Viability of Solar/Wind and Hybrid Water Pumping System for Off-Grid Rural Areas in Ethiopia

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A Dissertation Submitted to
School of Mechanical and Industrial Engineering

Presented in Fulfillment of the Requirements for the Degree of
Doctor of Philosophy (PhD) in Mechanical Engineering
(Thermal and Energy Conversion)

Addis Ababa Institute of Technology (AAIT)
Addis Ababa University
Addis Ababa, Ethiopia
June, 2016

ACKNOWLEDGEMENT

First, I would like to express my most profound gratitude to my supervisor, Dr. - Ing. Demiss Alemu for his unlimited professional guidance and support throughout my work. I thank him not only for his valuable advice on my work but also, for his help in personal matters. He was much more than an academic supervisor to me.

I would like to thank everyone at AAIT, Mechanical Engineering Department; this work would not have been possible without financial support from Addis Ababa University, SIDA project. I am also very grateful to Professor Marta Molina's and Stuart King for their advising and administrative support during my visit to Norway and stay at NTNU.

And thanks are extended to all my colleagues, Dr. Abdulkadir Aman, Dr. Sileshi Kore, Sine Girma, Tilahun Nigusse, Aklilu Tesfaye, Degene Kebede and Alemayehu Tenaw for their support and encouragement.

I am also very much grateful to my family; my husband Asmamaw Adefris and my daughter Makeda Asmamaw who showed great patience during the long period of my full dedication to this research work.

Most of all I would like to thank the almighty God who I strongly believe gave me the power and the strength to accomplish this task.

ABSTRACT

The tendency to use renewable energy resources has grown continuously over the past few decades, be it due to fear over warnings of global warming or because of the depletion and short life of fossil fuels or even as a result of the interest which has developed among researchers doing scientific research into it. This work can be considered as joining any of these groups with an objective of supplying drinking water to the society living in rural areas of the country.

The aim of this research is to study the Viability of solar/wind and hybrid water pumping system to remotely located communities detached from the main grid line in Ethiopia. Three regions of Ethiopia selected for the study; there solar and wind energy potential determined based on the data of National Metreology Services Agency (NMSA) and NASA satellite data. The regions are Tigray, Amhara and Oromia. In addition, for hybrid water pumping system Afar region included. Generally, in this study four geographically different regions considered for standalone solar /wind and hybrid water pumping system.

One potential site selected from each regions for solar photovoltaic water pumping system. From Amhara region Siadeberand Wayu site with an latitude 9º46' N, longitude 39º40' E and altitude 3009 m a.s.l; from Oromia region wolmera site with latitude 9º13' N, longitude 38º39' E and altitude 2400 m a.s.l and from Tigray region Enderta site with latitude 13º48' N, longitude 39º55' E and altitude 2247 m a.s.l. PVsyst 5.56 software used to study the feasibility of solar photovoltaic water pumping system. The designed system is capable of providing a daily average of 10.5, 7 and 6.5 m^3/day for 700, 467 and 433 people in Siadberand Wayu, Wolmera and Enderta sites respectively. Average radiation determined from the data used as an input for software The output of the simulation of solar photovoltaic water pumping expressed in terms of annual water delivered , missing water, excess (unused) PV energy, and system efficiency during the year (performance ratio) and economic analysis expressed by global investment, yearly cost and cost of water pumped.

Similarly, one potential site selected from each regions for wind power water pumping system. From Amhara region Siadeberand Wayu site with an latitude 9º46' N, longitude 39º40' E and altitude 2625 m a.s.l; from Oromia region Adami Tulu Site with latitude 7º52' N, longitude 38º42' E and altitude 1665 m a.s.l and from Tigray region East Enderta site with latitude 13º42' N, longitude 39º37' E and altitude 1926 m a.s.l. The design results show that a 5.7 m diameter windmill is required for pumping water from borehole through a total head of 75, 66 and 44 m for Siyadberand Wayu, Adami Tulu and East Enderta to meet the daily water demand of 10, 12 and 15 m^3, respectively.

MATLAB software was used for simulation of the performance of the selected wind pump and the result showed that monthly water discharge is proportional to the monthly average wind speed at the peak monthly discharge of 685 m^3 in June,888 m^3 in May and 1203 m^3 in March for Siyadberand Wayu , Adami Tulu and East Enderta sites, respectively. An economic comparison was carried out, between windmill and diesel water pumping system using LCC (life cycle cost) analysis method and the results show that windmill water pumping systems more feasible than Diesel systems.

In this research, a hybrid (solar/wind) water pumping system capable of supplying 20 m^3 of water per day for 1000 people with average daily water consumption of 20 liter per person at a total head of 50, 75 and 100 m has been designed. The feasibility study of hybrid water pumping system was carried out by selecting four sites from three different administration regions. Atsbi site from Tigray region, Awash Fentale site From Afar, Borena and Adami Tulu site from Oromia region. The system consists of two technologies: wind pump and solar pump. The MATLAB software was used to study the feasibility of hybrid water pumping system for the selected sites.

Comparison of unit cost of water shows that Standalone PV and Windmill system are economically optimal compared to the hybrid system.

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NOMENCLATURE

A_T	Area of Rotor [m^2]
A_y	Annualized Life Cycle Cost
C_{pd}	Design Power Coefficient of the Wind Rotor
C_y	Annualized Capital Cost
C_k	Present Worth of Replacement at Year K
d_s	Days of constant water supply
D_p	Diameter of Pump [m]
D_d	Diameter of pipe [m]
D_r	Diameter of Wind Rotor [m]
D	Discount Rate
E_D	Energy Density [kW/m^2]
E_s	Total energy available in the spectra
E_I	Energy available for the unit area of the rotor
f	Friction factor
f(v)	Cumulative distribution function
F(v)	Probability density function
g	Gravitational acceleration
h_f	Total friction head losses
H	Total Head [m]
I	Interest Rate
K	Sum of loss coefficient of the pipe, valve and fittings
K_o	Constant to Define the starting behavior of Piston Pumps
L_p	Length of pipe
M_y	Yearly Operating and Maintenance Cost of the Initial Capital Cost C
n	Number of wind data
N	Life Time Period
N_p	Total number of beneficiaries

P	Per capital water consumptions
P_{wind}	Specific wind power [W/m^2]
P_{hyd}	Hydraulic power required [watt]
Q	Volume flow rate
Q_p	Total water demand per day
Q_{VP}	Instantaneous discharge of the system
Q_{IP}	Discharge expected from the system installed at a given site, over a given period
R_a	Reference area of the rotor
R_k	Cost of Replacement of a System Component at Year K
R_y	Present worth of All Replacement, Incurred during the Life Time N
S	Storage tank capacity [m^3]
T	Time Period in Hours
V	Wind stream velocity [m/s]
V_o	Cut-Out Wind Speed [m/s]
V_i	Cut-In Wind Speed [m/s]
V_m	Average Wind Speed [m/s]
V_d	Design Wind Speed [m/s]
V_{Fmax}	The most frequent wind velocity [m/s]
V_{Emax}	The velocity contributing the maximum energy [m/s]

GREEK SYMBOLS

δ	Sun declination angle[^{o}]
ε	Emissivity [-]
θ_z	Zenith anlge[^{o}]
ρ_a	Density of air [kg/m^3]
ρ_w	Density of water [kg/m^3]
σ	Stefan Boltzmann constant [W/m^2.K^4]
φ	Latitude of location[^{o}]

ω_s	Mean sunrise hour angle[^{o}]

ABBREVIATIONS

AC	Alternative Current
AAIT	Addis Ababa Institute of Technology
AAU	Addis Ababa University
ADB	Africa Development Bank
AWF	Africa Water Facility
BDCM	Brushless Direct Current Motor
CC	Capital Cost
CRF	Capital Recovery Factor
DC	Direct Current
DP	Diesel Pump
DPS	Diesel Pumping System
EC	Energy Cost
FE	Fuel Escalation Rate
GOE	Government of Ethiopia
GEF	Global Environmental Facility
HAWT	Horizontal Axis Wind Turbine
LCC	Life Cycle Cost
MC	Maintenance Cost
MDG	Millennium Development Goal
MPP	Maximum Power Point
M&R	Maintenance and Replacement
NMSA	National Metreology Services Agency
O&M	Operation and Maintenance Cost
PDF	Probability density function
PV	Photovoltaic
PWF	Present Worth Factor
RC	Replacement Cost

R&D	Research and Development
RWSSP	Rural Water Supply and Sanitation Programm
SC	Salvage Cost
SPV	Solar Photovoltaic
UAP	Universal Access Program
UV	Ultra Violate
VAWT	Vertical Axis Wind Turbine
WECS	Wind Energy Conversion System
WHO	World Health Organization
WP	Windmill pump
WPS	Wind Pumping System

CHAPTER ONE

INTRODUCTION

Water is the primary source of life for mankind and one of the most basic necessities for rural development. Many people in the world still lack access to basic water and energy services. According to WHO and UNICEF report in 2013 around 768 million people remain without access to an improved source of water and 2.5 billion people remain without access to improved sanitation [1]. The lack of potable water is an issue of developing countries including Ethiopia.

In Ethiopia, 85% of the population live in rural areas and 15% lives in urban. According to the Growth and Transformation Plan (2010), the drinking water supply coverage is 65.8% (91.5% urban and 62% rural) [2]. While there has been significant progress in recent years, there are still close to 30 million Ethiopians who lack access to safe and reliable sources of drinking water [2]. Because of this reason, in Ethiopia 46% of under-five-year’s children die related to waterborne diseases [3].

In developing countries like Ethiopia, generally composed of several villages sparsely located and with different topography, it is very difficult to extend the electric grid to every location where it is required. In some areas of the country the traditional water pumping systems powered by diesel or gasoline engines have been used for long time, but fuel cost escalation, transportation problem, lack of skilled personnel makes the conventional water pumping system unreliable and expensive for rural communities. Now a days, different researches have been carried out all over the world and their results show that, renewable energies are the best alternative energy sources to replace the fossil energy.

Renewable energy water pumping systems are now emerging on the market and are rapidly becoming more attractive than the traditional power sources. These technologies, powered by renewable energy sources (solar and wind), are especially useful in remote locations where a steady fuel supply is problematic and skilled maintenance personnel are scarce.

Although traditional windmills have been used to pump water for centuries, small wind turbines are especially appealing because they can be located further from the borehole, where the wind is strongest. Because these turbines can directly produce alternating current (AC) power, they lend themselves to applications such as lighting and other infrastructure services when water does not need to be pumped. Similarly, PV technology converts the sun's energy into electricity through electromagnetic means when the PV module (array) is exposed to sunlight. PV produces direct current (DC) power, and an inverter can be used to convert DC power to AC power. PV is especially suitable for water pumping because energy need not be stored for night pumping. Instead, water can be stored to supply water at night. Currently, hybrids of PV and wind (with or without backup generators) are more promising for supplying uninterrupted power because they work independently of each other. Such systems do not require each component to be oversized.

The Government of Ethiopia (GOE) with the collaboration of Chinese government prepared solar and wind master plan for the whole country, which can be very useful to identify the gross amount and distribution condition of wind and solar energy resources in the country. Based on the analysis of this master plan the country has a capacity of 1,350 GW (>7m/s) wind energy potential. And in most areas of the country, there is a low and medium wind energy potential (> 2.8 m/s), which can be applicable for water pumping [4]. Ethiopia has huge potential for solar energy because it is located near to the equator with annual total solar energy reserve of 2.199 million TWh/annum [4].

Ethiopia has not used its renewable energy resources as compared to other African countries which have a potential of renewable energy. This is due to economical problem as well as local private investors who are not interested to participate in this area. In

addition to this, initial investment and lack of knowledge are basic problems to spread the renewable energy technology in the country.
However, now a days, different rural water supply projects are going on in the country. One of the projects among these is the Rural Water Supply and Sanitation Program (RWSSP) that the government has implemented in 2006, under the Universal Access Program (UAP), funded by the ADB and other donors. This Rural Water Supply and Sanitation Program cover 120 Woredas in all nine regions and the cost of the program estimated to be 180,370,000 EURO.

In this research, the feasibility of standalone solar and wind water pumping in rural areas of the country is investigated by selecting one potential site from three different regions of the country. The regions are Amhara, Oromia and Tigray. And the metrological data collected to determine whether a solar or wind pumping system is the best one to use for the selected site. After evaluating the energy source, appropriate technology is used to design and simulate the system. In addition, the viability of the hybrid system also takes place by selecting four different solar and wind potential site in the country.

1.1 Background

In Ethiopia, access to electric services is only about 17%, most rural areas do not have the opportunity to use grid electricity to drive the water pumps, and have instead relied on diesel and petrol driven generators to provide power. Diesel/petrol pumps have many drawbacks such as high running and maintenance costs, unreliable supply of fuel, and poor availability of spare parts.

Under suitable conditions wind and solar based pumping offer several advantages such as low running costs and minimal environmental impact than diesel/petrol pumps. While the upfront investment on solar or wind energy based water supply schemes is higher than for conventional systems, the financial costs on a life cycle basis are often more favorable since the much lower running costs due to the almost free supply of energy offsets the incremental initial investment cost. Maintenance costs of solar systems are low, since the photovoltaic cells have been proven to be very reliable in practice. As such the operation and maintenance costs can easily be covered by a community.

The overall impact of solar and wind based pumping systems is very positive on both the local and global environment. Comparing to a diesel based schemes, the amount of fossil fuels to be displaced by using solar and wind energy impacts the environment positively, with significant reductions in greenhouse gas (as CO_2 equivalent) and acid air emissions (as SO_2 equivalent). Solar or wind systems have little negative impact on the environment. Wind turbines do pose a modest risk to birds and noise created due to wind rotors, and care has to be taken that the wind turbines are not be located too close to residential areas or the habitat of endemic rare bird species.

However, the use of solar and wind technologies are not without challenges. Because of their peculiarities, solar and wind systems requires special design considerations that may differ from more conventional systems. Solar-based water pumping system design requires accurate data on such matters as the available resource, the water demand and well characteristics so that they can be designed as precisely as possible with the smallest possible allowance in power due to the expensive capital costs of the photovoltaic cells, which is currently about €5-7 per watt peak . As well, the intermittent availability of solar energy requires the construction of sizable storage reservoirs. Wind resources availability is also highly variable and often unpredictable. Therefore constructing large reservoirs to store the water pumped during periods of wind availability for later use is necessary.

For solar and wind technologies to gain widespread acceptance by the communities and supporting structures, it is necessary to create the necessary awareness and demonstrate the operation of these systems in real life situation. There is also a need to encourage participation of the local private sector in the supply of equipment, spare parts and after sales services. However, without a critical mass of installed systems, solar or wind technologies will likely suffer from weak supply chains and a lack of private sector capacity for maintenance. Consequently, sustainability would remain low despite their many advantages.

1.2 Statement of the Problem

In Ethiopia, there are many water pumping system that are currently used in rural areas including engine driven pump, manual powered pump and generator driven pump. However, there are inconveniences associated with these systems as follows:

1 Due to the steady increase in the price of fuel for the past few years, most of these systems have become expensive leading to an increase in the price of water for drinking water supply.

2 The engine driven, generator driven and manual powered pump have more moving parts. And most of these systems require high maintenance and running cost.

3 There is low grid power coverage in the country; therefore grid powered pump cannot be used in most of the parts in the country. To overcome the inconveniences, there is a need to design and construct a solar and wind powered water pumping system.

4 Due to lack of water supply peoples living in rural areas always forced to make a long journey to bring water for drinking, food preparing, washing clothes … etc. and this causes suffering and time wastage especially for women and children’s.

5 In the country the local private sector does not participate in energy production and distribution, equipment supply, spare parts and after sales services. The energy production and distribution sector is under the control of the government.

1.3 Objective of the Research

The general objective of the research is to study the viability of solar photovoltaic, wind and hybrid (solar/wind) water pumping system for rural areas of the country.

The specific objectives of the research are:

1. To collect the solar radiation and wind speed data for the selected sites from national Metreology service agency.
2. To evaluate solar and wind energy resource for the selected sites and based on the result the appropriate technology will be selected.
3. To design the solar photovoltaic, windmill and hybrid water pumping system
4. To simulate the solar photovoltaic water pumping system using PVsyst software

5. To simulate the wind and hybrid water pumping system using MATLAB software.
6. To study the economic feasibility and reliability of solar photovoltaic, windmill and hybrid system as compare to diesel powered water pumping system

1.4 Significance of the Project

This research has an advantage to develop sustainable water supply system at lower financial, economic, environmental and social costs than with fossil fuel powered pumping systems to remotely located areas in Ethiopia. Water is very crucial for population growth, national development and improved quality of life so, this can be achieved in rural areas by supplying adequate water through solar or wind powered pumping system. Solar/wind water pumping infrastructure functioning at selected locations shall benefit a lot of people.

In addition to this, the research has economical and environmental advantages; because renewable energy sources are freely available and environmentally friendly. Renewable energy sources have negligible greenhouse gas and carbon dioxide emission; this means it has less contribution to air pollution.

In general the research outcomes will have the following benefits:

- This project helps to promote the use of solar and wind (Renewable Energy) for water pumping in rural areas of Ethiopia.
- To increase demand for solar/wind technologies from end-users and stakeholders.
- Solar/wind pumping technology systematically considered as options in design of water pumping systems and implemented when feasible.
- Local market can be initiated to provide supply of equipment and after sales services including spare parts.
- Awareness shall be created to use renewable energy not only for water pumping but also for other purposes in developing country.

1.5 Limitation of the Study

This study is limited to investigating the feasibility of solar photovoltaic, wind and hybrid water pumping system for rural areas application in Ethiopia. There was the following limitation during this research work:

1. There are no metrological stations in remote areas of the country. Therefore, the solar radiation and wind speed data's are collected from the nearby stations.
2. To minimize the overall operational and maintenance cost of the system, the stand alone photovoltaic water pumping system is designed without considering MPPT methods and batteries for energy storage.
3. Due to financial problem we are not able to collect field solar radiation and wind speed data for long period of time in the selected site.
4. The capital cost of the system is high, therefore we are not able to implement and take an experimental data of the system.

1.6 Originality

There is very little activity in the field of Hybrid water pumping system for rural areas in the country. To our knowledge, the feasibility study of hybrid water pumping system using solar and wind energy only has not be done so far. Hence, the work presented in this research is a new innovation in the field of hybrid water pumping system in Ethiopia.

CHAPTER TWO

RESEARCH METHODOLOGY

This chapter gives an overview of the methodologies adopted to achieve the general and specific objectives of the research outlined in the previous chapter. The methodology includes data collection, determination of solar and wind energy potential, designing and simulation of the proposed system and financial analysis using LCC methods.

The data was collected from National Metrology Services Agency (NMSA) and NASA satellite web-site. PVsyst Software is used for design and simulation of solar photovoltaic water pumping system. In this project, MATLAB program also develop for design and simulation of wind and hybrid water pumping system. LCC method implemented for financial analysis of solar, wind and hybrid water pumping system.

2.1 Data Collection and Estimating of Energy Potential

The data was collected from National Metreology Services Agency (NMSA) and NASA web-site. The Monthly average global solar radiation and monthly average wind speed was determined from NASA satellite web-site based on the latitude, longitude and elevation of the location. There are no metrological stations in most remote areas of the country. Therefore, the sunshine hour and wind speed data's of the selected sites are collected from the nearby stations. And the well – known Angstrom equation used to determine the daily global solar radiation on horizontal surface from the collected sunshine hours. The Weibull distribution in wind regime analysis depends on the accuracy in estimating k and C. For the precise calculation of k and C, adequate wind data, collected over shorter time intervals are essential. But the available wind speed data was in the form of daily average wind speed. Therefore, in this paper, the Rayleigh distribution, the simplified case of the Weibull model can be used by approximating K as 2.

2.2 Design and Simulation

2.2.1 Design and Simulation of Solar Photovoltaic Water Pumping System

The design and simulation of SPV water pumping system conducted using PVsyst software. During the design and simulation process of SPV system, it is assumed that the solar panels are not shaded with free horizon and the simulations are performed based on the maximum possible annual water demand. The pump and solar panels selected from the PVsyst software database to meet the maximum possible annual demands. However, based on available solar irradiation data for the sites, it is assumed that missing water will be up to 5%.

2.2.2 Design and Simulation of Windmill Water Pumping System

The design of wind water pumping system includes the following steps. Water demand, total dynamic head, hydraulic power, wind power resource, design month and sizing of wind pump.

In this research, MATLAB program was written for the simulation of windmill water pumping system, based on different equations given in [Mathew, 2006], to determine the performance of wind driven piston pump. The instantaneous and integrated discharge of the system with respect to monthly average wind speed can be determined as given in [Mathew, 2006] using Eq. 5.21 & 5.22 respectively.

2.2.3 Design and Simulation of Hybrid Water Pumping System

The design of hybrid water pumping system (sizing of solar and wind pump) carried out using analytical method like the design of wind water pumping system. In this research, the hybrid system consist one submersible pump and one piston pump which is directly mounted on the well. Both pumps are placed together under the water. MATLAB program is used for simulation of hybrid system. The MATLAB program developed to determine the monthly average discharge of the solar pump, wind pump and also the cumulative discharge of the two pumps.

2.3 Financial Analysis

There are several methods for determining the financial analysis of the system. In this research, LCC method used to make the financial analysis. Annualized capital cost, maintenance and operation cost, replacement cost and cost of m^3 of water pumped analyzed in this paper. In addition, comparison of cost of pumping water between diesel, wind, solar and hybrid water pumping system also takes place using LCC method.

CHAPTER THREE

LITERATURE REVIEW

3.1 Country Background

Ethiopia is a large landlocked country consisting of nine regional states and two city administrations. The terrain is geographically diverse, ranging from mountainous highlands to tropical forests. It is the second most populous country in Sub-Saharan Africa, with a steadily growing population of 91.7million (2012). It is a mainly rural country with only 17% of the population living in urban areas. Christianity and Islam are the main religions, and there are more than 80 ethnic groups and 90 languages [5].

Table 3-1 Statistical data for Ethiopia

Total population (2012)	91,729,000
Gross national income per capita (PPP international $, 2012)	1,110
Life expectancy at birth m/f (years, 2012)	62/65
Probability of dying under five (per 1000 live births, 2012)	68
Probability of dying between 15 and 60 years m/f (per 1000 population, 2012)	250/212
Total expenditure on health per capita (Intl $, 2012)	44
Total expenditure on health as % of GDP (2012)	3.8

Source: Statistical data for Ethiopia, 2012

Ethiopia is well known as being unique among other African countries for its historical background. Ethiopia is the only African country beside Liberia that retained its sovereignty as a recognized independent country, and was one of only four African members of the League of Nations. Ethiopia is bordered by Somalia and Djibouti to the East, Sudan and South Sudan to the West, Eritrea to the North and Kenya to the South.

Figure 3-1 Map of Ethiopia and boarder countries

The climate in Ethiopia varies according to the different topographical regions with three climate zones classified according to elevation, namely: Dega (Cool zone), Woina Dega (Subtropical zone) and Kolla (Tropical zone).

Ethiopia’s economy is highly exposed to climate variability and extremes. Agriculture forms the basis of the economy supporting roughly 42% GDP and 85% employment [6]. The agricultural sector suffers from poor cultivation practices and frequent drought which is attributed to many factors. The agriculture is primarily rain-fed, means that production is sensitive to fluctuations in the climate.

Ethiopia ranked 173 in the 2014 Human Development Index [7], is one of the least developed countries in the world with a gross national income (GNI) per capita of 470 USD[8], with approximately 40% of its population below the poverty line. This development status makes the country more vulnerable to climate variability and change.

Economic Development and energy demand interact and co-evolve together over time. But, there is a large disparity between modern energy demands across the country between relatively poor and rich households.

The energy use per capita was about 16 GigaJoule (GJ) and the primary energy consumption was 1.3 ExaJoule (EJ) [9]. The majority of the energy needs of Ethiopia arise from natural resources. Households account for 88% of total energy consumption, industry 4%, transport 3% and services and others 5% [10] . The rural people exclusively use traditional sources for household cooking, while urban centers utilize a good portion of modern energy sources such as electricity.

3.2 Renewable Energy in Ethiopia

Climate variations always have had impacts on life and livelihoods in Ethiopia. Droughts, and, to a lesser extent, floods have been frequent and have exposed millions to hunger and displacement. The energy system of Ethiopia is vulnerable to climate variations because the major sources of energy supply, bio energy and hydropower, both depend directly on the climate. Diversity of supply is the key to addressing these problems, by substituting with indigenous and alternative Renewable energy sources.

The indigenous Renewable energy sources of Ethiopia consist of hydro, wind, geothermal and solar with some fossil resources in natural gas and coal. Currently, the country relies heavily on a limited set of renewable, energy mainly from hydropower for electricity generation. Ethiopia has yet to develop its other Renewable sources in significant scale.

Even though the main energy supply is from biomass (one form of Renewable energy), the level of its use is disparate with limited use of other resources. In general, the biomass use in Ethiopia has not been sustainable: according to recent study, in more than two-thirds of districts biomass uses surpass sustainable yields [11].

3.3 Solar Energy Potential of Ethiopia

Solar energy is the most abundant permanent energy source on earth and it is available for use in its direct or indirect form. The sun emits energy at a rate of 3.8×10^{23} kW. Of this total, only a tiny fraction, approximately 1.8×10^{14} kW is reaching the earth, which is located 150 million km from the sun. About 60% of this amount reaches the surface of the earth with the remaining portion reflected back into space and absorbed by the atmosphere.

In this research, the need to study the proposed solar photovoltaic and hybrid water pumping system requires a clear insight regarding the availability of solar energy, i.e., instantaneous fluxes of global, diffuse and more specifically direct (beam) radiation. Nevertheless, for the purpose of engineering design and simulation of solar and hybrid water pumping system, knowing the average monthly solar radiation of specific locations is sufficient to meet the scope of the study.

For Ethiopia as a whole, the yearly average daily radiation is 5.26 kWh / m^2. This varies significantly during the year, ranging from a minimum of 4.55 kWh / m^2 in July to a maximum of 5.55 kWh/m^2 in February and March. On a regional basis, the yearly average radiation ranges from values as low as 4.25 kWh/m^2 in the areas of Itang in the Gambella regional state (western Ethiopia), to as high as 6.25 kWh/m^2 around Adigrat in the Tigray regional state (northern Ethiopia) [21].

Recently, the HYDROCHINA CORPORATION has studied the Solar energy potential of Ethiopia, and the map shown in figure 3-2 indicate Distribution of average solar radiation in Ethiopia for 30 - year Period (MJ/m^2), from (1980-2009).

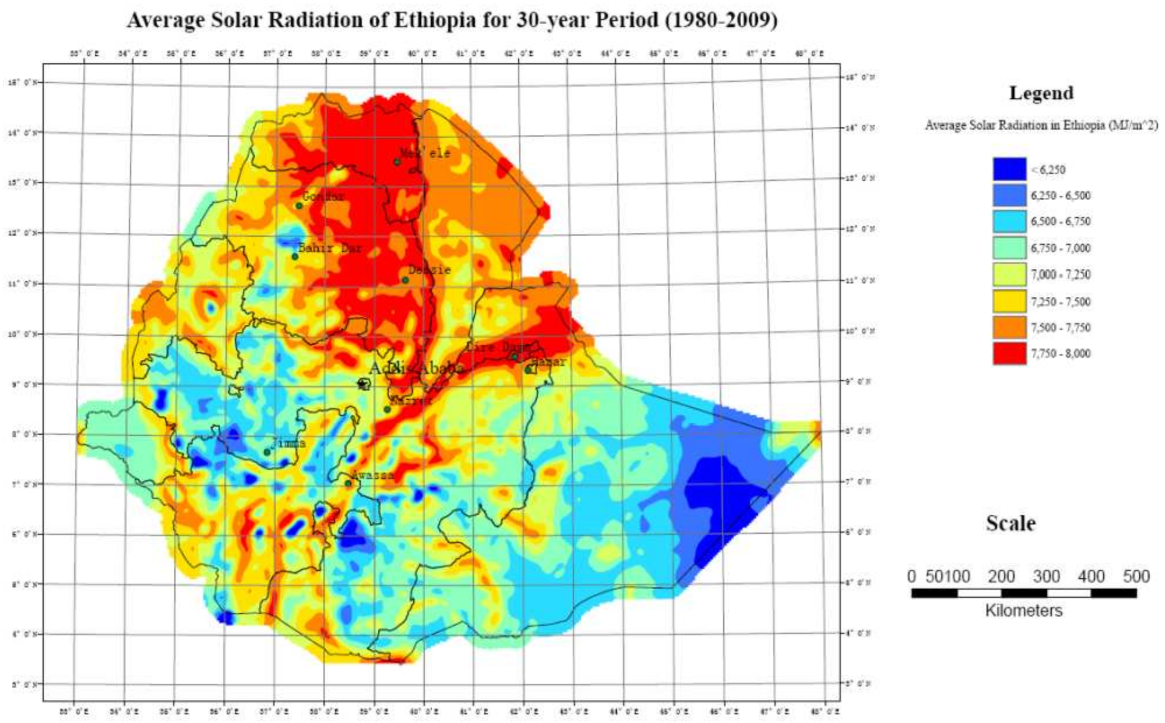


Figure 3-2 Distribution of average solar radiation in Ethiopia for 30 - year period (MJ/m^2), from (1980-2009)

3.3.1 Solar Energy (Basic Related Theory)

The appropriate design of many solar energy devices requires a detailed knowledge of global and diffuse radiation availability. Although there are several world maps of solar radiation, they are not detailed enough to be used for the determination of available solar energy on small areas. These circumstances have prompted the development of analytical procedures to provide radiation estimates for areas where measurements are not carried out and for stations when gaps in the measurement records occurred.

Several empirical models have been adopted to calculate global solar radiation using climatic parameters. These parameters include: extraterrestrial radiation, sunshine hours, mean temperature, maximum temperature, soil temperature, relative humidity, number of rainy days, altitude, latitude, total precipitation, cloudiness and evaporation. The most commonly used parameter for estimating global solar radiation is sunshine duration, which is easily measured and widely available data.

It is well known that most developing countries do not have properly recorded radiation data. What usually available is sunshine duration data. Solar radiation data is the best source of information for estimating the solar energy potential of a certain location, which is necessary for the proper design of a solar energy conversion system.

3.3.1.1 Global Irradiation on Horizontal Surface

The simplest model used to estimate monthly average daily global solar radiation on horizontal surface is the modified form of the Angström type equation given in Equation 3.1 (Duffie and Beckman, 1991).

$$\overline{H} = \overline{H_0}\left(a + b\left(\frac{\overline{n}}{N}\right)\right) \tag{3.1}$$

Where:

$\overline{H}$ = the monthly average daily global radiation on a horizontal surface,

$\overline{H_0}$ = the monthly average daily extraterrestrial radiation on a horizontal surface,

$\overline{n}$ = the monthly average daily hours of bright sunshine,

N = the monthly average day length and, a and b are empirical regression coefficients.

The monthly average daily extraterrestrial radiation on a horizontal surface $\overline{H_0}$ can be computed from the following equation.

$$\overline{H_0} = \frac{24 * I_{sc}}{\pi}\left[1 + 0.033\cos\left(\frac{360 n_d}{365}\right)\right] \times \left[\cos\varphi\cos\delta\sin\omega_s + \left(\frac{\pi.\omega_s}{180}\right)\sin\varphi\sin\delta\right] \tag{3.2}$$

Where: $I_{sc} = 1367\ W/m^2$, the solar constant,

n_d = the number of days of the year starting from first January,

φ = the latitude of location,

δ = the sun declination angle,

ω_s = the mean sunrise hour angle

The declination angle δ and the mean sunrise hour angle can be computed using the following equations (Duffie and Beckman, 1991).

$$\delta = 23.45 \sin\left[360\left(n_d + 284\right)/365\right] \tag{3.3}$$

$$\omega_s = \cos^{-1}\left(-\tan\varphi \tan\delta\right) \tag{3.4}$$

For a given month, the maximum possible sunshine duration (monthly average day length N) can be computed using the following Equation:

$$N = \frac{2}{15}\omega_s \tag{3.5}$$

Different correlations were developed by different researchers to estimate the regression coefficients a and b of Angström type equation for predicting monthly mean daily global solar radiation on horizontal surface.

A more general correlation is suggested Gopinathan [13] to express the regression coefficients in terms of latitude, elevation, and percent of possible sunshine duration to be applied to any location around the world. Gopinathan has given the following equation:

$$a = -0.309 + 0.539\cos\varphi - 0.0693Z + 0.290\frac{\bar{n}}{N} \tag{3.6}$$

$$b = 1.527 - 1.027\cos\varphi + 0.926Z - 0359\frac{\bar{n}}{N} \tag{3.7}$$

The accuracy of the estimated Global radiation data can be tested by calculating the mean percentage error which is defined as [13]:

$$MPE = \left[\sum \frac{H_{i,measured} - H_{i,calc.}}{H_{i,measured}} \times 100 / n\right] \tag{3.8}$$

Where: $H_{i,calc}$. is the i^{th} calculated value and $H_{i,mean}$ is the i^{th} measured value and n is the number of observations. The sign of the errors is neglected and the percentage error is added up to calculate the mean.

3.3.1.2 Global Irradiation on an Inclined Surface

A non-partitioned model (model requiring only global solar radiation) to estimate the global solar radiation on inclined surfaces is proposed by few of authors. Olmo et al. (1999) developed a model to estimate the global irradiance (I_β) on inclined surface from the corresponding Global radiation I collected on horizontal surface and based on clearness index using the following relation [14]:

$$I_\beta = I\psi_o F_c \tag{3.9}$$

Where ψo is a function that converts the horizontal global radiation to that incident on a tilted surface and is given as [15]:

$$\psi_o = \exp\left[-k_t\left(\theta^2 - \theta_z{}^2\right)\right] \tag{3.10}$$

Where: θ and θz (in radians) are the incidence and solar zenith angles, respectively, and kt is the hourly clearness index.

The multiplying factor Fc which is proposed by Olmo et al. (1999), to take in to account anisotropic reflections from ground is given as[14]:

$$F_c = 1 + \rho \sin^2\left(\frac{\theta}{2}\right) \tag{3.11}$$

3.4 Wind Energy Potential of Ethiopia

Ethiopia also has exploitable reserve of 10,000 MW of wind energy, with an average speed of 3.5 – 5.5 m/s, 6 hours/day [4]. Small towns, villages, farms and other scattered loads in remote areas provide ideal situations in which electricity generation from wind is convenient compared to conventional diesel generation or grid connection. The available information identifies two basic zones with homogeneous periodicity separated by the rift valley. In the first of these, covering most of the highland plateaus, there are two well-defined wind speed maximals occurring, respectively, between March and May and between September and November, according to location. In the second zone, covering most of the Ogaden and the eastern lowlands, average wind velocity reaches maximum values between May and August [4]. Figure 3-3 shows the average wind speed of Ethiopia at 50 and 10m height, (2000-2009).

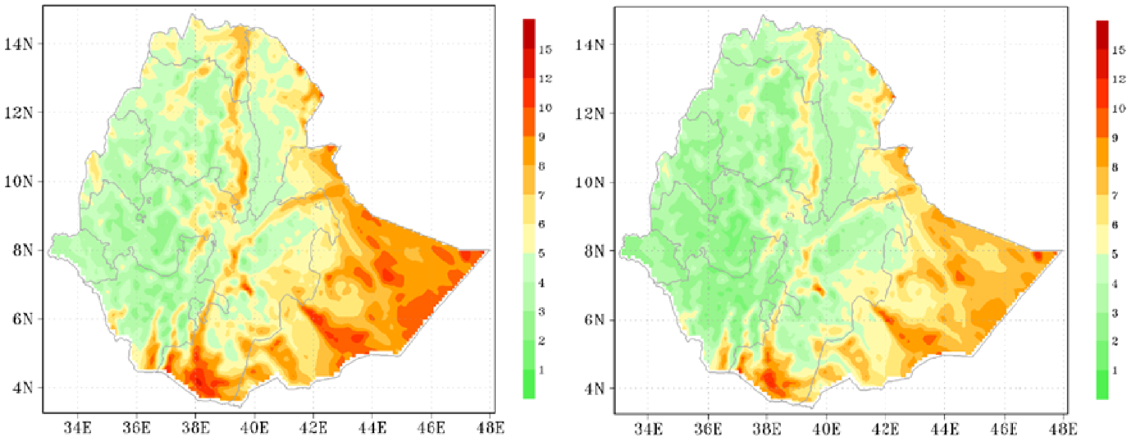


Figure 3-3 Distribution of average wind speed in Ethiopia at height 50 and 10 m respectively (2000-2009)

3.4.1 Wind Energy (Basics Related Theory)

The calculation procedures for determining the power available in the wind can be found in many standard text books on wind power. The following basic relationships can be found, for example, in (Gasch R. and Twele J. 2002, Manwell J.F. 2002, Gipe P. 1999). The energy the wind transfers to the rotor of a wind turbine is proportional to the density of the air, the rotor area, and the cube of the wind speed.

$$P_w = \frac{1}{2}\rho A V^3 \tag{3.12}$$

Where: P_w: Power in the wind (W), ρ: Density of the air (at normal atmospheric pressure and at 15° Celsius air weights some 1.225 kilograms per cubic meter), A: Rotor area (m^2) V: the wind speed (m/s)

It is to be noted that the mean wind speed should not be simply inserted into Eq. 3.12, as this will give an erroneous result because of the fact that the mean of the cubes of wind velocities will almost always be greater than the cube of the mean wind speed. The most accurate estimate for wind power density is that given by Eq. 3.13.

$$\frac{P}{A} = \frac{1}{2} \times \frac{1}{n} \sum_{j=1}^{n} \left(\rho_j \cdot v_j^3\right) \tag{3.13}$$

Where n is the number of wind speed readings and ρj and vj are the jth readings of the air density and wind speed. For a known pressure and temperature:

$$\rho = \frac{P_r}{RT} \tag{3.14}$$

Where: Pr is air pressure (Pa) and R is the specific gas constant (287 J/kg K) and T is air temperature in ^oK. For the available temperature data:

$$\rho = \frac{P_o}{RT}\exp\left(-\frac{gZ}{RT}\right) \tag{3.15}$$

Where: Po is standard sea level atmospheric pressure (101,325 Pa), g is the gravitational constant (9.8 m/s^2); and Z is the region's elevation (m) [Oklahoma Wind power, 2008].

If pressure and temperature data is not available, the following correlation may be used for estimating the density [Oklahoma Wind power, 2008]:

$$\rho = 1.225 - (1.194 \times 10^{-4}) \times Z \tag{3.16}$$

3.4.2 Energy Output

A Weibull distribution graph is usually used to describe wind variation over a certain period of time at a particular site. The mean wind speed can be obtained by summing up the products of each wind speed interval and the probability of getting that wind speed.

The Weibull probability density function (PDF) is given by equation Eq.3-17 [Manwell, 2002].

$$\mathbf{f}(U) = \frac{K}{C}\left(\frac{V}{C}\right)^{K-1} \times \exp\left[-\left(\frac{V}{C}\right)^{K}\right] \tag{3.17}$$

Where: V = the wind speed, K = a constant known as shape factor, as the value of K increases the curve will have a sharper peak, C = a scale parameter in m/s; the larger the scale parameter, the more spread out the distribution. The area under the curve is always unity. The power density can in this case be expressed by Eq.3.18.

$$\frac{\mathbf{P}}{\mathbf{A}} = \frac{1}{2}\sum_{j=1}^{n} \rho \times V_j^3 \times f_j \tag{3.18}$$

Where Vj is the median velocity in class j and fj is the frequency of occurrence in the same class. For k = 2 the Weibull PDF is commonly known as the Rayleigh density function in which case Eq. 3-17 may be rewritten as in Eq.3-19

$$\mathbf{f}(\mathrm{U}) = \frac{2\mathrm{V}}{\mathrm{C}^2} \times \exp[-(\mathrm{V})^2] \tag{3.19}$$

3.5 History of Wind, Solar and Hybrid Energy Use in Ethiopia

Nationwide renewable energy resource assessment has been conducted three times in Ethiopia. The first was the wind and solar resource assessment finished by CESEN-ANSALDO in 1980s, and the second was the wind and solar energy resource assessment finished by SWERA in 2007. And the last was the solar and wind energy resource assessment by the Chinese HYDROCHINA Corporation finished in 2012 [4].

The government of Ethiopia with the collaboration of Chinese government prepared solar and wind master plan for the whole country, which can be very useful to identify the gross amount and distribution condition of wind and solar energy resources, construction conditions, cost and other limiting factors of wind and solar power generation projects.

As we have seen in the previous section Ethiopia has good potential in solar and wind energy. But unfortunately these resources did not exploit well for the past many years. However, the government of Ethiopia planned to use the renewable energy potential of the country to achieve the millennium development goal. Therefore, now a day, there are different projects running on renewable energy in the country.

Currently, Ethiopia plans 800 MW of wind power. As the dry season is also the windy season, wind power is a good complement to hydropower. The first wind installation in the country was the 51 MW Adama I wind farm, built in 2011. The 120 MW Ashegoda Wind Farm opened in October 2013 and was the largest wind farm in Africa at that time. The larger 153 MW Adama II wind farm went online in May 2015, bringing Ethiopia's installed wind capacity to 324MW total [20]. Figure 3-4 and 3-5 shows Adama and Ashegoda wind project site.

