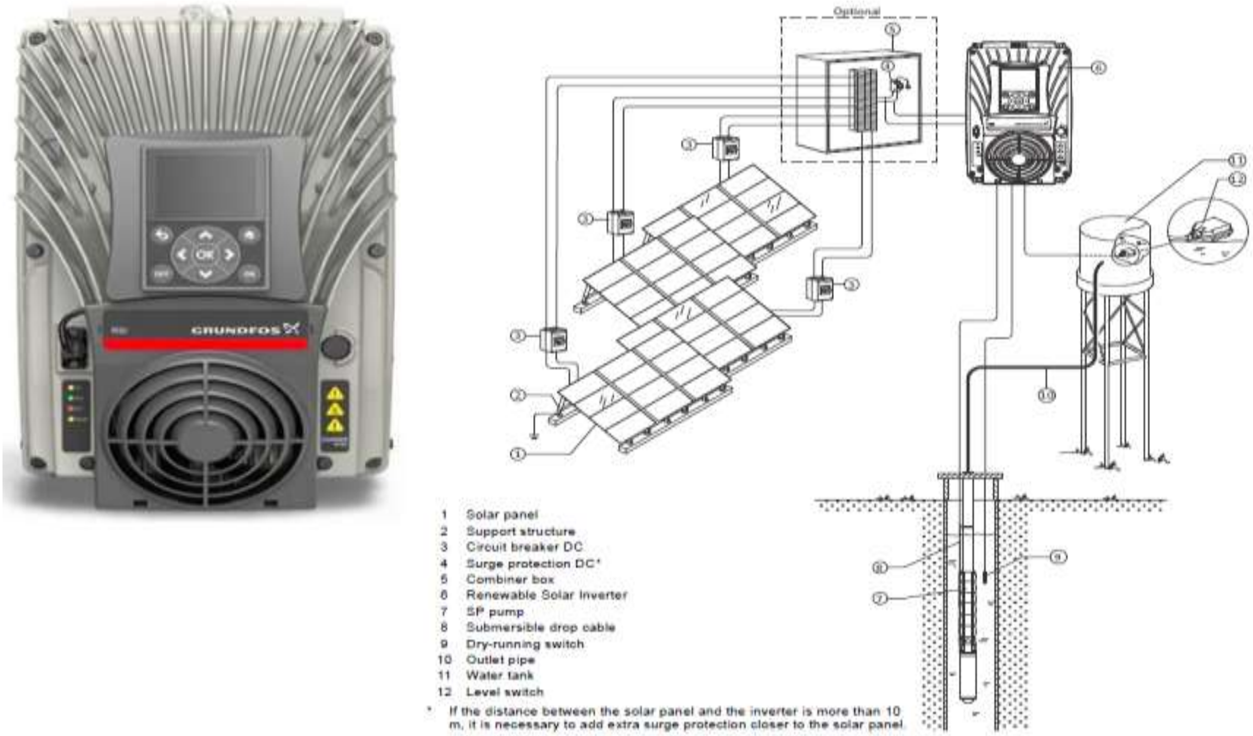
The motor is a canned type submersible motor offering good mechanical stability and high efficiency. Suitable for temperatures up to 40 °C. A 5.5 kW pump should receive an AC power from the Inverter output as a pump input. [34]



Figure(4. 4): Grundfos pump performance curve for SP 17-9

4.2.4 Inverter selecting and sizing

The selection of the inverter depends on the overall capacity of the PV Array. In this case, an inverter rated 5.5 kW was considered to be fully capable of converting the maximum output of the solar module. The overall efficiency of the inverter as specified by the manufacturer is 97%. The expected lifespan of the inverter was assumed 15 years; it means that this inverter must be replaced at least once during the project life-cycle of 25 years. The replacement cost of this inverter was assumed to be the same as the initial cost at $1,951 while its operating and maintenance cost is zero.[35] Figure (4.5) is showing the selected inverter and its position on the pumping system. The solar module output power is the inverter input to convert it into AC power which is the pump input power. There are DC solar pumps that do not require an inverter, however, it is considered very expensive, not available in the local market and not viable for small scale farms which is the case for this study farm.



Figure(4. 5): proposed Grundfos RSI 5.5KW Inverter and its position on a pumping system model[35]

4.2.5 Solar array sizing

The array capacity of the system depends on the power of the pump, inverter efficiency and the efficiency factor which is a factor considering all losses in the system due to temperature, module ageing, solar radiation variation, soiling and dirt and the cable losses. Considering the selected inverter efficiency is 95% with an efficiency factor of 80% (20% Total losses). The solar array size should be:

PV Power (kw) =

$$\text{Pump Power (KW)} \div [\text{ Efficiency Factor} \times \text{Inverter Efficiency}] \quad \text{Equation (4. 3)}$$

PV Power (kw) = 5.5 kW ÷ [0.80 × 0.97] = 7 kW

∴ The Array Capacity will be 7kW (7087 w). The number of panels needed to meet the energy demand requires selecting a suitable type. Based on the local market the 360 w monocrystalline solar panel was selected due to its availability and high efficiency. Electrical

Characteristics are shown in table (4.3). Division of the array capacity by the maximum power output of a single module gives the total number of modules.

Number of modules = 7087w /360w= 19.7 ~ 20 modules.

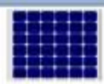
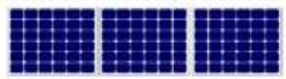
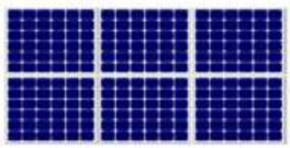
∴ Number of modules is 20 modules.

Table(4. 3): Selected module electrical characteristics

Maximum power voltage (VMP)	36.5 Volts
Open circuit voltage (VOC)	42.7 Volts
Max power current (IMP)	9.87 Amps
Module shortcut current (ISC)	10.79 Amps
Maximum power output (PM)	360 Watts
Module efficiency	20.8%

The final stage is deciding on the solar array connections and how to make the interconnections to achieve the desired voltage and current. Connecting the panels in series adds up the voltage of the panels while keeping the current fixed. While parallel connections add up the current while keeping the voltage fixed. The table (4.4) is showing the mechanism of calculating numbers of series panels and parallel panels to achieve the desired power output.

Table(4. 4): PV modules connections in parallel and series

Panel Connection	Connection	Voltage (Volts)	Current (Amps)
	None	36.5	9.87
	Series	109.5	9.87
	Parallel	36.5	19.74
	Series & Parallel	109.5	19.74

The number of solar modules (360 W each) connected in series = 10

Number of modules in parallel = 2

(20 modules in total)

Solar array rated power = 7kW.

In summery The estimated water pumping system performance through the year is shown in table(4.5).

Table(4. 5): Estimated pump performance

Array Capacity (kW)	Pump size (kW)	Pump Capacity (m3/h)	Minimum operating hours (hrs/day)	Daily Water Production (m3/day)
7kW	5.5	21	4	84

4.3 System Optimization

To optimize the proposed solar water system HOMER software were used to analyze the possible scenarios and recommend the optimum solar water pumping system. The software includes all the environmental factors (temperature, clearness index, etc.) and the solar potential depending on data obtained from NASA and Sudan Renewable Energy Agency for the specified location.

To analyze the optimum option, all the energy resources available included in the first design as shown in Figure (4.11). The software provides the techno-economic analysis of the pumping system with all the feasible solutions, and then recommend the optimum system. Based on the results a comparison between the solar system and the diesel pump was conducted to present the possible systems. For the current situation (diesel pump and water pump) there were two inputs for fuel prices; one is the official prices with government subsidy which suffer from scarcity and limited amount especially in rural areas. Another input was the parallel market prices (black market) which are very expensive and unstable. Two scenarios were modelled for the farm pumping system which are the base case scenarios where only diesel generator were used as power source even though fuel scarcity is the main reason for farming irregularity in the case study, the other scenario is the hybrid system where both solar and diesel were used to analyze the optimum pumping system, this advanced module was added to represent both the reliable and unreliable power sources to present all viable solution in case fuel scarcity is no longer a problem.