Figure 3-4 Ashegoda wind project site

Figure 3-5 Adama wind project site

Solar photovoltaic are being promoted to replace fuel-based lighting and off-grid electrical needs. Ethiopia is thought to have about 5 MW of off-grid solar. Almost all current uses of solar energy are for off-grid rural applications in homes, rural telecoms and in the social sectors (water pumping, health services, schools). Solar energy is also becoming an important alternative to water heating in the major cities. The current total installed photovoltaic power in Ethiopia is about 3.5MW, three-quarters installed in telecom stations (mostly in mobile towers but also in other stations). Solar water-heating installations are in thousands or so units in Addis Ababa and the major cities [21].

A current government initiative plans to bring solar power to 150,000 households by 2015. The first phase included 1 MW of panels. The first large installation of solar was a village grid of 10 kW in 1985, expanded to 30 kW in 1989. A solar panel assembly plant opened in Addis Ababa in early 2013 capable of making 20 MW of panel per year [20].

Hybrid renewable energy source is becoming popular because it is composed of two or more energy sources. This combination of two energy sources is an efficient way of generating energy. Hybrid energy systems are used in remote areas for power generation. The use of hybrid power generations came forward due to the high prices of oil. The use of hybrid energy systems can optimize the power supply especially in rural areas. However it is still considered expensive and difficult to combine two or three energy sources together, but it is a onetime expense. This onetime expense can be of many uses to people living in remote areas.

In Ethiopia there is not any progress towards the application of hybrid water pumping system, but there are some models developed in different institutes for demonstration purpose.

CHAPTER FOUR

SOLAR PHOTOVOLTAIC WATER PUMPING SYSTEM

4.1 Introduction

The focus of this section is to design and simulate solar photovoltaic water pumping system. In some areas of the country the traditional water pumping systems powered by diesel or gasoline engines have been used for long time, but fuel cost, transportation problem, lack of skilled personnel makes the conventional water pumping system unreliable and expensive for rural communities.

Many researchers have studied the application of solar photovoltaic water pumping systems; Asefa K. et al. [22] have studied the application of solar pump in rural areas of Ethiopia. N. Argaw et al. [23] have discussed the application of renewable energy in rural village. Kala M. et al. [24] have studied solar photovoltaic water pumping for remote location. Regarding the feasibility study A. Raturi [25] has studied the feasibility of a solar water pumping system by selecting one rural village of Fiji Island. C. Gopal et al. [26] have done a literature review of renewable energy source water pumping systems. In addition, many researchers have conducted different researches based on the design and modeling of the PVWPSs. Pietro E. et al. [27] have developed dynamic modeling tools of a PV water pumping system by combining the models of the solar PV power, the water demand and the pumping system, which can be used to verify the design procedure in terms of matching between water demand and water supply. A.A. Ghoneim [28] has developed a computer simulation program to determine the performance of the proposed photovoltaic-powered water pumping systems. C.K. Panigrahi et al. [29] have done a design and modeling of the photovoltaic water pumping system. K. G. Mansaray [30] has discussed the application of computer simulation for optimum design of the solar photovoltaic pumping system. The economic performance and comparison also carried out by Robert F. and Alma C. [31] focused on solar water pumping advances and comparative economics. According to, Robert F. and Alma C. Research PV water pumping is the most cost effective for steady pumping needs such as community water supply or livestock watering. Robert F. et al. [32] have done a life cycle cost analysis for photovoltaic water pumping system in Mexico. [33] He has discussed a cost and reliability comparison between solar and diesel powered pumps.

The main research and development (R&D) barriers for the implementation of solar photovoltaic water pumping systems in developing countries is not only the technology. There are limitations, including water resource availability, solar energy potential, water demand, acceptance and management of the system. The possibilities for development of this solution in a given site are related to the specific resources of the site and every study should start with a site resource assessment.

Now a days, the PV module costs are reduced all over the world. However, the capital cost of a solar photovoltaic water pumping system is still higher than the conventional diesel engines water pumping system. The capital cost of solar PV water pumping system can be considered as the major barrier for the application of the system in a developing country like Ethiopia. Therefore, optimization efforts are mainly focused on minimizing the capital cost of the system.

4.2 Water Pumping System and Photovoltaic Power

A water pumping system needs a source of power to operate. In general, AC system is economic and takes minimum maintenance when AC power is available from the nearby power grid. However, in many rural areas of the country, water sources are spread over many miles of land and power lines are scarce. Installation of a new transmission line and a transformer to the location is often prohibitively expensive. Today, many stand-alone type water pumping systems use internal combustion engines. These systems are portable and easy to install. However, they have some major disadvantages, such as: they require frequent site visits for refueling and maintenance, and furthermore diesel fuel is often expensive and not readily available in rural areas of many developing countries.

The consumption of fossil fuels also has an environmental impact, in particular the release of carbon dioxide (CO_2) into the atmosphere. CO_2 emissions can be greatly reduced through the application of renewable energy technologies; which are already cost competitive with fossil fuels in many situations. The use of renewable energy for water pumping systems is, therefore, a very attractive proposition. PV systems are highly reliable and are often chosen because they offer the lowest life-cycle cost, especially for applications requiring less than 10KW, where grid electricity is not available and where internal-combustion engines are expensive to operate [34].

4.3 The Proposed System

The solar photovoltaic water pumping system proposed in this research is a stand-alone type without backup batteries. As shown in Figure 4.1, the system is very simple and consists of a single PV module, storage tank and a DC water pump.

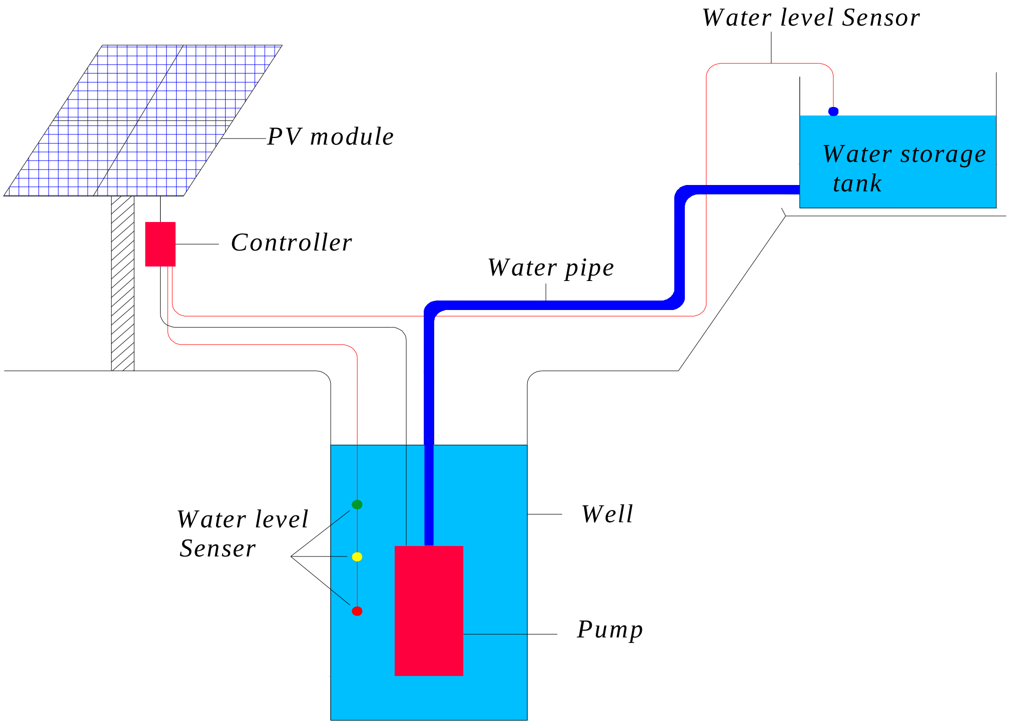
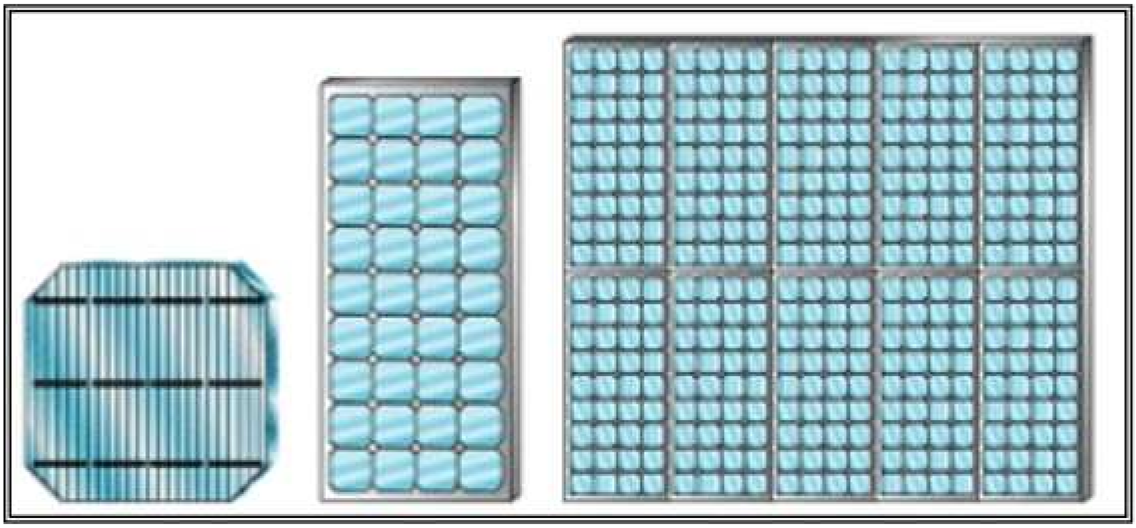


Figure 4-1 Schematic diagram of solar water pumping system

The target population selected from three different regions of the country that is from Amhara region Siadberand Wayu site, from Oromia region Wolmera site and from Tigray region Enderta site consisting 700, 467 and 433 rural communities with daily average water Demand of 10.5, 7 and 6.5 m^3/day, respectively. And approximate average daily water consumption of 20 liters per day per person was taken.

4.3.1 Photovoltaic Modules

The solar energy conversion into electricity takes place in a semiconductor device that is called a solar cell. A solar cell is a unit that delivers only a certain amount of electrical power. In order to use solar electricity for practical devices, which require a particular voltage or current for their operation, a number of solar cells have to be connected together to form a solar panel, also called a PV module. For large-scale generation of solar electricity the solar panels are connected together into a solar array. [Source: guide to solar powered water pumping systems in New York State].



PV Solar Cell PV Solar Panel Array of PV Solar Panels

Figure 4-2 Solar cell, PV solar panel and PV panel array

PV panels are made up of a series of solar cells, as shown in Figure 4-2 above. Each solar cell has two or more specially prepared layers of semiconductor material that produce DC electricity when exposed to sunlight. A single, typical solar cell can generate approximately 3 watts of energy in full sunlight. The semiconductor layers can be either crystalline or thin film. Crystalline solar cells are generally constructed out of silicon and have an efficiency of approximately 15%. Solar cells that are constructed out of thin films, which can consist of a variety of different metals, have efficiencies of approximately 8% to 11%. They are not as durable as silicon solar cells, but they are lighter and considerably less expensive. PV panels may be arranged in arrays and connected by electrical wiring to deliver power to a pump.

4.3.2 Solar (DC) Water Pumps

The other major component of SPV water pumping systems is the pump. Solar water pumps are specially designed to use solar power efficiently. Conventional pumps require steady AC current that utility lines or generators supply. Solar pumps use DC current from batteries and/or PV panels. In addition, they are designed to work effectively during low-light conditions, at reduced voltage, without stalling or overheating. Although wide ranges of sizes are available, most pumps used in livestock-watering applications are low volume, yielding 7-15 liters of water per minute. Low volume pumping keeps the cost of the system down by using a minimum number of solar panels and using the entire daylight period to pump water or charge batteries.

Two types of pumps are commonly used for PV water pumping applications: positive displacement and centrifugal. Positive displacement types are used in low-volume pumps and cost-effective. Centrifugal pumps have relatively high efficiency and are capable of pumping a high volume of water. A typical size of system with this type pump is at least 500W or larger. There is a growing trend among the pump manufacturers to use them with brushless DC motors (BDCM) for higher efficiency and low maintenance [35].

4.3.3 Storage Tank

A water storage tank is normally an essential element in an economically viable solar powered water pump system. A tank can be used to store enough water during peak energy production to meet water needs in the event of cloudy weather or maintenance issues with the power system. Ideally, the tank should be sized to store at least a three-day water supply. Multiple tanks may be required if a very large volume of water is to be stored.

The area where the tank is to be placed must be stripped of all organic material, debris, roots, and sharp objects, such as rocks. The ground should then be leveled. Six inches of well compacted ¾ -inch leveling rock underlain by a geotextile fabric should be provided as a base for the water tank. If an elevated platform or stand is required to provide adequate gravity induced pressure for the water delivery system to operate, the platform or stand will need to be evaluated by a qualified engineer.

An above-ground tank should be constructed out of structurally sound, UV-resistant material to maximize its lifespan. If it will be used in areas where freezing temperatures are encountered, care should be taken to frost proof the entire water delivery system. Tanks and pipes should be drained prior to the first freeze, and pipes should be buried below the frost line for added protection.

4.3.4 Pump Controller

The primary function of a pump controller in a battery coupled pumping system is to boost the voltage of the battery bank to match the desired input voltage of the pump. Without a pump controller, the PV panels' operating voltage is dictated by the battery bank and is reduced from levels, which are achieved by operating the pump directly off the solar panels. For example, under load, two PV panels wired in series produce between 30 to 34 volts, while two fully charged batteries wired in series produce just over 26 volts.

A pump with an optimum operating voltage of 30 volts would pump more water tied directly to the PV panels than if connected to the batteries. In the case of this particular pump, a pump controller with a 24-volt input would step the voltage up to 30 volts, which would increase the amount of water pumped by the system.

4.4 Description of the Study Areas

In this research, the feasibility of solar photovoltaic water pumping system studied selecting one potential site from three administrative regions of Ethiopia. The regions are Amhara, Oromia and Tigray regions. From the Amhara region Siadeberand Wayu was selected (latitude 9º46' N, longitude 39º40' E and altitude 3009 m a.s.l); from the Oromia region Wolmera was selected (latitude 9º13' N, longitude 38º39' E and altitude 2400 m a.s.l); and from Tigray region Enderta was selected (latitude 13º48' N, longitude 39º55' E and altitude 2247 m a.s.l). Solar radiation data for the three selected sites were collected from NASA-SSE satellite data [36]. And, then NASA satellite data imported to PVsyst software database using its meteorological tool.

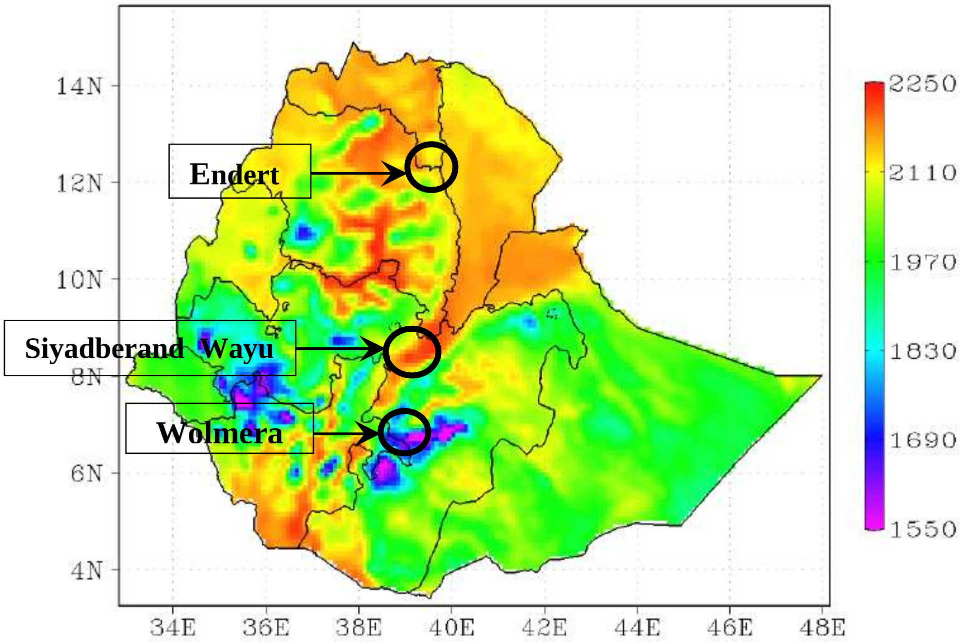


Figure 4-3 Selected sites for solar photovoltaic water pumping system

The monthly average solar irradiation values on horizontal surface for the selected three sites are shown in Figure 4-4, 4-5 and 4-6.

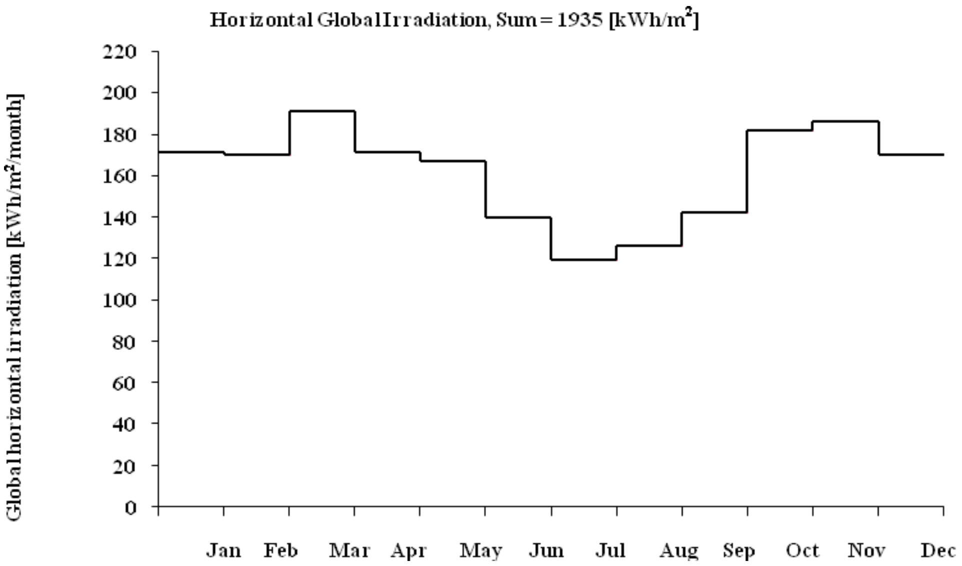


Figure 4-4 Year - long solar radiation data for Siyadbeand Wayu site

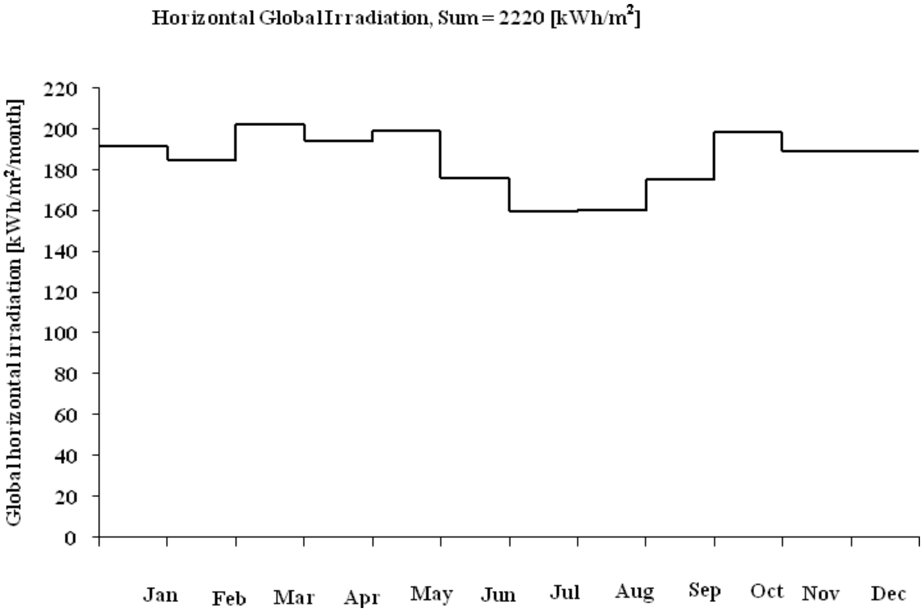


Figure 4-5 Year - long solar irradiation data for Wolmera site

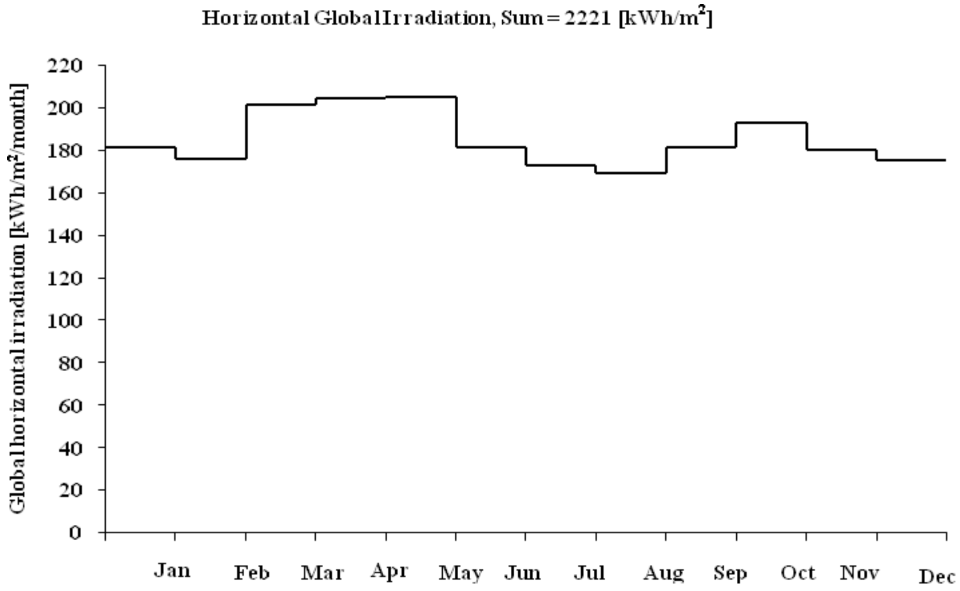


Figure 4-6 Year - long Solar irradiation data for Enderta site

4.5 Design and Simulation of Solar Powered Water Pumping System Using PVsyst Software

In this research, PVsyst software is used for design, simulation and economic analysis of solar photovoltaic water pumping system. The solar data, well characteristics, water demand, storage tank size, the cost and lifetime of PV modules are input to PVsyst software. In addition, the solar pump and controller are selected from the database of the software. The output of the software includes, amount of water delivered to the users, amount of missing water, excess (unused) PV energy and system efficiency (performance ratio) during the year. Furthermore, the economic analysis of the software helps to determine the global investment, yearly cost and cost of pumped water in cubic meters. The life cycle cost analysis is also carried out in this paper for the comparison between solar photovoltaic and conventional diesel water pumping system. The results of this comparison show that more SPV systems can be installed in the country, replacing the existing more expensive Diesel systems, which would play a significant role in achieving the country's MDG targets.

During the design and simulation process of SPV system, it is assumed that the solar panels are not shaded with free horizon and the simulations are performed based on the maximum possible annual water demand. The pump and solar panels are selected from the PVsyst software database to meet the maximum possible annual demands. However, based on available solar irradiation data for the sites, it is assumed that missing water will be up to 5%. The main design and simulation parameters are listed in the Table 4-1.

Table 4-1 Simulation input parameter for the three selected sites

Parameters	Siyadberand Wayu	Wolmera	Enderta
Water requirement per day	10.5m^3/day, two days autonomy	7 m^3/day, two days autonomy	6.5 m^3/day, two days autonomy
Total head	37 m	100 m	76 m
Water storage tank volume	21.5m^3	14 m^3	13 m^3
Well depth	58 m	47 m	43 m
Borehole diameter	15 cm	15 cm	15 cm
Pipe length	300 m	450 m	376 m
Tilt	15º	15º	15º
Azimuth	0º	0º	0º
Solar panels type	Model:GES-5M5, 5W, si-mono, Manuf. Sainty solar	Model:GES-5M5, 5W, si-mono, Manuf. Sainty solar	Model:GES-5M5, 5W, si-mono, Manuf. Sainty solar
Pump type	Model: PS20-HR-07-MPPT, 300W, 48V, Manuf. Lorentz	Model: PS20-HR-04-MPPT, 240W, 48V, Manuf. Lorentz	Model: PS20-HR-07-MPPT, 300W, 48V, Manuf. Lorentz
Power conditioning	Direct coupling	Direct coupling	Direct coupling

4.5.1 Simulation Result and Discussion

In this research, PVsyst 5.56 has been used to design and simulate the solar photovoltaic water pumping system. During simulation analysis using PVsyst software the following points should be considered. The initial point is determining the global effective irradiation and the maximum power point (MPP), once irradiation and MPP determined, the simulation is dependent on the Pumping Type and Configuration [37].

For any running hour, the simulation has to determine the Flow rate delivered by the pump, as a function of the Head and the available electrical energy. The simulation has to manage the situations where the tank is full (limiting the pump's flow at the user's draw, and stopping the pump during the rest of the hour), and when the tank is empty. For obtaining a consistent balance, all energies should be carefully accounted for, in any running situation [37].

The final relevant results include mainly the water delivered to the users, the missing water, the excess (unused) PV energy, and the system efficiency during the year (or performance ratio). And, if economical features are defined, the global investment, yearly costs and cost of the water pumped in m³ determined. After running the simulation for the selected sites based on input parameters for each site the following results are obtained.
The main simulation results for the Amhara Region, Siadberand Wayu site, the Oromia Region, Wolmera site and the Tigray Region, Enderta site are shown in Table 4-2, 4-3 and 4-4, respectively.

According to the simulation result shown in Table 4-2, the selected PV size and pump power is able to provide 95% of water need for the community of Siyadberand Wayu site. During the month of July there is a significant water supply reduction 21.29% and in May there is 0.49% water supply reduction.

Table 4-2 Simulation result for Amhara region, Siyadberand Wayu site

PV size	5W$_p$, 100 modules, 4 in series and 25 in parallel
Total area	10.1 m^2
Pump power	300 W, 48 V, well DC progressive cavity, 1 pump
Water pumped annually	3639 m^3
Missing water	5%
Energy at pump	2180 kWh
Unused energy	60 kWh
System efficiency	75.2%
Pump efficiency	20.1%
Water pumped	Average 9.97 m^3/day, and minimum 8.26 m^3/day
Maximum loss of load	21.29% in July

Table 4-3 Simulation result for Oromia region, Wolmera site.

PV size	5 W$_p$, 68 modules, 4 in series and 17 in parallel
Total area	6.9 m^2
Pump power	240 W, 48 V, well DC progressive cavity, 1 pump
Water pumped annually	2465 m^3
Missing water	3.55%
Energy at pump	1553 kWh
Unused energy	0.0 kWh
System efficiency	70% (global system efficiency or performance ratio)
Pump efficiency	24%
Water pumped	Average 6.753 m^3/day, and minimum 6.106 m^3/day in July
Maximum loss of load within the year	12.8% in July

Table 4- 4 Simulation result for Tigray region, Enderta site.

PV size	5W_p, 88 modules, 4 in series and 22 in parallel
Total area	5.8 m^2
Pump power	240 W, 48 V, well DC progressive cavity, 1 pump
Water pumped annually	2284 m^3
Missing water	3.7%
Energy at pump	2002 kWh
Unused energy	0.0 kWh
System efficiency	70.1%
Pump efficiency	36.5%
Water pumped	Average 6.258 m^3/day, and minimum 5.939 m^3/day
Maximum loss of load within the year	8.7% in July

The selected PV size and pump power for the Oromia Region, Wolmera sites capable of providing 96.5% of water need of the community, as shown in table 4-3. From May to October, there is a reduction of water supply and during the month of July there is a significant water supply loss of 12.8%.

The simulation result shown in Table 4-4 reveals that the proposed PV size and pump power is able to provide 96.3% of water need for the community of Enderta site. During the month of July there is significant water supply loss of 8.7%.

Figure 4-7, 4-8 and 4-9 show the energy balance of the proposed solar Photovoltaic water pumping system for the Amhara Region, Siyadberand Wayu site, the Oromia Region, Wolmera site and the Tigray Region, Enderta site respectively. As the result shows, the unused energy is very low for all sites. This is because, the system is designed based on the maximum possible water production volume within the year.

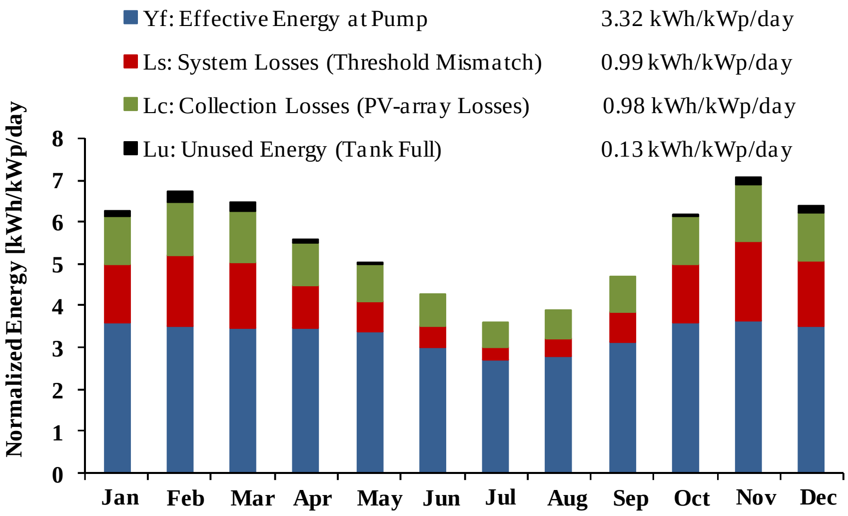


Figure 4-7 Energy balance of the SPV system for Siyadberand Wayu site

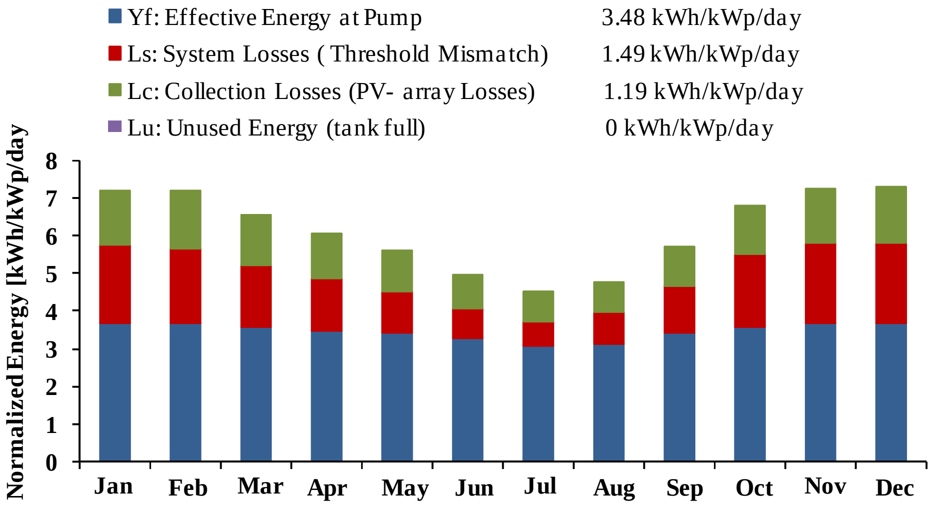


Figure 4-8 Energy balance of the SPV system for Wolmera site

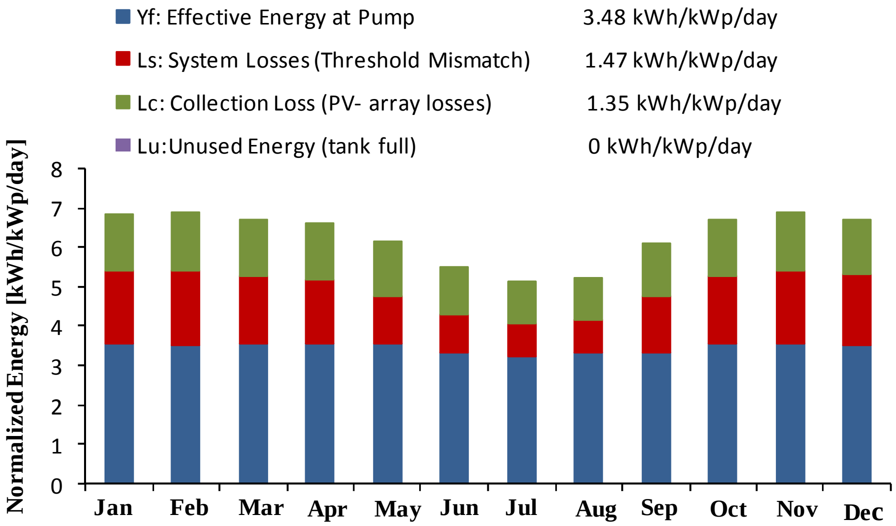


Figure 4-9 Energy balance of the SPV system for Enderta site

The above three figures show the normalized values of, effective energy at pump, collection loss, system loss and unused energy (tank full) in the system.

As we have seen from the above three figures the unused energy in the system for all sites are minimum and the system and collection losses seem a little bit higher. This is because the system is designed to pump maximum possible amount of water per day using all available energy on the system. When the production is maximized the system is subjected to high losses, but if we reduce the amount of water pumped by the system per day, we can minimize the losses but the unused energy in the system will be maximized.

Figure 4-10 shows the function of flow rate with respect to pump power. Since all graphs for all sites have similar behavior, only the graph of the Siyadberand Wayu site has been presented here.

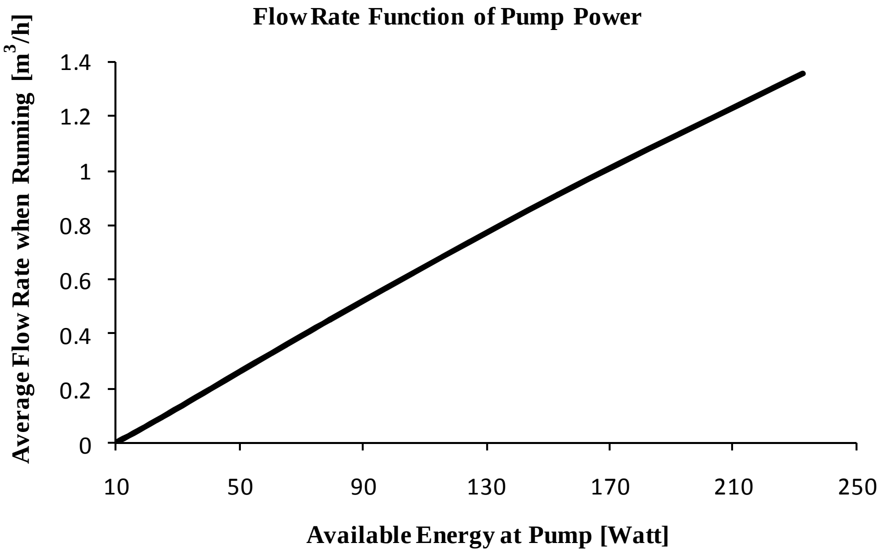


Figure 4-10 Flow rate function of pump power graph for Siyadberand Wayu site

The above graph shows the linear relationship between the flow rate and available energy at the pump. In addition, this figure indicates how the size of the pump depends on the available power. If the available power at the pump varies the size of the pump or the flow rates also vary. Therefore, pump controller play a great role for adjusting the size of the pump according to the available power at the pump. Without pump controller it is impossible to operate solar pumps.

4.6 Economic Analysis of SPV Water Pumping System

The economic analysis of solar photovoltaic water pumping system has been assessed using PVsyst software. A detailed economic analysis has only been shown for Siyadberand Wayu site and summary of the economic analysis for the three sites is given in Table 4-5.

4.6.1 Economic Analysis for Siyadberand Wayu Site Using PVsyst

During economic evaluation, the following approximate values have been considered. Investment: (all costs below taken from manufacturer web-page based on the specification of components)

- ✓ PV module cost: 100 units of 5Wp = 0.896 $/Wp (20 year life span assumed)
- ✓ Supporting / Integration: 0.5936 $/piece (one support for each module assumed)
- ✓ Pump cost, including controller: 1 unit of 300W = 1523.88 $/piece (10 year life span assumed)
- ✓ Setting and wiring. etc.: 20% of the subtotal cost is assumed (multiply the subtotal cost by 0.2 to cover the balance of the system)
- ✓ Running costs (including pump replacement after 10 years) = 5% of the subtotal cost is assumed (includes provision for pump replacement after 10 years and maintenance cost)

Net Investment for Siadberand Wayu site: Sum of the above listed investment costs plus 15% tax = 3001.9$

Assuming a loan period of 20 years and interest rate of 5% with annual factor of 8.02%, the annuity (yearly cost without including the running costs) is equal to 241 $/year, and the total yearly cost including the running costs (maintenance, taxes and replacement costs) is equal to: 372 $/year.

Based on the above data, the water cost is equal to 0.1 $/m^3, without any subsidies.
If 20% subsidy by the government is assumed to motivate internal and external investors, the cost of the water will reduce to 0.09 $/m^3.

Similar economic Analysis is carried out using PVsyst software for the other two sites and the values are given in Table 6 below.

Table 4-5 includes the economic analysis results of the PVsyst software for the three selected sites. The table includes the net investment cost, annuities, total yearly cost and water cost with and without any subsidy. Annuities without any subsidy mean annual cost without including the running costs and subsidization from the government or any other organization. The total yearly cost includes the running costs of the system but annuities does not include. Based on the input parameter, the water cost per m^3 for each sites are calculated using PVsyst software and included in Table 4-5.

Table 4-5 Summary of economic analysis using PVsyst software for the selected three sites.

Site	**Net Investment ($)**	**Water Pumped (m^3/year)**	**Annuities ($/year)**	**Total Yearly Cost ($/year)**	**Water Cost ($/$m^3$)**	**Water Cost with 20% subsidy ($/$m^3$)**
Siadberand Wayu	3001.9	3639	241	372	0.1	0.09
Wolmera	2691.1	2465	215.95	345	0.14	0.13
Enderta	2832.7	2284	227.31	355.23	0.16	0.15

4.6.2 Financial Comparison for SPV and Diesel Pumping System

In the financial comparison between solar photovoltaic and diesel water pumping, the main question is how the financial costs of both systems can be calculated. The whole costs of a pumping system have a certain life expectancy in years that is made up of the capital cost, operating cost and maintenance and replacement cost (M & R). And these costs altogether refer to the life cycle cost (LCC) [38-42]. The life-cycle cost can be calculated using the following formula:

$$LCC=CC+M_{PC}+E_{PC}+R_{PC}-S_{PC} \qquad (4.1)$$

The Capital Cost (CC) of a project includes the initial capital expense for equipment, the system design, engineering, and installation.

The Maintenance Cost (MC) is the sum of all yearly operation and maintenance (O&M) costs discounted to present. Maintenance cost through life cycle is calculated using the following equation:

$$\mathbf{MC=A*}\left[\frac{(i+1)^{N}-1}{i*(i+1)^{N}}\right] \tag{4.2}$$

Where, A is the annual worth, i interest rate, N life cycle time (year)

The Energy Cost (EC) of a system is the sum of the yearly fuel cost. Therefore differential fuel inflation rates may be used. Fuel cost through the life time of the system is calculated using this equation:

$$\mathbf{E}\mathrm{C=A*}\left[\left(\frac{1+FE}{i+FE}\right)*\left(1-\left(\frac{1+FE}{1+i}\right)^{N}\right)\right] \tag{4.3}$$

Where, FE is the fuel escalation rate

This equation belongs only to diesel engine life cycle cost of fuel. Because there is no energy cost considered in case of PV system.

The Replacement Cost (RC) is the sum of all equipment that will need to be replaced through the life of the system.

Pump for the PV water pumping system assumed to be replaced after 10 years and all components of the diesel pumping system also have to be replaced after 10 years. The total replacement cost through the life time is calculated using this equation:

$$RC=F^{*}\left[\frac{1}{(i+1)^{N}}\right] \qquad (4.4)$$

Where, F is the future worth of money

The Salvage Value (SC) of a system is its net worth in the final year of the life-cycle period. The salvage value through the life time is calculated using the following equation:

$$SC=F^{*}\left[\frac{1}{(i-1)^{N}}\right] \qquad (4.5)$$

The cost comparison using the LCC method between the SPV and DP systems for the Siadberand Wayu site was shown in Figure 4-11 below. Figure 4-12 also shows that the present cost comparison between the SPV and DP. In addition, the cost of m^3 of water for all sites is compared with diesel system and the result was shown in Table 4-9.

For the analysis of a 20 year life cycle cost comparison between SPV and DP for Siadberand Wayu site the following assumptions are considered.

- ✓ The operating life of the PV panel was assumed to be 20 years and for the diesel engine 10 years were assumed.
- ✓ The maintenance cost of a PV system assumed to be a 1% of total capital cost per year.
- ✓ Available sunshine hours 2190 hours considered in a year, The available sunshine hour’s data from national metrology agency of Ethiopia indicates an average sunshine hour in Siadberand Wayu varies from 4.65 hr in July up to 9.42 hr in November, and the annual average sunshine hour’s is 7.77 hr/day. Therefore, for this analysis 6 hr/day working time was assumed for the system to provide the required daily water demand.
- ✓ Maintenance cost of diesel engine assumed to be a 10% of total capital cost per year.

- ✓ Cost of 500 Wp diesel generator = $200 and its consumption of diesel fuel is assumed to be 0.20 l/hr.
- ✓ The diesel generator can be selected based on its maximum output (Kilowatt). During selection of the diesel generator, it is important to select the one whose output power is slightly higher than the total power needed, to be sure the generator will supply enough power for the pump. Operating hours = 6 hr/day (similar as solar pumping)
- ✓ The replacement costs are evaluated to be once during the life analysis for diesel generator.
- ✓ Salvage value of diesel engine was assumed to be a 20% of capital cost of engine and for PV module 5% assumed.
- ✓ The pump, storage tank and distribution line costs are not included in this analysis because, it is considered as the same for both case.

$$\text{Annual Fuel Cost} = \text{Specific Fuel Consumption} \times \text{Total Operating Hours in a Year} \times \text{Fuel rate}$$

$$= 0.20\,\text{liter/hr} \times (6\,\text{hr/day} \times 365\ \text{day/year}) \times 0.805\ \text{\$/liter} = 352.6\,\text{\$/year}$$

$$\text{Fuel Cost of Diesel Generator for 20 years} = 20\ \text{Year} \times 352.6\ \text{\$/year} = 7052\ \text{\$}$$

Table 4-6 SPV and DP system cost comparison using LCC for Siadberand Wayu site.

Costs ($)	**PV system ($)**	**Diesel Generator ($)**
Capital cost (CC), the pump cost is not included	1126.72	200
Maintenance cost (MC)	225.34	400
Fuel/Energy cost (EC) for 20 years	None	7052
Replacement cost (RC) for generator	None	200
Total cost	1352	7852
Salvage value (SC)	56.34	40
Life Cycle Cost (LCC)	1295.66	7812

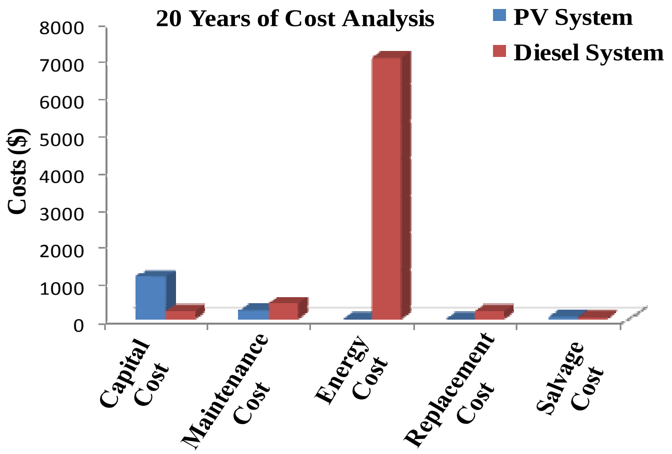


Figure 4-11 Cost comparison of PV and Diesel system for pumping water

As shown in Figure 4-11 above, the diesel powered pumping system has lower initial cost than the PV pumping system, but its other costs are higher if we compare with PV system. In the reverse, the initial cost of PV systems is high, but the maintenance, operation and replacement costs are lower. In addition, there is no energy cost needed in PV system and as a result the present cost of PV systems is much lower than the diesel powered system as shown in Figure 4-12. Its lower operation and maintenance costs, the longer expected useful life as well as the higher reliability of PV systems could make the system more suitable for remote areas.

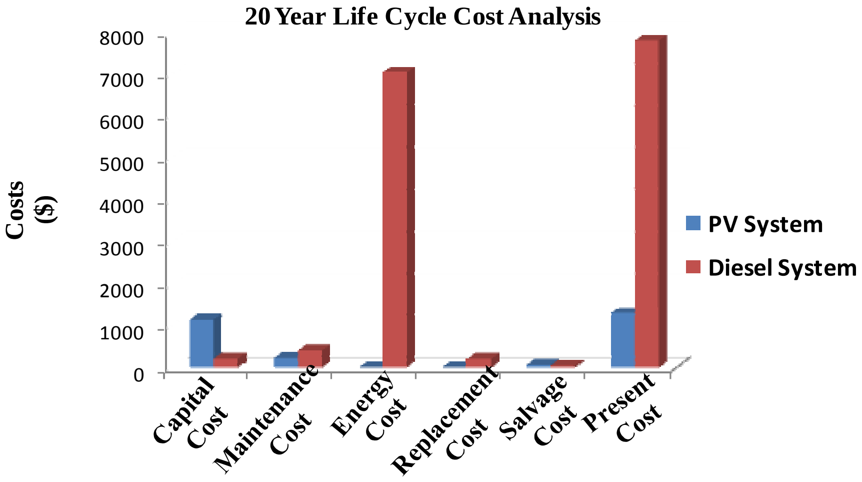


Figure 4-12 Present cost comparisons of PV and Diesel pumping system

4.6.3 Cost of Pumping Water

The cost of m^3 of the pumped water by PV water pumping system was calculated by PVsyst software. But the cost of m^3 of water for diesel water pumping system is not calculated. Therefore, the cost of m^3 of the pumped water by diesel water pumping system is calculated using the cost annuity method based on the LCC analysis [43, 44]:

$$\text{Cost of m}^3\text{ of water pumped} = \frac{\text{Annualised life cycle cost of the system}}{\text{Total pumped water}} \tag{4.6}$$

The annualized life cycle costs are calculated from the relations:

$$\mathrm{CRF}=\frac{(i(1+i)^N)}{((1+i)^N-1)} \tag{4.7}$$

$$\mathrm{PWF}=\frac{1}{(i+1)^N} \tag{4.8}$$

$$C_y=C*\mathrm{CRF} \tag{4.9}$$

$$C_K=R_K*\mathrm{PWF} \tag{4.10}$$

$$R_y=\Sigma_K\, C_k \tag{4.11}$$

$$A_y=C_y+M_y+R_y \tag{4.12}$$

Table 4-7 below consists different assumption was made during cost comparison between solar and diesel water pumping system.

Table 4-7 Economic assumptions for all sites.

Parameters	**Values**
Interest rate (%)	5
Discount rate (%)	10
Life time of PV generator(years)	20
Life time of motor-pump(years)	10
Life time of diesel generator(years)	10
PV unit cost ($/w$_p$)	0.896
Diesel fuel cost ($/l)	0.805
PV operation and maintenance (%)	1
Diesel operation and maintenance (%)	10

Table 4-8 shows the total initial gross investment cost of PV and diesel water pumping system and table 4-9 shows the cost of pumping m^3 of water using PV and Diesel water pumping systems for three sites. Based on the annual life cycle cost, the PV water pumping system is more economical than the Diesel system.

Table 4-8 Total initial gross investment cost of PV and diesel system (USD).

Pump	**Siadberand W**	**Wolmera**	**Enderta**
PV module			
Total cost of the Module	432	293.76	380.16
Cost of pump	1523.88	1523.88	1523.88
Support structure cost	57.24	38.92	50.37
Wiring and Other miscellaneous	597.24	482.98	508.25
Total initial cost for PV	2610.36	2340.12	2462.66
Diesel system			
Unit cost	200	200	200
Total initial cost for Diesel	1723.88	1723.88	1723.88

Table 4-9 Annuity and water cost calculation for the PV and diesel system (USD).

Pump	**Siadberand Wayu**	**Wolmera**	**Enderta**
PV system			
Annualized capital cost	306.72	274.96	289.4
Operation and maintenance cost	19.56	18.18	19
Replacement cost	46.76	46.76	46.76
Annualized life cycle cost for PV system	373.04	339.91	355.23
Water cost for PV system (\$/m^3)	**0.1**	**0.14**	**0.16**
Diesel system			
Annualized capital cost	202.6	202.6	202.6
Operation and maintenance cost	20	20	20
Replacement cost	105.85	105.85	105.85
Annual Fuel cost	352.6	232.3	290.37
Annualized life cycle cost for Diesel system	681.05	560.75	618.82
Water cost for Diesel system (\$/m^3)	**0.2**	**0.23**	**0.27**

CHAPTER FIVE

WIND POWERED WATER PUMPING SYSTEM

5.1 Introduction

Wind power technology dates back many centuries. There are historical claims that wind machines which harness the power of the wind date back to the time of the ancient Egyptians. By the late part of the 17th century, the typical 'European Windmill' had been developed and this became the norm until further developments were introduced during the 18th century. The major advances in the design of the wind pump, however, took place in the USA. By the 1920's, 6 million wind pumps were being used in the USA alone and their manufacture and use had become commonplace on every continent [45].
Water is the primary source of life for mankind and one of the most basic necessities for rural development. The rural demand of water for domestic and crop irrigation supplies is increasing [36]. People living in rural areas of Ethiopia use different water sources for their domestic purpose, such as spring, pond, ground…etc. but the ground water is the best one for clean drinking water supply.

Therefore, mechanized water pumping system will be the only reliable alternative for lifting water from the ground. Diesel, gasoline and kerosene pumps including windmills have traditionally been used to pump water [46]. However, reliable solar photovoltaic (PV) and wind turbine pumps are now emerging on the market and are rapidly becoming more attractive than the traditional power sources. In addition, nowadays with regular fuel crises and rising prices there has been a revival of interest in wind pump technology.

In Ethiopia, Diesel water pumping systems have been applicable for many years. Currently, however, because of rising of fuel price all over the world, including Ethiopia, almost all the systems have become none functional. Therefore, in 2006 the Government planned to replace all Diesel water pumping systems by solar/wind water pumping systems. According to the recent report prepared by HYDROCHINA Corporation the country has a capacity of 1,350 GW (>7m/s) wind energy potential. Andin most areas of the country, there is a low and medium wind energy potential (> 2.8 m/s), which can be applicable for water pumping.

In a previous section of this research the feasibility of PV water pumping system was studied [47]. In this section, the feasibility of wind powered water pumping system in Ethiopia is studied by selecting three rural areas from three regions of the country. The design and simulation of the proposed system is carried out using analytical method and MATLAB software. An economical comparison is carried out between wind and Diesel water pumping systems, using life cycle cost analysis method.

5.2 The Proposed System

In this research, windmill water pumping system with direct driven piston pump was selected. As shown in Figure 5.1, the main components of the system consists of a windmill, piston pump and storage tank.

The target population is selected from three different regions of the country that is from Amhara region Siadberand Wayu site, from Oromia region Adami Tulu site and from Tigray region East Enderta site consisting 500, 600 and 1000 rural communities with daily average water Demand of 10, 12 and 20 m^3/day respectively. And approximate average daily water consumption of 20 liters per day per person was taken. Figure 5.1 show the schematic diagram of the windmill water pumping system.

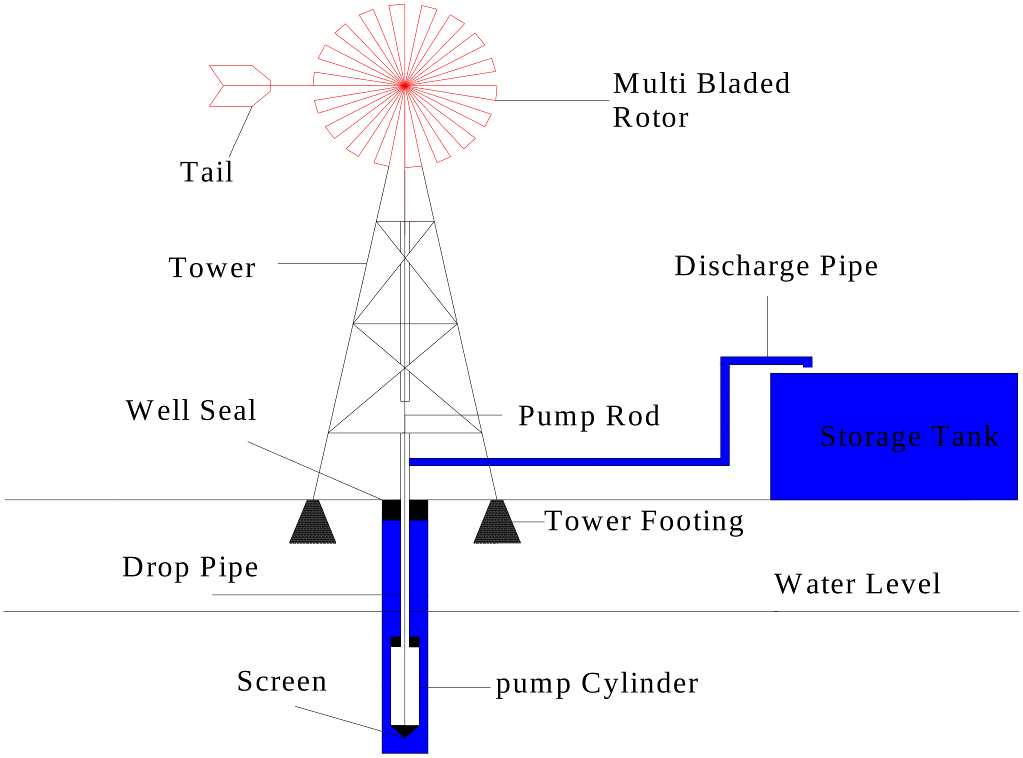


Figure 5-1 Schematic diagram of windmill water pumping system

5.3 Description of the Study Areas

In this section, feasibility of wind powered water pumping system has been studied in Siyadberand Wayu site (latitude 9°46'N, longitude 39°40'E and altitude 2625m a.s.l), Adami Tulu site (latitude 7°52'N, longitude 38°42'E and altitude 1665m a.s.l) and East Enderta site (latitude 13°42'N, longitude 39°37'E and altitude 1926m a.s.l) located in Amhara, Oromia and Tigray regional states of Ethiopia, respectively. The wind speed data for all sites are obtained from the NMSA (National Metrology Service Agency). Since there are no stations at the selected sites, nearby stations were considered during data collection for all sites. For confirmation purposes, data are also collected from Weather base ^{SM} [48], Meteonorm software [49] and NASA-SSE Satellite [36] using the latitude and longitude of the sites. Based on the data obtained from NMSA, the monthly average wind speed for the three sites at 10 m height is shown in Figure 5-2.

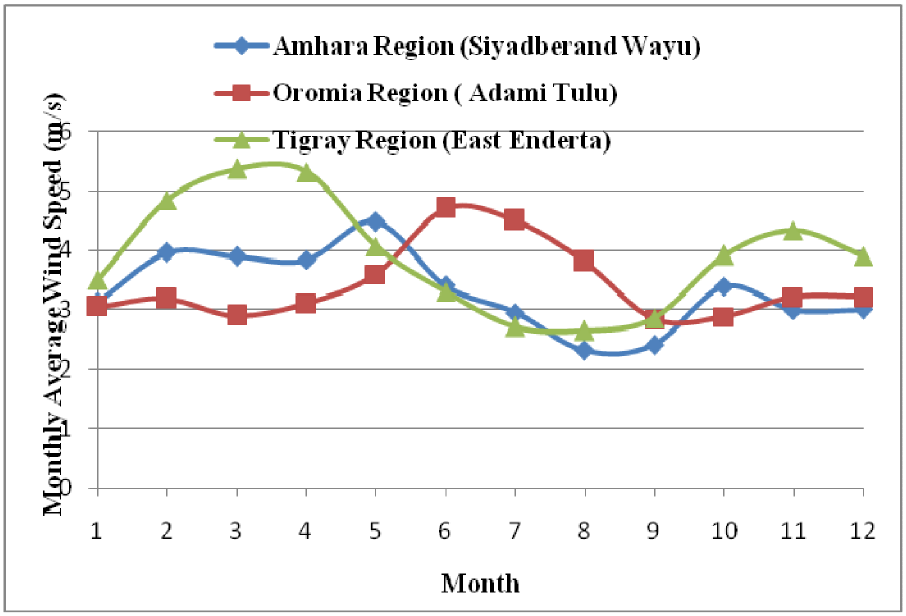


Figure 5-2 Monthly average wind speed at 10m for the selected sites

5.4 Analysis of Wind Data

For estimating the wind energy potential of a site, the wind data collected from the location are analyzed and interpreted. Long term wind data from the meteorological stations near to the candidate site can be used for making wind energy potential estimation. These data, which may be available for long periods, should be carefully extrapolated to represent the wind profile at the potential site [50].

In this research, five year wind speed data were collected from NMSA for each site which is grouped on a daily average basis. These data are, therefore, analyzed using the Weibull method to get the average monthly wind speed data for the selected sites.

5.4.1 Average Wind Speed

One of the most important information on the wind spectra available at a location is its average velocity. In simple terms, the average velocity (V_m) is given by:

$$V_m=\frac{1}{n}\sum_{i=1}^{n}V_i \qquad (5.1)$$

Where V is the wind velocity and n is the number of wind data.

However, for wind power calculations, averaging the velocity using Eq. 5.1 is often misleading. That means we can under estimate the wind energy at the site by using the above formula. Therefore, for wind energy calculations, the velocity should be weighed for its power content while computing the average. Thus the average wind velocity is give by Eq. 5.2

$$V_m=\left(\frac{1}{n}\sum_{i=1}^{n}V_i^{3}\right)^{1/3} \qquad (5.2)$$

Then, if we use equation 5.2 for the mean velocity calculation and using this mean velocity we can get the correct energy estimation of the site.

5.4.2 Distribution of Wind Velocity

Apart from the average strength of wind over a period, its distribution is also a critical factor in wind resource assessment. Wind turbines installed at two sites with the same average wind speed may yield entirely different energy output due to differences in the velocity distribution. If the velocity data for the site is presented in the form of frequency distribution, the average and standard deviation are given by Eq. 5.3 and 5.4 respectively

$$V_m=\left(\frac{\sum_{i=1}^{n} f_i\, V_1^{3}}{\sum_{i=1}^{n} f_i}\right)^{1/3} \qquad (5.3)$$

$$\sigma_v=\sqrt{\frac{\sum_{i=1}^{n} f_i\,(V_i-V_m)^2}{\sum_{i=1}^{n} f_i}} \qquad (5.4)$$

Where: f_i is frequency and V is the mid value of the corresponding interval.

5.4.3 Statistical Models for Wind Data Analysis

In this research, Rayleigh method which is the simplified form of Weibull distribution was used to describe the wind variation in the selected regions.

5.4.3.1 Rayleigh Distribution

The Weibull distribution in wind regime analysis depends on the accuracy in estimating k (Weibull shape factor) and C (scale factor). For the precise calculation of k and C, adequate wind data, collected over shorter time intervals are essential. In many cases, such information may not be readily available. The existing data may be in the form of the mean wind velocity over a given time period (for example daily, monthly or yearly mean wind velocity). Under such situations, a simplified case of the Weibull model can be derived, approximating k as 2. This is known as the Rayleigh distribution [50].

Therefore, the cumulative distribution and probability density function in case of Rayleigh distribution is given by the following two formulas respectively [Mathew, 2006]

$$\mathbf{f}(V)=\frac{\pi}{2}\frac{V}{V_m{}^2}e^{-\left[{}^{\pi}/_{4}\left({}^{V}/_{V_m}\right)^2\right]} \qquad (5.5)$$

$$\mathbf{F}(V)=1-e^{-\left[{}^{\pi}/_{4}\left({}^{V}/_{V_m}\right)^2\right]} \qquad (5.6)$$

5.5 Energy Estimation of Wind Regime

Wind energy density and the energy available in the regime over a period are usually taken as the yardsticks for evaluating the energy potential. The wind energy density (E_D) is the energy available in the regime for a unit rotor area and time. The total energy available in the spectra (E_S) can be arrived at by multiplying the wind energy density by the time factor [50].

Based on the Rayleigh approach the energy density (E_D) and the total energy available in the spectra (E_S) can be calculated using Eq. 5.7 and 5.8, respectively

$$\mathbf{E}_D=\frac{3}{\pi}\rho_a V_m{}^3 \tag{5.7}$$

From E_D, energy available for the unit area of the rotor, estimated using the expression

$$\mathbf{E}_I=TE_D=\frac{3}{\pi}T\rho_a V_m{}^3 \tag{5.8}$$

Other factors of interest for evaluating the energy potential of the site are the most frequent wind velocity (V_{Fmax}) and the velocity contributing the maximum energy (V_{Emax}) to the regime.

$$\mathbf{V}_{Fmax}=\sqrt{\frac{2}{\pi}}V_m \tag{5.9}$$

$$\mathbf{V}_{Emax}=2\sqrt{\frac{2}{\pi}}V_m \tag{5.10}$$

Therefore, the energy density (kW/m^2), the available energy for a certain period of time (kW/m^2/month), the most frequent wind velocity (m/s) and velocity contributing the maximum energy (m/s) for each selected site are calculated using the above formulas and the values are given in Table 5-1.

Table 5-1 Monthly average wind energy density, available energy within the month, maximum velocity frequency and velocity corresponding to maximum energy for the selected three sites

	Siyadberand Wayu					**Adami Tulu**					**East Enderta**				
Month	**V_m**	**E_D**	**E_I**	**V_{Fmax}**	**V_{Emax}**	**V_m**	**E_D**	**E_I**	**V_{Fmax}**	**V_{Emax}**	**V_m**	**E_D**	**E_I**	**$V_{F\ max}$**	**$V_{E\ max}$**
Jan	3.12	0.03	19.89	2.49	4.98	3.05	0.03	20.66	2.43	4.87	3.51	0.04	30.51	2.80	5.60
Feb	3.96	0.05	36.75	3.16	6.32	3.18	0.03	21.22	2.54	5.08	4.84	0.11	72.41	3.87	7.73
Mar	3.90	0.05	38.78	3.11	6.22	2.89	0.02	17.58	2.31	4.61	5.37	0.15	109.51	4.29	8.57
Apr	3.84	0.05	35.85	3.07	6.13	3.11	0.03	21.18	2.48	4.96	5.32	0.14	102.78	4.25	8.49
May	4.48	0.08	58.95	3.58	7.16	3.60	0.05	33.98	2.87	5.75	4.06	0.06	47.29	3.24	6.49
Jun	3.40	0.03	24.97	2.72	5.43	4.70	0.10	73.04	3.75	7.50	3.30	0.03	24.62	2.64	5.27
Jul	2.95	0.02	16.78	2.35	4.71	4.50	0.09	66.23	3.59	7.18	2.71	0.02	14.02	2.16	4.32
Aug	2.31	0.01	8.06	1.84	3.69	3.81	0.05	40.26	3.04	6.08	2.65	0.02	13.12	2.11	4.23
Sep	2.41	0.01	8.82	1.92	3.84	2.84	0.02	16.14	2.27	4.53	2.86	0.02	15.92	2.28	4.56
Oct	3.39	0.03	25.54	2.71	5.42	2.88	0.02	17.43	2.30	4.60	3.92	0.06	42.56	3.13	6.26
Nov	3.00	0.02	17.01	2.39	4.78	3.21	0.03	23.38	2.56	5.13	4.33	0.08	55.53	3.46	6.92
Dec	3.00	0.02	17.74	2.40	4.80	3.21	0.03	24.14	2.56	5.13	3.91	0.06	42.13	3.12	6.24

5.6 Wind Energy Conversion System (WECS)

A WECS is a structure that transforms the kinetic energy of the incoming air stream into electrical energy. This conversion takes place in two steps, as follows. The extraction device, named wind turbine rotor turns under the wind stream action, thus harvesting a mechanical power. The rotor drives a rotating electrical machine, the generator, which outputs electrical power [51].

5.6.1 Wind Turbine

Wind Turbines are one of the recent machines for wind energy conversion. Wind turbines are mainly classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT).The recent wind turbines are mostly used for electricity generation and also for water pumping. However, to use the recent wind turbines for water pumping, the average wind velocity of the region should be greater than 5m/s.

Windmills are one of the oldest methods of harnessing the wind energy to pump water. But currently, the technology has revived because of increasing price of fossil fuel all over the world [52]. Different researchers suggested that windmills are the best options to harvest the wind energy for water pumping at low wind speed regions.

Most windmills for water-pumping applications are of the horizontal-axis variety, and have multi-bladed rotors that can supply the high torque required to initiate operation of a mechanical pump. Figure 5.1 illustrates a typical water-pumping windmill.

5.7 Wind Pump

Wind pumps can be classified as mechanical and electrical systems. Mechanical wind pumps can further be categorized as systems with positive displacement and Roto-dynamic pumps. Various types of pumps like the screw pump, piston pump, centrifugal pump, regenerative pump and compressor pump are being used in mechanical wind pumping option [50]. In this research, direct driven piston pump was selected from mechanical water pumping system.

5.7.1 Wind Powered Piston Pumps

Positive displacement piston pumps are used in most of the commercial wind pumps. The system consists of a high solidity multi-vane wind rotor, drive shaft, crank, connecting rod and a reciprocating pump. Rotary motion of the windmill rotor is translated to reciprocating motion of the connecting rod by the crank. The connecting rod operates the pump's piston up and down through the cylinder during its strokes. Two check valves, both opening upwards, are fitted on the piston and the bottom of the pump. These valves allow the flow only in upward direction. When the connecting rod drives the piston in the upward direction, the piston valve is closed and thus the water column above the piston is lifted up, until it is delivered out through the discharge line [50].

In this research, horizontal axis multi bladed windmill operated with positive displacement piston pump was selected for all sites. And the detail design steps of the windmill water pumping system are given in the next section.

5.8 Wind Water Pumping System Design

In this section, the main components of windmill water pumping system such as the rotor, piston pump, discharge pipe, storage tank and other accessories are designed for the selected three sites. The actual data have been collected from field and Ministry of Water, Energy and Irrigation office for designing the system. The design of wind water pumping system includes the following main points:

- Determination of the water demand;
- Determination of total head
- Determination of the hydraulic power requirement;
- Determination of the available wind power resource;
- Identification of the design month; and
- Sizing of the wind pump

5.8.1 Determination of Water Demand

Determination of the water demand depends on the total number of beneficiaries of the site and the daily per capita water consumptions. In Ethiopia, the daily per capita water consumption for rural communities is estimated to be 20 l/person within the range of 0.5 to 1 km from the dwelling place [52, 53]. Table 5-2 includes important data of the selected three sites.

If the daily per capita water consumption and the total number of beneficiaries of the selected sites are known then, the total daily water demand for each selected sites can be calculated using Eq. 5.11

$$Q_p = N*q \qquad (5.11)$$

Table 5-2 Important Input Parameters for the Selected Three Sites

Input Parameters	**Siyadberand Wayu**	**Adami Tulu**	**East Enderta**
No. of Beneficiary	500	600	1000
Wind Speed(m/s)	4-5	5-6	4-5
Bore Hole, Elevation(m) a.s.l	2625	1665	1926
Storage Tank, Elevation(m) a.s.l	2645	1665	1936
Well Depth(m)	73	85	60
Static Water Level (m)	36	50	25
Pumping level(m)	40	56	30
Pump Position(m)	62	68	52
Distance of Storage Tank to Well(m)	500	10	230
Base of Storage a.s.l (m)	10	10	4
Per capital water consumption (l/day)	20	20	20
Vertical Elevation (m)	30	10	14

Source: Ministry of Water, Irrigation and Energy Office

5.8.2 Determination of Total Head (H)

The total head is the sum of the static head (the distance from water level below ground to water outlet at the water storage container), friction head and velocity head. According to Figure 5-3, the total head is the sum of pumping level and total discharge head.

$$\text{Total Head} = \text{Static head} + \text{Friction head} + \text{Velocity head} \tag{5.12}$$

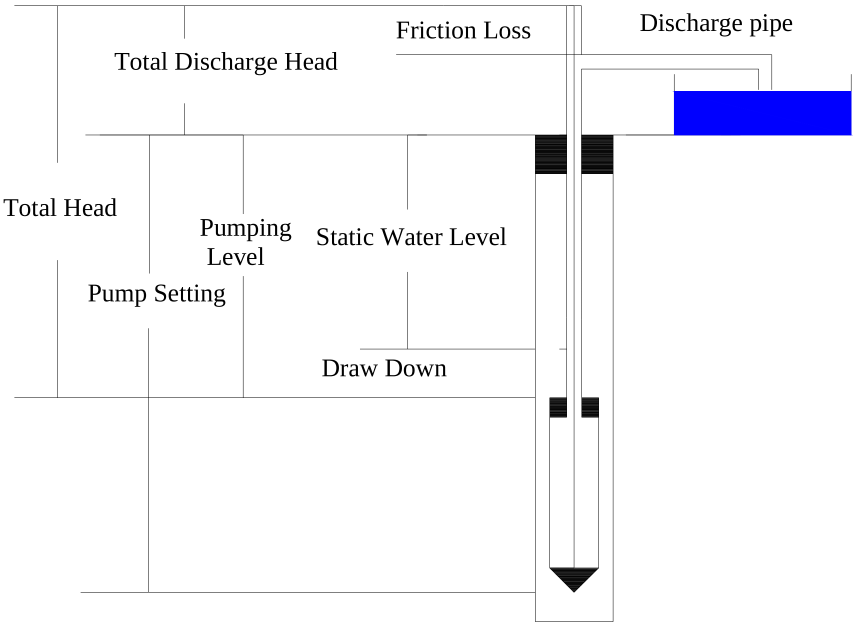


Figure 5-3 Diagram to show the total head in water pumping system

Friction losses of the system can be calculated using Darcy-Weisbach formula (Eq. 5.13), taking into consideration losses on the pipe and minor losses (losses due to valves and fittings) and velocity head.

$$h_f = \frac{8Q^2}{\pi^2 D_d^4 g}\left[f\frac{L_P}{D_d} + K_{fittings} + 1\right] \tag{5.13}$$

Furthermore, the loss coefficient and friction factor values are read from the Moody diagram and pipe friction loss charts based on the flow rate and pipe diameter to determine the total head of the system.

According to the above schematic diagram the total head is the sum of pumping level and total discharge head. Pumping level (dynamic water level) is the sum of static water level and drawdown. And total discharge head is the sum of the vertical rise and friction losses. Therefore static head is the sum of static water level, vertical rises and drawdown.

Let us first determine the pipe diameter before calculating the total head. The fluid flow velocity in water piping and pumping system should not exceed certain limits to avoid noise and damaging wear and tear of piping and fittings. Table 5-3 below shows the recommended fluid flow velocity ranges in water systems for different services.

Table 5-3 Recommended Velocities for Design of Piping

Services	Velocity (ft/s)	Reference
General Service	4 to 10	a, b, c
City Water	3 to 7	a, b
	2 to 5	C
Boiler feed	6 to 15	a, c
Pump suction and drain lines	4 to 7	a, b

[a] crane co. 1976 flow of fluid through pipe , valve, and fittings. Technical paper 410.

[b] system design manual, 1960. Carrier air conditioning co. Syracuse.NY

[c] piping design and engineering, 1951. Ginnell company.inc., Cranston, RJ

Source: Ashrae Fundamentals Handbook, Chapter 33, Pipe Sizing, 1989

Once we select the appropriate velocity for the system then we can calculate the pipe diameter based on the velocity and flow rate using Eq. (5.14).

$$D_d = \sqrt{\frac{4\,Q}{\pi\,v}} \tag{5.14}$$

Where: D_d internal diameter of pipe; v is mean velocity of water

Furthermore, we need to determine the loss coefficient and friction factor based on the flow rate and pipe diameter from the Moody diagram and pipe friction loss chart which are given in the appendix G and H respectively.

Taking the Amhara region (Siyadberand Wayu site) as an example, the detail calculation has been worked out for the determination of the water demand, total head, piping diameter and pump size. And the results of all calculation for all selected sites summarized and given in table form at the end of this section.

5.8.3 Determination of Hydraulic Power

The hydraulic power required to lift water from the source (borehole) to the storage tank can be calculated using Eq. (5.15) given in [Mathew, 2006].

$$\mathbf{P}_{hyd}=Q_p*\rho_w*g*H \qquad (5.15)$$

The hydraulic power requirement is constant for all months within a year because there is no pumping variation in water supply for the rural selected community, assuming constant supply.

5.8.4 Wind Power Potential Determination

The wind power potential is given as the specific wind power or power per unit area. For a unit area of the rotor, power available (P_{wind}) in the wind stream of velocity V is given in [Mathew, 2006]

$$\mathbf{P}_{wind}=\frac{1}{2}*\rho_a*V^3 \qquad (5.16)$$

5.8.5 Reference Area and Size of Windmill

The ratio of the hydraulic power of each month divided by specific wind power potential for that same month has the dimension of area and is referred as the reference area [54]. The reference area can be calculated based on Eq. (5.17).

$$R_a = \frac{P_{hyd}}{P_{wind}} \tag{5.17}$$

The size of the windmill which depends on the diameter of the rotor can be obtained from the reference area given in Eq. (5.17). The rotor diameter is given in Eq. (5.18).

$$D_r = \sqrt{\frac{4R_a}{\pi}} \tag{5.18}$$

The sizing methodology for standalone windmill water pumping systems is based on the concept of the critical month or design month. This is the month in which the water demand is highest in relation to the wind power potential, i.e. the month when the system will be most heavily loaded [54]. The design month is found by calculating the ratio of the hydraulic power requirement to the wind power potential for each month. The month in which this ratio is a maximum is the design month [54].

5.8.6 Capacity of Storage Tank

The capacity of the storage tank can be determined from the product of the daily water requirement and the number of days required for constant water supply as given in Eq. (5.19).

$$S = Q_p * d_s \tag{5.19}$$

5.9 Wind Pump Simulation

In this research, MATLAB code was prepared, based on different equations given in

[Mathew, 2006], to determine the performance of wind driven piston pump. The instantaneous discharge of the system with respect to monthly average wind speed can be determined as given in [Mathew, 2006] using Eq.5.20.

$$Q_{VP} = 2\, C_{Pd}\,\eta_{(T,P)} \left[\frac{\rho_a}{\rho_w}\right]\left[\frac{A_r V^3}{gH}\right]\left[1\text{-}K_O\left(\frac{V_I}{V}\right)^2\right]K_O\left(\frac{V_I}{V}\right)^2 \qquad (5.20)$$

The overall performance coefficient of a wind rotor coupled to a piston pump can be modeled as in (Mathew and Pandey, 2000) which is given as discharge expected from a wind driven piston pump installed at a given site, over a period T as given in (Mathew, 2006). Eq. (5.21) gives the discharge expected from a wind driven piston pump, installed at a given site, over a period T.

$$Q_{IP} = 2\, T C_{Pd}\,\eta_{(T,P)} \frac{\rho_a}{\rho_w}\frac{A_r V_O^3}{gH}\left[1\text{-}K_O\left(\frac{V_I}{V_O}\right)^2\right]K_O\left(\frac{V_I}{V_O}\right)^2 \left[\left(\frac{4V_m^2}{\pi(V_o^2 - V_I^2)}(e^{-x_I} - e^{-x_o})\right)(e^{-x_o})\right] \qquad (5.21)$$

$$X_I = \frac{\pi}{4}\left(\frac{V_I}{V_m}\right)^2 \text{ and } X_O = \frac{\pi}{4}\left(\frac{V_O}{V_m}\right)^2$$

5.10 Result and Discussion

Hydraulic power, specific wind power, reference area, rotor diameter and design month for the three sites were calculated using the equations given in the previous section and results are summarized in Table 5-4.

Table 5-4 Hydraulic power, specific wind power, reference area and rotor diameter calculation for three sites

Siyadberand Wayu Site	**Adami Tulu Site**	**East Enderta Site**

Months	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Hydraulic Power P_{hydr}(W)	337	337	337	337	337	337	337	337	337	337	337	337
Specific Wind Power P_{wind} (W/m^2)	30.3	27.7	23	18.8	16.9	23	20.8	15.2	13.6	15.2	20.8	22.9
Reference Area P_{hydr}/P_{wind} (m^2)	11.1	12.	14.7	17.9	19.9	14.7	16.2	22.2	24.9	22.2	16.2	14.7
Rotor Diameter (m)	3.76	3.94	4.32	4.78	5.03	4.32	4.54	5.32	5.63	5.32	4.54	4.32
Design Month									DM			
Hydraulic Power P_{hydr}(W)	363	363	363	363	363	363	363	363	363	363	363	363
Specific Wind Power P_{wind} (W/m^2)	21	24	18	22	34	76	67	41	17	18	24	24
Reference Area P_{hydr}/P_{wind} (m^2)	17	15	20	16	10	5	5	9	21	20	15	15
Rotor Diameter (m)	4.7	4.4	5.1	4.5	3.6	2.4	2.6	3.4	5.2	5.1	4.3	4.3
Design Month									DM			
Hydraulic Power P_{hydr}(W)	300	300	300	300	300	300	300	300	300	300	300	300
Specific Wind Power P_{wind} (W/m^2)	31	81	110	107	48	26	14	13	17	43	58	42
Reference Area P_{hydr}/P_{wind} (m^2)	10	4	3	3	6	12	21	23	18	7	5	7
Rotor Diameter (m)	3.5	2.2	1.9	1.9	2.8	3.9	5.2	5.4	4.8	3.0	2.6	3.0
Design Month								DM				

Table 5-5 Wind pump parameters as obtained from design calculations for the selected sites

Parameters	**Siyadberand Wayu**	**Adami Tulu**	**East Enderta**
Water consumption (m^3/day)	10	12	15
Total head (m)	75	66	44
Density of air (kg/m^3)	0.92	1.024	0.992
Reference area (m^2)	24.87	21.32	22.71
Rotor diameter (m)	5.63	5.21	5.38
Pipe diameter (mm)	25	40	50
Pump diameter(mm)	115	125	125
Hydraulic power (W)	337	360	300
Design month	September	September	August
Tower height (m)	16	16	16
Transmission/gear ratio/	direct	direct	direct

AV55 (Aureka) wind pump with 5.7m (19 ft) rotor diameter, 24 blades and direct driven single acting piston pump was selected Based on the design calculation results a for the selected three sites [55].

The instantaneous discharge with respect to the monthly average wind speed can be determined using MATLAB program based on Eq. (5.21). The results for the selected three sites are shown in Figure 5-4.

Figure 5-4 shows that instantaneous discharge varies from 395 m^3 to 254m^3, 888m^3 to 307 $m^3$and 1203 m^3 to 455 m^3 in Siyadberand Wayu, Adami Tulu and East Enderta sites, respectively. The minimum discharges satisfy the monthly water demand in East Enderta site, there is 10% water missing in Siyadberand Wayu and Adami Tulu site.

Table 5-6 Detail specification of AV55 (Aureka) wind pump

AV55 (Aureka) Wind Pump	
Rotor	Horizontal axis; upwind position
Rotor diameter (m)	5.7m (19ft)
Operating wind speed	2.8 m/s
No. of blades	24
Transmission ratio	1:1 direct driven
Control systems	Fully automatic
Pump system	Single acting piston pump
Pump strock (mm)	160-230mm
Cut in wind speed	1.5 m/s
Cut out wind speed	10 m/s
Survival wind speed	40 m/s

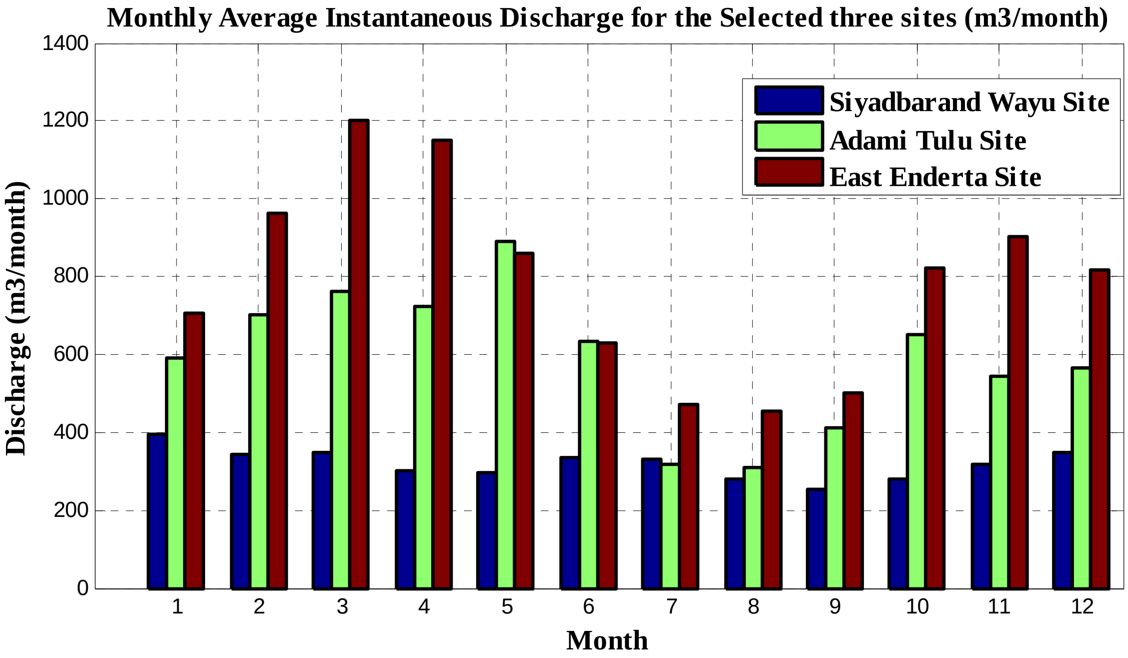


Figure 5-4 Monthly average discharge for the selected sites (m^3/month)

By considering the characteristics of the rotor, pump and wind region integrated system performance was developed by Mathew et.al [50]. In this research, a MATLAB program was developed based on Eq. (5.22) to determine the integrated discharge for all sites within a given period of time.