4.3.1 Input data

HOMER software requires specific data. The more detailed data were added the more accurate the results would be. Starting by case study location which is the case study farm (Latitud**e** 15°16 North, Longitude: 32 ° 59.21 East) then it is possible to get the Average solar radiation and clearness index by downloading the data from the internet or import it from a time series data file or the software's library. Average solar radiation and clearness index over twenty years are shown in figure (4.3). Same procedures used for the average daily temperature throughout the year as shown in figure (4.6). There were data obtained by Sudan Renewable Energy Agency such as the average daily direct normal irradiation (DNI).

Figure(4. 6): the average daily temperature

Other input data were obtained from the farmer and decision makers interviews such as daily water demands and their change through the year, the fuel prices, types of solar module available and fuel prices.

4.3.1.1 Deferrable load

The deferrable load is an electrical load that requires a certain amount of energy within a given time period, but the exact timing is not important; it can wait until power is available. Loads are normally classified as deferrable when they are associated with storage other than regular batteries such as storage tank. Which water pumping is considered a common example since there is some flexibility as to when the pump actually operates, provided the water tank does not run dry.[29]

Due to the implemented method of irrigation in the case study, the location climate and type of vegetables and fruits implanted the average monthly load (kWh/d) and the scaled annual average (kWh/d) calculated. The storage capacity was around three days of energy demand as recommended. However, since the irrigation method followed by the farmer is twice a week the storage capacity can be as small as one cubic meter (1 m3) to meet the drinking water for the farm animals because the daily demand was obtained from calculating the weekly demand from this twice a week irrigation method. The peak load and minimum load ratio which is defined as the minimum amount of power that can serve the pump to operate, this data is obtained from the selected pump datasheet as 5.5 kW for the peak load and 60% for minimum load ratio[34]. All the deferrable load input data are shown in Figure (4.7) below. The water demand reaches its maximum level during the summer season (March to June) where fortunately the average solar radiation also reaches its maximum at more than 7.29 kWh/m^2 per day during April (see figure (4.3)). During the month of August was the water demand at its minimum (12kWh/d) due to the rainy season from July to early September.

Figure(4. 7): HOMER input; the deferrable load for the water pumping system

4.3.1.2 The base case

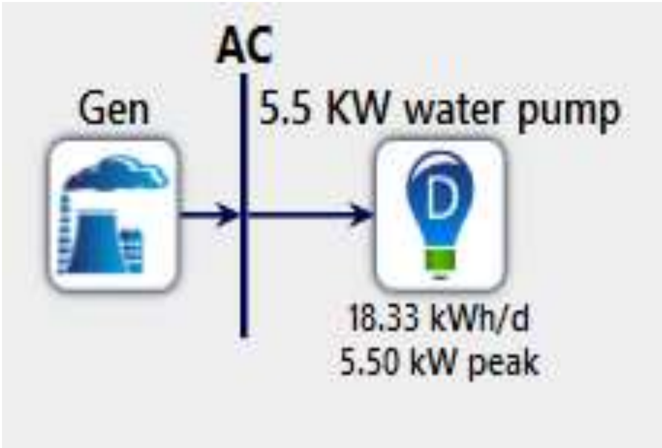
The diesel generator pumping system is considered the base case for HOMER input data, generator specification was modified a little especially the generator capacity since 11 kW (the actual case) is used for bigger farms with much higher energy and water demands, in HOMER input the size of the generator was left for the software to size it accurately to give a relative capital cost for the system, the selected diesel is an autosize Generac generator. Design Parameters for the Diesel Generator are shown in table(4.6).

Economically, from the interview; the maintenance cost is around 1400 Sudanese pounds (25 USD) which conducted twice a year and fuel cost is around 1160 Sudanese pounds (21 USD) per week (fuel price is $0.58/L). The water pump is been replaced every 10 to 12 years. Figure (4.8) presents the HOMER diagram for the base case.

Table(4. 6): Design Parameters for the Diesel Generator

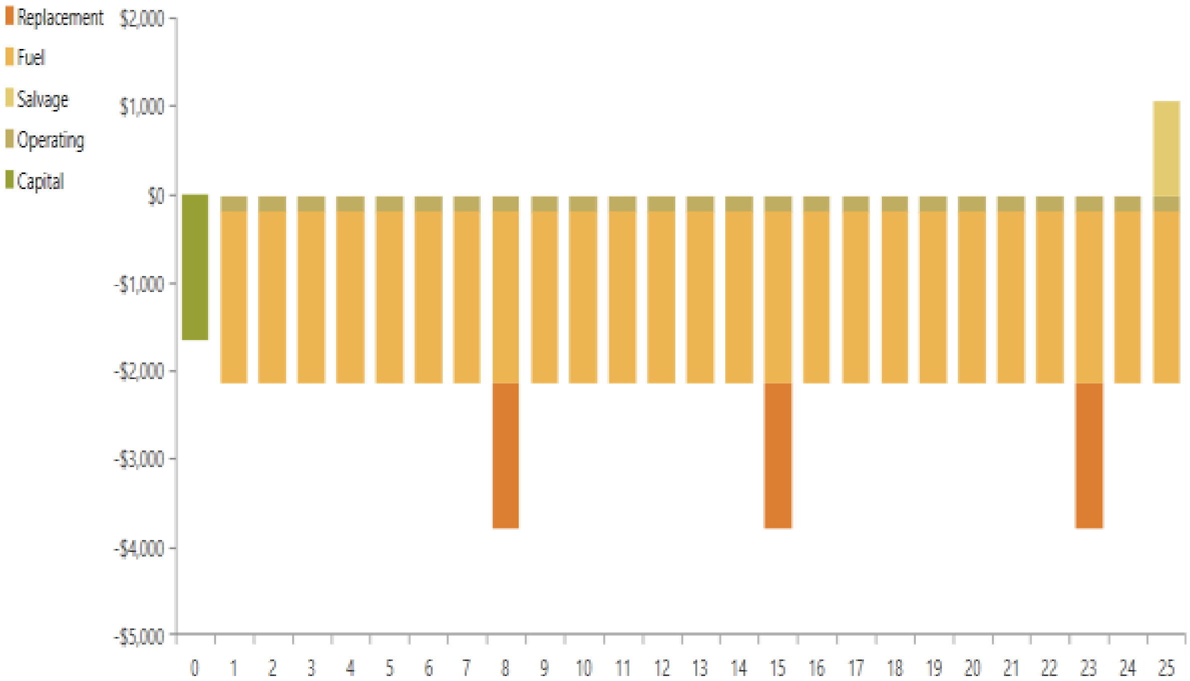
Parameter	**Units**	**Value**
Capital cost	$/kW	1650
Replacement cost	$/kW	1650
Operation and maintenance cost	$/op.h	0.03
Operational lifetime	Hours	15,000
Fuel curve intercept	L/h	0.538
Fuel curve slope	L/h/kW	0.303

The HOMER Pro software is used to size and evaluate both the environmental and economic viability of the diesel pumping systems by taking into account the total emission of Carbon Dioxide, Carbon Monoxide, Unburned Hydrocarbons, Particulate Matter, Sulfur Dioxide and Nitrogen Oxides through the year (kg/yr) and the variations of diesel prices. The costs of diesel systems for irrigation are increasing sharply due to the lack of availability of diesel fuel in the markets. According to the Central Bank of Sudan (CBS) oil prices is the major drivers of inflation that reached 32.4% in 2017[12].