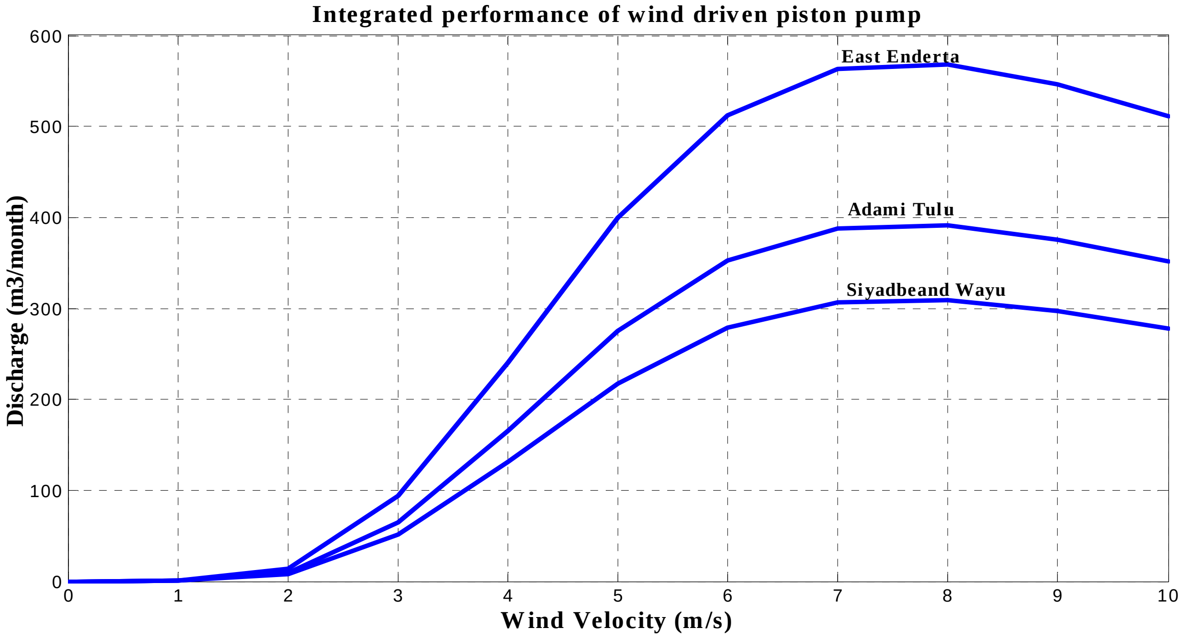


Figure 5-5 Integrated discharge within a given period of time for selected sites

Figure 5-5 shows the integrated discharge of wind driven piston pump for the three sites at a given period of time. As can be observed from the graph, the integrated discharge curves are similar for all sites with a higher discharge rate for the site that has a higher water demand per day.

Table 5-7 shows the monthly average water discharge (m^3/month) for the three sites. According to the simulation result, the annual discharges for the sites are 3830.42, 7098 and 9477m^3 for Siyadberand Wayu, Adami Tulu and East Enderta sites, respectively.

Table 5-7 Monthly average discharges for the selected sites (m^3/month).

Months	Siyadberand Wayu Site	Adami Tulu Site	East Enderta Site
Jan	395.5322	590.887	707.2
Feb	342.6349	701.317	962.1
Mar	346.5323	761.794	1203.1
Apr	302.931	725.375	1151.1
May	297.4014	888.152	858.2
Jun	335.3538	632.295	628.6
Jul	329.8755	317.259	471.8
Aug	280.1304	307.367	455.4
Sep	254.1291	413.735	500.8
Oct	280.1304	650.886	819.7
Nov	319.2343	544.965	901.8
Dec	346.5323	564.396	817.3

5.11 Financial Comparison between Wind and Diesel Water Pumping System

In the financial comparison between windmill and diesel water pumping, the main question is how the financial costs of both systems can be calculated. The whole costs of a pumping system have a certain life expectancy in years that is made up of the capital cost, operating cost and maintenance and replacement cost (M&R). And all these costs refer to the life cycle cost LCC. Table 5-8 below includes assumptions that were made for financial comparison between WPS and DPS.

$$\text{Annual Fuel Cost}=\text{Specific Fuel Consumption}*\ \text{Total Operating Hours in a Year}*\text{Fuel Rate}$$

$$=\frac{0.23\text{liter}}{\text{hr}}*\left(\frac{6\text{hr}}{\text{day}}*365\,\frac{\text{day}}{\text{year}}\right)*0.77\,\frac{\$}{\text{liter}}=387.85\ \$/\text{year}$$

Fuel Cost of Diesel Generator for 20 years=20 Year*387.85 $/year=7757 $

Table 5-8 Economic assumptions

Parameters	**Values**
Interest rate (%)	5
Discount rate (%)	10
Life time of windmill (years)	20
Life time of submersible pump (years)	10
Life time of Diesel generator (years)	10
Diesel fuel cost ($/l)	0.77
Salvage value for windmill (%)	20
Salvage value for Diesel (%)	20

Table 5- 9 WP and DP system cost comparison using LCC for Adami Tulu site.

Costs (USD)	**WP (USD)**	**DP (USD)**
Capital Cost (CC) of windmill heads completed with tower and pump	2329.38	250
Maintenance cost (MC) :	1. for windmill and tower 313.2 $ is required within 20 years	500
	2. for maintenance of pump, pump rod, delivery pipe 1100 $ is required within 20 years	
Fuel/Energy cost (EC) for 20 years	None	7757
Replacement cost (RC) for generator	None	500
Replacement cost for submersible pump	None	400
Total cost	3742.58	9407
Salvage value (SC)	Negligible	40
Life Cycle Cost (LCC)	3742.58	9367

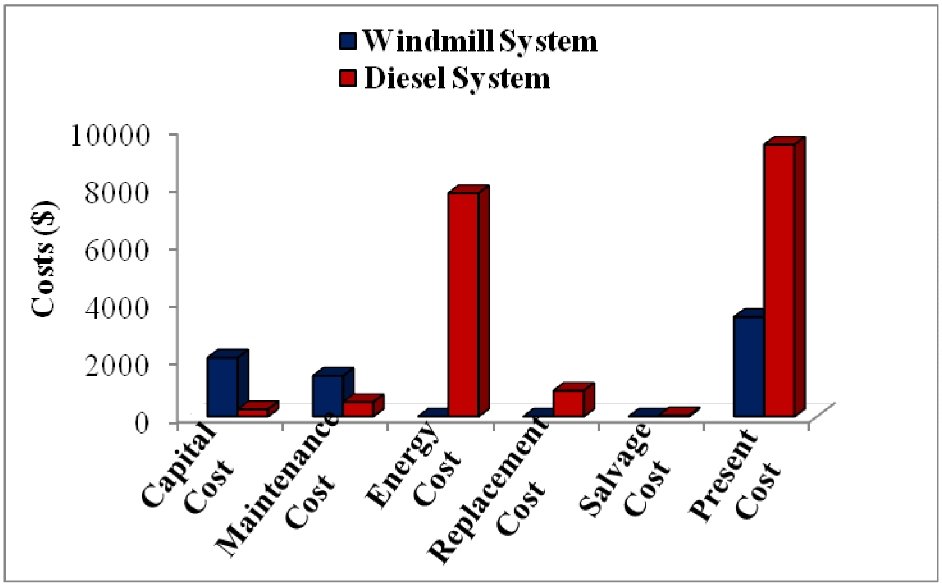


Figure 5- 6 Life cycle cost analysis of windmill and diesel water pumping system for Adami Tulu site

As shown in Figure 5-6, the capital cost of diesel water pumping system is lower than the windmill water pumping system. However, the fuel cost of diesel water pumping system is higher than the windmill system. Therefore, if we compare the two systems based on their present cost windmill water pumping system is more economical.

5.11.1 Cost of Pumping Water

As we have discussed in the previous chapter the cost of water pumped by windmill and diesel water pumping system can be calculated using the cost annuity method [44].

Table 5-10 shows the cost of pumping m^3 of water using PV and Diesel water pumping systems for three sites. Based on the unit cost of water, the PV water pumping system is more economical than the Diesel system.

Table 5-10 Annuity and water cost calculation for the windmill and diesel system (USD).

Pump	**Siadberand Wayu**	**Adami Tulu**	**East Enderta**
Windmill			
Annualized capital cost	240.4	273.7	273.7
Operation and maintenance cost	70.66	70.66	70.66
Annualized life cycle cost for windmill	311.06	344.36	344.36
Water cost for Windmill system ($/m^3)	**0.06**	**0.05**	**0.04**
Diesel			
Annualized capital cost	52.875	52.875	52.875
Operation and maintenance cost	25	25	25
Replacement cost	27.625	27.625	27.625
Annual Fuel cost	337.26	387.85	306.9
Annualized life cycle cost for Diesel system	442.76	493.35	412.4
Water cost for Diesel system**($/m^3)**	**0.08**	**0.07**	**0.04**

CHAPTER SIX

HYBRID (SOLAR/WIND) WATER PUMPING SYSTEM

6.1 Introduction

The term hybrid system is used to describe any power with more than one type of resources, usually a conventional generator or power by dies el or gas engine and renewable energy sources such as a Photovoltaic unit, wind generator, batteries …etc.[56] Today, depletion of oil and gas reserves, combined with the growing concerns about global warming, has made the expectation to seek alternative/renewable energy sources. The integration of renewable energies such as solar and wind energy is becoming increasingly attractive and is being used widely, for substitution of oil-produced energy [57].

In recent years, photovoltaic power generation has been receiving considerable attention as one of the more promising energy alternative. The reason for this rising interest lies in the direct conversion of sunlight into electricity. However, the PV power generation cannot be used wide spread because of economic factor. Now a days, efforts are being made worldwide to reduce the cost/watt through various technological innovations.

Wind energy also is equally and effectively used in large scale wind farms to provide electricity to rural areas and other far reaching locations. Wind energy is being used extensively in areas like Denmark, Germany, Spain, India and in some areas of the United States of America. It is one of the largest forms of Green Energy used in the world today.
The performance of solar and wind energy systems are strongly dependent on the climatic conditions at the location. The power generated by a PV system is highly dependent on weather conditions. For example, during cloudy periods and at night, a PV system would not generate any power. In addition, it is difficult to store the power generated by a PV system for future use. To overcome this problem, a PV system can be integrated with other alternate power sources.

Combined wind and solar systems are becoming more popular for stand–alone power generation applications, due to advances in renewable energy technologies and subsequent rise in prices of petroleum products. The Economic aspects of these technologies show sufficient promise to include them in developing power generation capacity for developing countries. Research and development efforts in solar, wind, and other renewable energy technologies are required to continue improving their performance, establishing techniques for accurately predicting their output and reliably integrating them with other conventional generating sources [57].

Before building a system with several intermittent energy sources and variable consumption, guidance on the dimensioning of the individual components should be obtained by simulating the system operation under the local conditions, including as appropriate the weather, insulation, wind etc. In general a key objective of such systems is to use the maximum proportion of renewable energy, but other factors including the financial investment, social aspects, local infrastructure, durability etc. must also be considered [57].

The components and subsystems of a stand-alone system based on renewable sources are interconnected to optimize the whole system. The design of a hybrid system will depend on the requirements of the user (isolated or not isolated location, rural or urban, DC or AC supply), and on the power supply system (or water supply system in the case of water pumping applications). Usually, most of hybrid systems are designed to supply electric power for lighting fixtures, radio/TV, domestic appliances, submersible water pumps etc. This is typical in isolated areas for rural households as well as of some public buildings such as schools, cultural establishments, etc.

The term hybrid system is used to describe any power with more than one type of resources, usually a conventional generator or power by diesel or gas engine and renewable energy sources such as a Photovoltaic unit, wind generator, batteries …etc.

The adoption of one form of energy conversion or another depends on solar or wind potential. The use of diesel system raises numerous problems (fuel transport, spare parts, and repair shops) which bring the designers to think about the possibility of combined renewable energy systems. To address this problem, hybrid systems that use more than one power supply has been employed where the demand for water is critical and outages cannot be tolerated.

6.2 Investigation of Hybrid Energy Application in Ethiopia

In Ethiopia, different researchers have been studied on the feasibility of standalone solar/ wind and hybrid energy production system for remote area applications. [Alfa Hailemariam et.al, 2013] studied the hybrid solar-wind-diesel systems for rural areas application in north Ethiopia using Homer Software. [Getachew Bekele and Bjorn Palm, 2010] studied the feasibility of a standalone solar-wind based hybrid energy system for rural electrification application in Ethiopia. [Solomon Teklemichael, 2013] designed and analyzed an off-grid hybrid renewable energy system to supply electricity for rural areas. [Zelalem Girma, 2013] also studied the design of hybrid renewable energy system for rural areas electrification in Ethiopia. [Moges Ashagrie] worked on modeling, simulation and analysis of a hybrid wind-hydrogen energy system in Ethiopia. In addition to this [Samuel Tesema] worked on resource assessment and optimization study of efficient type hybrid power system for electrification of rural district in Ethiopia. However, all previously mentioned studies focused on rural electrification applications. Therefore, the objective of this research is studying the viability of solar/wind and hybrid based water pumping system for rural application in Ethiopia.

6.3 Description of the Study Area

In this research, A hybrid powered pumping system capable of supplying 20 m^3 of water per day for 1000 people with average daily water consumption of 20 liter per person at different water level has been designed. Design criteria are based on requirement for drinking water supplies to small villages in Ethiopia. In this research, four sites selected from three different administration Regions. The sites are Atsbi from Tigray, Awash

Fentale from Afar, Borena and Adami Tulu from Oromia regions respectively. Site selection was done based on available solar and wind energy potential of the site. Most areas of the country covered by good and moderate solar energy potential sites however there is few good wind energy potential in the country.

Table 6-1 Selected Sites for Hybrid Water Pumping System

Site Name	**Lat.**	**Long.**	**Annual Average Global Solar Radiation**	**Annual Average Wind Speed at 10 m**	**Site Category**
Atsbi	13.87	39.75	6.73	4.25	High solar and medium wind
Awash Fentale	8.75	39.83	6.42	2.89	High solar and low wind
Borena	5.0	38.25	5.53	3.5	Medium solar and wind
Adami Tulu	7.52	38.42	5.96	2.96	Medium solar and low wind

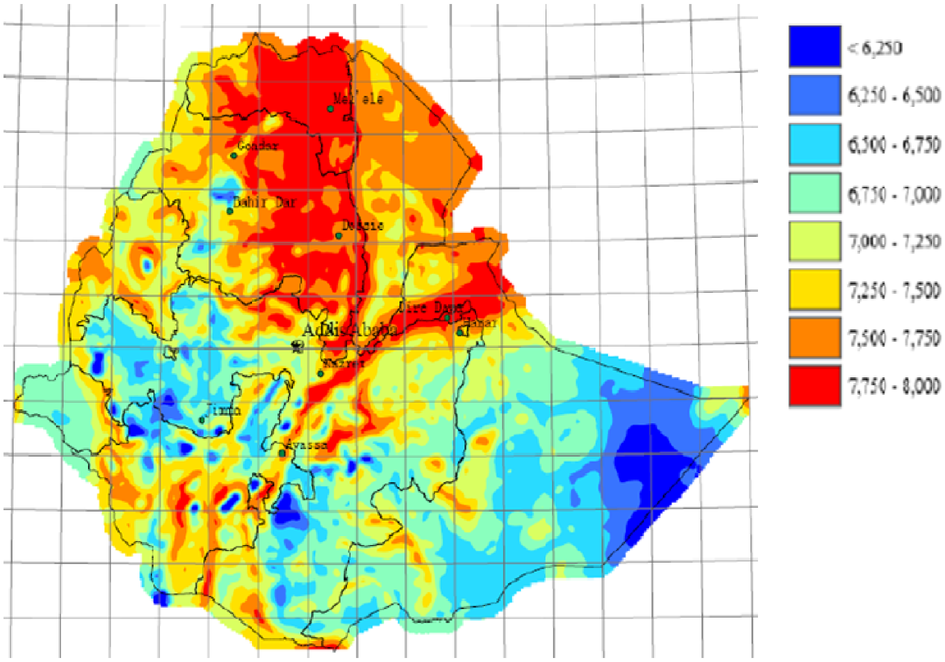


Figure 6-1 Average solar radiation of Ethiopia for 30 year period (1980-2009)

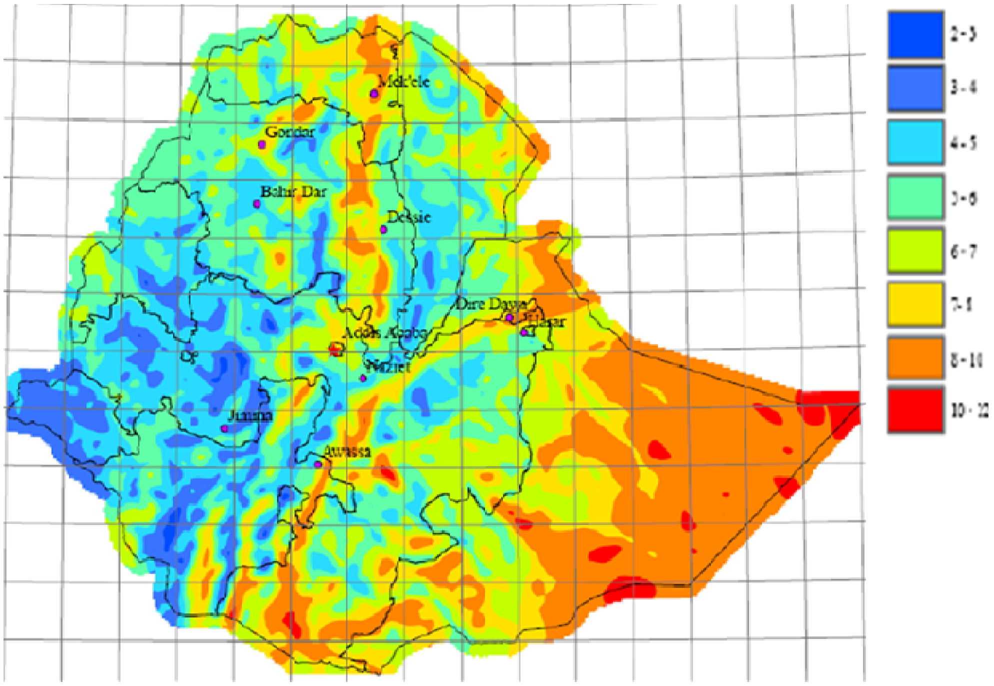


Figure 6-2 Average wind speed of Ethiopia at 50m for 30-year period (1980-2009)

Figure 6-1 and 6-2 show the average solar radiation and wind speed distribution of the country for 30-years period. And table 6-1 shows annual average global solar radiation and wind speed for all selected sites.

6.4 The Proposed Hybrid System Configuration

Possible available technologies for hybrid water pumping systems are:

- ✓ Wind turbine for electric generation and solar PV system with inverter for electric power generation supplying electric power for electric submersible pump. Electric power wind turbine is only feasible for high wind speed although there are some locations in Ethiopia with high wind speed. Definitely in most location in Ethiopia the wind speed is low or medium.

- ✓ In addition well for water supply has to be located in the village which must be appropriate to the spot of wind. Therefore, this option can be appropriate for few locations in Ethiopia where not considered.
- ✓ The second available technology for hybrid water pumping system is Windmill with piston pump and PV module With DC Submersible pump. Windmill are not operate with low speed and can be considered for water pumping application starting from average wind speed 3.5 m/s. Therefore, in this research, PV with DC submersible and windmill with piston pump are selected for hybrid application. Figure 6-3 shows the schematic diagram of hybrid water pumping system.

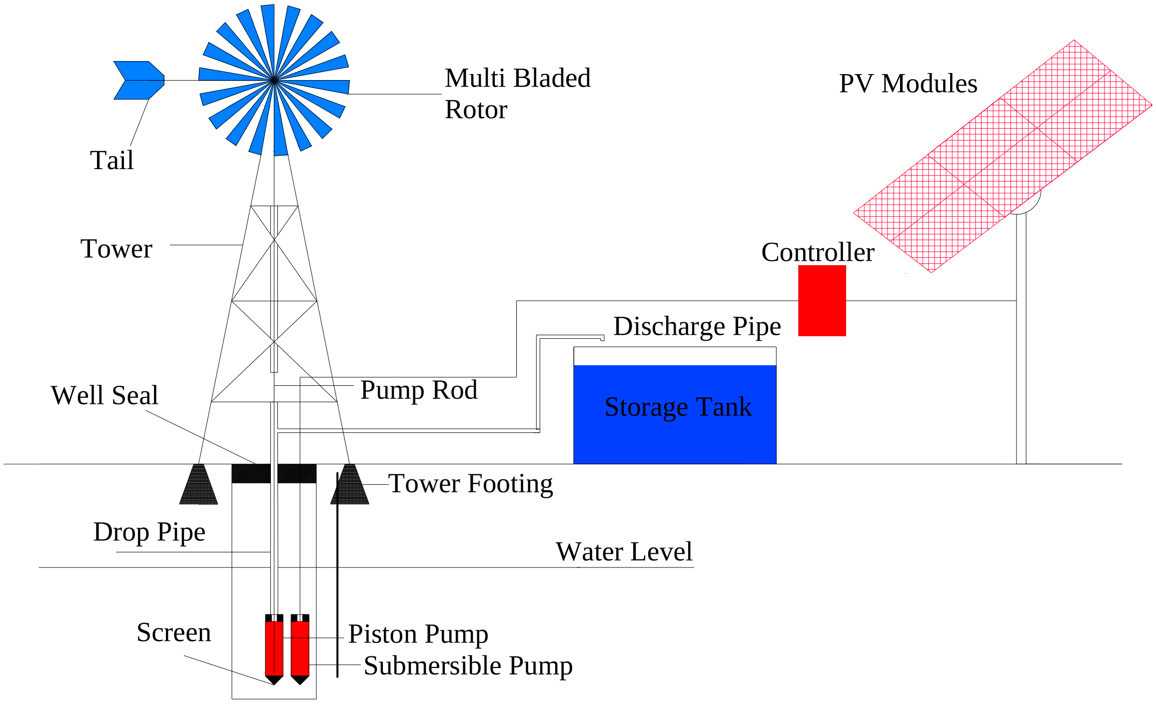


Figure 6-3 Schematic diagram of hybrid water pumping system

6.5 Design and Simulation of Hybrid Water Pumping System

6.5.1 Introduction

Combining wind and solar energy into hybrid generation system could satisfy the energy needs. The two sources of energy, which are individually unreliable could as a whole have a higher reliability. It has been found that a hybrid wind/PV system is better than an individual wind or PV power system [58].

Wind speed and solar radiation data of the selected site shows that it is possible to apply the hybrid technology in Ethiopia. However, generally wind and solar options have unpredictable nature being dependent on weather and climatic changes. Figure 6-4, 6-5, and 6-6 show monthly average wind speed at 10 m, monthly average wind speed at 50 m and monthly average direct normal solar radiation for the selected sites.

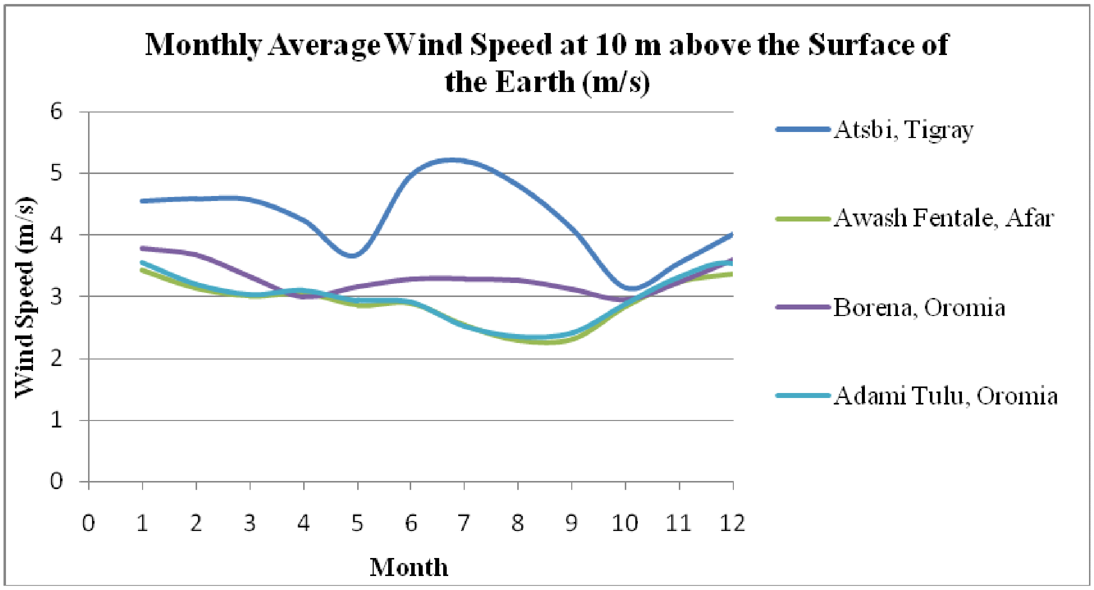


Figure 6-4 Monthly average wind speed at 10m for all selected sites

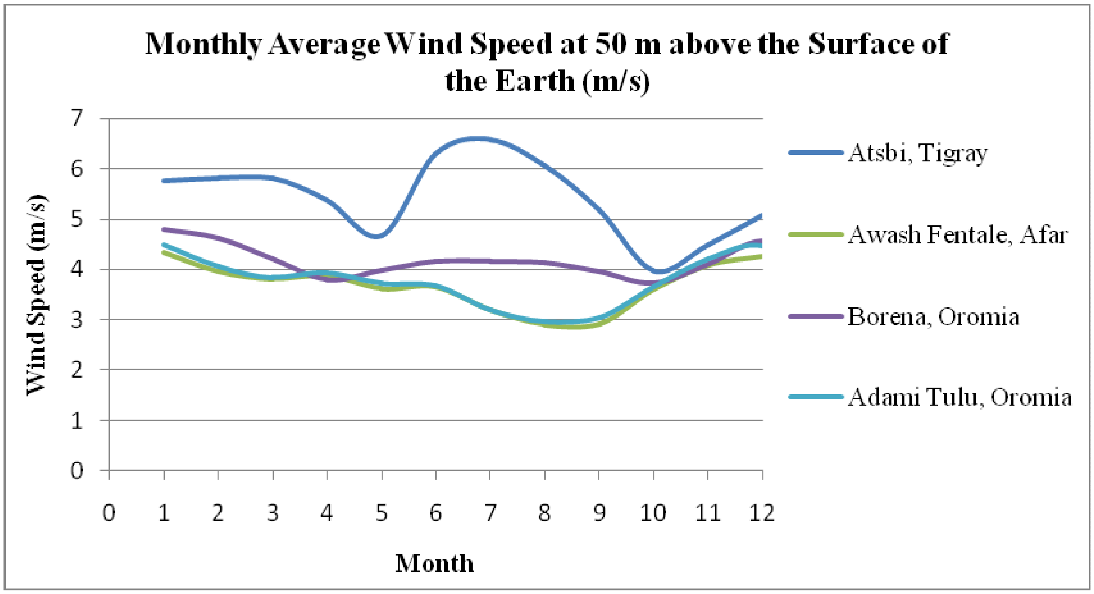


Figure 6-5 Monthly average wind speed at 50m for the selected sites

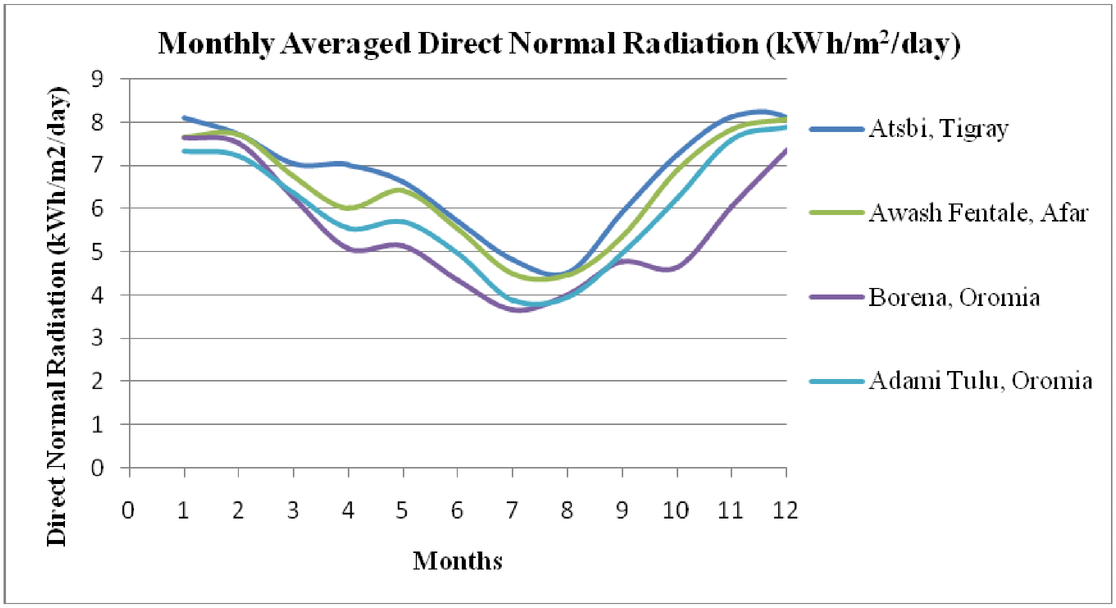


Figure 6-6 Monthly average direct normal solar radiation for the selected sites (kWh/m^2/day)

Table 6-2 Monthly Average Solar Radiation and Wind Speed Data for Tigray Region, Atsbi Site

Tigray Region, Atsbi Site			
Months	**Radiation on a Horizontal (kWh/m^2/day)**	**Direct Normal Radiation (kWh/m^2/day)**	**Wind Speed at 10 m above the Surface of the Earth (m/s)**
Jan	5.85	8.1	4.55
Feb	6.27	7.73	4.59
Mar	6.5	7.03	4.58
Apr	6.82	7.02	4.24
May	6.62	6.62	3.68
Jun	6.05	5.7	4.97
Jul	5.57	4.8	5.2
Aug	5.46	4.51	4.79
Sep	6.05	5.91	4.09
Oct	6.22	7.23	3.14
Nov	6	8.12	3.56
Dec	5.66	8.09	4.01

Table 6-3 Monthly Average Solar Radiation and Wind Speed Data for Afar Region, Awash Fentale Site

Afar Region, Awash Fentale			
Months	**Radiation on a Horizontal (kWh/m^2/day)**	**Direct Normal Radiation (kWh/m^2/day)**	**Wind Speed at 10 m above the Surface of the Earth (m/s)**
Jan	6.08	7.66	3.42
Feb	6.57	7.71	3.14
Mar	6.52	6.73	3.01
Apr	6.31	6.01	3.06
May	6.36	6.42	2.86
Jun	5.77	5.53	2.89
Jul	5.23	4.48	2.53

Aug	5.36	4.47	2.29
Sep	5.84	5.34	2.31
Oct	6.31	6.88	2.84
Nov	6.27	7.84	3.24
Dec	6.08	8.06	3.37

Table 6-4 Monthly Average Solar Radiation and Wind Speed Data for Oromia Region, Borena Site

Oromia Region, Borena Site			
Months	**Radiation on a Horizontal (kWh/m^2/day)**	**Direct Normal Radiation (kWh/m^2/day)**	**Wind Speed at 10 m above the Surface of the Earth (m/s)**
Jan	6.31	7.64	3.8
Feb	6.66	7.51	3.7
Mar	6.36	6.25	3.5
Apr	5.74	5.08	3.33
May	5.57	5.15	3.38
Jun	4.98	4.35	3.4
Jul	4.61	3.65	3.5
Aug	5.01	4.01	3.39
Sep	5.56	4.77	3.37
Oct	5.28	4.65	3.33
Nov	5.68	6.07	3.5
Dec	6.05	7.36	3.8
Annual average	5.64	5.53	3.5

Table 6-5 Monthly Average Solar Radiation and Wind Speed Data for Oromia Region, Adami Tulu Site

Oromia Region, Adami Tulu Site			
Months	**Radiation on a Horizontal ($kWh/m^2/day$)**	**Direct Normal Radiation ($kWh/m^2/day$)**	**Wind Speed at 10 m above the Surface of the Earth (m/s)**
Jan	6.02	7.33	3.55
Feb	6.41	7.22	3.21
Mar	6.35	6.34	3.03
Apr	6.04	5.55	3.1
May	5.95	5.7	2.94
Jun	5.42	4.97	2.9
Jul	4.83	3.88	2.52
Aug	5.01	3.95	2.34
Sep	5.64	4.95	2.41
Oct	6.04	6.23	2.89
Nov	6.25	7.61	3.32
Dec	6.1	7.88	3.53

6.6 Hybrid Water Pumping System Design

6.6.1 Technical Analysis

Transfer of technology should be taken with great care to suit the local climatic geographical and social conditions of the community concerned. Davis & Shirtliff Trading PLC is one of solar pump supplier in Ethiopia, supplying different models of solar pump such as GRUNDFOS, PEDROLLO and DAVEY.

In this research, different types of GRUNDFOS solar submersible well pump are selected based on the design. The design considers one submersible pump and piston pump in one borehole. Mechanically driven wind pump is selected because of not feasibility of electric turbine. One controller is wired between the PV-array and the pump to optimize the relationship b/n array voltage and current to maximize the amount of water pumped under variable sunlight condition.

Table 6-6 Well characteristics and other important parameters

Parameters	**Values**
Total Number of Beneficiaries	1000
Water Volume Required Per Day per person	20 m^3/day
Well Depth	60m
Static Water Level	25m
Pump Position	52m
Vertical Elevation	14m
Horizontal Distance b/n well & storage	23m
Well yield	2 l/s

6.6.2 Design of Solar and wind pump

6.6.2.1 Sizing of Solar Pump

During the design of the solar pump the following main points should be considered:

- ✓ **Daily water requirement:** the daily water requirement can be determined based on equations discussed in chapter 4 and 5.
- ✓ **The storage tank capacity:** for drinking water pumping system the storage tank capacity is considered for 3 days.
- ✓ **Solar resource:** a good rule of thumb is that the solar resource must be greater than 3 kWh/m^2/day for choosing a solar site.
- ✓ **Pumping requirement:** total dynamic head (TDH) is vertical distance that the pump must move the water. TDH is the sum of static head, friction loss due to pipe length and fittings.
- ✓ **Hydraulic workload:** hydraulic workload is an excellent indication of the power that will be required to meet the designed system constraints.

- ✓ **Flow rate:** the volume of water that is pumped in a set of time period $\text{flow rate (Q)} = \frac{\text{Total daily water requirment}}{\text{total daily solar isolation} \times 60 \frac{\text{min}}{\text{hr}}}$
- ✓ Pump power can be determined using the following equation respectively: $\text{pump power (W)} = (0.1885 \times \text{TDH} \times \text{Q})/\eta$
- ✓ **PV determination (array sizing):** the number of modules in series and in parallel can be determined using the following equations respectively
- ✓ $\text{Modules in series} = (\text{pumps motor voltage})/(17.4\ \text{V})$

  $\text{Modules in parallel} = (\text{pumps peak parallel wattage})/(\text{module in series} \times$
- ✓ $17.4\ \text{V} \times 3.11\ \text{A} \times 0.80)$

The size of the array and pump depends on daily solar radiation and hydraulic energy requirement, which can be express as volume-head product (duty in m^4/day). The actual power required to pump water is:

$$P_{req} = \frac{(9.81 \times H \times Q)}{\eta} \tag{6.1}$$

Where: P_{req} power required in W, H= total pumping head in m, Q= flow rate in liter per second (liter/s), η= subsystem efficiency

A more accurate way of estimating the size of the solar array needed to pump given amount of water is to use the following formula [59].

$$\text{Array Size } W_p = \frac{9.81 \times H \times Q}{H_t \times 3.6 \times F_m \times F_t \times \eta} \tag{6.2}$$

Where: Wp = peak watts, H_t = global solar irradiation in the array plane (kWh / m^2/day), F_m = array/load matching factor, 0.9 for centrifugal pumps, 0.8 for the other pumps, F_T = de-rating factor for operating temperature of array output cells (0.8 for warm climate and 0.9 for cool)

The Peak Watt can be calculated using equation 6.2 and assumed F_T = 0.8 (de-rating factor 0.8 for warm climate and 0.9 for cool), F_m= 0.8 (array matching factor 0.9 for centrifugal pump, 0.8 for any other pump) and η = 0.35 (subsystem efficiency).

Because of the relatively high cost of PV modules, solar pumping is most economical for small power demand application. Therefore, half of the calculated number of module was considered in order to provide a power that would produce a half of the required water.

Again Peak Watt can be calculated using half of the calculated number of module for each site. And using this Peak Watt and the same assumption, the solar pump flow rate (Q) in m^3/day can be expressed in terms of pumping head and solar radiation for each site.

6.6.2.2 Sizing of the Wind Pump

The Wind machines convert the energy in wind into mechanical or electrical energy. Windmills work very well at low wind speeds, so they tend to give more reliable water supply than wind electric systems. But, the wind-electric systems are more efficient over a wide range of wind speeds, they can pump higher volumes of water, and the wind turbine can be placed far from the well. Perhaps most important, wind-electric systems need much less maintenance. In this research, different type windmills are selected based on the design result.

The power developed by the system in pumping water is given by:

$$\boldsymbol{P_w} = C_p\eta \times 0.5 \times \rho_a \times A \times V^3 \qquad (6.3)$$

Where P_w = power developed by the system in watts, ρ_a = air density in kg /m^3, V = velocity in (m/s), A = cross-sectional area of wind being intercepted

$C_p\eta$ = overall (wind to water) efficiency of the system, C_p= power coefficient (the maximum possible power coefficient is Bentez coefficient C_P= 0.59)

The Average hydraulic output at a site with an average wind speed can be calculated as given by (E.H. Lysen, 1983)

$$P_{hydr} = 0.1 \times A \times V^3 \tag{6.4}$$

The hydraulic power needed to lift the water from the source to an overhead tank can be calculated as follows:

$$\text{Hydraulic Power} = \rho_w \times g \times Q \times H \tag{6.5}$$

By equating equations 6.4 and 6.5 the flow of water pumped over a head of H meter by the hydraulic power P_{hydr} is given by:

$$Q\left(\frac{m^3}{s}\right) = \frac{P_{hydr}}{\rho_w \times g \times H} \tag{6.6}$$

This expression can be reduced to:

$$Q\left(\frac{m^3}{day}\right) = \frac{0.69 \times d^2 \times V^3}{H} \tag{6.7}$$

6.7 Simulation of Hybrid Water Pumping System at Different Head Level

MATLAB program has been written for hybrid system / wind and solar pump working together /. The computer program is written for the two pumps to give the demand of water equal to or greater than 20 m^3/day. In this section, the simulation results of all selected sites are discussed in detail.

6.7.1 Scenario one: Simulation Result for Atsbi Site / High Solar and Medium Wind site/ at 50, 75 and 100 m Head.

From Tigray region Atsbi was selected to represent high solar radiation and high wind speed site. The annual average solar radiation on horizontal surface for this site is 6.73 kWh/m^2/day and annual average wind speed at 10 m is equal to 4.3 m/s. Table 6-7 and figure 6-7 below shows the cumulative discharge of the hybrid system in Atsbi site at 50, 75 and 100 m head. Figure 6-8 also shows monthly average discharge of the site.