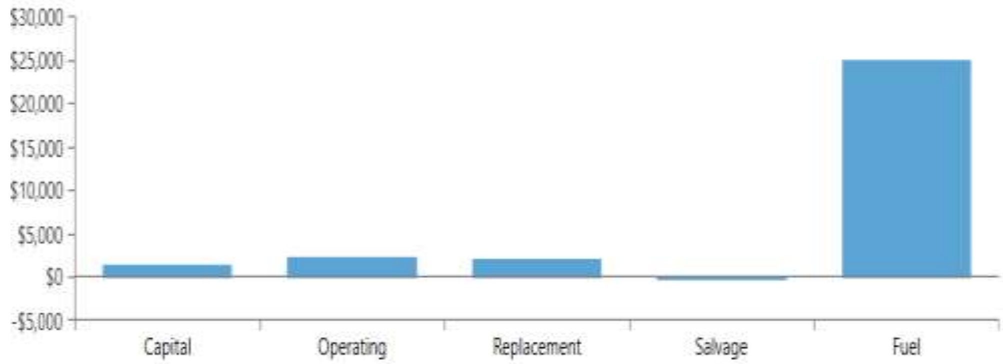


Figure(4. 8): Schematic diagram of the base case

The software simulation results suggested a 3.3 kW diesel generator that consumes 0.184L/h with an average of $199 annual maintenance and requires replacement every seven years to meet this system demand efficiently. The capital cost of the generator is $1650. The diesel system (base case) can serve the load at the lowest cost under this modelled conditions, figure (4.9) and figure (4.10) are showing the cash flow over 25 years, the cost of capital, replacement, fuel, operating and salvage were analyzed as shown below.



Figure(4. 9): The cash flow base case by type over 25 years



Figure(4. 10): The cash flow base case by type over 25 years

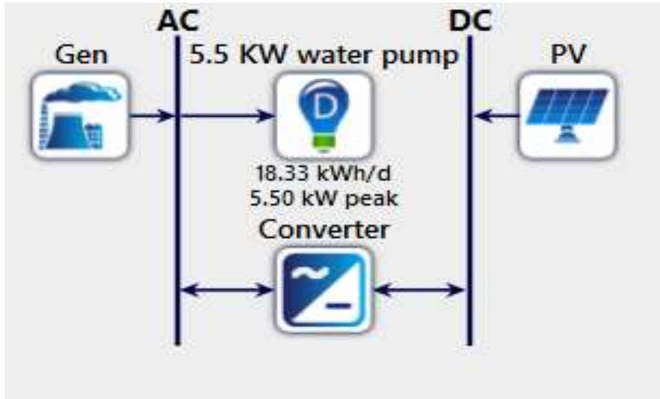
Figure (4.9) and figure (4.10) are describing how each type of cost over 25years contribute to the total cost of the system. The total cost is estimated (in the present) to be $31,277.47 where fuel cost counts for 80.1% of the total cost. The system levelized cost of energy (LCOE) is $0.3642 as shown in table (4.7) below.

Table(4. 7): Economic analysis of the system

	Gen (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Production (kWh)	Fuel (L)	O&M Cost ($/yr)	Fuel Cost ($/yr)
	3.30	$31,277	$0.364	$2,292	$1,650	6,643	1,939	199	1,939

4.3.2 The hybrid system

This scenario is included to examine all the possible scenarios and grantee the optimum one despite fuel scarcity and its instable prices. The hybrid system consists of a 3.3 kW diesel generator a solar module with a inverter as shown in figure (4.11). Two hundred simulations were run in HOMER Pro, of which one hundred and fifty were found feasible and the rest infeasible due to capacity storage constrains. Of the feasible solutions ninety-nine of them were hybrid system, forty-seven solution were using only solar modules and four solution diesel generator one of which was the base case.



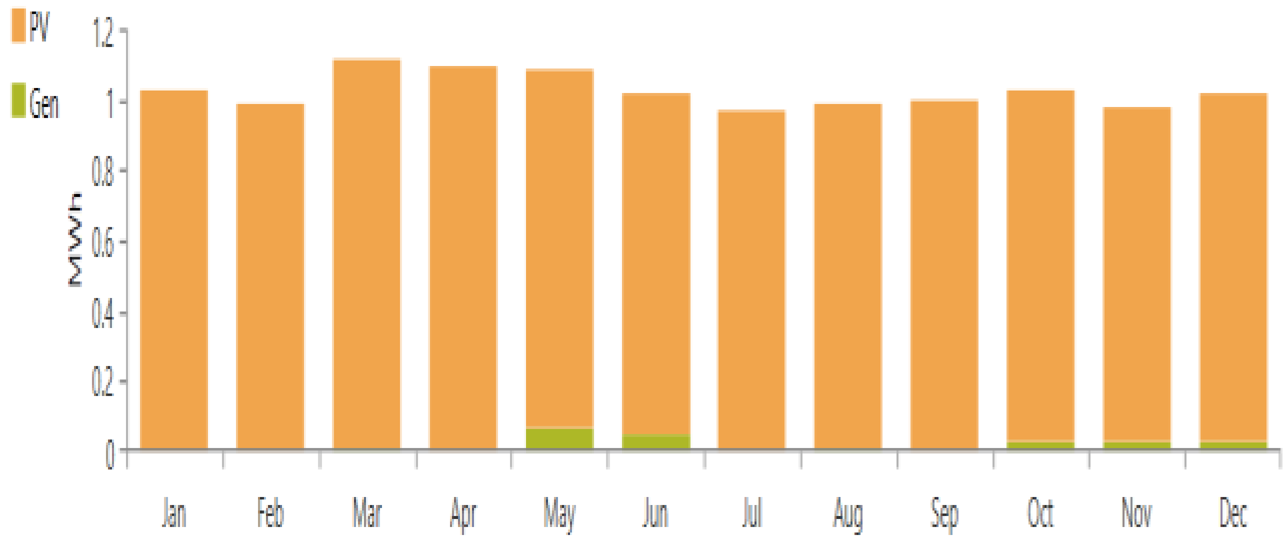
Figure(4. 11): Schematic diagram of the hybrid system

The optimization results has shown the best scenarios of all feasible solutions. The optimal solution that HOMER pro presented is a hybrid system with a 3.3 kW diesel generator and 6.14 kW solar models with a converter size 4.41. Followed by 7.5 kW solar system with 4.40 kW converter and then a 3.3 kW diesel generator. HOMER Pro presented the three optimal solutions in different categories for assessment as shown in Table (2).

Table(4. 8): Systems components and their sizes

NO.	System Configuration	Size of Solar PV (kW)	Size of Diesel Generator (kW)	Size of Converter (kW)
1	Solar PV, diesel hybrid system	6.14	3.30	4.41
2	Solar PV system	7.50		4.40
3	Diesel generator		3.30	

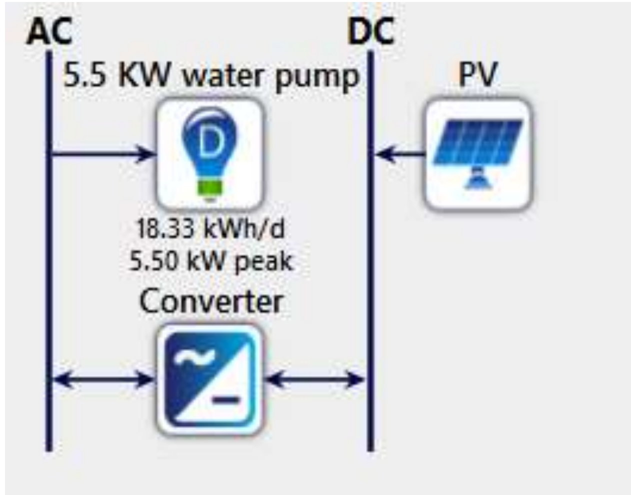
The Diesel generator system configuration was considered as the most expensive option for the water pumping system out of the three optimal configurations. As for the hybrid system 96% of the energy production comes from solar energy where the diesel generator works as a backup system during demand peaks and rainy season if needed, figure (4.12) is presenting the monthly energy production for the hybrid system and the role of the diesel generation throughout the year.