Table 6-7 Total and cumulative discharge of Atsbi site at different head level

Months	**Cumulative Discharge (Q_T) in m^3**			**Cumulative Demand (Q_D) in m^3**
	50 m	**75 m**	**100 m**	
Jan	744	745	745	620
Feb	1446	1448	1447	1180
Mar	2232	2235	2234	1800
Apr	2917	2921	2920	2400
May	3490	3494	3493	3020
Jun	4351	4356	4355	3620
Jul	5301	5307	5305	4240
Aug	6099	6107	6105	4860
Sep	6711	6719	6717	5460
Oct	7174	7182	7180	6080
Nov	7677	7685	7683	6680
Dec	8270	8279	8277	7300

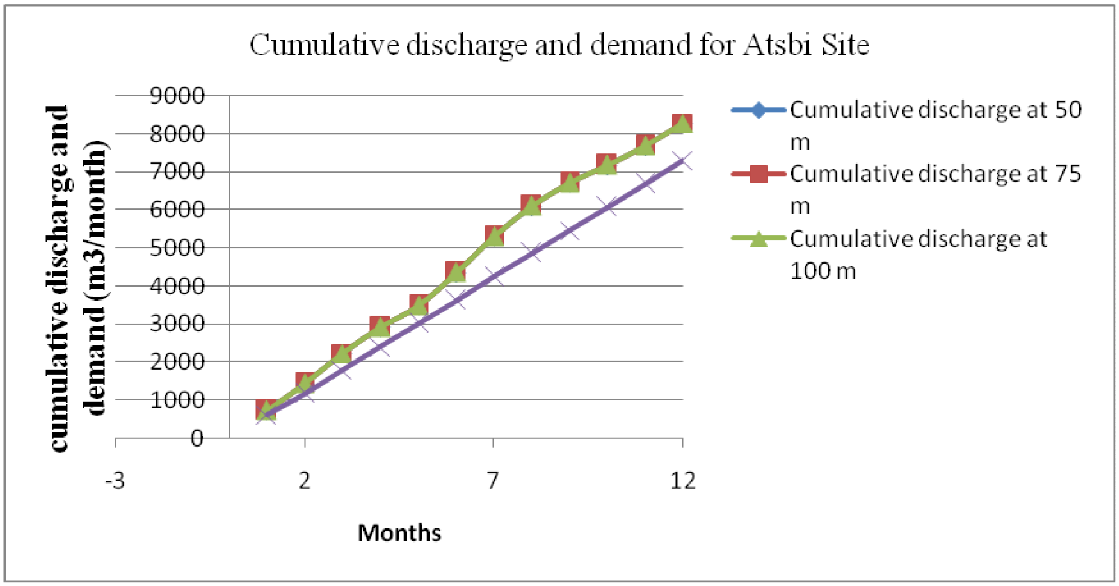


Figure 6-7 Cumulative discharge and demand for Atsbi site at different head level

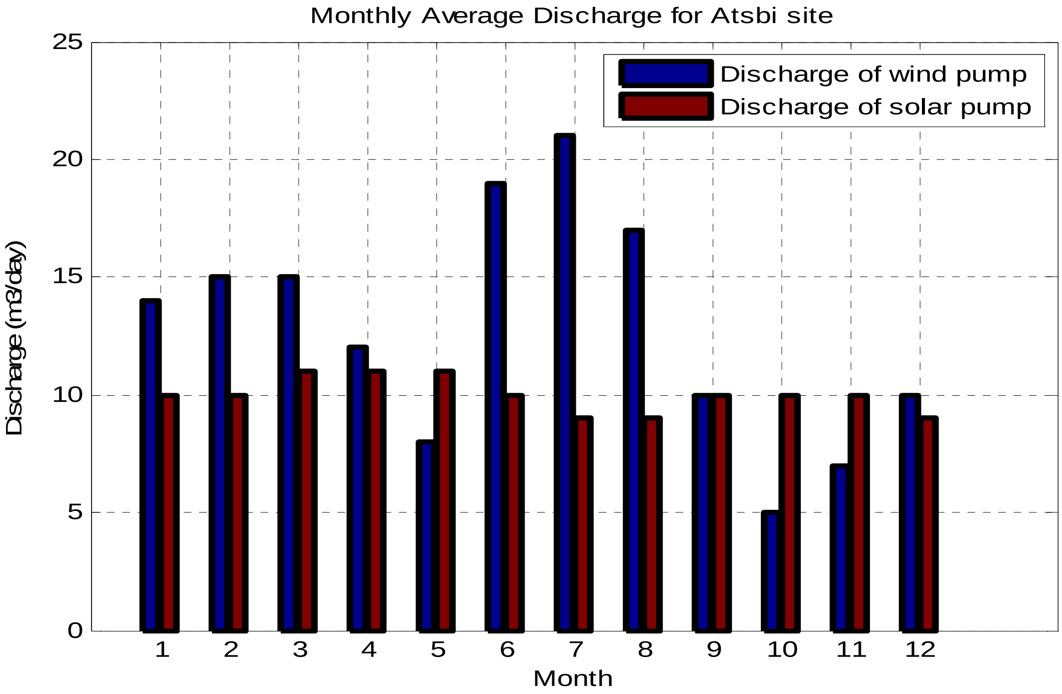


Figure 6-8 Monthly average discharge for Atsbi site at 50m

As shown in table 6-16 the total water supply is equal to 8270, 8279 and 8277 m^3/ annual for 50 , 75 and 100 m head respectively. As we have seen from simulation result the monthly average discharge and cumulative discharge of the site is almost the same in all head level.

6.7.2 Scenario Two: Simulation Result for Awash Fentale site / high Solar and Low Wind site/ at 50, 75 and 100 m Head.

In this scenario the site has good solar radiation and low wind speed. The annual average solar radiation for Awash Fentale site is 6.42 kWh/m^2/day and the annual average wind speed is equal to 2.89 m/s. As shown in table 6-8 the total water supply is equal to 8148, 8150 and 8149 m^3/annual at 50, 75 and 100 m head respectively. Therefore, the surplus water can be used for animal watering. Figure 6-9 and figure 6-10 shows the cumulative discharge and monthly average discharge of Awash Fentale site respectively.

Table 6-8 Cumulative discharge at different head level for Awash Fentale site

Months	**Cumulative Discharge (Q_T) in m^3**			**Cumulative Demand (Q_D) in m^3**
	50 m	**75 m**	**100 m**	
Jan	904	905	904	620
Feb	1622	1623	1622	1180
Mar	2359	2360	2360	1800
Apr	3083	3084	3083	2400
May	3754	3755	3755	3020
Jun	4386	4387	4387	3620
Jul	4893	4894	4894	4240
Aug	5344	5346	5345	4860
Sep	5809	5811	5810	5460
Oct	6471	6473	6472	6080
Nov	7269	7272	7271	6680
Dec	8148	8150	8149	7300

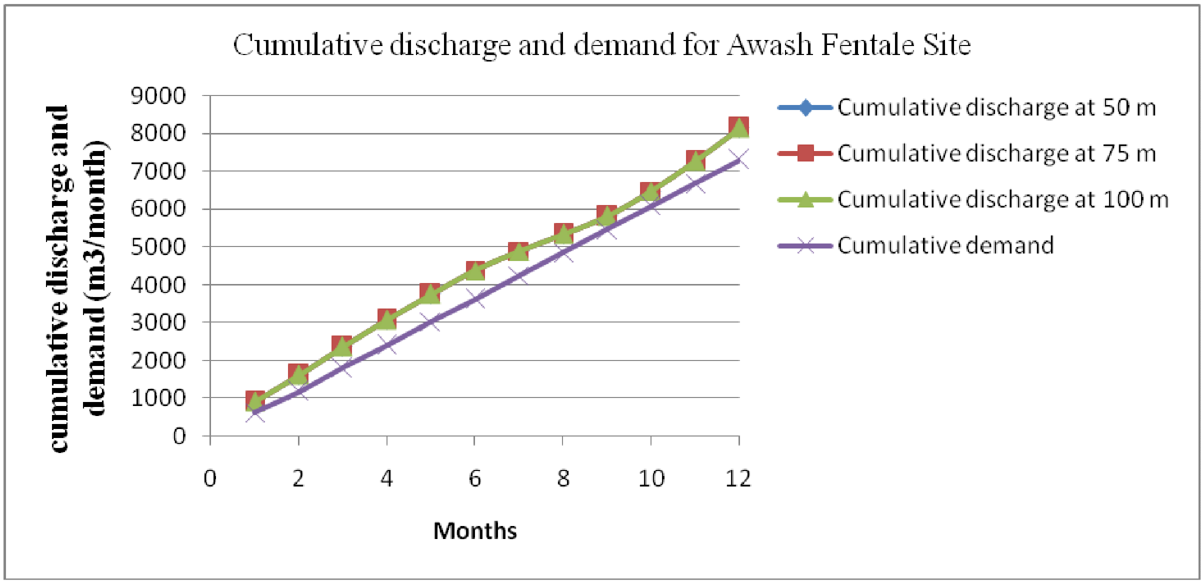


Figure 6-9 Cumulative discharge of Awash Fentale site at different head level

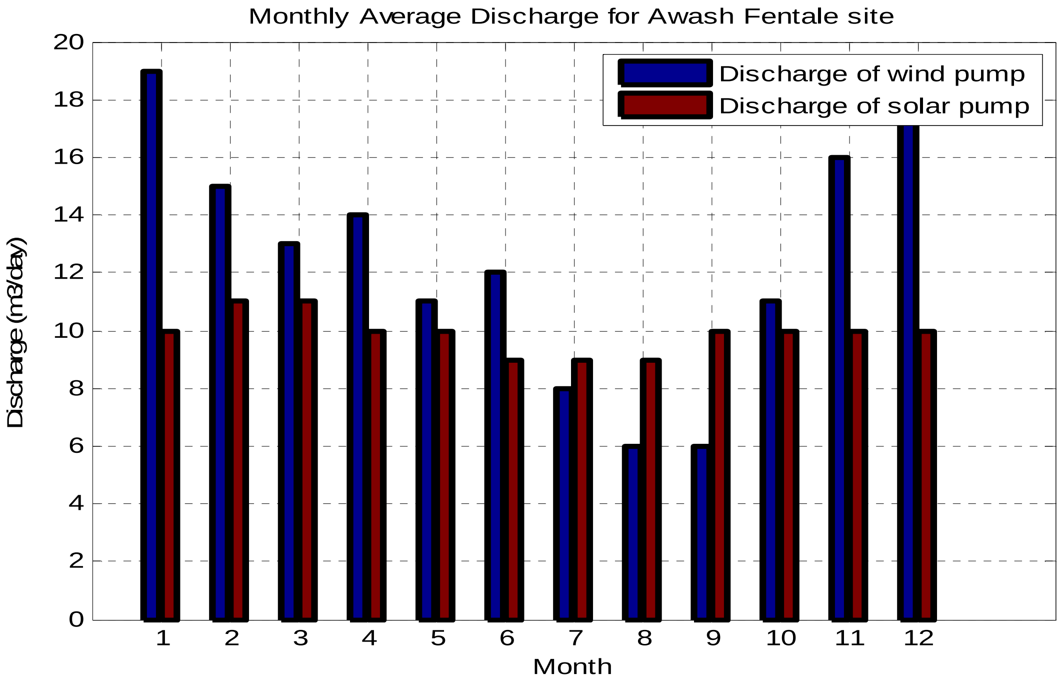


Figure 6-10 Monthly average discharge for Awash Fentale site

Even if the wind speed is low, the cumulative discharge of the site is greater than the cumulative demand throughout the year.

6.7.3 Scenario three: Simulation Result for Borena site / medium Solar and Wind site / at 50, 75 and 100 m Head.

In this scenario Borena site selected from Oromia region with annual average solar radiation 5.53 kWh/m^2/day and annual average wind speed 3.5m/s. Table 6-9 show that the total water pumped by solar and wind water pumping system is equal to 8053, 8052 and 8053 m^3/ annual at 50, 75 and 100m head respectively.

Table 6-9 Cumulative discharge at different head level for Borena site

Months	**Cumulative Discharge (Q_T) in m^3**			**Cumulative Demand (Q_D) in m^3**
	50 m	**75 m**	**100 m**	
Jan	822	822	822	620
Feb	1549	1549	1549	1180
Mar	2270	2270	2270	1800
Apr	2885	2884	2885	2400
May	3525	3525	3525	3020
Jun	4120	4119	4119	3620
Jul	4744	4744	4744	4240
Aug	5357	5356	5357	4860
Sep	5974	5973	5974	5460
Oct	6584	6583	6583	6080
Nov	7245	7244	7245	6680
Dec	8053	8052	8053	7300

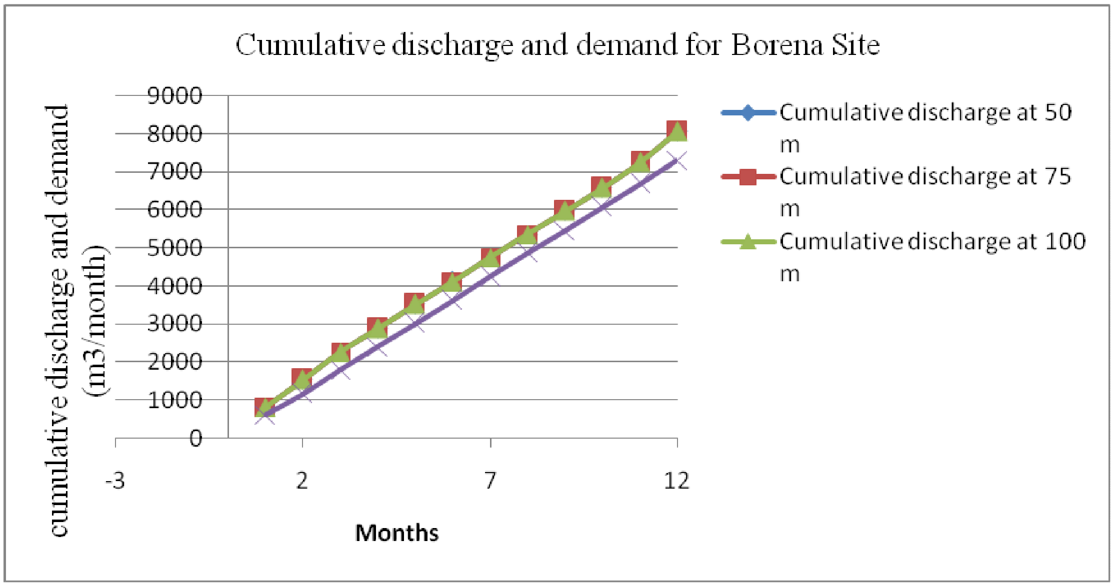


Figure 6-11 Cumulative discharge of Borena site at different head level.

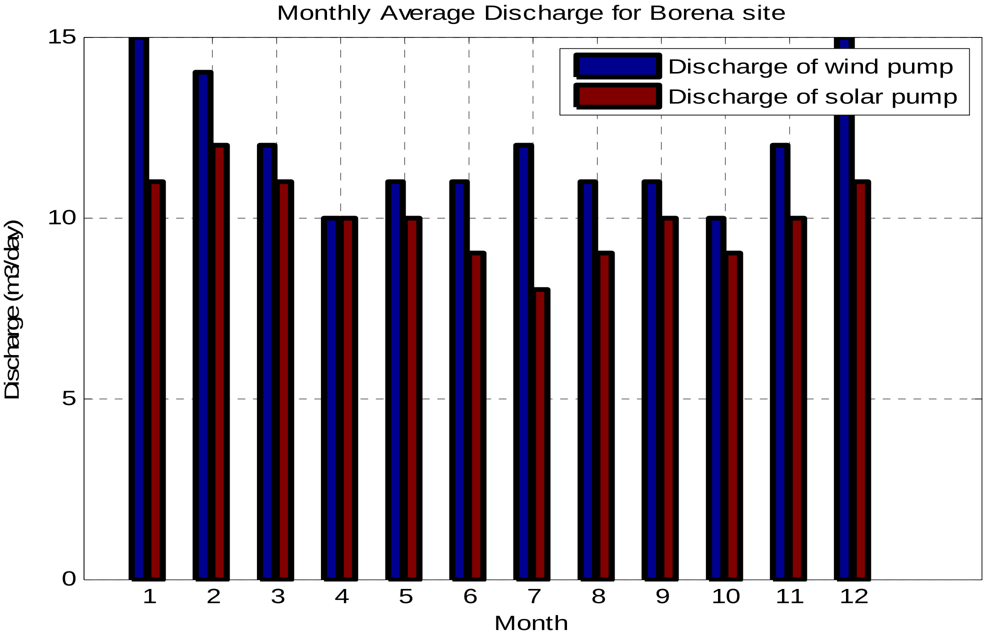


Figure 6-12 Monthly average discharge for Borena site

6.7.4 Scenario four: Simulation Result for Adami Tulu site / medium Solar and low Wind site/ at 50, 75 and 100 m Head.

In this section, Adami Tulu site selected from Oromia region to represent the site with medium solar radiation and low wind speed. Adami Tulu has annual average solar radiation 5.96 kWh/m^2/day and annual average wind speed 2.96 m/s. Table 6-10 show that the total water pumped by solar and wind water pumping system is 8071, and m^3/annual at 50, 75 and 100m. Figure 6-13 and 6-14 show that the monthly average discharges and cumulative discharge and demand respectively.

Table 6-10 Cumulative discharge at different head level for Adami Tulu

Months	**Cumulative Discharge (Q_T) in m^3**			**Cumulative Demand (Q_D) in m^3**
	50 m	**75 m**	**100 m**	
Jan	949	949	949	620
Feb	1676	1676	1676	1180
Mar	2403	2404	2403	1800
Apr	3118	3119	3118	2400
May	3790	3792	3790	3020
Jun	4400	4402	4400	3620
Jul	4881	4882	4881	4240
Aug	5325	5327	5325	4860
Sep	5804	5806	5804	5460
Oct	6463	6466	6463	6080
Nov	7282	7285	7282	6680
Dec	8225	8227	8225	7300

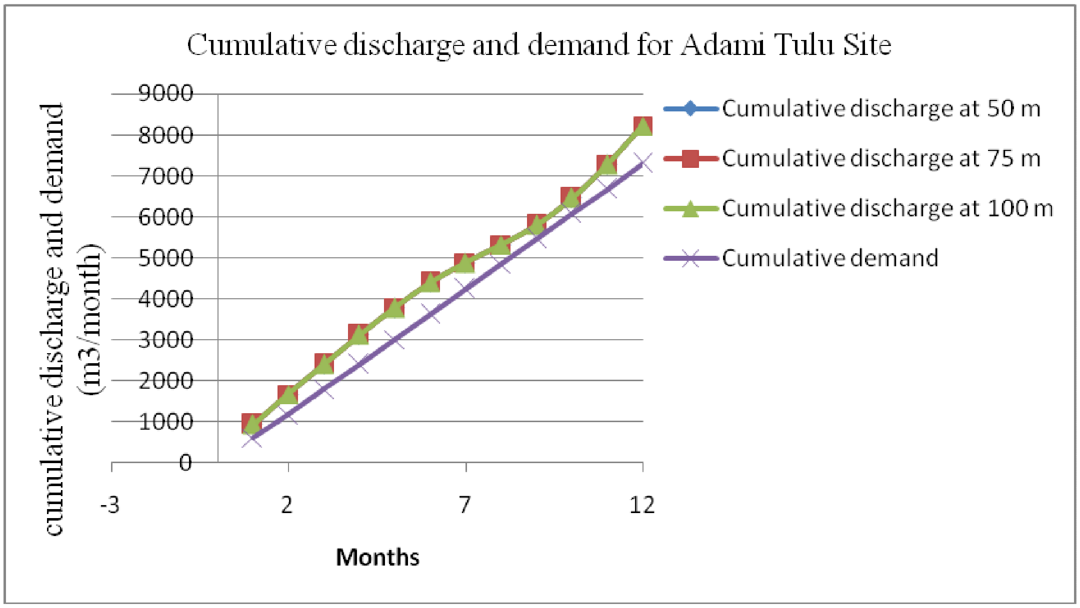


Figure 6-13 Cumulative discharge of Adami Tulu site at different head level

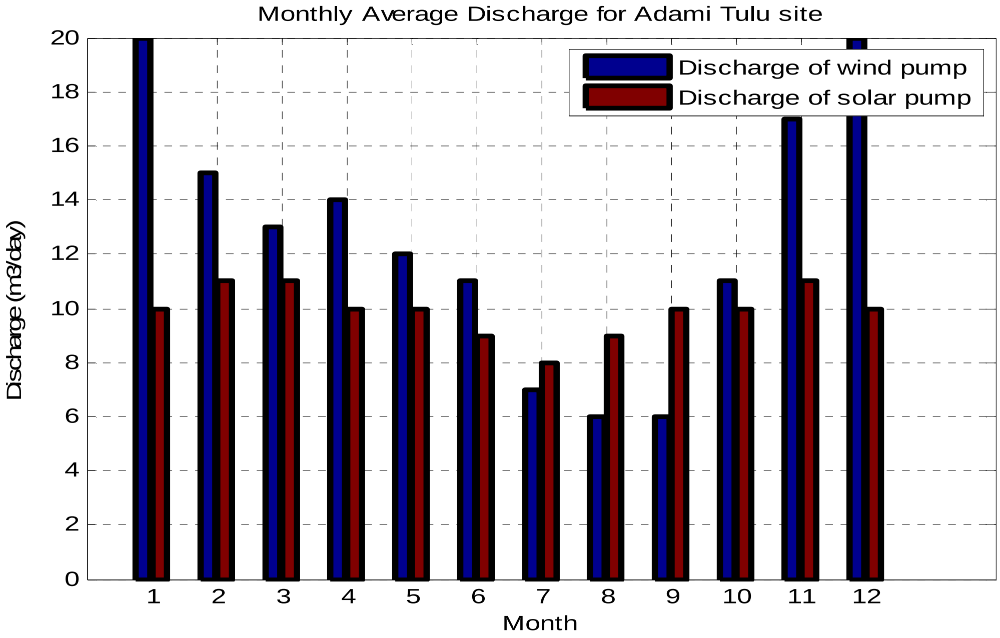


Figure 6- 14 Monthly average discharge for Adami Tulu site

6.8 Cumulative discharge for all selected site

In the previous section, the simulation of hybrid water pumping system was done by selecting different head (minimum, medium and large head) for each selected sites. Table 6-11 shows annual water discharge at different head level for each selected site.

Table 6-11 Annual discharge for all selected site at different head

Sites	**Annual discharge in m^3**			**Annual Demand in m^3**
	50 m	**75 m**	**100 m**	
Atsbi (high solar and medium wind)	8270	8279	8277	7300
Borena (medium solar and medium wind site)	8053	8052	8053	7300
Awash Fentale (high solar and low wind site)	8148	8150	8149	7300
Adami Tulu (medium solar and low wind site)	8225	8227	8225	7300

As we have seen from the simulation result the cumulative discharge of each site is the same in all head. However, based on the design result different solar and wind pumps are selected for each head.

CHAPTER SEVEN

ECONOMIC ANALYSIS FOR HYBRID WATER PUMPING SYSTEM

7.1 Life Cycle Cost Analysis Method

While there are many kinds of comparative economic analysis methods, the life cycle cost analysis is a convenient method for assessing the relative costs of different pumping systems. This method analyzed all costs associated with installation and the use of the pumping system by reducing them to a single number called the annualized life cycle cost. Dividing annualized life cycle cost by the total volume of water pumped over the system's lifetime, gives a unit cost for water pumped. To make direct financial and economic comparison between the two or more pumping system, the unit costs must be calculated. In this Research, the solar/wind hybrid water pumping system compared with standalone PV and windmill water pumping system.

- **Methodology**

The following economic assumption made during life cycle cost analysis. Generally speaking, Table 7-1show the assumptions made during economic analysis.

Table 7-1 Different Assumption for each System

Parameters	Values
Interest rate (%)	5
Discount rate (%)	10
Life time of PV and windmill (years)	20
PV operation and maintenance (1%) of the capital cost	1
Windmill operation and maintenance (10%) of the capital cost	10

7.2 Calculation of cost of m^3 of water for hybrid and standalone windmill and PV water pumping system

As we have discussed in chapter 4 and 5 Cost of m^3 of water is determined by dividing annualized life cycle cost of the system to the total pumped water. The hybrid pumping system depends mainly on wind and solar pump. Therefore, the total annualized life cycle cost for the hybrid system is the sum of annualized cost of PV and windmill system.

In this financial analysis the cost of m^3 of water for hybrid system is also compared with standalone PV and Windmill water pumping system. The following tables show the total initial investment cost, annualized life cycle cost and cost of m^3 of water for hybrid and standalone windmill and PV system.

Table 7-2 Total initial investment cost of PV system for Atsbi site in USD

Pump	**50m head**	**75 m head**	**100 m head**
PV module			
Total Module cost	1171.9	1757.9	2343.8
Cost of pump	2050.0	2050.0	2050.0
Supporting structure cost	44.8	67.2	89.6
Subtotal cost	3266.7	3875.1	4483.4
Wiring and other miscellaneous (20% of the subtotal cost to BOS)	653.3	775.0	896.7
Total initial cost for PV system	**3920.0**	**4650.1**	**5380.1**

Table 7-3 Annuity and water cost calculation of PV system for Atsbi site in USD

Annualized life cycle cost for Atsbi site			
Pump	**50 m head**	**75 m head**	**100 m head**
PV system			
Annualized capital cost	460.41	546.15	631.89
Operation and maintenance cost	29.13	34.55	39.97
Replacement cost	79.03	79.03	79.03
Annualized life cycle cost for PV system	568.56	659.73	750.89
Annual water pumped	7295.21	7295.21	7295.21
Water cost for PV system ($/m^3)	**0.08**	**0.09**	**0.10**

Table 7-4 Total initial investment cost of windmill system for Atsbi site in USD

Pump	**50m head**	**75 m head**	**100 m head**
Windmill system			
Capital Cost (CC) of windmill heads and pump	1456.0	3626.0	5782.0
Windmill tower cost	1651.2	1651.2	1651.2
Subtotal Capital	3107.2	5277.2	7433.2
Other miscellaneous (20% of the CC or BOS)	621.4	1055.4	1486.6
Total initial cost for windmill system	3728.7	6332.7	8919.9

Table 7- 5 Annuity and water cost calculation of windmill system for Atsbi site in USD

Annualized life cycle cost for Atsbi site windmill pump			
Pump	**50 m head**	**75 m head**	**100 m head**
Wind pump			
Annualized capital cost	437.93	743.77	1047.64
Operation and maintenance cost	27.70	47.05	66.27
Annualized life cycle cost for windmill system	465.64	790.82	1113.91
Annual water pumped	10806.41	10806.49	10806.46
Water cost for windmill (\$/m^3)	**0.04**	**0.07**	**0.10**

Table 7-6 Total initial investment cost of hybrid system for Atsbi site in USD

Pump	50 m head	75 m head	100 m head
PV system			
Total module cost	585.9	878.9	1171.9
Cost of pump	2050.0	2050.0	2050.0
Support structure cost	22.4	33.6	44.8
Subtotal cost	2658.3	2962.5	3266.7
Wiring and other miscellaneous	531.7	592.5	653.3
Total capital cost of PV system	3190.0	3555.0	3920.0
Windmill system			
Capital cost (CC) of windmill heads and pump	843.0	1127.0	1456.0
Windmill tower cost	897.0	897.0	1651.2
Subtotal cost	1740.0	2024.0	3107.2
Other miscellaneous (20% of the CC or BOS)	348.0	404.8	621.4
Total capital cost for windmill	2088.0	2428.8	3728.7

Table 7-7 Annuity and water cost calculation of hybrid system for Atsbi site (USD).

Annualized life cycle cost for Atsbi Site			
Pump	50 m head	75 m head	100 m head
PV system			
Annualized capital cost	374.67	417.54	460.41
Operation and maintenance cost	23.70	26.41	29.13
Replacement cost	79.03	79.03	79.03
Annualized life cycle cost for PV system	477.40	522.98	568.56
Windmill system			
Annualized capital cost	245.24	285.26	437.93
Operation and maintenance cost	15.51	18.05	27.70
Annualized life cycle cost for windmill system	260.75	303.31	465.64
Total annualized life cycle cost for hybrid system	738.15	826.29	1034.20
Water pumped per year (m^3/year)	8270.22	8279.34	8276.84
Water cost for hybrid system (\$/m^3)	**0.09**	**0.10**	**0.12**
Water cost for hybrid system (ETB/m^3)	**1.90**	**2.13**	**2.67**

Table 7-8 Total initial investment cost of PV systemfor Awash Fentale site (USD)

pump	50m head	75 m head	100 m head
PV module Cost			
Total cost of the Module	1177.70	1766.60	2355.43
Cost of pump ($)	2050.00	2050.00	2050.00
Support structure cost	44.80	67.20	89.60
Subtotal cost	3272.50	3883.80	4495.03
Wiring and Other miscellaneous (20% of the subtotal cost to BOS)	654.50	776.76	899.01
Total initial cost for PV	3927.00	4660.56	5394.04

Table 7-9 Annuity and water cost calculation of PV system for Awash Fentale site (USD).

Annualized life cycle cost for Awash Fentale site			
Pump	50 m head	75 m head	100 m head
PV system			
Annualized capital cost	461.23	547.38	633.53
Operation and maintenance cost	29.18	34.63	40.08
Replacement cost	79.03	79.03	79.03
Annualized life cycle cost for PV system	569.43	661.04	752.63
Annual water pumped	7256.98	7256.98	7256.98
Water cost for PV system ($/m^3)	**0.08**	**0.09**	**0.10**

Table 7-10 Total initial investment cost of windmill system for Awash Fentale site (USD)

Pump	50m head	75 m head	100 m head
Windmill system			
Capital Cost (CC) of windmill heads and pump and including tower	6468.00	10000.00	11000.00
Windmill Tower cost	1931.00	-	-
Subtotal Capital	8399.00	10000.00	11000.00
Other miscellaneous (20% of the CC or BOS)	1679.80	2000.00	2200.00
Total initial cost for windmill	10078.80	12000.00	13200.00

Table 7-11 Annuity and water cost calculation of windmill system for Awash Fentale site (USD).

Annualized life cycle cost for Awash Fentale site			
Pump	50 m head	75 m head	100 m head
Windmill			
Annualized capital cost	1183.76	1409.40	1550.34
Operation and maintenance cost	74.89	89.16	98.08
Annualized life cycle cost for windmill system	1258.64	1498.56	1648.42
Annual water pumped	10551.66	10551.65	10551.65
Water cost for windmill ($/m3)	**0.12**	**0.14**	**0.16**

Table 7-12 Total initial investment cost of hybrid system (USD) for Awash Fentale site

hybrid water pumping system for Awash fentale Site			
Pump	50 m head	75 m head	100 m head
PV system			
Total module cost	588.85	883.30	1177.72
Cost of solar pump	2050.00	2050.00	2050.00
Support structure cost	22.40	33.60	44.80
Subtotal cost	2661.25	2966.90	3272.52
Wiring and Other miscellaneous	532.25	593.38	654.50
Total capital cost of PV system	3193.50	3560.28	3927.02
Windmill System			
Capital Cost (CC) of windmill heads and pump	3626.00	5782.00	6468.00
Windmill Tower cost	1931.00	1931.00	1931.00
Subtotal Cost	5557.00	7713.00	8399.00
Other miscellaneous (20% of the CC or BOS)	1111.40	1542.60	1679.80
Total initial cost for windmill	6668.40	9255.60	10078.80

Table 7-13 Annuity and water cost calculation of hybrid system for Awash Fentale site (USD).

Annualized life cycle cost for Awash Fentale Site			
Pump	50 m head	75 m head	100 m head
PV system			
Annualized capital cost	375.08	418.15	461.23
Operation and maintenance cost	23.73	26.45	29.18
Replacement cost	79.03	79.03	79.03
Annualized life cycle cost for PV system	477.83	523.64	569.43
Windmill system			
Annualized capital cost	783.20	1087.07	1183.76
Operation and maintenance cost	49.55	68.77	74.89
Annualized life cycle cost for windmill system	832.75	1155.84	1258.64
Total annualized life cycle cost for hybrid system	1310.58	1679.47	1828.07
Water pumped per year (m^3/year)	8147.74	8150.41	8149.37
Water cost for hybrid system (USD/m^3)	**0.16**	**0.21**	**0.22**
Water cost for hybrid system (Birr/m^3)	**3.43**	**4.40**	**4.79**

Table 7-14 Total initial investment cost of PV system for Borena site (USD)

pump	50m head	75 m head	100 m head
PV system			
Total module cost	1263.34	2871.50	3828.30
Cost of pump	2050.00	2050.00	2050.00
Support structure cost	44.80	67.20	89.60
Subtotal cost	3358.14	4988.70	5967.90
Wiring and Other miscellaneous (20% of the subtotal cost to BOS)	671.63	997.74	1193.58
Total initial cost for PV system	4029.77	5986.44	7161.48

Table 7-15 Annuity and water cost calculation of PV system for Borena site (USD).

Pump	50 m head	75 m head	100 m head
PV system			
Annualized capital cost	473.30	703.11	841.12
Operation and maintenance cost	29.94	44.48	53.21
Replacement cost	79.03	79.03	79.03
Annualized life cycle cost for PV system	582.26	826.61	973.35
Annual water pumped	7293.00	7292.45	7292.59
Water cost for PV system ($\$/m^3$)	**0.08**	**0.11**	**0.13**

Table 7-16 Total initial investment cost of windmill system ($) for Borena site

Wind pump	50m head	75 m head	100 m head
Windmill Cost			
Capital Cost (CC) of windmill heads and pump	5782.00	6468.00	10000.00
windmill Tower cost	1931.00	1651.23	0.00
Total Capital	7713.00	8119.23	10000.00
Other miscellaneous (20% of the CC or BOS)	1542.60	1623.85	2000.00
Total initial cost for windmill	9255.60	9743.08	12000.00

Table 7-17 Annuity and water cost calculation of windmill system for Borena site

Annualized life cycle cost for Borena site windmill pump			
Pump	50 m head	75 m head	100 m head
Windmill system			
Annualized capital cost	1087.07	1144.32	1409.40
Operation and maintenance cost	68.77	72.39	89.16
Annualized life cycle cost for windmill system	1155.84	1216.72	1498.56
Annual water pumped	10280.00	10282.20	10282.10
Water cost for windmill ($/m3)	**0.11**	**0.12**	**0.15**

Table 7-18 Total initial investment cost of hybrid system for Borena site

Hybrid water pumping system for Borena Site			
pump	50 m head	75 m head	100 m head
PV system			
Total module cost	631.67	1435.75	1914.15
Cost of pump	2050.00	2050.00	2050.00
Supporting structure cost	22.40	33.60	44.80
Subtotal cost	2704.07	3519.35	4008.95
Wiring and Other miscellaneous	540.81	703.87	801.79
Total capital cost of PV system	3244.88	4223.22	4810.74
Windmill System			
Capital Cost (CC) of windmill heads and pump	1127.00	1456.00	3626.00
Windmill Tower cost	897.00	1931.00	1931.00
Subtotal cost	2024.00	3387.00	5557.00
Other miscellaneous (20% of the CC or BOS)	404.80	677.40	1111.40
Total initial cost for windmill	2428.80	4064.40	6668.40

Table 7-19 Annuity and water cost calculation of hybrid system for Borena site

Annualized life cycle cost for Borena Site			
Pump	50 m head	75 m head	100 m head
PV system			
Annualized capital cost	381.11	496.02	565.02
Operation and maintenance cost	24.11	31.38	35.74
Replacement cost	79.03	79.03	79.03
Annualized life cycle cost for PV system	484.25	606.42	679.79
Windmill system			
Annualized capital cost	285.26	477.36	783.20
Operation and maintenance cost	18.05	30.20	49.55
Annualized life cycle cost for windmill system	303.31	507.56	832.75
Total annualized life cycle cost for hybrid system	787.56	1113.99	1512.54
Water pumped per year (m^3/year)	8053.00	8051.00	8052.00
Water cost for hybrid system (\$/m^3)	**0.10**	**0.14**	**0.19**
Water cost for hybrid system (ETB/m^3)	**2.09**	**2.95**	**4.01**

Table 7-20 Total initial investment cost of PV system for Adami Tulu site (USD)

pump	50m head	75 m head	100 m head
PV system			
Total module cost	1222.00	1833.11	2444.20
Cost of pump	2050.00	2050.00	2050.00
Support structure cost	44.80	67.20	89.60
Subtotal cost	3316.80	3950.31	4583.80
Wiring and Other miscellaneous (20% of the subtotal cost to BOS)	663.36	790.06	916.76
Total initial cost for PV system	3980.16	4740.37	5500.56

Table 7-21 Annuity and water cost calculation of PV system for Adami Tulu site (USD).

Pump	50 m head	75 m head	100 m head
PV system			
Annualized capital cost	467.47	556.76	646.04
Operation and maintenance cost	29.57	35.22	40.87
Replacement cost	79.03	79.03	79.03
Annualized life cycle cost for PV system	576.07	671.01	765.94
Annual water pumped	7239.55	7245.23	7239.55
Water cost for PV system ($/m3)	**0.08**	**0.09**	**0.10**

Table 7-22 Total initial investment cost of windmill system ($) for Adami Tulu site

Pump	50m head	75 m head	100 m head
Windmill system			
Capital Cost (CC) of windmill heads and pump	6468.00	10000.00	11000.00
Windmill Tower cost	1931.00	-	-
Subtotal cost	8399.00	10000.00	11000.00
Other miscellaneous (20% of the CC or BOS)	1679.80	2000.00	2200.00
Total initial cost for windmill	10078.80	12000.00	13200.00

Table 7-23 Annuity and water cost calculation of windmill system for Adami Tulu site (USD).

Pump	50 m head	75 m head	100 m head
Windmill system			
Annualized capital cost	1183.76	1409.40	1550.34
Operation and maintenance cost	74.89	89.16	98.08
Annualized life cycle cost for windmill system	1258.64	1498.56	1648.42
Annual water pumped	10727.00	10744.00	10737.00
Water cost for windmill ($/m^3)	**0.12**	**0.14**	**0.15**

Table 7-24 Total initial investment cost of hybrid system ($) for Adami Tulu site

pump	50 m head	75 m head	100 m head
PV system			
Total module cost	611.00	916.56	1222.10
Cost of pump	2050.00	2050.00	2050.00
Support structure cost	22.40	33.60	44.80
Subtotal cost	2683.40	3000.16	3316.90
Wiring and Other miscellaneous	536.68	600.03	663.38
Total capital cost of PV	3220.08	3600.19	3980.28
Windmill System			
Capital Cost (CC) of windmill heads and pump	3626.00	5782.00	6468.00
Windmill tower cost	1931.00	1931.00	1931.00
Subtotal cost	5557.00	7713.00	8399.00
Other miscellaneous (20% of the CC or BOS)	1111.40	1542.60	1679.80
Total capital cost for windmill	6668.40	9255.60	10078.80

Table 7-25 Annuity and water cost calculation of hybrid system for Adami Tulu site (USD).

Pump	50 m head	75 m head	100 m head
PV system			
Annualized capital cost	378.20	422.84	467.48
Operation and maintenance cost	23.93	26.75	29.57
Replacement cost	79.03	79.03	79.03
Annualized life cycle cost for PV system	481.15	528.62	576.08
Windmill system			
Annualized capital cost	783.20	1087.07	1183.76
Operation and maintenance cost	49.55	68.77	74.89
Annualized life cycle cost for windmill system	832.75	1155.84	1258.64
Total annualized life cycle cost for hybrid system	1313.90	1684.46	1834.73
Water pumped per year (m^3/year)	8225.00	8227.00	8225.00
Water cost for hybrid system (\$/m^3)	**0.16**	**0.20**	**0.22**
Water cost for hybrid system (ETB/m^3)	**3.41**	**4.37**	**4.76**

7.3 Financial summary

Table 7-26 below shows cost of m^3 of water pumped using hybrid, standalone PV and windmill system for all site at different head level. To make direct economic comparison between the two or more pumping system, the unit costs must be calculated.

Table 7- 26 Cost of m^3 of water for all selected site at different head level

Site		**PV System**			**Windmill System**			**Hybrid System**		
		50m	75m	100m	50m	75m	100m	50m	75m	100m
High solar and medium wind (Atsbi site)	**Cost (USD/m^3)**	0.08	0.09	0.10	0.04	0.07	0.10	0.09	0.10	0.12
High solar and low wind (Awash Fentale)	**Cost (USD/m^3)**	0.08	0.09	0.10	0.12	0.14	0.16	0.16	0.21	0.22
Medium solar and wind (Borena)	**Cost (USD/m^3)**	0.08	0.11	0.13	0.11	0.12	0.15	0.11	0.14	0.19
Medium solar and low wind (Adami Tulu)	**Cost (USD/m^3)**	0.08	0.09	0.10	0.12	0.14	0.15	0.16	0.20	0.22

Based on the result of financial analysis standalone PV system is more feasible than windmill and hybrid system in most selected areas. However, in Atsbi site windmill system is feasible than PV and hybrid system because the average wind speed is greater than 4 m/s. Therefore, windmill system can be feasible for locations with average wind speed greater than 4m/s. According to the financial analysis the hybrid system is not feasible in all selected site.

CHAPTER EIGHT

CONCLUSION AND RECOMMENDATION

8.1 Conclusion

In simple terms what has been accomplished in this work is firstly the determination of solar and wind energy potentials at different sites in Ethiopia. Then, based on these potentials, a Viability of solar, wind and hybrid water pumping system conducted for a model community living in rural areas.

The viability of solar photovoltaic water pumping system has been investigated for three different sites in Ethiopia. The designed system is capable of providing a daily average of 10.5, 7 and 6.5 m^3/day for 700, 467 and 433 rural communities in Siadberand Wayu, Wolmera and Enderta sites respectively.

According to the simulation result, the selected PV size and pump power is able to provide 95%, 96.5% and 96.3% of water demand for the community of Siyadberand Wayu, Wolmera and Enderta sites respectively. From the result of economic analysis and comparison between SPV and diesel only system, we can conclude that the SPV water pumping system is more economical and feasible.

The viability study of wind powered water pumping system also conducted for three different sites in Ethiopia. The designed system having a capacity to supply a daily average water of 10, 12 and 15 m^3/day for 500, 600 and 1000 rural community in Siadberand Wayu, Adami Tulu and East Enderta sites, respectively. And the cost for pumping water is 0.06, 0.05 and 0.04 \$/m^3 respectively. If diesel generator is used instead of windmill, the unit cost of water become 0.08, 0.07 and 0.04 \$/m^3 respectively for the particular sites.

For wind water pumping system the result shows Enderta site satisfy monthly water demand of the community throughout the year. Whereas, there is 10% water missing in Siyadberand Wayu and Adami Tulu Site.

The feasibility study of hybrid water pumping system was carried out by selecting four sites from three different administration regions. According to the simulation result of the hybrid system, the cumulative discharge of all selected site in different head is higher that the cumulative demand.

The unit cost comparison between hybrid system and standalone PV and windmill system shows that PV only system is more economically feasible than the hybrid and windmill system in all sites. However, standalone windmill water pumping system is feasible in Atsbi site, because the wind energy potential is good in the site. The results of this study are encouraging for the use of PV system for drinking water supply in the remote areas of the country.

According to the result of financial analysis the unit cost of water pumped in hybrid system is greater than standalone PV and windmill water pumping system. Therefore, the hybrid system is not economically feasible as compared to standalone PV and windmill system. However, these hybrid systems are eco friendly and seek to preserve the environment by reducing pollution levels by a considerable amount when compared to diesel only system.

8.2 Recommendation

There are no metrological stations in remote areas of the country. Therefore, the solar radiation and wind speed data’s are collected from the nearby stations. The recommendation is that, to study the solar, wind and hybrid water pumping system in the future using on site data could give best result than using data from nearby station.

In this research, to minimize the overall operational, maintenance and replacement cost of the system, solar photovoltaic, Windmill and Hybrid water pumping system are designed without considering MPPT methods and batteries for energy storage. However, using MPPT and batteries storage system has its own advantage to maximize overall efficiency of the system.