Figure(4. 12): monthly energy production of the hybrid system

4.3.3 Solar water pumping system (SWP)

The energy produced by solar photovoltaic is directly proportional to solar irradiation available. The amount of solar energy production varies depending on how solar panel is mounted to capture solar irradiations onto its surface area; the solar panel can be mounted either on fixed tilt angle or on the system which tracks the sun. In this study, the solar panels were presumed a fixed tilt angle. Moreover, the energy required for the water pump is a result of solar irradiations hitting the solar panel. This system contains a 5.5 kW water pump, DC/AC converter since the DC pumps are considered expensive and not available in the local market[33], and finally the solar PV module. Figure(4.13) shows the solar water pumping system diagram in HOMER.



Figure(4. 13): Schematic diagram of the Solar system

In this scenario, forty-seven feasible simulations were run in HOMER Pro, one of which is the optimal solution shown in Figure(4.14) the system has 7.5kW solar module with 4.4KW DC/AC converter. This optimal solution is the same option in the Hybrid system modeling shown in table(4.8). Technically the system is very efficient meeting the water demands on a daily bases year-round. All system equipment are available in the local market. The system neither requires major maintenance nor it requires fuel which makes economically attractive and environmentally friendly. From an economic point of view, the system is slightly more expensive than the hybrid system since the size of the solar module is bigger. However, this system is a much better option than diesel. Since most of the solar system cost is an upfront cost, the system is immune to the prices fluctuation due to economic instability which is a common occurrence in developing countries such as Sudan.

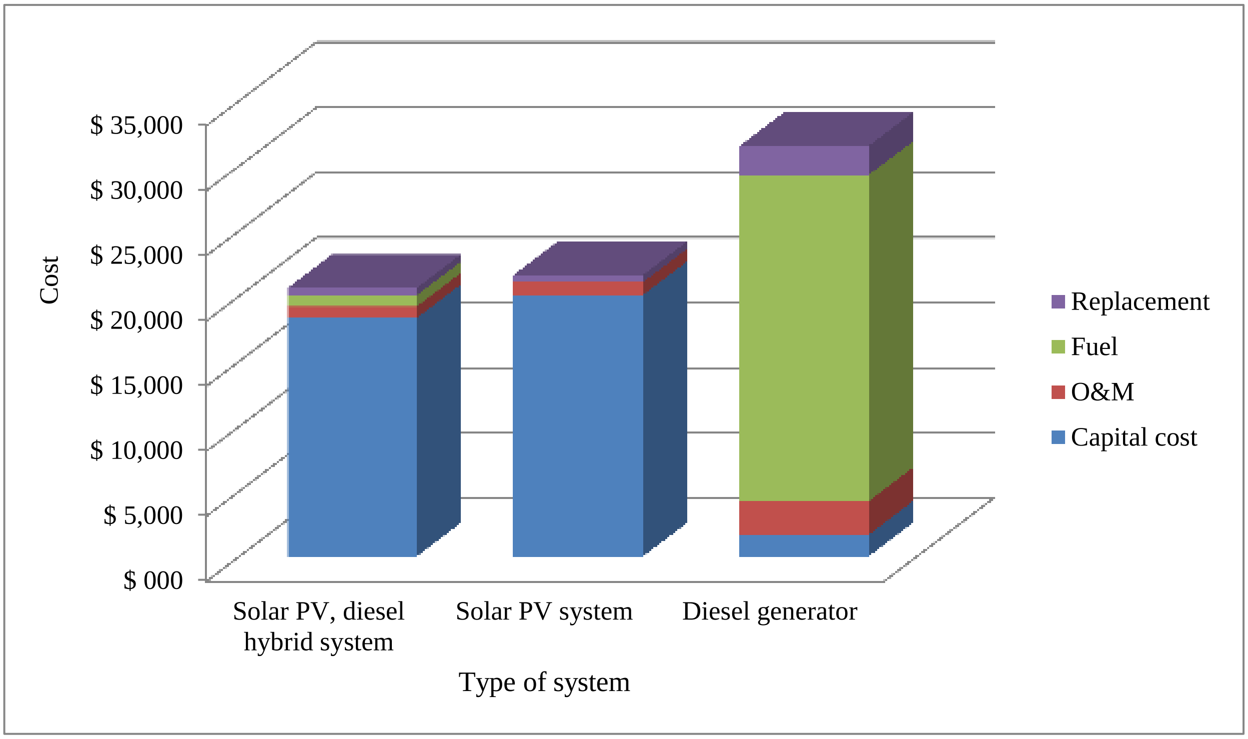
Figure(4. 14): Solar system cash flow by component over 25 years

4.4 Costs Analysis Of The Systems

High capital costs is a well-known characteristic of renewable energy systems due to the upfront costs of equipment that need to be installed before the production of energy. The RES often need equipment installed over a large piece of land to harness the energy, especially solar and wind systems, thus it is quite essential to establish an optimal system for a particular location. The costs of the system configurations are broken down into different classes from capital costs to salvage value.

4.4.1 Net present value

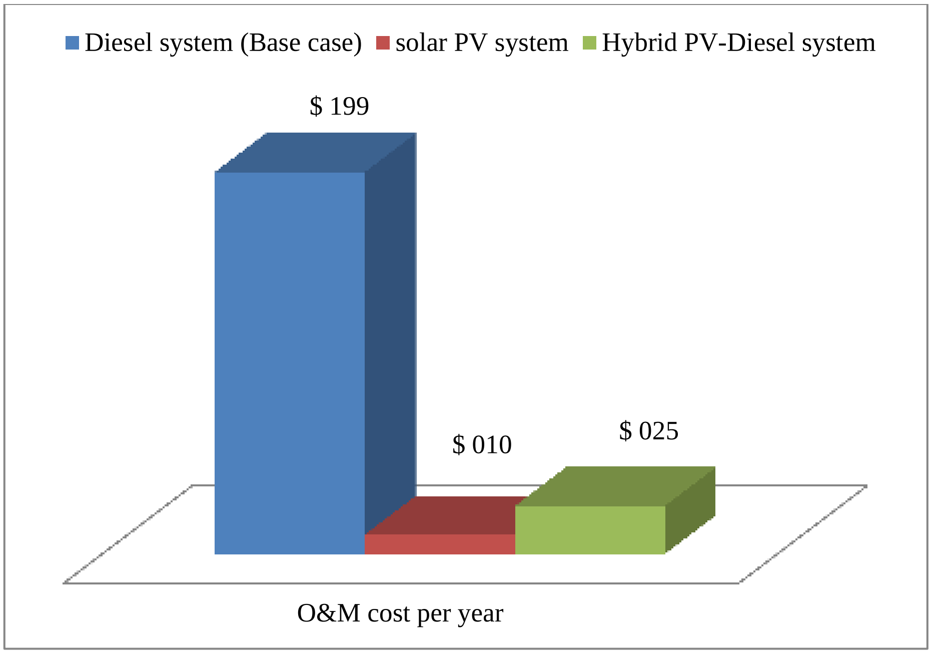
System configurations that comprised of Solar PV gave a relatively high initial capital cost as compared to those using a diesel generators for energy production, Figure (4.13). Capital costs for system (1) and system (2) were $18,310 and $18,751.37 respectively as compared to those of system (3) at $1,650. The high initial costs are mainly due to the balance of the system equipment apart from the solar panels. Despite the reduction in the pricing of solar modules, most of the balance of system equipment is still expensive. The balance of the system costs for systems that have solar includes converter and battery " if there is any" costs whereby the price varies according to the size of the capacity of the system. System (2) has higher solar capacity which could lead to higher capital cost due to the bigger size of solar module.



Figure(4. 15): Net present costs of pumping systems configurations

4.4.**2** Operation and maintenance cost (O&M)

The operation and maintenance costs (O&M) of the systems decrease with using PV water pumping system since solar panels require nothing other than regular cleaning for the panels from dust and sands and minor stuff. The O&M cost of the PV system is considered to be around $10 per year by the manufacturer. This is about 5% of the Diesel system O&M cost and about 40% of the hybrid PV-Diesel system O&M cost. It is clear that due to a very high running cost of diesel system, O&M costs of the Diesel system is higher than that of the PV and hybrid PV-Diesel systems as shown in Figure(4.16).

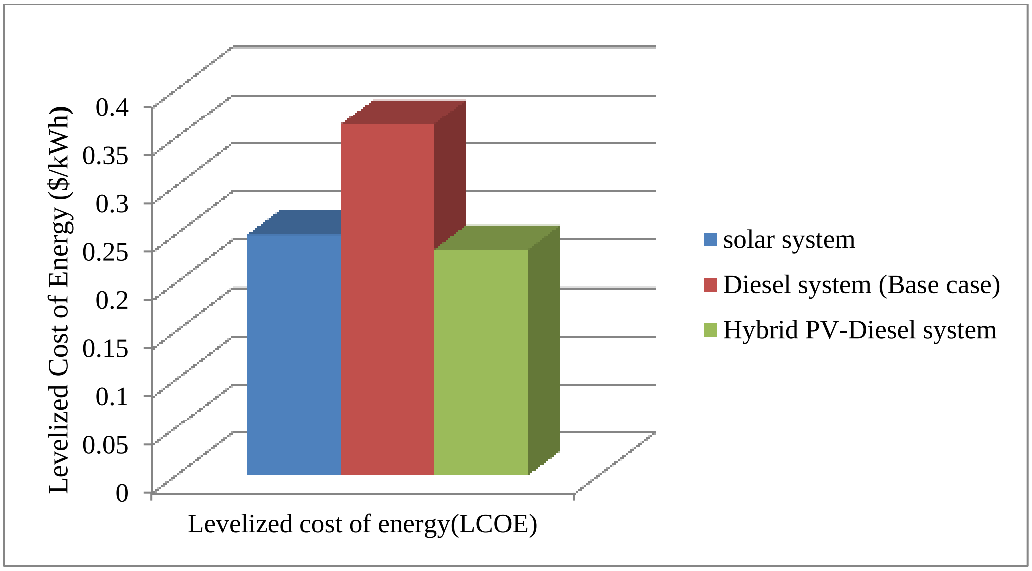


Figure(4. 16) : O&M costs for the PV, Diesel and hybrid PV-Diesel water pumping systems

4.4.3 Levelized cost of energy (LCOE)

The comparison of the renewable (solar) and conventional energy resources can be examined by the COE method, which represents the total cost required for generating one kWh as a unit of electricity. As shown in figure (4.17) below, the COE for a PV system is lower than the diesel system and slightly higher than the Hybrid system. However, the fact that the hybrid system requires fuel for the diesel generator is a disadvantage due to fuel scarcity and its increasing prices in the country. The HOMMER results show that LCOE for solar PV, Diesel and hybrid PV-Diesel systems are 0.249, 0,364 and 0,234 $/kWh respectively. LCOE of PVWP system is lower because it requires minor maintenance and it is fuel independent. The PVWP system has low PBP varying between 7 and 8 years showing high economic profitability.

From the above economic analysis, PV water pumping system can be more attractive and suitable energy technology deployed alongside diesel systems in different areas with good solar radiation and where the cost of the transmission system to on-grid is very high.



Figure(4. 17): LCOE for PV, Diesel and hybrid PV-Diesel water pumping systems

4.5 Environmental Analysis For Water Pumping Systems

The operating principle of the diesel-powered generator involves the injection of diesel fuel in mix ratio with the compressed air into the combustion chamber. The burning of this mixture produces polluting unburned hydrocarbon and other poisonous particulates such as Carbon dioxide (CO_2), Carbon monoxide (CO), Sulfur dioxide (SO_2) and Nitrogen oxides (NOx), these products are able to affect the environment and our health. In this environmental analysis, it was chosen CO_2 gases in comparison to the proposed water pumping systems. The use of renewable energy sources such as solar energy would ensure the security of supply amidst fears of diminishing reserves of the conventional energy sources in the foreseeable future with a lower environmental impact as compared to fossil fuels.

From the environment point of view, PVWP system contributes to the reduction in greenhouse effect as shown in table (4.9) below. Table 4.5 presents the comparison between these systems where the total emissions for standalone diesel system are 5151.049kg/yr while the introduction of a PV system as the hybrid system can lower the total emission to 175.59832kg/yr.

Table(4. 9): Pollutants emission per year from the pumping system

Emission (kg/yr)			
Pollutant	Diesel	Hybrid PV/Diesel	Solar PV
Carbon Dioxide	5075	173	0
Carbon Monoxide	32.0	1.09	0
Unburned Hydrocarbons	1.40	0.0477	0
Particulate Matter	0.194	0.00662	0
Sulfur Dioxide	12.4	0.424	0
Nitrogen Oxides	30.1	1.03	0
Total emission	5151.049	175.59832	0

4.6 Socio Economic Analysis

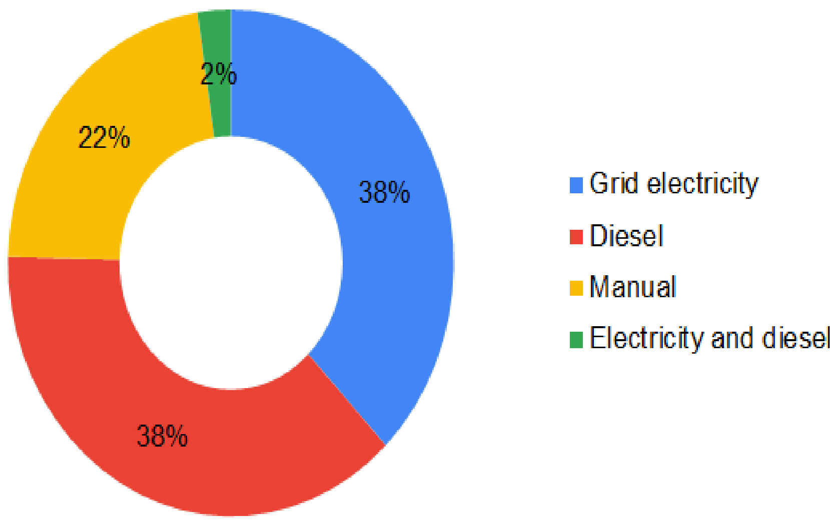
This section discusses the survey results where sixty farmers have been interviewed from three different locations. Fifty small farmers from two villages in Algazera state and the third location was Al- Ailafun southern Khartoum where ten farmers have been interviewed. This survey aims to provide an Economic, Social and technical assessment of the existing irrigation systems and identifying the barriers for the solar water pumping system.

The survey structured of twenty- short questions with fifteen closed questions and five open questions (Appendix III). 16.67% of the respondents were using rainfall irrigation while the rest is depending on manual and powered irrigation. As for irrigation water source, more than 50% of the farmers depend on the river Nile, its Dams and reservoirs and floods, 25% of them are using borehole while the rest is depending on rainfall and/or more than one source. The size of the farms varies from two Fadden to thirty Fadden (8400 to 126000) Square Meters.

The main agricultural products produced by the sample respondents in this survey were classified into three main categories namely vegetables (onion, carrot, tomato, okra, cucumber and others), fruits (citrus, banana and mango) and cereal crops (wheat, corn, sesame, lentils etc.). The majority cultivated fields are located near the Nile bank and reservoirs where the farmers can get water easily. According to the information from the Ministry of Agriculture, Sudan cultivable land is estimated at 74 million hectares, only 19 million hectares (25%) of which is currently under cultivation.