Due to financial problem we cannot able to collect solar radiation and wind speed data for long period of time in the selected site. However, taking field data is very important to get best simulation results for the proposed system.

The capital cost of the system is high, therefore we are not able to implement and take an experimental data of the system. But, if the fund is available experimental data should be compared with the simulation result for better design of the system.

For solar and wind technologies to gain widespread acceptance by the communities and supporting structures, it is necessary to create the necessary awareness and demonstrate the operation of these systems in real life situation. There is also a need to encourage participation of the local private sector in the supply of equipment, spare parts and after sales services. However, without a critical mass of installed systems, solar or wind technologies will likely suffer from weak supply chains and a lack of private sector capacity for maintenance. Consequently, sustainability would remain low despite their many advantages.

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APPENDIXES

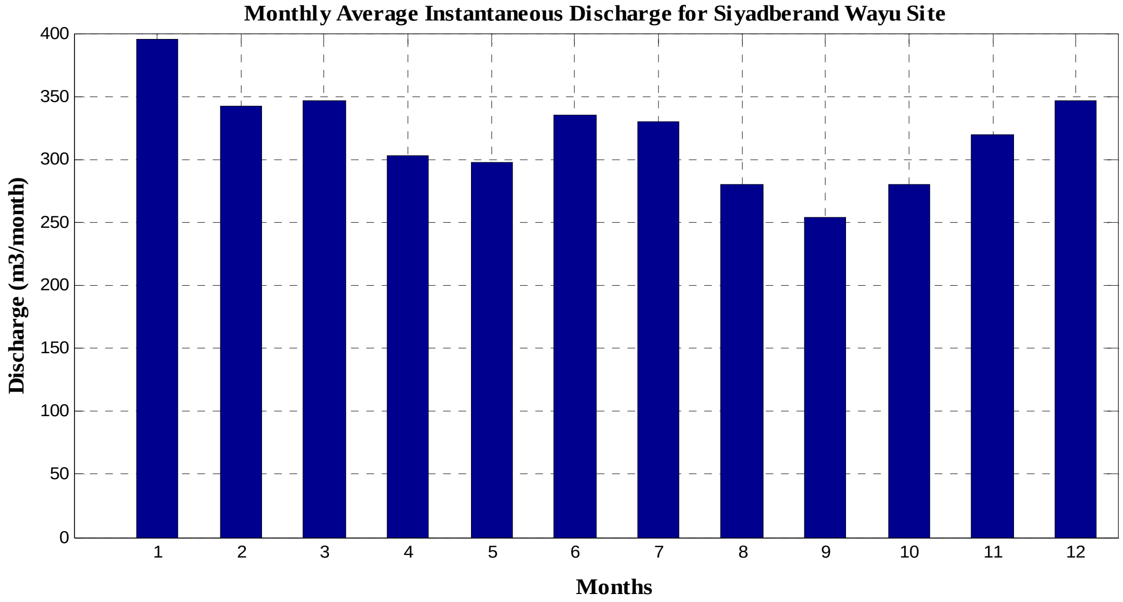
Appendix A: MATLAB Program for Instantaneous Discharge of Windmill Water Pumping

```
%-------------------------------------------------------------------
% Instantaneous discharge of windmill water pumping system for Amhara  region
%--------------------------------------------------------------------
h1=75;              % head in meter
g=9.81;             % gravity constant
rho_a1=0.92;        % density of air
rho_w=1000;          % density of water
Ar=23.76;            % area of rotor
eff=0.95;           % combined efficiency (for rotor and pump)
Cp=0.3;             % coefficient
Ko=0.25;             % coefficient
VI=3.2;             % cut in velocity (m/s)
VO=11;              % cut out velocity / the maximum possible velocity in the specific site/
Pi= 3.14;
n = [31 28 31 30 31 30 31 31 30 31 30 31];  % number of day in each month
v = [4.04 3.92 3.68 3.44 3.33 3.68 3.56 3.21 3.09 3.21 3.56 3.68]; % monthly average wind speed (m/s)
Qvpsiya=(2.*3600.*Cp.*eff.*(rho_a1./rho_w).*((Ar.*(v.^3))./(g.*h1)).*(1-
(Ko.*(Vi./v).^2)).*Ko.*(Vi./v).^2).*24.*n;       % multiplied by 3600 to convert from m3/s into m3/hr and
multiplied by ( 24*30) to convert from m3/hr into m3/month
width = 0.25;
bar (Qvpsiya), grid on
xlabel('Months')
ylabel('Discharge (m3/month)')
title ('Monthly Average Instantaneous discharge for Siyadberand Wayu Site')
hold off, pause
%--------------------------------------------------------------------
% Instantaneous discharge of windmill water pumping system for Oromia region
%-------------------------------------------------------------------
h2=66.58;           % head in meter
g=9.81;             % gravity constant
rho_a2=1.024;       % density of air
```

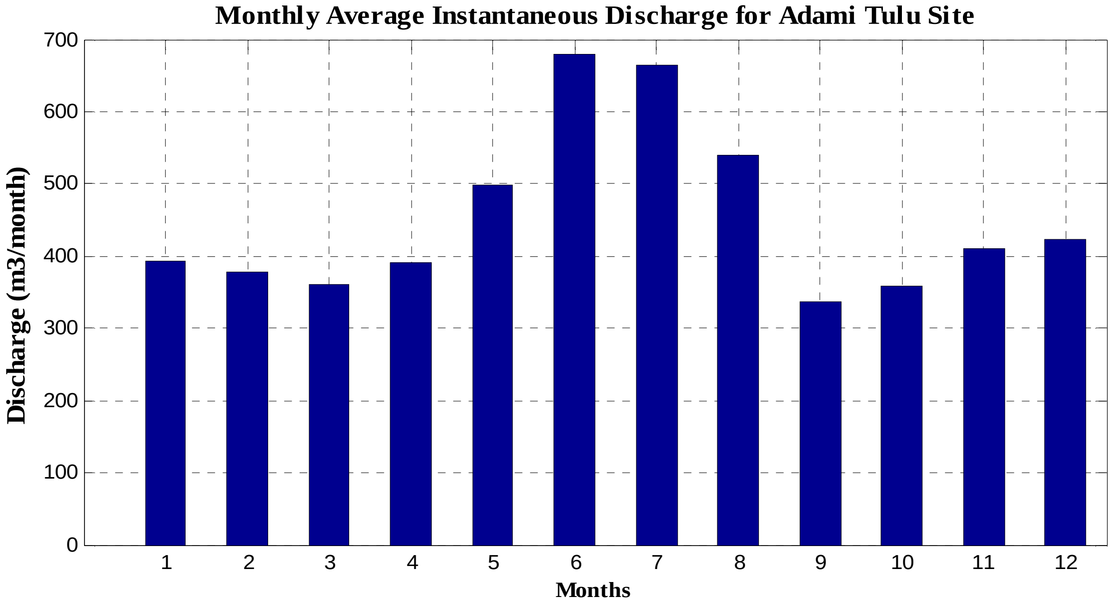
```
n = [31 28 31 30 31 30 31 31 30 31 30 31];
v = [3.44 3.59 3.26 3.51 4.06 5.30 5.07 4.30 3.20 3.25 3.62 3.62];
Qvpadami=(2.*Cp.*eff.*(rho_a2./rho_w).*((Ar.*(v.^3))./(g.*h2)).*(1-
(Ko.*(Vi./v).^2)).*Ko.*(Vi./v).^2).*3600.*24.*n;           % multiplied by 3600 to convert from m3/s into
m3/hr
bar(Qvpadami), grid on
xlabel('Months')
ylabel('Discharge (m3/month)')
title('Monthly Average Instantaneous discharge for Adami Tulu Site')
hold off, pause
%---------------------------------------------------------------------
% Instantaneous discharge of windmill water pumping system for Tigray  region
%---------------------------------------------------------------------
h3=44;                  % head in meter
g=9.81;                 % gravity constant
rho_a3=0.992;           % density of air
n = [31 28 31 30 31 30 31 31 30 31 30 31];
v = [3.96 5.46 6.06 6.00 4.58 3.73 3.05 2.99 3.22 4.42 4.89 4.41];
Qvpenderta=(2.*Cp.*eff.*(rho_a3./rho_w).*((Ar.*(v.^3))./(g.*h3)).*(1-
(Ko.*(Vi./v).^2)).*Ko.*(Vi./v).^2).*3600.*24.*n;           % multiplied by 3600 to convert from m3/s into
m3/hr
bar (Qvpenderta), grid on
xlabel('Months')
ylabel('Discharge (m3/month)')
title ('Monthly Average Instantaneous discharge for East Enderta Site')
hold off, pause
%---------------------------------------------------------------------
%The Monthly Average Discharge For All Three Selected Sites
%---------------------------------------------------------------------
x= [395.5322 590.887    707.2
342.6349    701.3165    962.1
346.5323    761.7935    1203.1
302.9310    725.3746    1151.1
297.4014    888.152     858.2
335.3538    632.2952    628.6
329.8755    317.2593    471.8
280.1304    307.3674    455.4
254.1291    413.7349    500.8
```

```
280.1304    650.8864    819.7
319.2343    544.9651    901.8
346.5323    564.3962    817.3];
hold off, pause
width = 0.5;
bar3(x,width), grid on
xlabel('Months')
ylabel('Discharge (m3/month)')
title ('Monthly Average Instantaneous Discharge for for the selected Site')
hold off, pause
bar(x, 'grouped','linewidth',1.5), grid on
xlabel('Month')
ylabel('Discharge (m3/month)')
title ('monthly average discharge for the Selected three sites (m3/month)')
legend ( 'Siyadbarand Wayu Site','Adami Tulu Site','East Enderta Site')
```

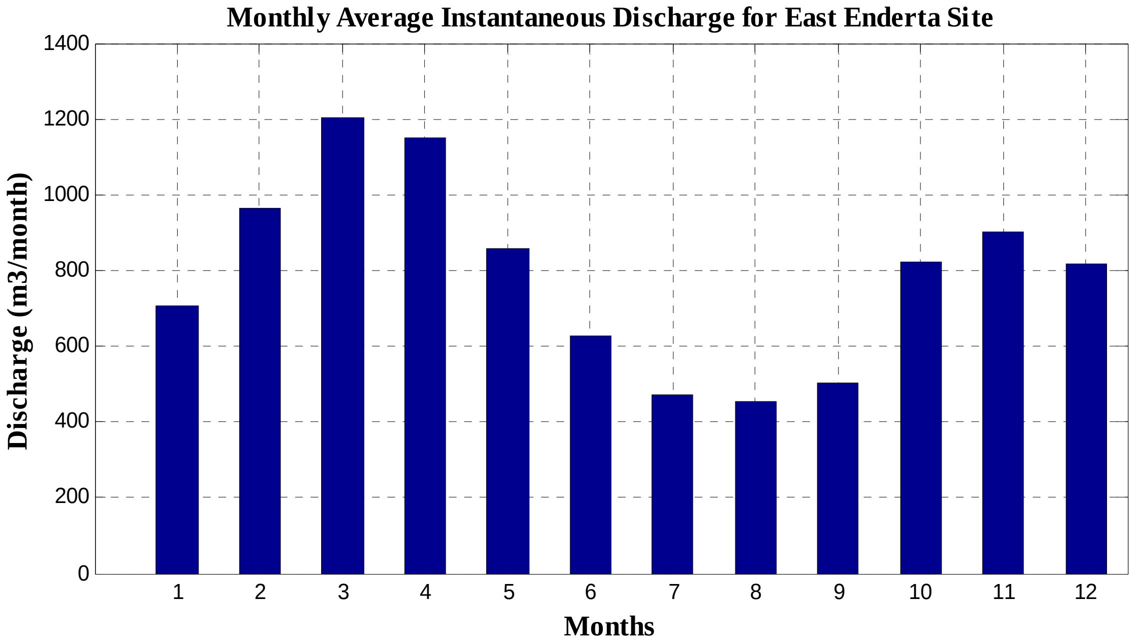
Appendix B: Graphs for Instantaneous Discharge of Windmill Water Pumping system



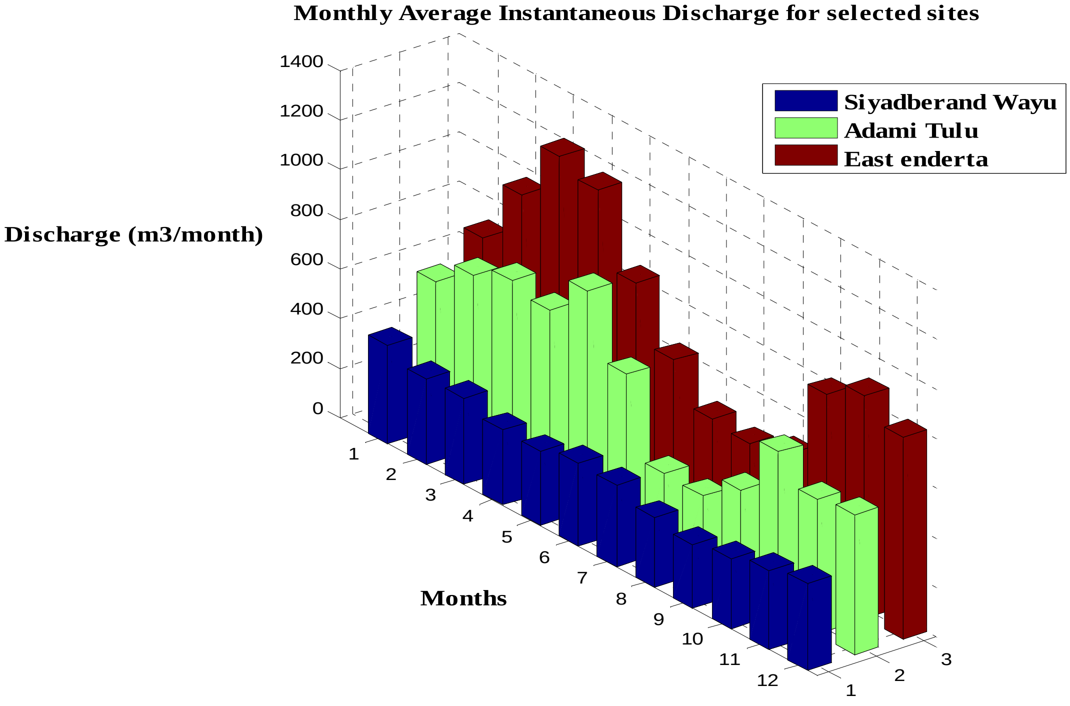
Monthly average instantaneous discharge for Siyadberand Wayu site



Monthly average instantaneous discharge for Adami Tulu site



Monthly average instantaneous discharge for East Enderta site.



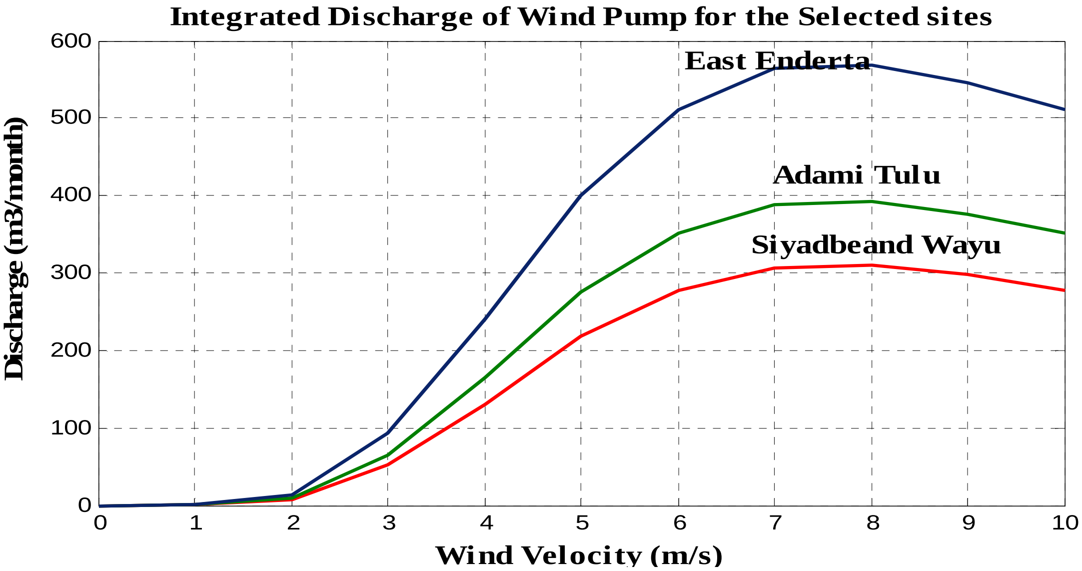
Monthly average instantaneous discharge for three selected site together

Appendix C: MATLAB Program for Integrated Discharge of Windmill Water Pumping system

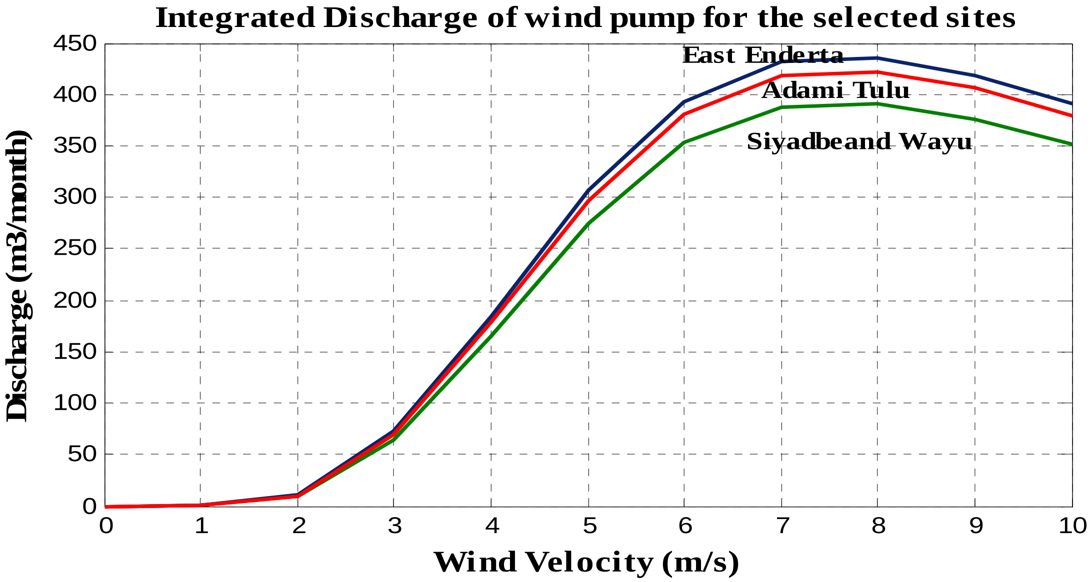
```
%----------------------------------------------------------------------
% Integrated Monthly Average Discharge for Siyadberand Wayu Site
%----------------------------------------------------------------------
h=75;                   % head in meter
g=9.81;                 % gravity constant
rho_a=0.92;             % density of air
rho_w=1000;             % density of water
Ar=23.76;               % area of rotor(with rotor diameter 3m)
eff=0.95;               % combined efficiency (for rotor and pump)
Cp=0.3;                 % coefficient
Ko=0.25;                % coefficient
VI=3.2;                 % cut in velocity (m/s)
VO=11;                  % cut out velocity / the maximum possible velocity in the specific site/
pi= 3.14;
Vm1=0:1:10;
Xi= (pi. /4).*(Vi. /Vm1).^2;
Xo= (pi. /4).*(Vo. /Vm1).^2;
A=2*3600*24*30*Cp.*eff.*(rho_a/rho_w).*((Ar*(Vo^3))./(g*h));
B= (1-(Ko.*(Vi. /Vo).^2));
C=Ko.*(Vi. /Vo). ^2;
D= (4*(Vm1).^2)./(pi*(Vo.^2-Vi.^2));
E= (exp(-(pi./4).*(Vi./Vm1).^2)-exp(-(pi./4).*(Vo./Vm1).^2));
F= (exp(-(pi./4).*(Vo./Vm1).^2));
Qvmsiya=A.*B.*C.*((D.*E)-F);
plot(Vm1,Qvmsiya), grid on
gtext('Siyadbeand Wayu');
hold on
%---------------------------------------------------------------------
% Integrated Monthly Average Discharge for Oromia Region/ADAMI TULU/
%---------------------------------------------------------------------
h=66;                   % head in meter
g=9.81;                 % gravity constant
rho_a=1.024;            % density of air
Vm1=0:1:10;
Xi=(pi./4).*(Vi./Vm1).^2;
```

```
Xo=(pi./4).*(Vo./Vm1).^2;
A=2*3600*24*30*Cp*eff*(rho_a/rho_w).*((Ar*(Vo^3))./(g*h));
B=(1-(Ko.*(Vi./Vo).^2));
C=Ko.*(Vi./Vo).^2;
D=(4*(Vm1).^2)./(pi*(Vo.^2-Vi.^2));
E=(exp(-(pi./4).*(Vi./Vm1).^2)-exp(-(pi./4).*(Vo./Vm1).^2));
F=(exp(-(pi./4).*(Vo./Vm1).^2));
Qvmadami=A.*B.*C.*((D.*E)-F);
plot(Vm1,Qvmadami), grid on
gtext('Adami Tulu');
hold on
%---------------------------------------------------------------------
% Integrated Monthly Average Discharge for Tigray Region/ EAST ENDERTA/
%--------------------------------------------------------------------
h=44;                   % head in meter
g=9.81;                 % gravity constant
rho_a=0.992;            % density of air
Vm1=0:1:10;
Xi= (pi./4).*(Vi./Vm1).^2;
Xo= (pi./4).*(Vo./Vm1).^2;
A=2*3600*24*30*Cp*eff*(rho_a/rho_w).*((Ar*(Vo^3))./(g*h));
B= (1-(Ko.*(Vi./Vo).^2));
C=Ko.*(Vi./Vo).^2;
D= (4*(Vm1).^2)./(pi*(Vo.^2-Vi.^2));
E= (exp(-(pi./4).*(Vi./Vm1).^2)-exp(-(pi./4).*(Vo./Vm1).^2));
F= (exp(-(pi./4).*(Vo./Vm1).^2));
Qvmenderta=A.*B.*C.*((D.*E)-F);
plot (Vm1,Qvmenderta), grid on
xlabel('Wind Velocity (m/s)')
ylabel('Discharge (m3/month)')
title ('Integrated performance of wind driven piston pump')
gtext('East Enderta')
```

Appendix D : Graph of Integrated Discharge of Windmill Water Pumping system



Integrated discharge of the selected three site with different head and flow rate



Integrated discharge of the selected three site with the same head and flow rate

Appendix E : MATLAB Program for Hybrid Water Pumping System

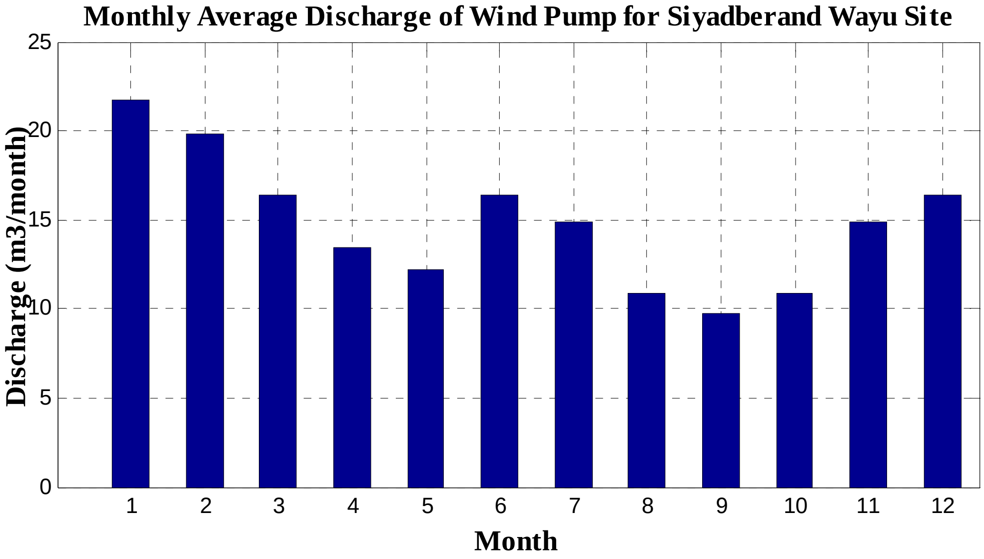
```
%----------------------------------------------------------------------
% MATLAB program for hybrid water pumping system,  Monthly average Discharge Calculation for Wind and Solar pump for Amhara  region (Siadberand Wayu site)
% ----------------------------------------------------------------------
H=68;                    % Head in meter
d=5.7;                   % rotor diameter in meter
month=[1 2 3 4 5 6 7 8  9 10 11 12];
VSiad=[4.04 3.92 3.68 3.44 3.33 3.68 3.56 3.21 3.09 3.21 3.56 3.68];    % Monthly Average wind Speed in m/s
RadSiad=[5.97 6.33 6.3 6.21 6.27 5.61 5.05 5.09 5.71 6.22 6.13 5.95];    % horiZontal Solar Radiation Kmh/m2/day
Qw =(0.69*((VSiad).^(3)).*(d.^(2)))./H                    % discharge using water pumping system for siadberand wayu
Qs = (115.3*RadSiad)./H                    % discharge using solar photovoltaic water pumping system
bar(Qw),grid on
xlabel('Month')
ylabel('Discharge (m3/month)')
title('Monthly Average Discharge of Wind Pump for Siyadberand Wayu Site')
hold off,pause
bar(Qs), grid on
xlabel('Month')
ylabel('Discharge (m3/month)')
title('Monthly average Discharge of Solar Pump for Siyadberand Wayu Site')
hold off, pause
%----------------------------------------------------------------------
%Cumulative DISCHARGE of wind Pump for siadberand wayu site
%----------------------------------------------------------------------
VSiad1=4.04; VSiad4=3.44; VSiad7=3.56; VSiad10=3.21;
VSiad2=3.92; VSiad5=3.33; VSiad8=3.21; VSiad11=3.56;
VSiad3=3.68; VSiad6=3.68; VSiad9=3.09; VSiad12=3.68;
Qw1=(0.69*((VSiad1).^(3)).*(d.^(2)))./H ;
Qw2=Qw1+((0.69*((VSiad2).^(3)).*(d.^(2)))./H);
Qw3=Qw2+((0.69*((VSiad3).^(3)).*(d.^(2)))./H);
Qw4=Qw3+((0.69*((VSiad4).^(3)).*(d.^(2)))./H);
Qw5=Qw4+((0.69*((VSiad5).^(3)).*(d.^(2)))./H);
```

```
Qw6=Qw5+((0.69*((VSiad6).^(3)).*(d.^(2)))./H);
Qw7=Qw6+((0.69*((VSiad7).^(3)).*(d.^(2)))./H);
Qw8=Qw7+((0.69*((VSiad8).^(3)).*(d.^(2)))./H);
Qw9=Qw8+((0.69*((VSiad9).^(3)).*(d.^(2)))./H);
Qw10=Qw9+((0.69*((VSiad10).^(3)).*(d.^(2)))./H);
Qw11=Qw10+((0.69*((VSiad11).^(3)).*(d.^(2)))./H);
Qw12=Qw11+((0.69*((VSiad12).^(3)).*(d.^(2)))./H);
%--------------------------------------------------------------------
VSiad= [1 2 3 4 5 6 7 8 9 10 11 12];
QwSiad= [19.9761 38.2245 53.3222 65.6545 76.8411 91.9388 105.6072 115.6275 124.5656 134.585 148.2543 163.3520];
plot(VSiad,QwSiad), grid on
xlabel('Month')
ylabel('Cumulative Discharge (m3/month)')
title('Cumulative Discharge of Wind Pump for Siyadberand Wayu Site')
gtext('Wind Pump')
hold on,pause
%--------------------------------------------------------------------
%Cumulative Discharge of Solar Pump for Siadberand Wayu Site
%--------------------------------------------------------------------
SSiad1=5.97;SSiad4=6.21;SSiad7=5.05;SSiad10=6.22;
SSiad2=6.33;SSiad5=6.27;SSiad8=5.09;SSiad11=6.13;
SSiad3=6.3;SSiad6=5.61;SSiad9=5.71;SSiad12=5.95;
Qs1=(115.3*SSiad1)./H;
Qs2=Qs1+((115.3*SSiad2)./H);
Qs3=Qs2+((115.3*SSiad3)./H);
Qs4=Qs3+((115.3*SSiad4)./H);
Qs5=Qs4+((115.3*SSiad5)./H);
Qs6=Qs5+((115.3*SSiad6)./H);
Qs7=Qs6+((115.3*SSiad7)./H);
Qs8=Qs7+((115.3*SSiad8)./H);
Qs9=Qs8+((115.3*SSiad9)./H);
Qs10=Qs9+((115.3*SSiad10)./H);
Qs11=Qs10+((115.3*SSiad11)./H);
Qs12=Qs11+((115.3*SSiad12)./H);
month= [ 1 2 3 4 5 6 7 8 9 10 11 12];
QSSiad= [ Qs1 Qs2 Qs3 Qs4 Qs5 Qs6 Qs7 Qs8 Qs9 Qs10 Qs11 Qs12]
plot(month,QSSiad), grid on
```

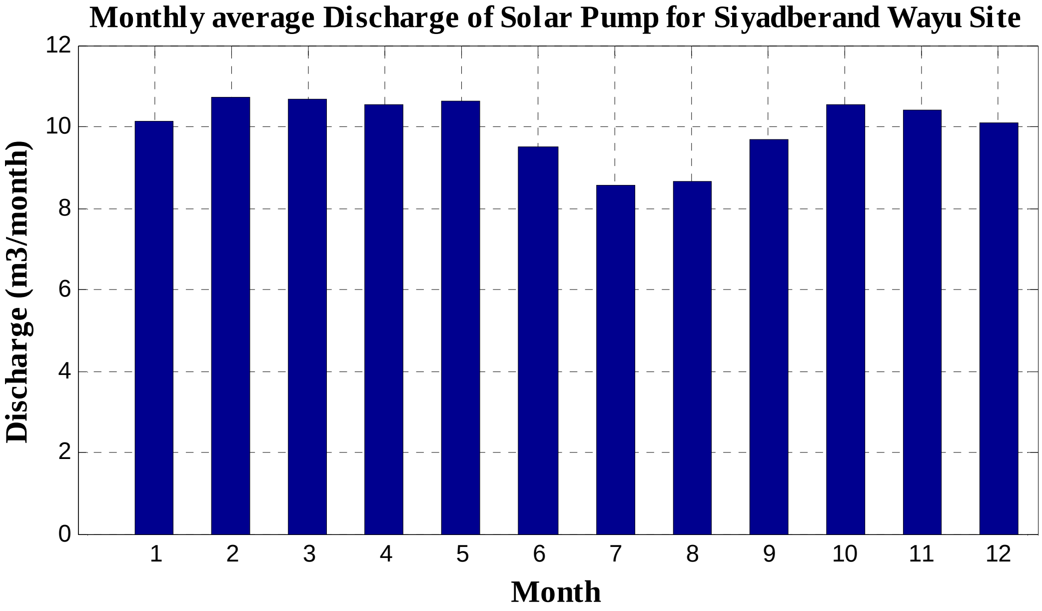
```
xlabel('Month')
ylabel('Cumulative Discharge (m3/month)')
title('Cumulative Discharge of Solar Pump for Siyadberand Wayu Site')
gtext('Solar Pump')
hold off,pause
%---------------------------------------------------------------------
% Monthly Average Discharge of Wind and Solar Pump Bar Chart
%---------------------------------------------------------------------
x=[21.7387  10.1227
19.8586 10.7331
16.4298 10.6822
13.4204 10.5296
12.1737 10.6313
16.4298 9.5122
14.8744 8.5627
10.9045 8.6305
9.7267  9.6818
10.9045 10.5466
14.8744 10.394
16.4298 10.0887];
bar(x, 'grouped','linewidth',2), grid on
xlabel('Month')
ylabel('Discharge (m3/month)')
title('Monthly Average Discharge for Siyadberand Wayu Site (m3/month)')
legend ( 'Discharge using Wind pump','Discharge using Solar pump')
hold off, pause
% --------------------------------------------------------------------
% Cumulative Discharge of Wind Pump and Solar Pump for Siyadberand Wayu Site
% --------------------------------------------------------------------
x=[Qw1 Qs1
Qw2 Qs2
Qw3 Qs3
Qw4 Qs4
Qw5 Qs5
Qw6 Qs6
Qw7 Qs7
Qw8 Qs8
Qw9 Qs9
```

```
Qw10 Qs10
Qw11 Qs11
Qw12 Qs12];
bar(x, 'grouped','linewidth',2), grid on
xlabel('Month')
ylabel('Cumulative Discharge (m3/month)')
title('Monthly Cumulative Discharge for Siyadberand Wayu Site (m3/month)')
legend ( 'Cumulative Discharge for Wind pump','Cumulative Discharge Solar pump')
```

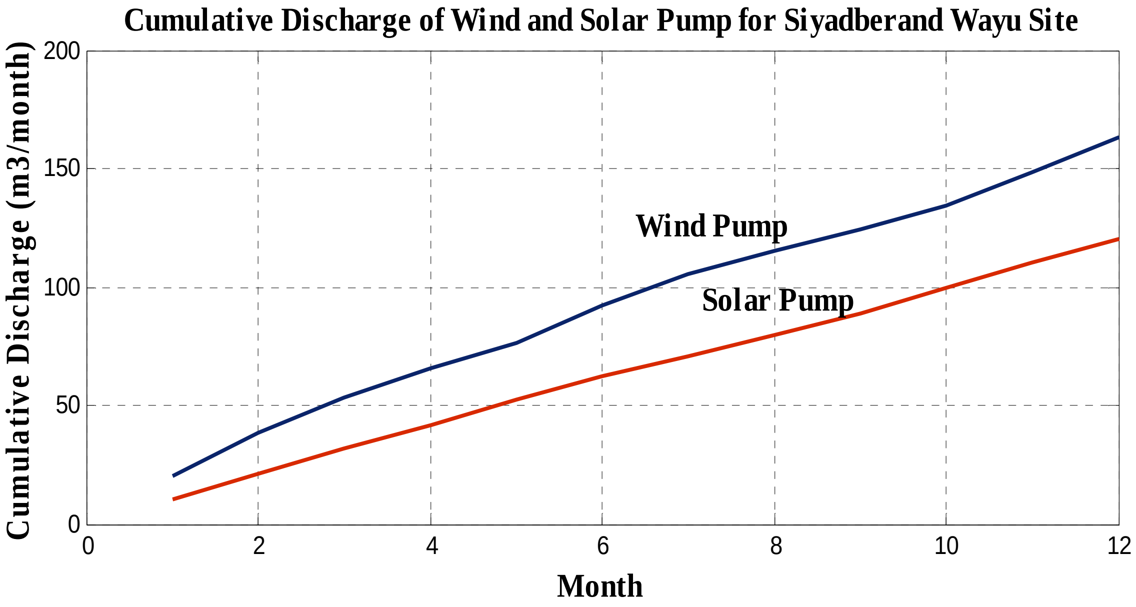
Appendix F: Graph of Hybrid Water Pumping System in Siyadberand Wayu Site



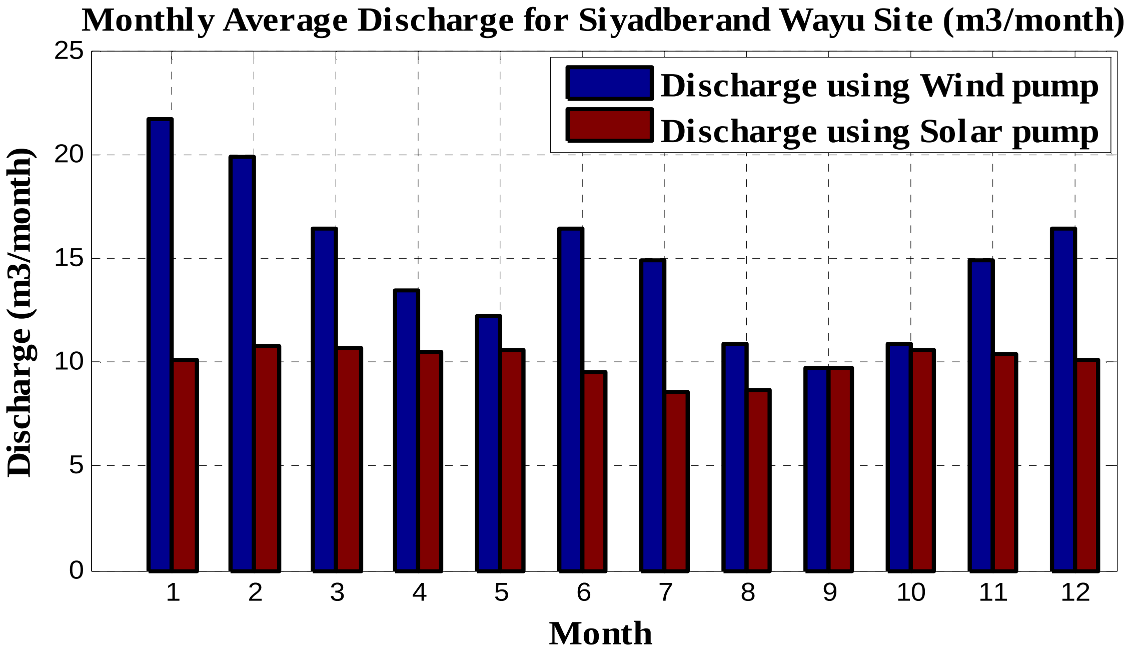
Monthly average discharge of wind pump for Siyadberand Wayu site



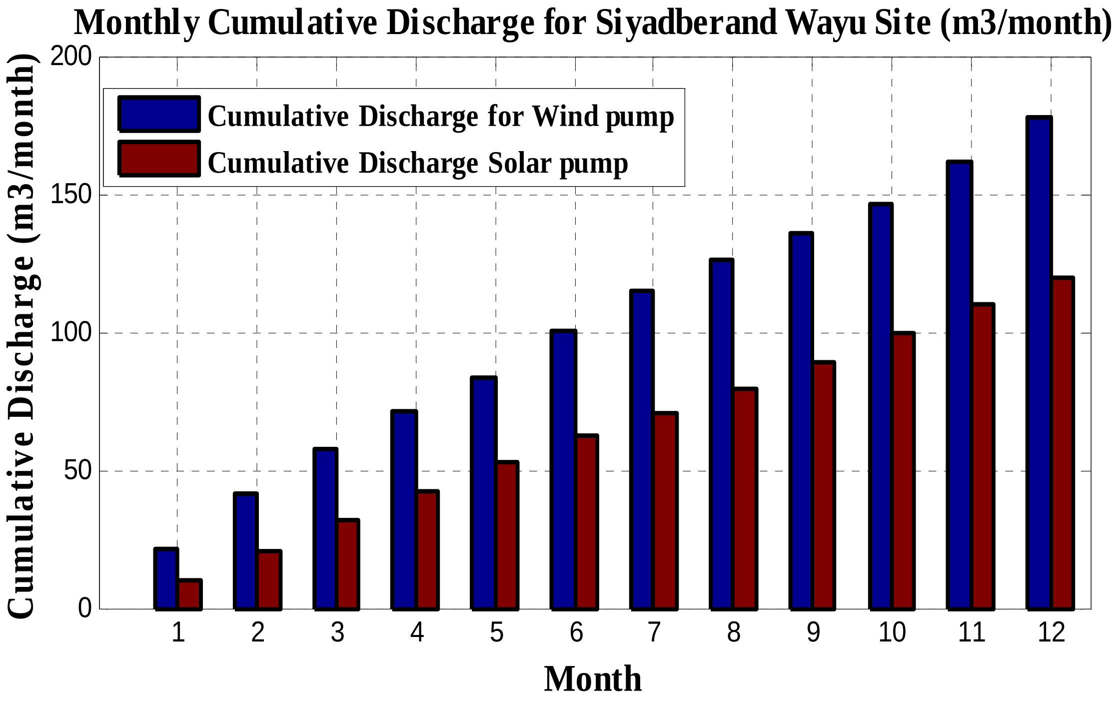
Monthly average discharge of solar pump for Siyadberand Wayu site