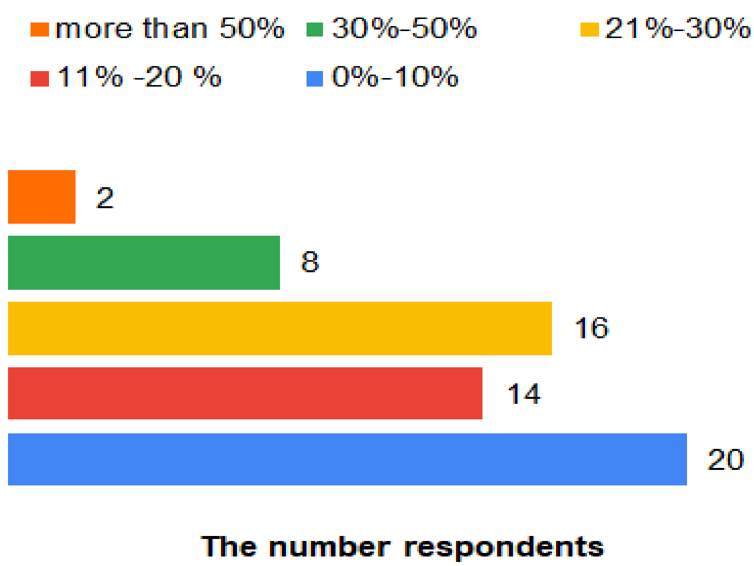
4.6.1 Analysis of the respondents results

The power sources for irrigation are grid electricity, diesel power and manual. Some of the farmers use more than one energy sources usually electricity with a diesel generator as a backup due to the high rate of electricity outages in the past few years. Figure (4.18) represents the percentage of each source of energy.



Figure(4. 18): Type of energy sources used for irrigation

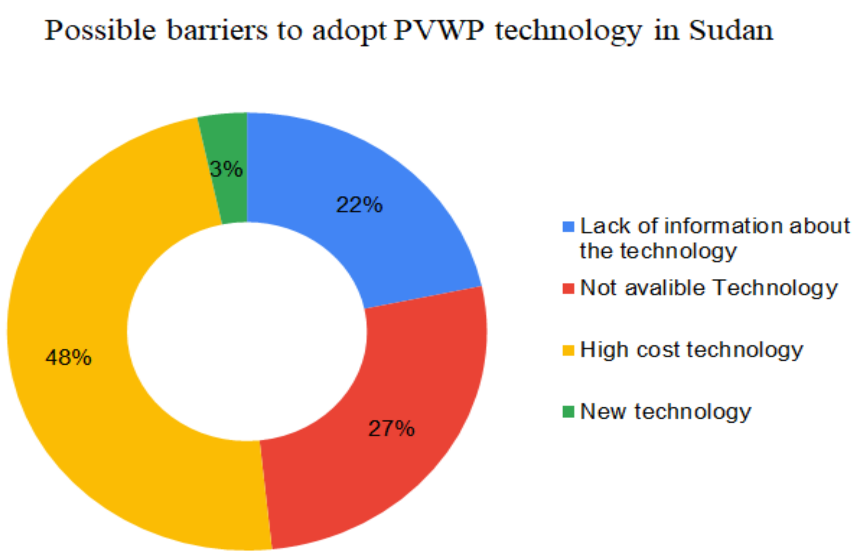
The cost of the irrigation varies depending on the type of the irrigation used by the farmer, water source for irrigation, location and size of the farm and depending on the type of the crops implanted in the farm. In the interview, each farmer gave a percentage of the irrigation cost out of the total cost of the agriculture per season. Farmers who are depending on rainfall for irrigation has the cheapest irrigation cost followed by electricity user. Figure (4.19) shows a chart of the sixty respondents and the percentage of irrigation cost out of the total cost of the agriculture season.



Figure(4. 19) : the percentage of irrigation cost out of total cost

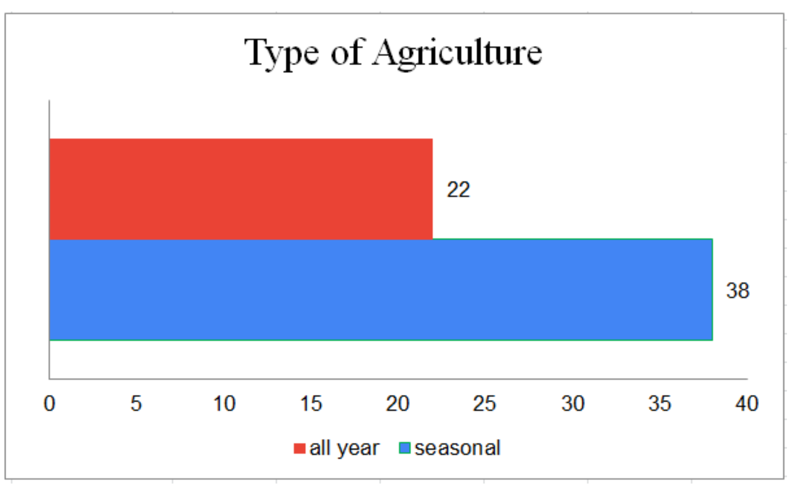
Even though none of the respondents used solar water pumping system, 40 % of the respondents think that the best way for irrigation is by implementing solar water pump, 35% think electricity is the best way for irrigation. 21.6% diesel and the rest chose electricity and diesel. Reasons behind this variation are the frequent electricity outages during summer where the irrigation demands increase which made it not attractive option considering its cheap prices source for irrigation. In the last three year the average of electricity outage reached forty-two hours per week during summer. 90% of the respondents would switch to solar energy if it has a warranty and if they have the financial ability.

Since PVWP is more reliable technology than diesel and it is environmentally friendly, one of the respondents pointed out that solar pumps do not cause noise pollution compared to diesel especially for farms close to residents houses. However, from the farmer's points of view, the challenges facing the implementation and expansion of solar energy technology in Sudan are shown in figure (4.20). The assumption that solar technology is an expensive technology was supported by 48% of respondents. The rest of the respondents considered the lack of education and Capacity building on this emerging technology is the main barrier for adopting this technology.



Figure(4. 20): Possible barriers to adopt solar energy technology in Sudan

One of the survey questions was about the effect of the frequent electricity outage and the fuel instability or scarcity since it affected all the economic aspects in the country including the agriculture sector. 47 respondents explained how this issue affected their farms' production such as reduction of the farm production and quality due to thirst of the crops, cancellation of the whole season to avoid financial loses, moving from year-round farming to seasonal farming to reduce the total cost as shown in Figure(4.21).



Figure(4. 21): Type of agriculture used by the farmers

4.6.2 Socio-economic barriers for solar water pumping

During the interviews and survey with decision-makers and sample respondents farmers, some issues appeared as the barriers for harnessing of solar energy for agricultural irrigation in Sudan. Those barriers include;

- Farmers' financial capacity, as renewable energy technologies such as solar PV the upfront capital cost is very high (87% of total cost) what makes it difficult to purchase especially for small scale farmers without government support.
- Financial and technical support, even though the government have several programs to promote the diffusion of solar PV technology. The small scale farmers in rural areas are still struggling to implement the technology.
- Lack of education and Capacity building on this emerging technology. The government plays a crucial role in establishing a market to implement solar technology by funding education and research to improve awareness and increase skills, by creating policies and adopting subsidy program to enable easy accessibility.
- Lack of infrastructure (road, storage systems) and advisory services since there is a deficit in training programs among farmers regarding modern irrigation.
- Lack of firm legislative framework, practical policy, the legal and regulatory environment for the private sector to be attracted to invest in solar energy technology.

Despite all the mention barriers, solar energy technology, especially in the irrigation sector, it has strong derivers one of which is the high potential solar energy in Sudan, the technology is being attractive compared to diesel due to environmental concerns and the reduction in solar PV prices with the time on the contrary to diesel prices which keep increasing each year. Most importantly the results of the survey with farmers respondents confirm that their awareness of adoption solar pumping systems would be helpful to increase and sustain crop production through the year which would lead to increase their incomes since solar water pumps expand seasonal growing cycles and mitigate periods of low or irregular rainfall. moreover, the environmental benefits of solar water pumps, compared to alternatives such as diesel pumps, contribute toward furthering SDG 7: Affordable and renewable energy and SDG 13: Climate action.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

In Sudan, like many countries in the world, the agriculture sector has a significant impact on the country economy whereby 80% of the population in rural areas depend on agriculture. Approximately 90% of farmed land relies solely on unpredictable seasonal rainfall to meet water needs. This study aimed at analyzing the techno-economic feasibility of the solar water pumping system for off-grid irrigation in Sudan, taking a farm in Al-Ailafun district as a case study. Firstly, interviews were conducted with decision-makers such as the director of the Renewable Energy Agency in Sudan, members from private companies specialized in solar energy technology, consultant and engineers in the SWP project in the northern state and a consultant in the solar project for the IDP camps in Darfur. This interviews aim to identify the key factor and limitation for Promoting the Use Of solar Water Pumping System for Irrigation purposes in Sudan. Secondly, a survey was carried out to determine the energy and water demand for the case study farm. The case study interview results, using Microsoft Excel, concluded that the water peak demand of the farm was 84 m^3/day which required a 5.5KW pump. Secondly, HOMER Pro was used to model, optimize and simulate water pumping systems. The system load is considered a deferrable load that requires a certain amount of energy within a given time period, but the exact timing is not important. Finally, the optimal system for irrigation of the farm was determined based on the results from the simulation.

Different system components were chosen from the database of Homer Pro to model the water pumping system. During the modelling phase, three scenarios were chosen, that is the base case diesel system, Hybrid solar/ diesel system and stand-alone solar system. The first scenario was introduced to optimize the diesel system size from 11KW the actual size to 3.3KW. For the second scenario component were chosen to carry out the study included the Genset 3.3kW, 6.14KW solar panels with 4.41KW converter. The optimal system was found to be solar PV –diesel hybrid system at NPC of $20,157 and an LCOE of 0.234 $/kWh. The third scenario was a solar system contains a 7.5KW solar panel with 4.4KW DC/AC converter, the NPV of the system is 21,495 and the LCOE is 0.249 $/kWh. This scenario was considered more applicable than the Hybrid system since it does not depend on Diesel fuel which suffers from scarcity and price instability.

the survey purpose was identifying the barriers and drivers for implementation of the solar water pumping technology in Sudan. The barriers include financial constraints especially for the small scale farmers, insufficient market information and lack of infrastructure facilities. Furthermore, the research shows that many farmers are struggling to sustain their agriculture activity due to fuel scarcity and electricity outages, this is affecting the production of the farms. Therefore, in order to improve the agriculture sector expanding the irrigated land is a necessity and in order to achieve that to solve the above-mentioned issues is a must, which can be achieved through the involvement of all stakeholders including government institutions, the farming communities, researchers, private sector and non-government organizations to fill the capacity gaps.

Finally, relying on an interview, software results and observations, it is concluded that Sudan in general and Al-Ailfun district specifically have abundant resources for irrigation schemes using solar water pumping technology, this could significantly improve agricultural production and the status of food security which lead to improving the standard of living for farmers and country’s economic development.

5.2 Recommendation

This study represents the technical and economic analysis of a solar water pumping system for agricultural irrigation to support the sustainable development goals and agriculture prosperity in Sudan. This section addresses some of the recommendations and the issues that require further investigation.

- The off-grid solar irrigation technology is more likely to attract governmental support and success when it is connected to major national development efforts, typically including agricultural transformation, electrification, and industrialization. The coordination among ministries of agriculture, water and energy will be critical to achieve integrated policies and programs. To spark growth in the space, interventions should target both the demand and supply-side of the market. These can include smart subsidies, VAT, or tariff policies to lower-end retail prices.

- The storage tank of solar water pumping system needs to be evaluated in deep because batteries are a too expensive option. Moreover, investigations are also required to study the possibility of harnessing the entire solar system for multiple applications, such as providing power for irrigation as well as for other off-grid energy application, which was not taken into account in this study. This could be more economically profitable since irrigation loads vary through the year and not required as much during rainy season and harvesting.
- The private sector needs to be more involved in the irrigation sector especially using solar energy technology. The government needs to find ways to attract private agricultural producers and encourage the availability of finance for business start-ups in the agriculture sector especially in irrigation.
- The Policy developers in the agricultural sector should work closely with the government's related institutions, researchers and all stakeholders for better outcomes in the irrigation system. This would help to design a better plan and projection toward the country's future goals of agriculture and irrigated areas.
- This study for solar energy technology was limited to the agricultural irrigation system only. However, solar technology could be extended to cover other agriculture-related applications such as crops drying, conservation, crop value-added processing using solar energy technologies. It is recommended for researchers to consider that as well.
- The future work needs to be related to the modelling and controlling of the water pumping system. Developing an experimental work and comparing the performance of both approaches under many scenarios is one of the strategies that could be investigated. This would help for a better understanding of the behavior of such systems in different ways.

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APPENDIX

APPENDIX I: DESCISIONS MAKERS QUESTIONNAIRE

PAN AFRICAN UNIVERSITY

INSTITUTE FOR WATER AND ENERGY SCIENCES

(Including CLIMATE CHANGE)

MSc. ENERGY ENGINEERING

QUESTIONNAIRE FOR DECISION MAKER:

(……………………………………………………………………………………….)

Prepared by: Shimaa ABDELHAFEZ

TECHNO-ECONOMIC ANALYSIS FOR STAND ALONE SOLAR WATER PUMPING SYSTEM IN SUDAN "FOR IRRIGATION"

ORGANIZATION NAME: ……………………………………………………………

ADRESS: ….…………………………………………………………

PHONE NUMBER: ….…………………………………………………………

EMAIL ADRESS: **…..…………………………………………………………**

Disclaimer:

The information collected is strictly for research purpose only, therefore it should not be used beyond this purpose. Information will secretly be treated as strictly confidentially and will be presented in the form of statistic report only.

1. Can you you give us a brief description about the irrigation sector in Sudan? Types, most used,

………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………

2. Can you you give us a brief introduction about the history of solar water pumping in the country?

………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………

3. Which regions in the country have the highest installed capacity of solar water pumping systems?

……………………………………………………………………………………….

4. Please cite the most key application of solar water pumping systems in the country.

(Put them in order (1) for the most implemented application)

application	(1, 2, 3)
Agriculture	
Residential	
Others (Specify)	

5. Specify the ownership of solar water pumping systems in the country (in percentage)?

Systems owner	Percentage (%)
Government	
Private sector	
Nonprofit organizations	
Individual ownership	

6. Does the private sectors/individuals needs approval from the government prior to the installation of solar water pumping systems? (YES/NO). priefly describe the protocols.

…………………………………………………………………………………………

…………………………………………………………………………………………

…………………………………………………………………………………………

7. How do you rank your knowledge and skills level in solar water pumping for small scale irrigation schemes and water supply in the country? explain your answer how many projects did you work/ing on?.

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

8. Can you give an examples of one of the projects you worked on that related to solar water pumping?

   - Project name:

……………………………………………………………………………………………

   - Location:

……………………………………………………………………………………………

   - Ownership:

……………………………………………………………………………………………

   - Project size: kw/ number of pumps.

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

   - How did the SWP implementation affected project production? (from seasonal to all year?, increased the production?)

……………………………………………………………………………………………

……………………………………………………………………………………………

- Was the project depending on diesel? If your answer is yes, how much eas the consumption?