Cumulative discharge of wind and solar pump for Siyadberand Wayu site

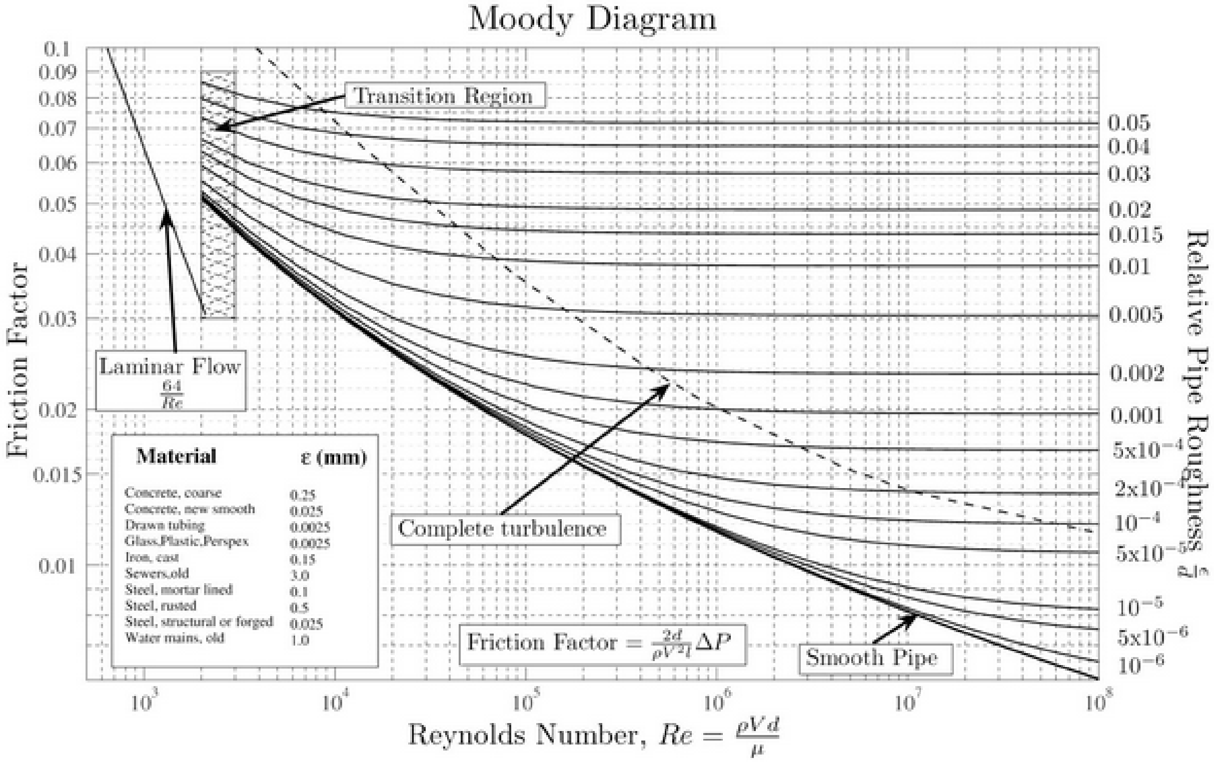


Monthly average discharge of wind and solar pump bar chart

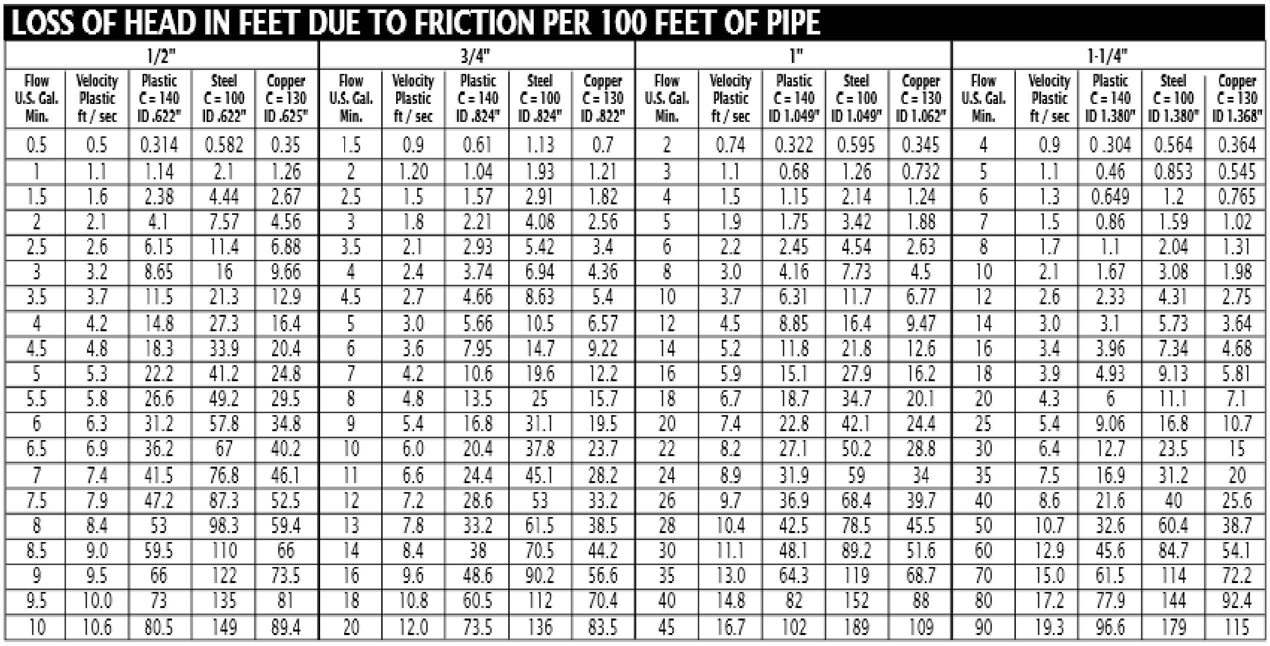


Cumulative discharge of wind pump and solar pump for Siyadberand Wayu site

Appendix G Moody Diagram

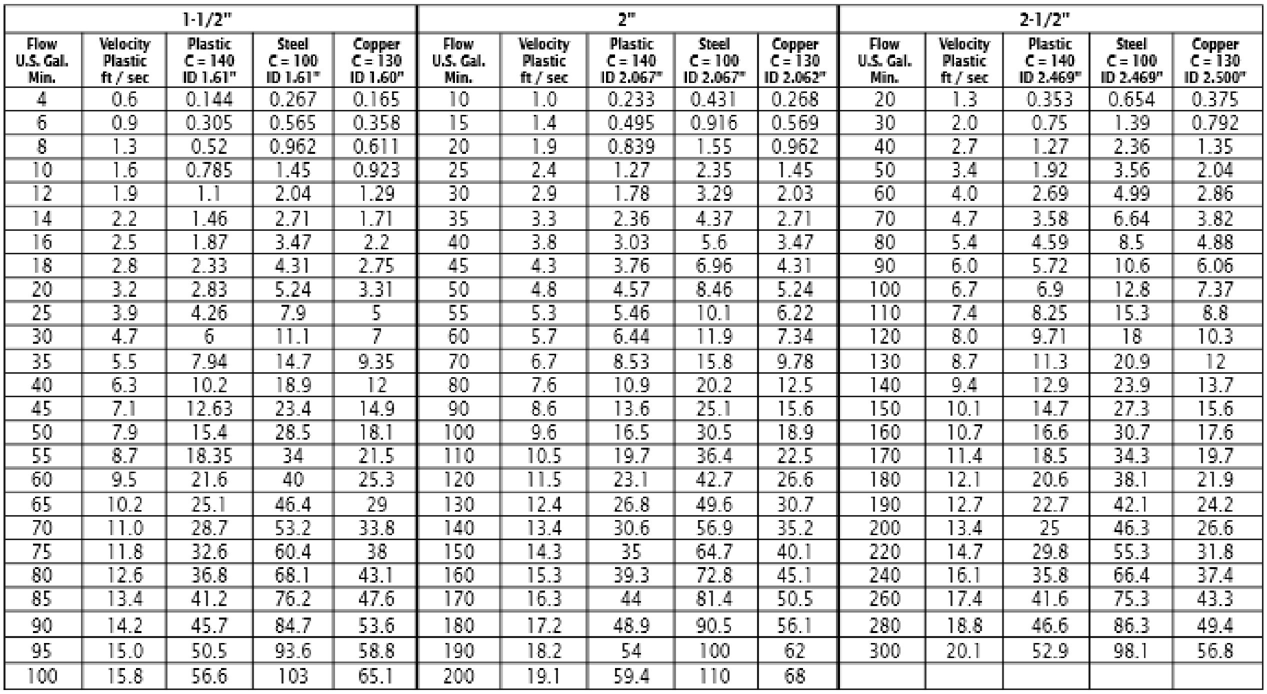


Appendix H : Pipe Friction Loss Chart



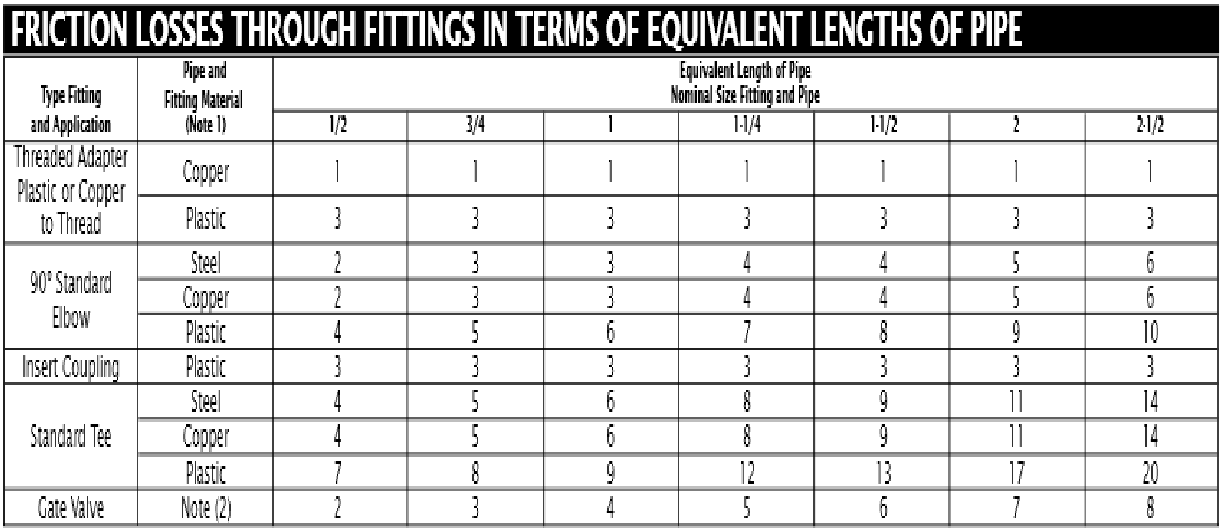
LOSS OF HEAD IN FEET DUE TO FRICTION PER 100 FEET OF PIPE

1/2"					3/4"					1"					1-1/4"				
Flow U.S. Gal. Min.	Velocity Plastic ft / sec	Plastic C = 140 ID .622"	Steel C = 100 ID .622"	Copper C = 130 ID .625"	Flow U.S. Gal. Min.	Velocity Plastic ft / sec	Plastic C = 140 ID .824"	Steel C = 100 ID .824"	Copper C = 130 ID .822"	Flow U.S. Gal. Min.	Velocity Plastic ft / sec	Plastic C = 140 ID 1.049"	Steel C = 100 ID 1.049"	Copper C = 130 ID 1.062"	Flow U.S. Gal. Min.	Velocity Plastic ft / sec	Plastic C = 140 ID 1.380"	Steel C = 100 ID 1.380"	Copper C = 130 ID 1.368"
0.5	0.5	0.314	0.582	0.35	1.5	0.9	0.61	1.13	0.7	2	0.74	0.322	0.595	0.345	4	0.9	0 .304	0.564	0.364
1	1.1	1.14	2.1	1.26	2	1.20	1.04	1.93	1.21	3	1.1	0.68	1.26	0.732	5	1.1	0.46	0.853	0.545
1.5	1.6	2.38	4.44	2.67	2.5	1.5	1.57	2.91	1.82	4	1.5	1.15	2.14	1.24	6	1.3	0.649	1.2	0.765
2	2.1	4.1	7.57	4.56	3	1.8	2.21	4.08	2.56	5	1.9	1.75	3.42	1.88	7	1.5	0.86	1.59	1.02
2.5	2.6	6.15	11.4	6.88	3.5	2.1	2.93	5.42	3.4	6	2.2	2.45	4.54	2.63	8	1.7	1.1	2.04	1.31
3	3.2	8.65	16	9.66	4	2.4	3.74	6.94	4.36	8	3.0	4.16	7.73	4.5	10	2.1	1.67	3.08	1.98
3.5	3.7	11.5	21.3	12.9	4.5	2.7	4.66	8.63	5.4	10	3.7	6.31	11.7	6.77	12	2.6	2.33	4.31	2.75
4	4.2	14.8	27.3	16.4	5	3.0	5.66	10.5	6.57	12	4.5	8.85	16.4	9.47	14	3.0	3.1	5.73	3.64
4.5	4.8	18.3	33.9	20.4	6	3.6	7.95	14.7	9.22	14	5.2	11.8	21.8	12.6	16	3.4	3.96	7.34	4.68
5	5.3	22.2	41.2	24.8	7	4.2	10.6	19.6	12.2	16	5.9	15.1	27.9	16.2	18	3.9	4.93	9.13	5.81
5.5	5.8	26.6	49.2	29.5	8	4.8	13.5	25	15.7	18	6.7	18.7	34.7	20.1	20	4.3	6	11.1	7.1
6	6.3	31.2	57.8	34.8	9	5.4	16.8	31.1	19.5	20	7.4	22.8	42.1	24.4	25	5.4	9.06	16.8	10.7
6.5	6.9	36.2	67	40.2	10	6.0	20.4	37.8	23.7	22	8.2	27.1	50.2	28.8	30	6.4	12.7	23.5	15
7	7.4	41.5	76.8	46.1	11	6.6	24.4	45.1	28.2	24	8.9	31.9	59	34	35	7.5	16.9	31.2	20
7.5	7.9	47.2	87.3	52.5	12	7.2	28.6	53	33.2	26	9.7	36.9	68.4	39.7	40	8.6	21.6	40	25.6
8	8.4	53	98.3	59.4	13	7.8	33.2	61.5	38.5	28	10.4	42.5	78.5	45.5	50	10.7	32.6	60.4	38.7
8.5	9.0	59.5	110	66	14	8.4	38	70.5	44.2	30	11.1	48.1	89.2	51.6	60	12.9	45.6	84.7	54.1
9	9.5	66	122	73.5	16	9.6	48.6	90.2	56.6	35	13.0	64.3	119	68.7	70	15.0	61.5	114	72.2
9.5	10.0	73	135	81	18	10.8	60.5	112	70.4	40	14.8	82	152	88	80	17.2	77.9	144	92.4
10	10.6	80.5	149	89.4	20	12.0	73.5	136	83.5	45	16.7	102	189	109	90	19.3	96.6	179	115



1-1/2"					2"					2-1/2"				
Flow U.S. Gal. Min.	Velocity Plastic ft / sec	Plastic C = 140 ID 1.61"	Steel C = 100 ID 1.61"	Copper C = 130 ID 1.60"	Flow U.S. Gal. Min.	Velocity Plastic ft / sec	Plastic C = 140 ID 2.067"	Steel C = 100 ID 2.067"	Copper C = 130 ID 2.062"	Flow U.S. Gal. Min.	Velocity Plastic ft / sec	Plastic C = 140 ID 2.469"	Steel C = 100 ID 2.469"	Copper C = 130 ID 2.500"
4	0.6	0.144	0.267	0.165	10	1.0	0.233	0.431	0.268	20	1.3	0.353	0.654	0.375
6	0.9	0.305	0.565	0.358	15	1.4	0.495	0.916	0.569	30	2.0	0.75	1.39	0.792
8	1.3	0.52	0.962	0.611	20	1.9	0.839	1.55	0.962	40	2.7	1.27	2.36	1.35
10	1.6	0.785	1.45	0.923	25	2.4	1.27	2.35	1.45	50	3.4	1.92	3.56	2.04
12	1.9	1.1	2.04	1.29	30	2.9	1.78	3.29	2.03	60	4.0	2.69	4.99	2.86
14	2.2	1.46	2.71	1.71	35	3.3	2.36	4.37	2.71	70	4.7	3.58	6.64	3.82
16	2.5	1.87	3.47	2.2	40	3.8	3.03	5.6	3.47	80	5.4	4.59	8.5	4.88
18	2.8	2.33	4.31	2.75	45	4.3	3.76	6.96	4.31	90	6.0	5.72	10.6	6.06
20	3.2	2.83	5.24	3.31	50	4.8	4.57	8.46	5.24	100	6.7	6.9	12.8	7.37
25	3.9	4.26	7.9	5	55	5.3	5.46	10.1	6.22	110	7.4	8.25	15.3	8.8
30	4.7	6	11.1	7	60	5.7	6.44	11.9	7.34	120	8.0	9.71	18	10.3
35	5.5	7.94	14.7	9.35	70	6.7	8.53	15.8	9.78	130	8.7	11.3	20.9	12
40	6.3	10.2	18.9	12	80	7.6	10.9	20.2	12.5	140	9.4	12.9	23.9	13.7
45	7.1	12.63	23.4	14.9	90	8.6	13.6	25.1	15.6	150	10.1	14.7	27.3	15.6
50	7.9	15.4	28.5	18.1	100	9.6	16.5	30.5	18.9	160	10.7	16.6	30.7	17.6
55	8.7	18.35	34	21.5	110	10.5	19.7	36.4	22.5	170	11.4	18.5	34.3	19.7
60	9.5	21.6	40	25.3	120	11.5	23.1	42.7	26.6	180	12.1	20.6	38.1	21.9
65	10.2	25.1	46.4	29	130	12.4	26.8	49.6	30.7	190	12.7	22.7	42.1	24.2
70	11.0	28.7	53.2	33.8	140	13.4	30.6	56.9	35.2	200	13.4	25	46.3	26.6
75	11.8	32.6	60.4	38	150	14.3	35	64.7	40.1	220	14.7	29.8	55.3	31.8
80	12.6	36.8	68.1	43.1	160	15.3	39.3	72.8	45.1	240	16.1	35.8	66.4	37.4
85	13.4	41.2	76.2	47.6	170	16.3	44	81.4	50.5	260	17.4	41.6	75.3	43.3
90	14.2	45.7	84.7	53.6	180	17.2	48.9	90.5	56.1	280	18.8	46.6	86.3	49.4
95	15.0	50.5	93.6	58.8	190	18.2	54	100	62	300	20.1	52.9	98.1	56.8
100	15.8	56.6	103	65.1	200	19.1	59.4	110	68					

Appendix I : Friction Losses through Fittings



FRICTION LOSSES THROUGH FITTINGS IN TERMS OF EQUIVALENT LENGTHS OF PIPE

Type Fitting and Application	Pipe and Fitting Material (Note 1)	Equivalent Length of Pipe Nominal Size Fitting and Pipe						
		1/2	3/4	1	1-1/4	1-1/2	2	2-1/2
Threaded Adapter Plastic or Copper to Thread	Copper	1	1	1	1	1	1	1
	Plastic	3	3	3	3	3	3	3
90° Standard Elbow	Steel	2	3	3	4	4	5	6
	Copper	2	3	3	4	4	5	6
	Plastic	4	5	6	7	8	9	10
Insert Coupling	Plastic	3	3	3	3	3	3	3
Standard Tee	Steel	4	5	6	8	9	11	14
	Copper	4	5	6	8	9	11	14
	Plastic	7	8	9	12	13	17	20
Gate Valve	Note (2)	2	3	4	5	6	7	8

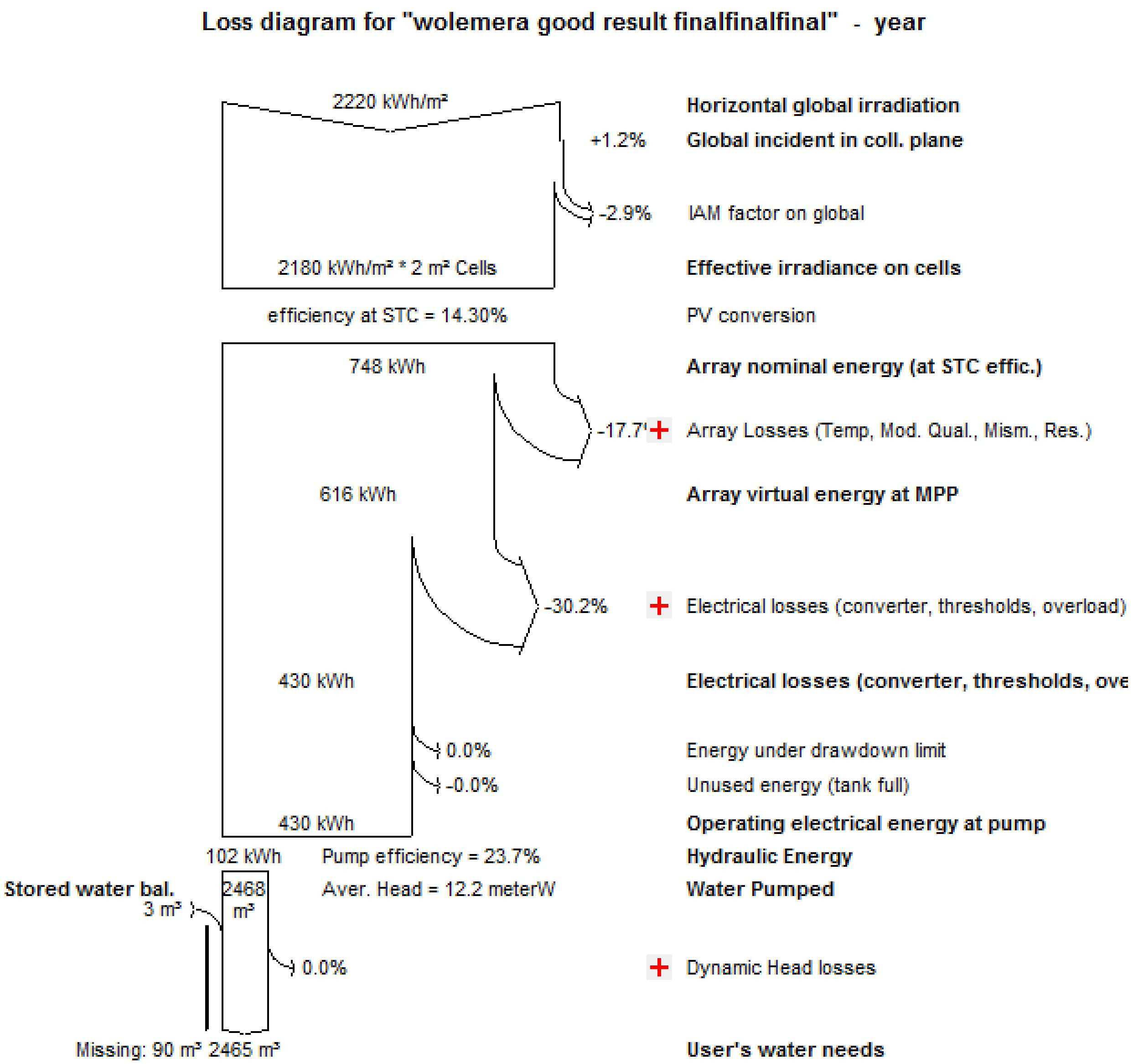
Appendix J: Selected Solar and Wind Pump for Hybrid Water Pumping System

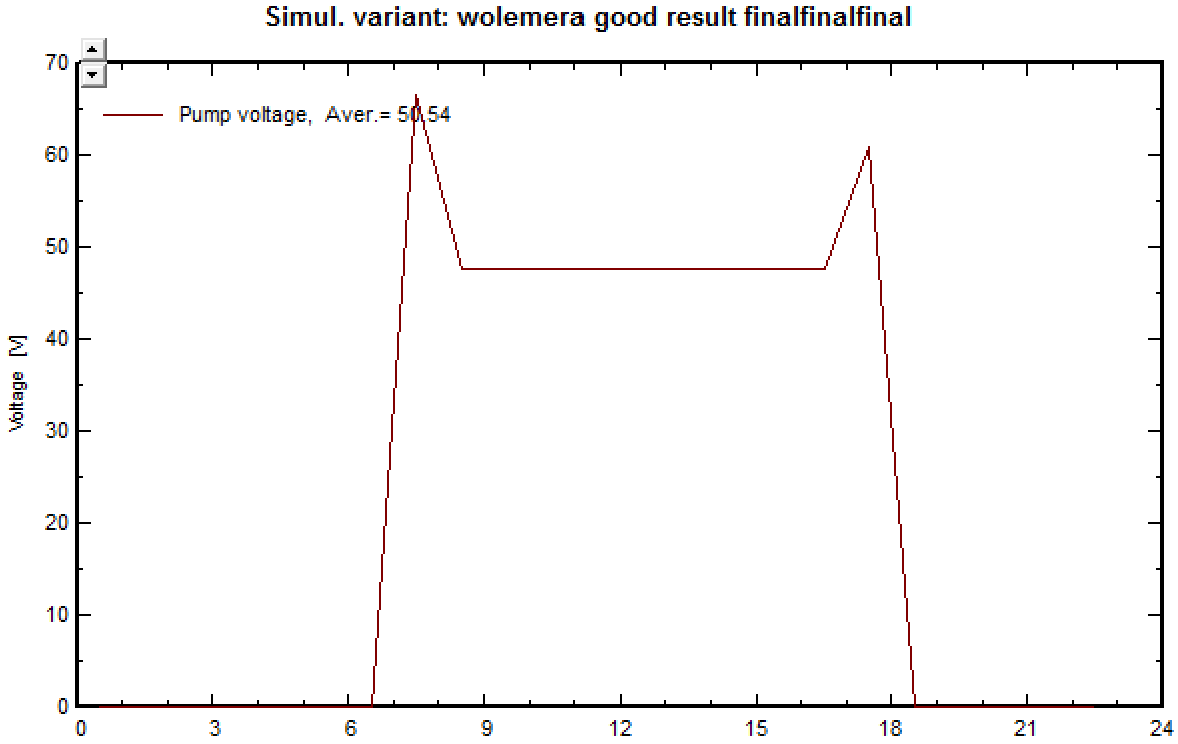
Site	**Head (m)**	**Selected Solar Pump**	**Number of Modules**	**Selected Windmill**
Atsbi (High solar and Medium wind)	50	Model- 11 SQF-2 Max. flow rate- 8.8 gpm	4 module with 230 peak watt power	Model- southern cross, IZC Rotor diameter: 3m Transmission: gear and crank , ratio: 2.6:1 Pump system: piston pump(diameter up to=203mm)
	75	Model- 11 SQF-2 Max. flow rate- 9.6 gpm	6 module with 230 peak watt power	Model- southern cross, IZD Rotor diameter: 3.7 m Transmission: gear and crank , ratio: 2.3:1 Pump system: piston pump(diameter up to=203mm)
	100	Model- 6 SQF-3 Max. flow rate- 5.7 gpm	8 module with 230 peak watt power	Model- southern cross, IZD Rotor diameter: 3.7 m Transmission: gear and crank , ratio: 2.3:1 Pump system: piston pump(diameter up to=203mm)
Awash Fentale (High solar and Low wind)	50	Model- 11 SQF-2 Max. flow rate- 8.8 gpm	4 module with 230 peak watt power	Model- southern cross, RF Number of blade: 24 Rotor diameter: 5.2 m Transmission: direct by crank , ratio: 1:1 Pump system: piston pump with brass (diameter up to=203mm)

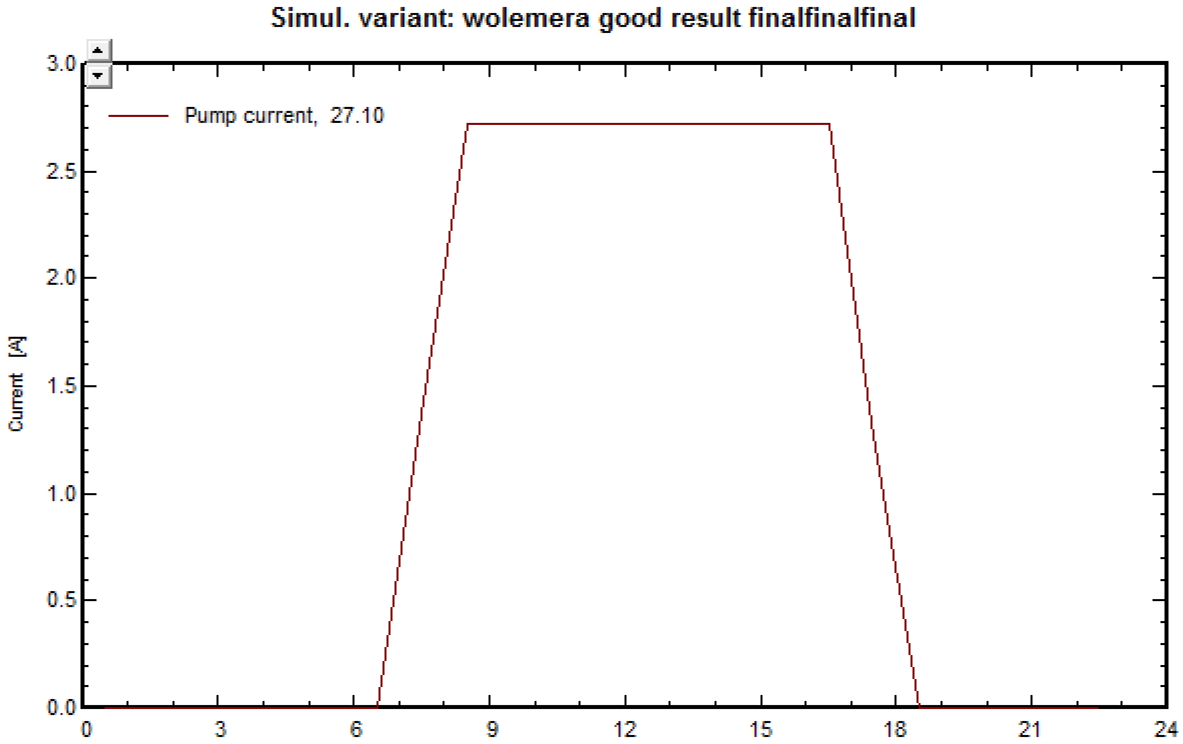
	75	Model- 11 SQF-2 Max. flow rate- 9.6 gpm	6 module with 230 peak watt power	Model- southern cross, RG Number of blade: 30 Rotor diameter: 6.4 m Transmission: direct by crank , ratio: 1:1 Pump system: piston pump with brass (diameter up to=203mm)
	100	Model- 6 SQF-3 Max. flow rate- 5.7 gpm	8 module with 230 peak watt power	Model- southern cross, RH Number of blade: 36 Rotor diameter: 7.6 m Transmission: direct by crank , ratio: 1:1 Pump system: piston pump with brass (diameter up to=203mm)
Borena (Medium solar and Medium wind)	50	Model- 11 SQF-2 Max. flow rate- 8.8 gpm	4 module with 230 peak watt power	Model- southern cross, IZE Number of blade: 24 Rotor diameter: 4.3 m Transmission: gear and crank , ratio: 2.3:1 Pump system: piston pump with brass (diameter up to=203mm)
	75	Model- 11 SQF-2 Max. flow rate- 9.6 gpm	6 module with 230 peak watt power	Model- southern cross, RF Number of blade: 24 Rotor diameter: 5.2 m Transmission: direct by crank , ratio: 1:1 Pump system: piston pump with brass (diameter up to=203mm)

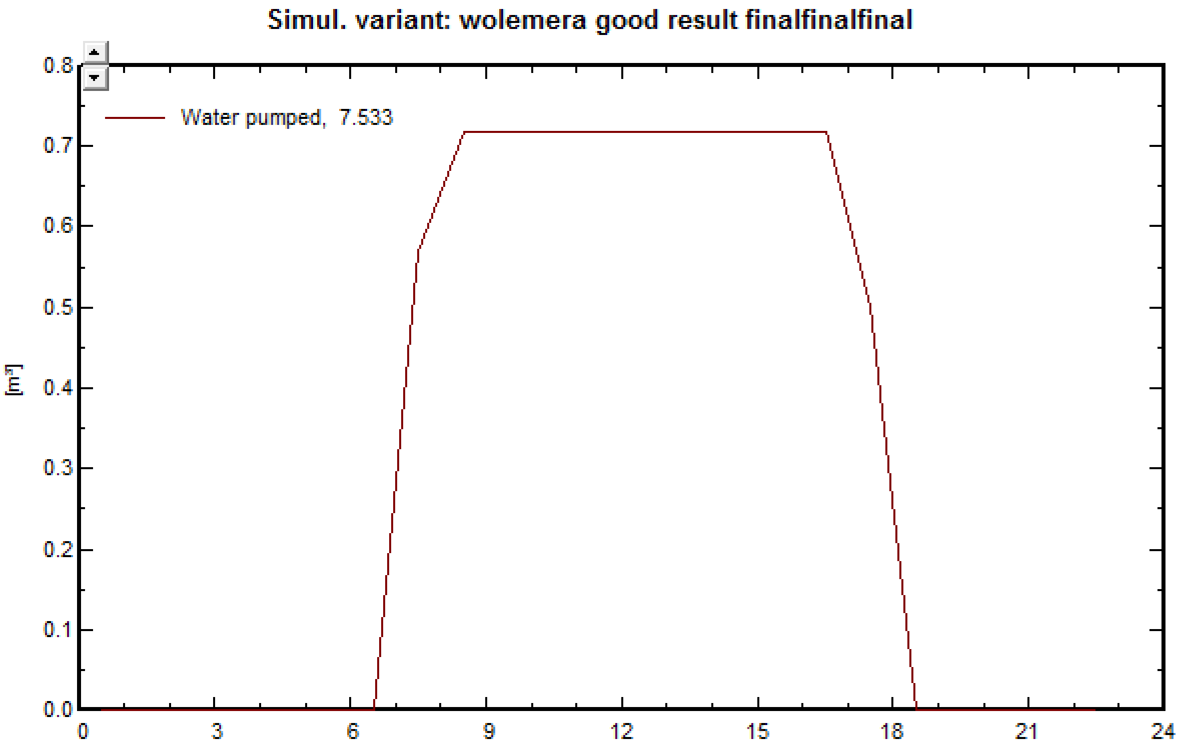
	100	Model- 6 SQF-3 Max. flow rate-5.7 gpm	8 module with 230 peak watt power	Model- southern cross, RG Number of blade: 30 Rotor diameter: 6.4 m Transmission: direct by crank , ratio: 1:1 Pump system: piston pump with brass (diameter up to=203mm)
Adami Tulu (Medium solar and Low wind)	50	Model- 11 SQF-2 Max. flow rate-8.8 gpm	4 module with 230 peak watt power	Model- southern cross, IZE Number of blade: 24 Rotor diameter: 4.3 m Transmission: gear and crank , ratio: 2.3:1 Pump system: piston pump with brass (diameter up to=203mm)
	75	Model- 11 SQF-2 Max. flow rate-9.6 gpm	6 module with 230 peak watt power	Model- southern cross, RG Number of blade: 30 Rotor diameter: 6.4 m Transmission: direct by crank , ratio: 1:1 Pump system: piston pump with brass (diameter up to=203mm)
	100	Model- 6 SQF-3 Max. flow rate-5.7 gpm	8 module with 230 peak watt power	Model- southern cross, RH Number of blade: 36 Rotor diameter: 7.6 m Transmission: direct by crank , ratio: 1:1 Pump system: piston pump with brass (diameter up to=203mm)

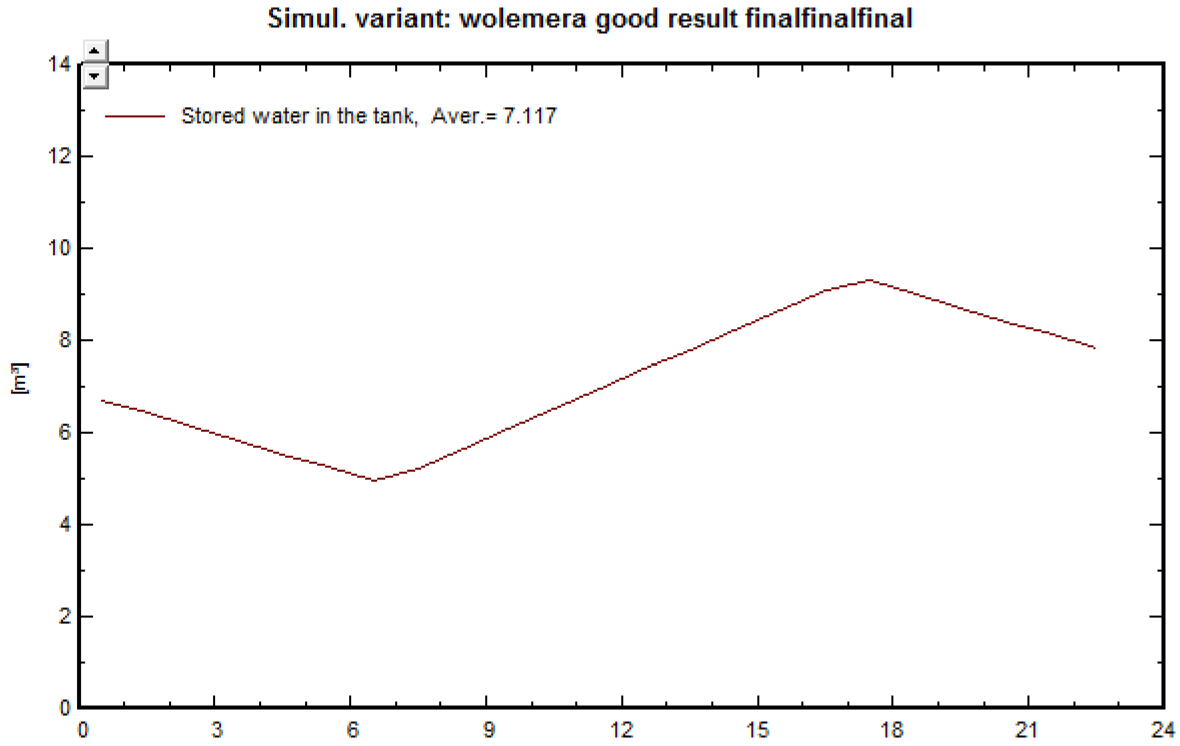
Appendix K: Different Simulation Variant Graph for Wolmera Photovoltaic Water Pumping Site



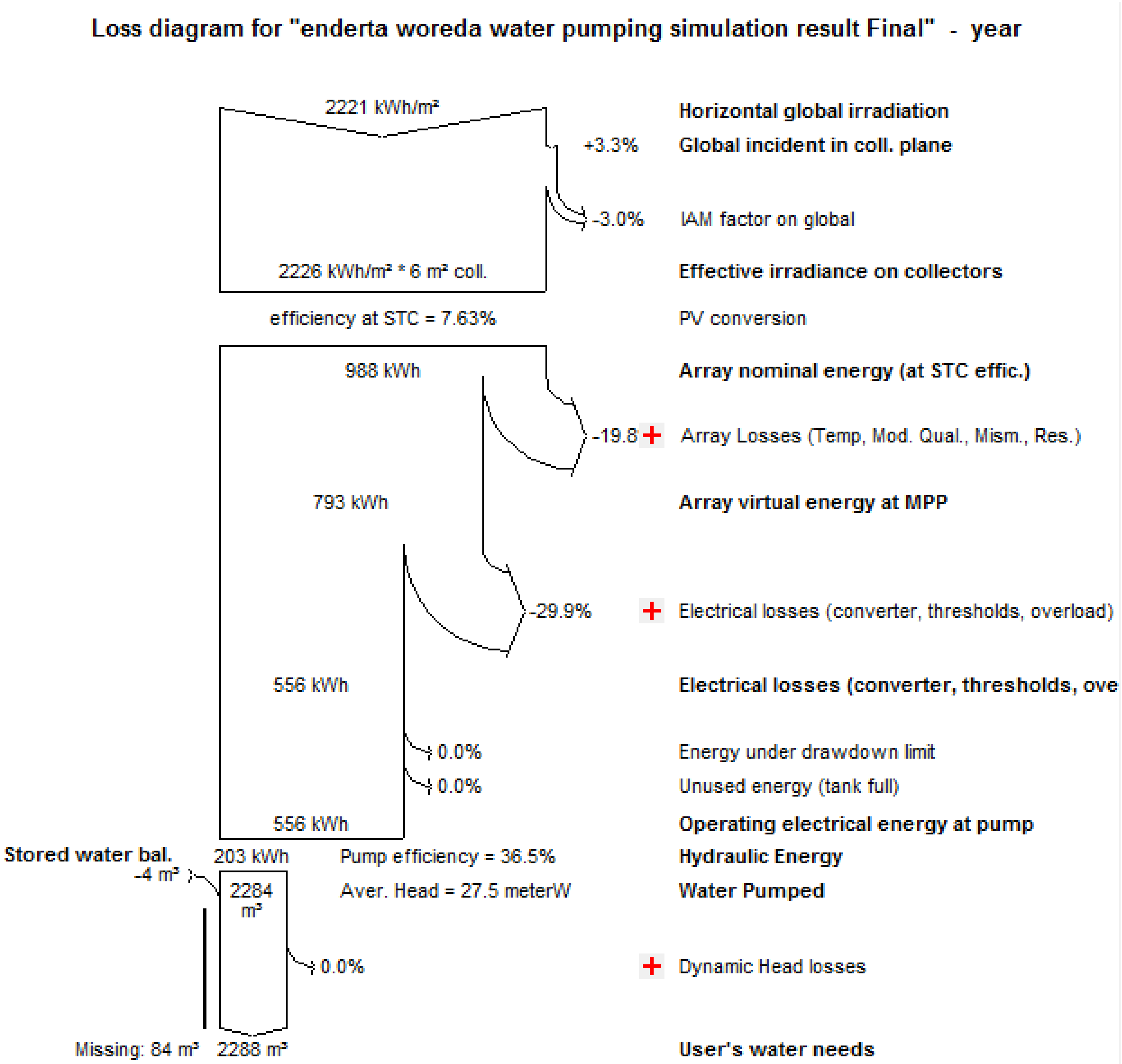

Simul. variant: wolemera good result finalfinalfinal
Pump voltage, Aver.= 50.54
Voltage [V]
70
60
50
40
30
20
10
0
0
3
6
9
12
15
18
21
24