……………………………………………………………………………………………

9. Is there any enabling environments to support this kind of project intervention in the country the following fields?

Field	Yes/no (if yes briefly explain)
Government support (Subsidy, Legal Framework, Financial arrangements)	
Technology and material availability	
Socio-Cultural acceptance (community awareness)	
Personnel training (Skills and Capacities)	

10. List the main challenges for solar water pumping implementation in the country?

a) ……………………………….

b) ……………………………….

c) ……………………………….

d) ……………………………….

e) ……………………………….

11. What are the future plans for expanding the solar water pumping applications in the country?

…………………………………………………………………………………………………
…………………………………………………………………………………………………
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12. Is there any information that were not covered in this questionnaire that seem so important to be known. please provide details below.

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APPENDIX II: CASE STUDY FARM INTERVIEW

PAN AFRICAN UNIVERSITY

INSTITUTE FOR WATER AND ENERGY SCIENCES

(Including CLIMATE CHANGE)

MSc. ENERGY ENGINEERING

QUESTIONNAIRE FOR CASE STUDY:

(……………………………………………………………………………………….)

Prepared by: Shimaa Abdelhafez

TECHNO-ECONOMIC ANALYSIS FOR STAND ALONE SOLAR WATER PUMPING SYSTEM IN SUDAN "FOR IRRIGATION"

FARMER NAME: ……………………………………………………………

ADRESS: ....…………………………………………………………….

PHONE NUMBER: ....…………………………………………………………….

EMAIL ADRESS: **.....………………………………………………………….**

Disclaimer:

The information collected is strictly for research purpose only, therefore it should not be used beyond this purpose. Information will secretly be treated as strictly confidentially and will be presented in the form of statistic report only.

1. Age

- 18-29
- 30-39
- 40-49
- Above 50

2. Education

- Primary
- High school
- College
- Graduate
- (OTHER): …………………………………………………………………….

3. Work status as a farmer

- Full time
- Part time

4. Do you have another source of income?

- YES
- NO

5. Economic status; can you making saving for future projects? You live comfortably with farming, struggle with paying life necessities. Do you consider yourself:

- Rich
- Average
- Below Average
- poor

………………………………………………………………………………………
………………………………………………………………………………………

6. Farming experience

- 1–3 years
- 4 - 6 years

- 7 - 9 years
- Above 10 years

7.**Farm location:**

Street Address ……………………………………………………………

City ……………………………………………………………

Province ………………………………………………………...

8. What is the water source used in the farm?

- borehole
- River / Dam
- Other: ………………………………………………..

9. What is the power source for irrigation

- Grid electricity
- Diesel power
- Manual
- Other: ………………………………………………..

10. Type of Agriculture

- All year
- Seasonal

11. what do you think is the best way for irrigation.

- Rainfall.
- Diesel.
- Solar water pump.
- Other: ……………………………………………..

12. In your opinion what are the challenges facing solar irrigation pump?

- High cost.
- Technology scarcity .
- lack of information.

- Other: …………………………………………….

13. if you have the ability to switch to solar energy would you do it?

- YES
- NO

14. Explain your previous answer "why".

………………………………………………………………………………………

15. what is the percentage of irrigation cost out of total cost?

- 0%-10%
- 11% -20 %
- 21%-30%
- more than 30%

16. Farm size?

……………………………………………………………………………………………

17. Area Cultivated last season?

……………………………………………………………………………………………

18. Have you increased the plots you cultivated during the last five years and by how much?

……………………………………………………………………………………………

19. Planted Crops names?

……………………………………………………………………………………………

……………………………………………………………………………………………

20. Cost of production?

……………………………………………………………………………………

21.Energy consumption (per week /per month/per year) ?

…………………………………………………………………………………………

…………………………………………………………………………………………

22. Is the farm production affected by the fuel instability or scarcity?

- YES
- NO

23. Explain your previous answer "how".

…………………………………………………………………………………………

…………………………………………………………………………………………

24.Amount of water needed for irrigation?

…………………………………………………………………………………………

…………………………………………………………………………………………

25. What are your daily water requirements? gallons per day , liters per day (if possible)

…………………………………………………………………………………………

26. Depth of well/level of the water source from the surface (Meters)

…………………………………………………………………………………………

27. Transmission Pipe length

…………………………………………………………………………………………

28.Do you want another source of water besides the solar pump?

- YES
- NO

If yes, please explain:

…………………………………………………………………………………………
…………………………………………………………………………………………

29. What is the distance between the pump and the closest location where solar panels can be located without being shaded?

…………………………………………………………………………………………

30. please describe the pump and power source:
i.e.: horsepower/watts, voltage in AC/DC, flow rate in gallons/liters per minute.

…………………………………………………………………………………………

…………………………………………………………………………………………

31. Subsides and taxes :

…………………………………………………………………………………………

…………………………………………………………………………………………

32. Is there any information that were not covered in this questionnaire that seem so important to be known. please provide details below.

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APPENDIX III: FARMERS QUESTIONNAIRE

PAN AFRICAN UNIVERSITY

INSTITUTE FOR WATER AND ENERGY SCIENCES

(Including CLIMATE CHANGE)

MSc. ENERGY ENGINEERING

QUESTIONNAIRE FOR FARMERS:

(………………………………………………………………………………………)

Prepared by: Shimaa Abdelhafez

TECHNO-ECONOMIC ANALYSIS FOR STAND ALONE SOLAR WATER PUMPING SYSTEM IN SUDAN "FOR IRRIGATION"

FARMER NAME: ………………………………………………………………

ADRESS: ....……………………………………………………………….

PHONE NUMBER: ....……………………………………………………………….

EMAIL ADRESS: **.....………………………………………………………………….**

Disclaimer:

The information collected is strictly for research purpose only, therefore it should not be used beyond this purpose. Information will secretly be treated as strictly confidentially and will be presented in the form of statistic report only.

1. Age

- 18-29
- 30-39
- 40-49
- Above 50

2. Education

- Traditional “Khalawi”
- Primary
- High school
- College
- (OTHER): …………………………………………………………………….

3. Work status as a farmer

- Full time
- Part time

4. Do you have another source of income?

- YES
- NO

5. Economic status; can you making saving for future projects? You live comfortably with farming, struggle with paying life necessities. Do you consider yourself:

- Rich
- Average
- Below Average
- poor

…………………………………………………………………………………………………
…………………………………………………………………………………………………

6. Farming experience

- 1–3 years
- 4 - 6 years
- 7 - 9 years

- Above 10 years

7.Farm location:

- Khartoum
- Algazira state "Somtubar"
- Algazira state "Deneigela"

8. What is the water source used in the farm?

- borehole
- Rain
- River / Dam
- Other: ………………………………………………..

9. What is the power source for irrigation

- Grid electricity
- Diesel power
- Manual
- Other: ………………………………………………..

10. Type of Agriculture

- All year
- Seasonal

11. what do you think is the best way for irrigation.

- Rainfall.
- Diesel.
- Solar water pump.

- Other: ……………………………………………..

12. In your opinion what are the challenges facing solar irrigation pump?

- High cost.
- Technology scarcity .
- lack of information.
- Other: …………………………………………….

13. If you have the ability to switch to solar energy would you do it?

- YES
- NO

14. Explain your previous answer "why".

……………………………………………………………………………………………

15. what is the percentage of irrigation cost out of total cost?

- 0%-10%
- 11% -20 %
- 21%-30%
- more than 30%

16.Energy consumption (per week /per month/per year) ?

……………………………………………………………………………………………

17. Is the farm production affected by the fuel instability or scarcity?

- YES
- NO

18. Explain your previous answer "how".

…………………………………………………………………………………………

…………………………………………………………………………………………

19**. Subsides and taxes :**

…………………………………………………………………………………………

…………………………………………………………………………………………

20. Is there any information that were not covered in this questionnaire that seem so important to be known. please provide details below.

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