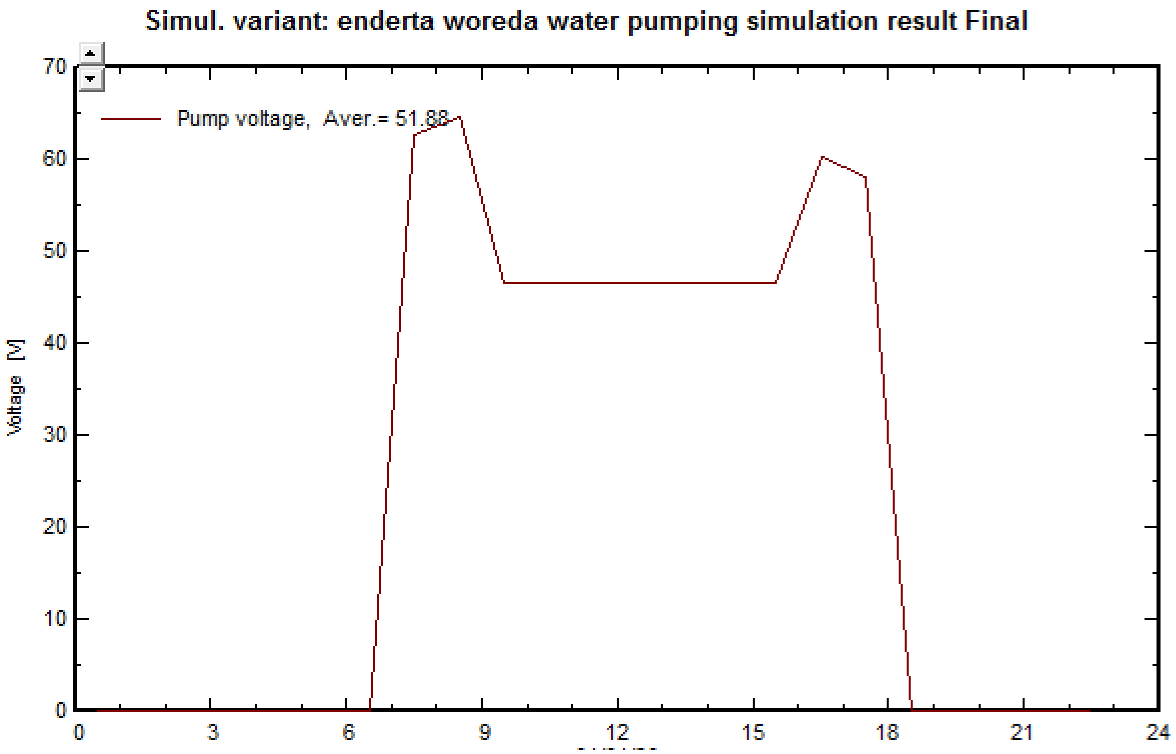

Simul. variant: wolemera good result finalfinalfinal
Pump current, 27.10
Current [A]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
3
6
9
12
15
18
21
24

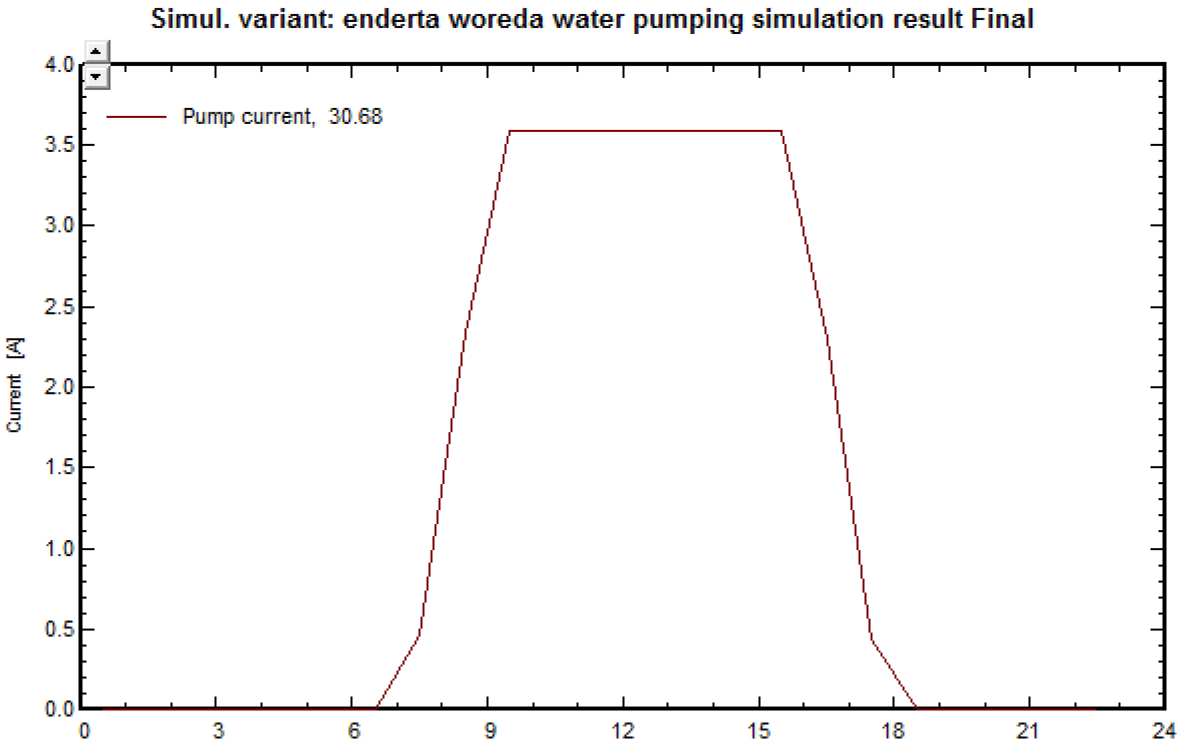

Simul. variant: wolemera good result finalfinalfinal
Water pumped, 7.533
[m³]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
3
6
9
12
15
18
21
24

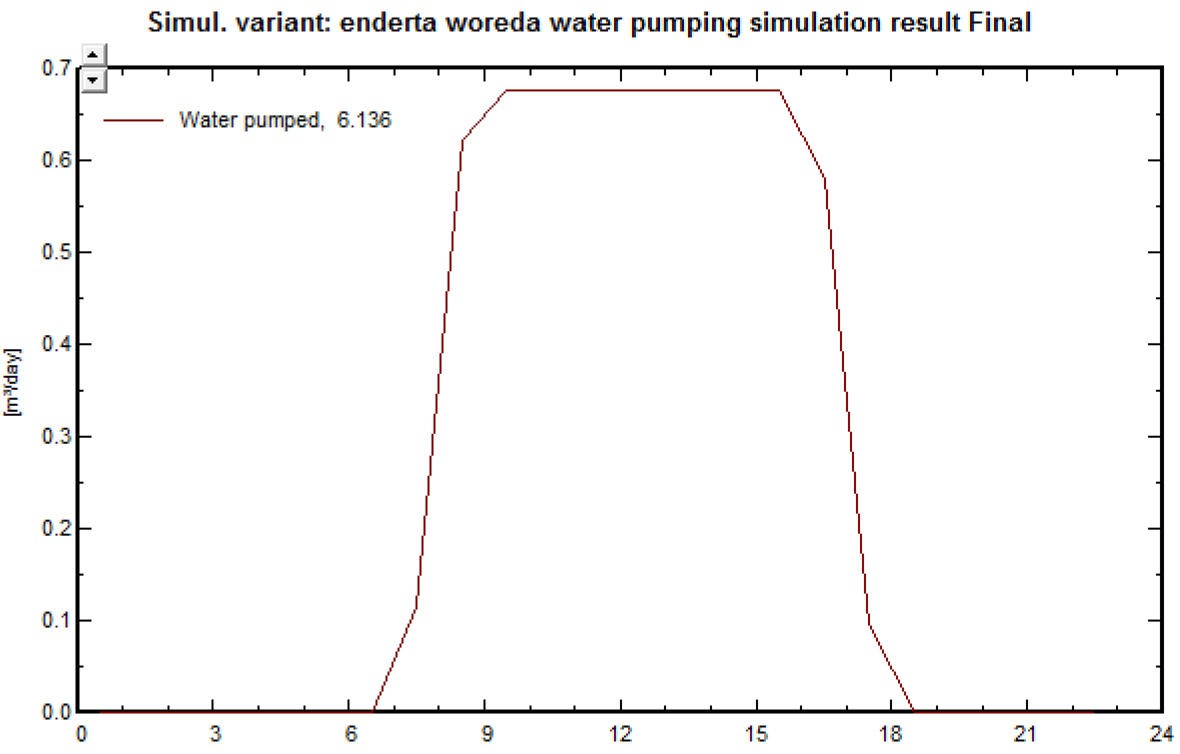

Simul. variant: wolemera good result finalfinalfinal
Stored water in the tank, Aver.= 7.117
[m³]
14
12
10
8
6
4
2
0
0
3
6
9
12
15
18
21
24

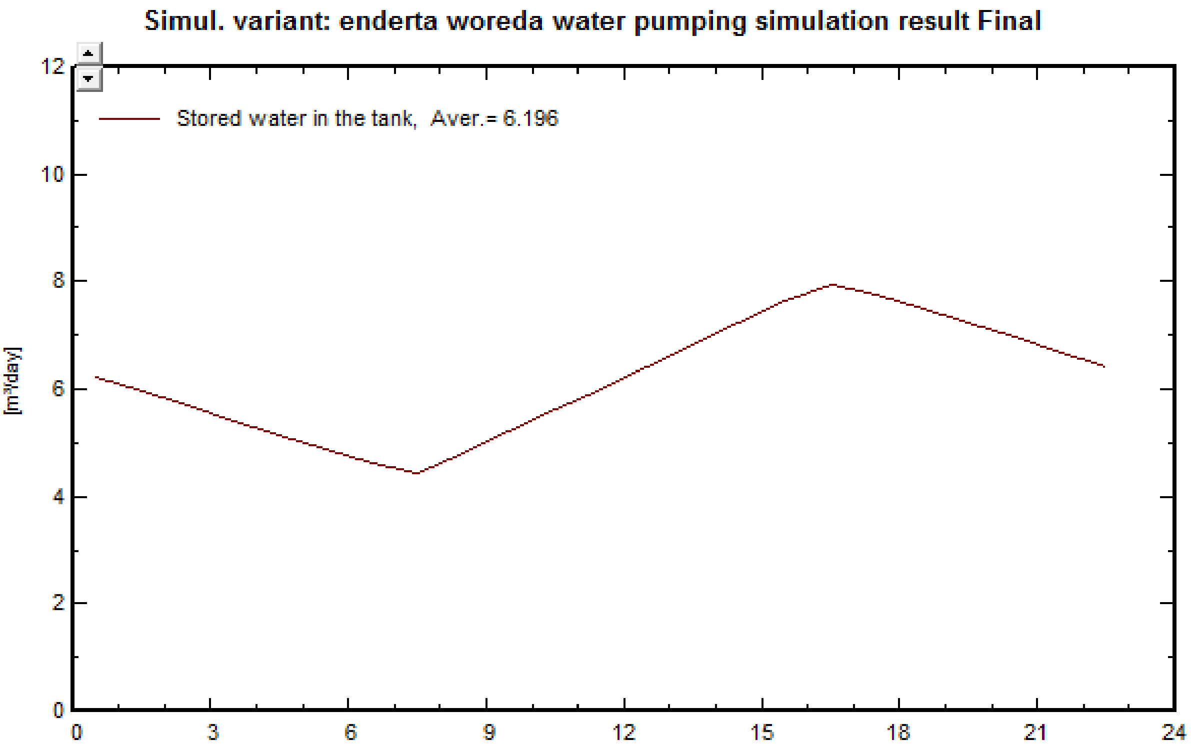
Appendix L: Different Simulation Variant Graph for Enderta Photovoltaic Water Pumping Site



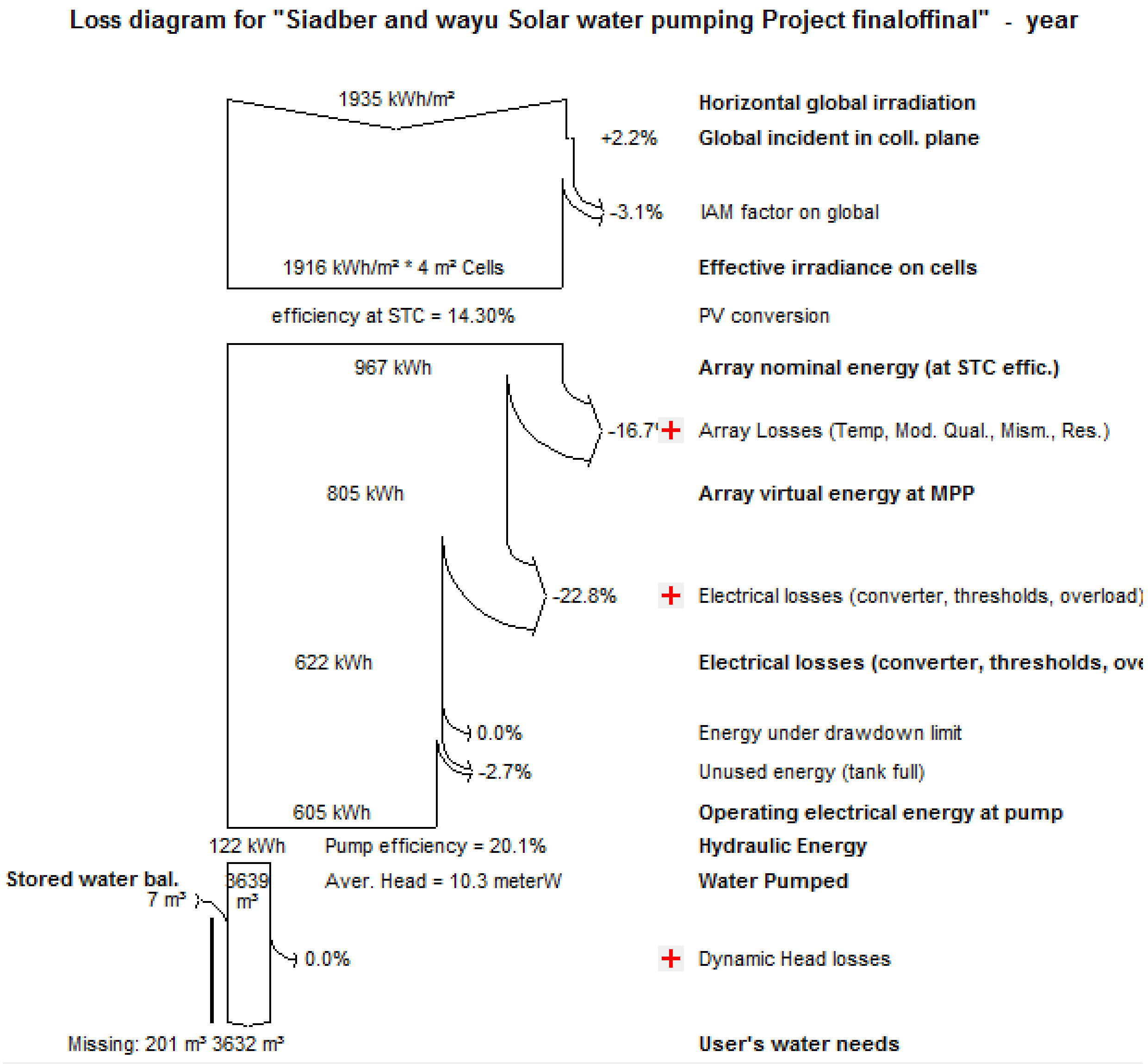

Simul. variant: enderta woreda water pumping simulation result Final
Pump voltage, Aver.= 51.88
Voltage [V]
0
10
20
30
40
50
60
70
0
3
6
9
12
15
18
21
24

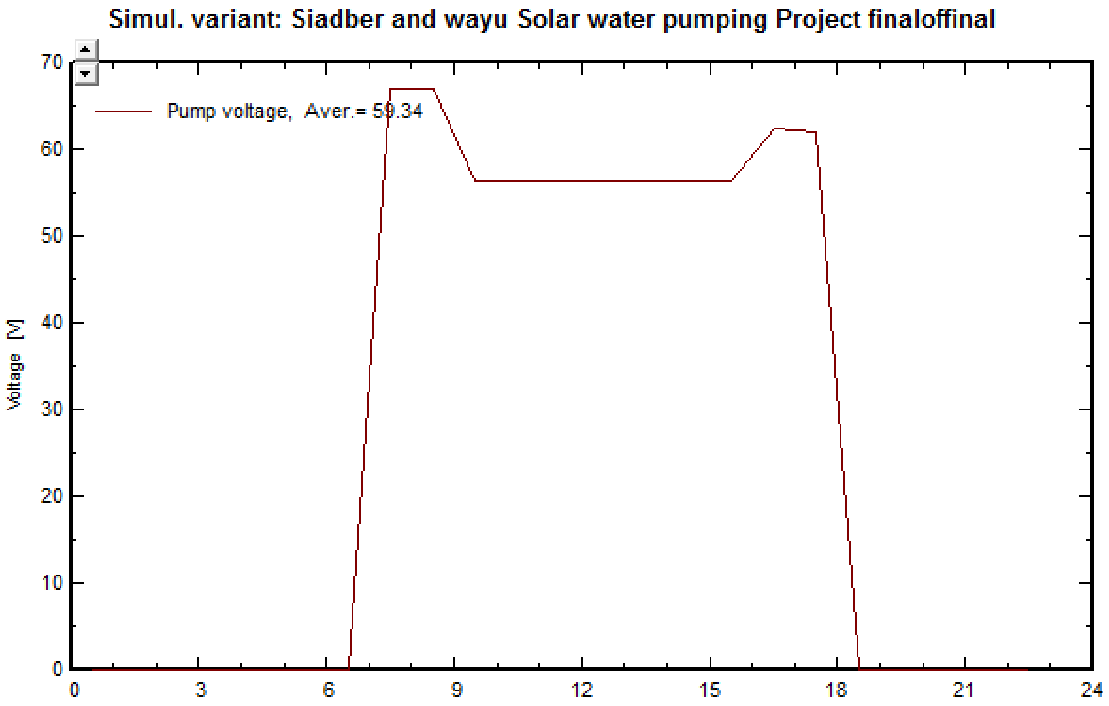

Simul. variant: enderta woreda water pumping simulation result Final
Pump current, 30.68
Current [A]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
3
6
9
12
15
18
21
24

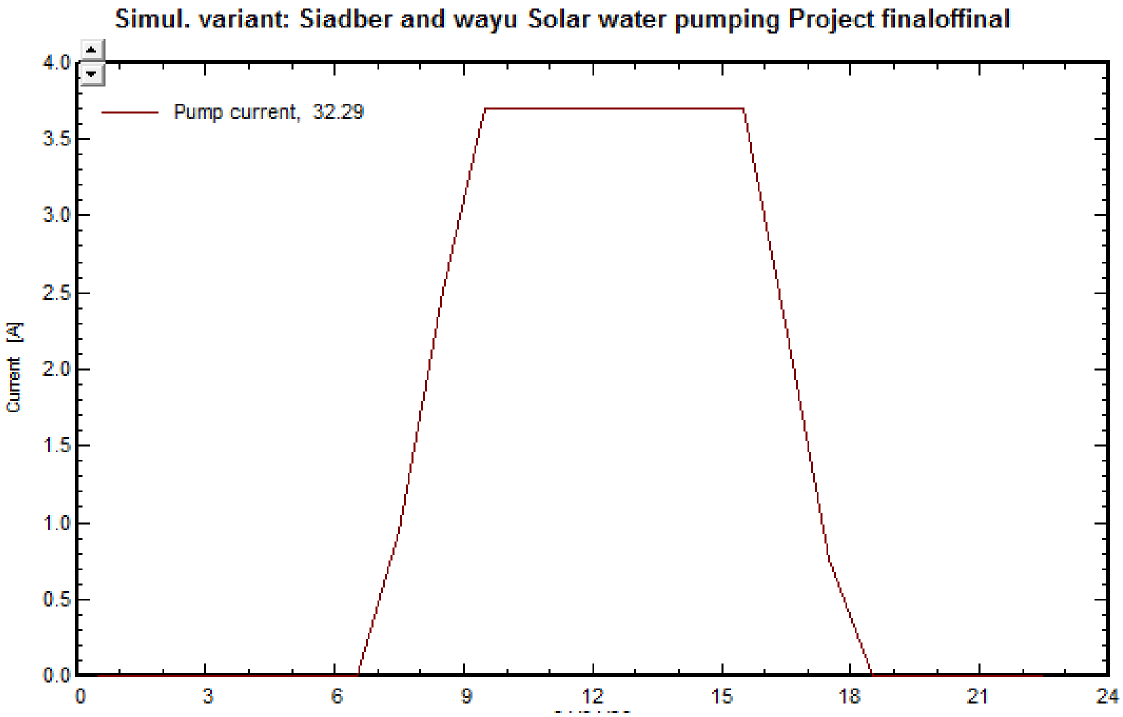

Simul. variant: enderta woreda water pumping simulation result Final
Water pumped, 6.136
[m³/day]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
3
6
9
12
15
18
21
24

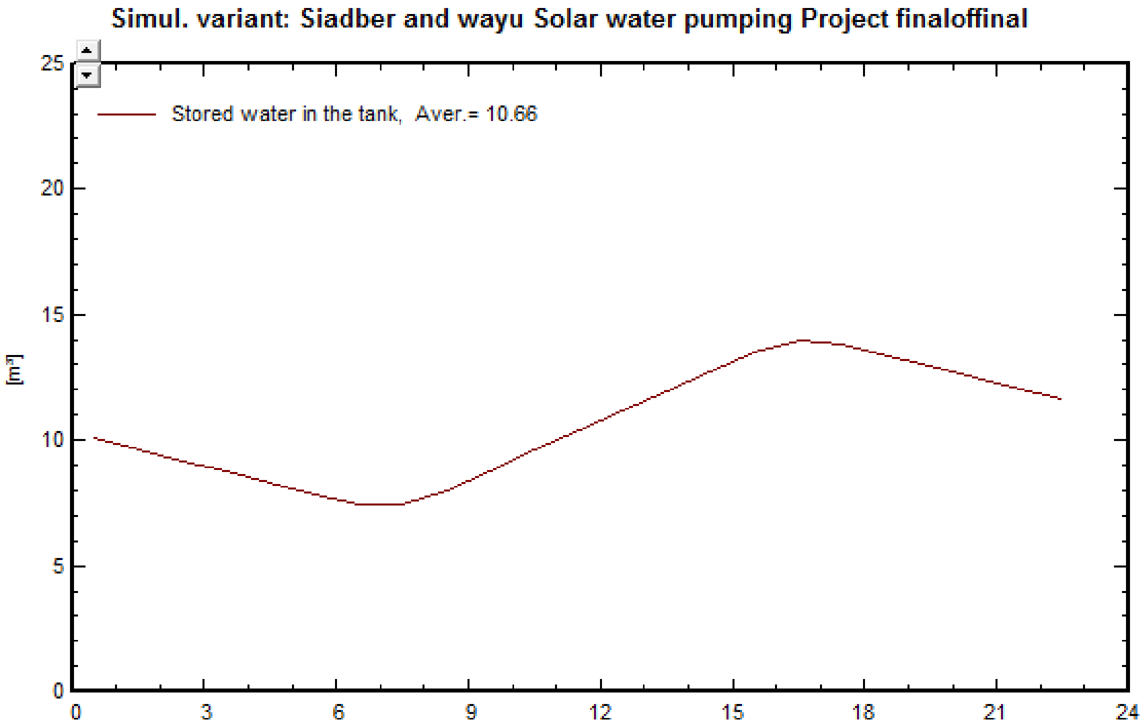

Simul. variant: enderta woreda water pumping simulation result Final
Stored water in the tank, Aver.= 6.196
[m³/day]
12
10
8
6
4
2
0
0
3
6
9
12
15
18
21
24

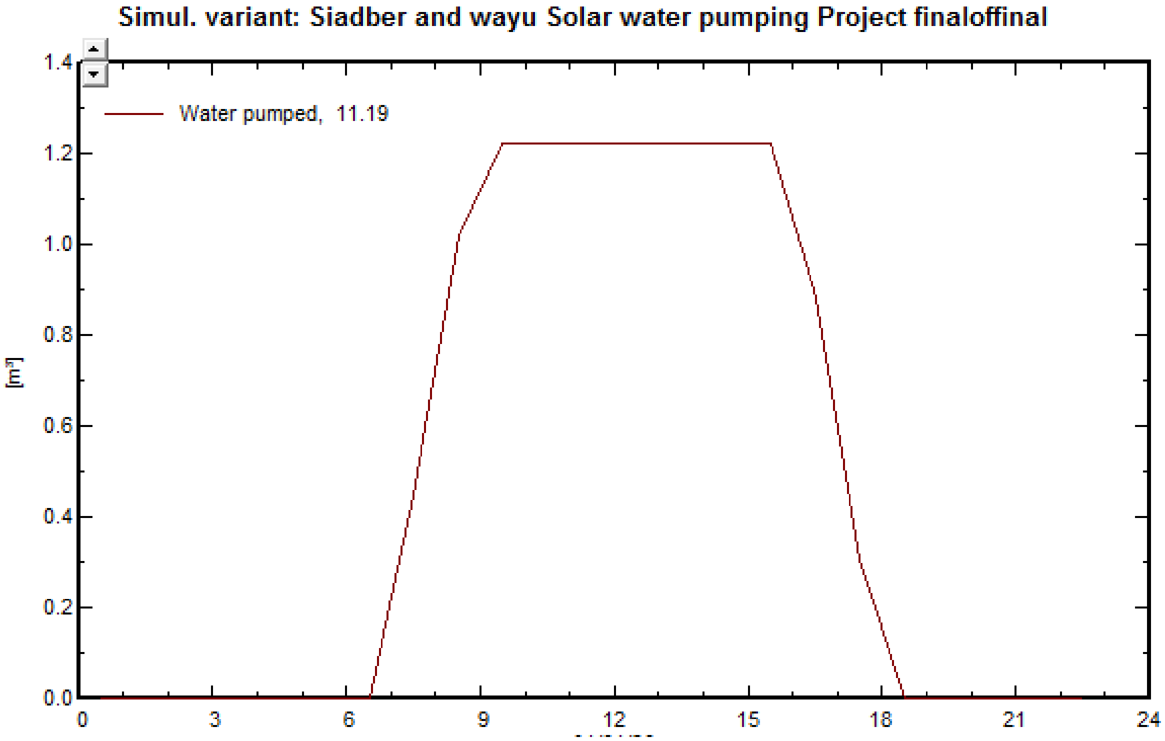
Appendix M: Different Simulation Variant Graph for Siadberand Wayu Photovoltaic Water Pumping Site




Simul. variant: Siadber and wayu Solar water pumping Project finaloffinal
Pump voltage, Aver.= 59.34
Voltage [V]
70
60
50
40
30
20
10
0
0
3
6
9
12
15
18
21
24

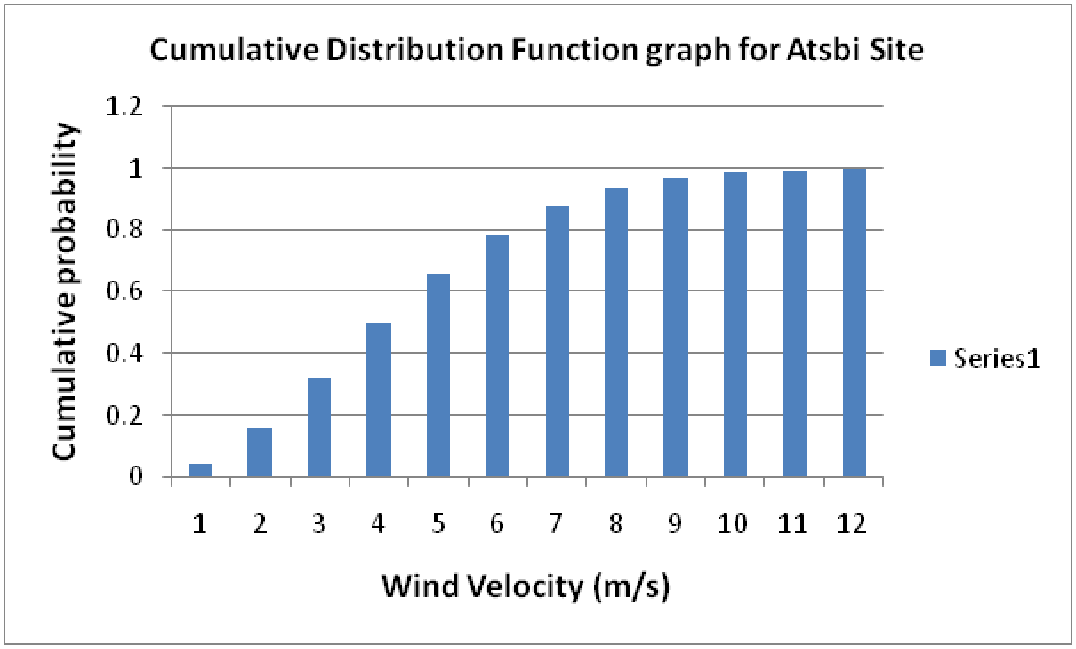

Simul. variant: Siadber and wayu Solar water pumping Project finaloffinal
Pump current, 32.29
Current [A]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
3
6
9
12
15
18
21
24

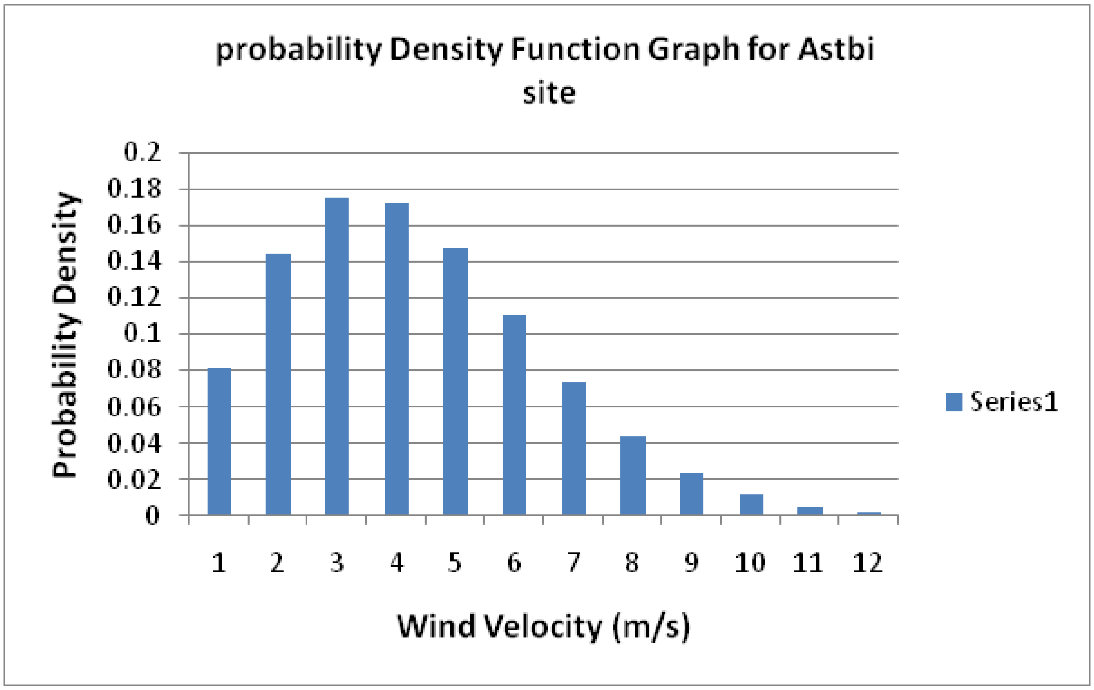

Simul. variant: Siadber and wayu Solar water pumping Project finaloffinal
Stored water in the tank, Aver.= 10.66
[m³]
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24


Simul. variant: Siadber and wayu Solar water pumping Project finaloffinal
Water pumped, 11.19
[m³]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
3
6
9
12
15
18
21
24

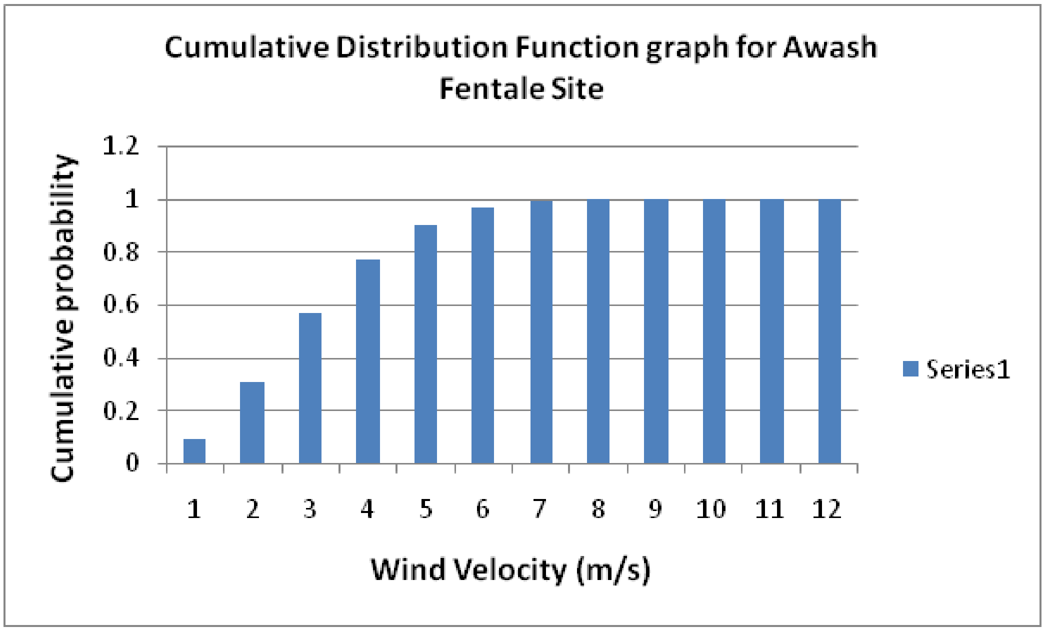
Appendix N: Probability Density and Cumulative probability distribution graph for the selected site

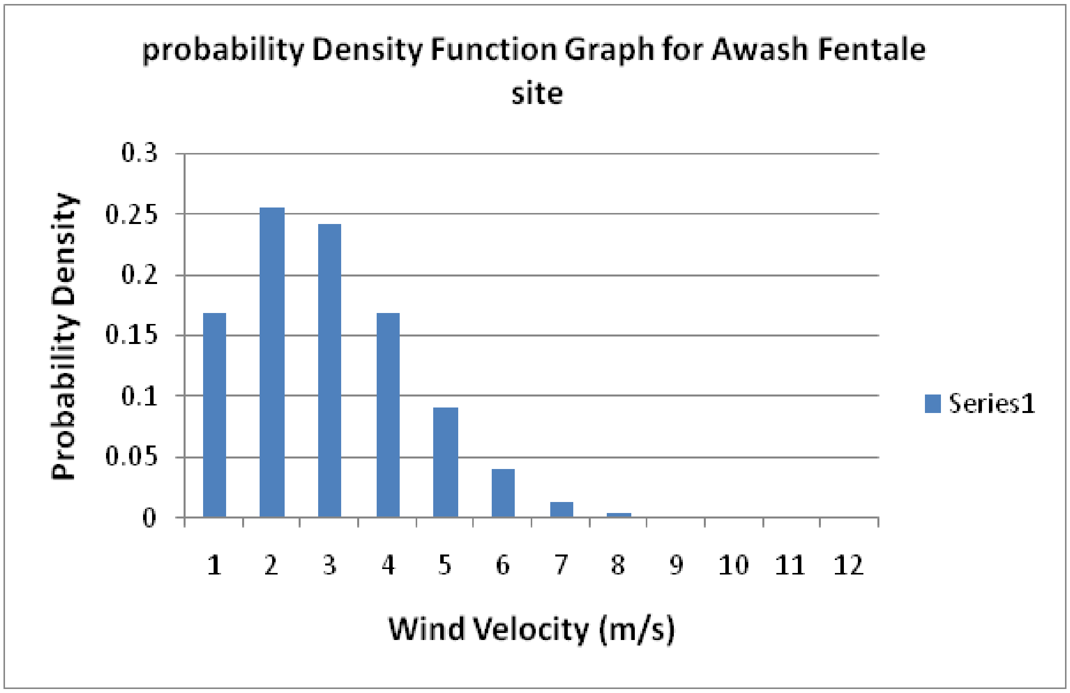
A. Cumulative distribution and probability density graph for Atsbi site



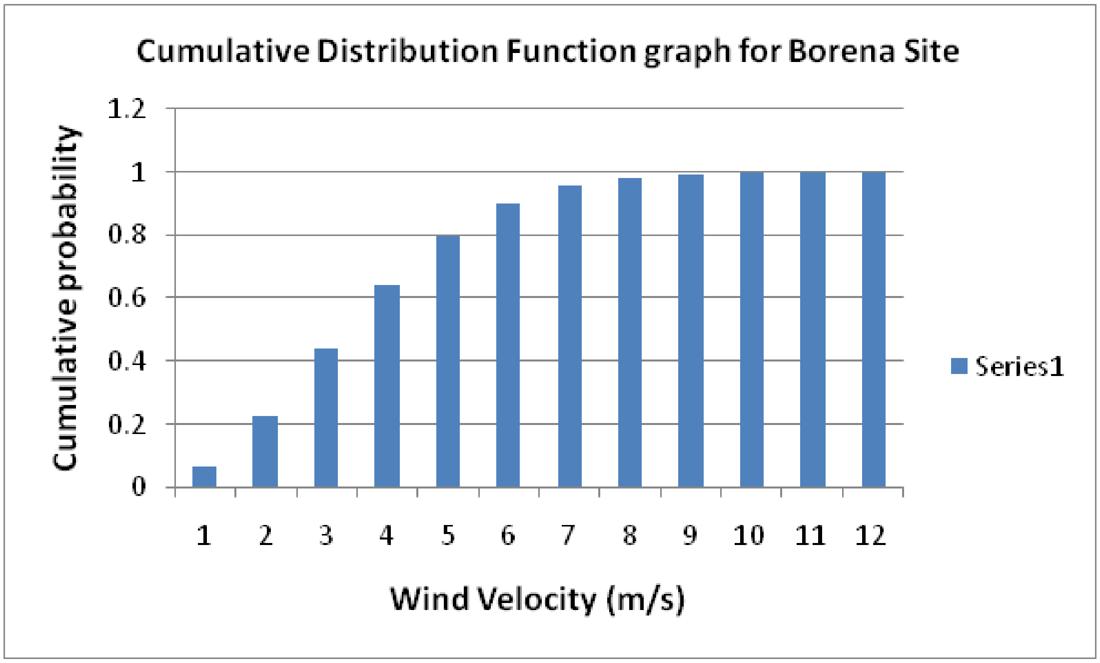


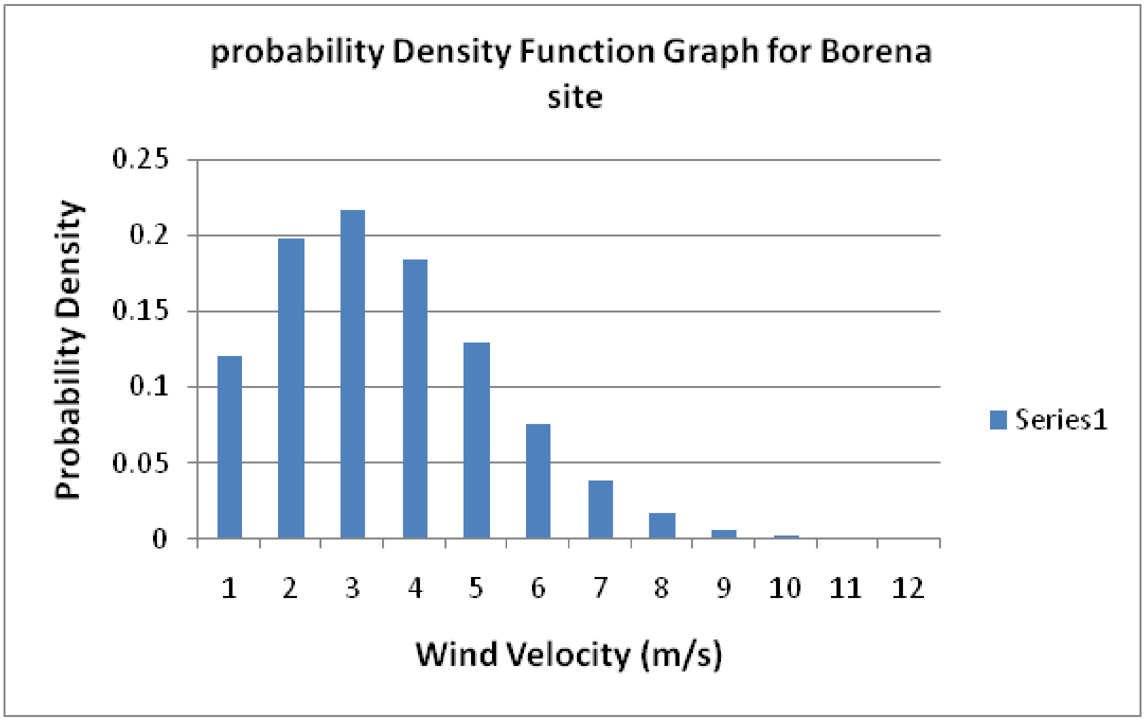
B. Cumulative distribution and probability density graph for Awash Fentale site





C. Cumulative distribution and probability density graph for Borena site





D. Cumulative distribution and probability density graph for Adame Tulu site