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Comparative Analysis of Feasibility of Solar PV, Wind and Micro Hydro Power Generation for Rural Electrification in the Selected Sites of Ethiopia

A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the Degree of Masters of Science in Mechanical Engineering
(Thermal Engineering Stream)

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July 2007

ACKNOWLEDGMENT

Primarily, I would like to give glory to God and the Virgin Mary without which the completion of this thesis would have been unthinkable.

Next, I would like to express my deepest gratitude to my advisors, Dr.-Ing. Demiss Alemu for his expert guidance, constructive comments, suggestions and encouragement without which this work could have not been completed. He has been a constant source of inspiration throughout my study period.

I am also grateful to Dr.-Ing Edessa Dribsa and Dr.-Ing Abebayehu Assefa for their kind help on different materials.

I would like to extend my appreciation to Dr. Abisolom Kiros and other importers of solar PV components who supplied the necessary cost data for the successful completion of this thesis.

Last but not least, I would like to thank my family and friends who stood always by my side.

ABSTRACT

Rural electrification has long been top on the development agenda of many developing countries. Nevertheless, the vast majority of the rural population in these countries did not have access to electricity. Electric light is still a luxury enjoyed only by a few in least developed countries like Ethiopia. The population living in uraban and semi urban areas connected to the national grid makes only 15% of the total. The remaining 85% of the population in scattered rural villages and have very remote chance to get electricity from the grid. The only realistic approach to electrify the rural areas seems therefore to be the off grid or self contained system. At present, diesel generation sets are popular and well known in the country. The contribution of renewable sources of energy like micro-hydro power, wind and solar energy to rural electrification are minimal. This thesis focuses on comparative analysis of feasibility of the three of the most well known renewable source of energy micro-hydro, solar photovoltaic and wind power generation for rural electrification.

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NOMENCLATURE

E_u = Energy mean consume (Wh/day)

R_d = Total daily solar irradiation (kWh/m^2/day)

η_b = Efficiency of the battery (%)

E_b = Energy storage in the battery (Wh/day)

C_{bn} = Net capacity of the battery (Ah)

V_{cc} = Working voltage in direct current (V)

DDP = Depth of discharge (%)

C_b = Commercial capacity of the battery.

η_c = Efficiency of the charge controller.

Ep = Energy supplied by the solar panel.

A_P = Area of the photovoltaic panel (m^2)

I_C = The Minimum Discharge current of the controller (A)

P_p = Peak power of the solar panel (W_P)

E_h = Energy available to the load and Battery in (Wh/m^2)

N = number of days

δ = declination angle

ϕ = Latitude angle,

$\omega_s = sunrise\ hour\ angle$

Ho = Extraterrestrial radiation on a horizontal surface, J/m2day

I_{sc} = solar constant equal to 1367 W/m^2

$\bar{H}$ = *monthly* average daily solar radiation on a horizontal surface

$\bar{H}_o$ = Monthly average extraterrestrial daily solar radiation on a horizontal surface.

$\bar{n}_s$: Monthly average daily hours of bright sunshine

$\bar{N}_s$ = Monthly average of the maximum possible daily hours of bright sunshine

ST = solar time in hour

$\bar{I}$ = hourly total radiation

ω = Solar hour angle

r_d = ratio of hourly total to daily total diffuse radiation.

ρ = diffuse reflectance of the ground, = 0.2 for ground reflectance

β = slope of the PV array

R_b = ratio of beam radiation on the PV array to that on the horizontal

θ = Angle of incident on an inclined surface

θ_z = Angle of incident on a horizontal surface

OCT = nominal operating cell temperature

$\bar{K}_T$ = monthly clearance index

η_r = PV module efficiency at reference temperature T_r

β_p = the temperature coefficient for module efficiency

A_P = module area

C_p = Coefficient of performance

P_m = Mechanical power out put wind turbine

P_w = Wind Power

K = the shape factor ranging from 1 to 3

C = the scale factor

f (x) = the probability to have a wind speed x during the year

V_{ava} = average wind speed at anemometer height (m/s

V_{avh} = Average wind Speed at the hub height (m/s)

H = hub height (30m) for both Villages

Ho = anemometer height (10m) for Dillamo Village and 20m for Gode Village

α = Shear exponent and commonly 0.2

P_{eR} = The rated electrical power (kW)

u_c = The cut-in wind speed (m/s)

u_R = The rated wind speed (m/s)

u_F = furling wind speed (m/s)

$f(u)$ = probability density function of wind speed

C = scale parameter (m/s)

K = Weibull shape parameter (Which is 2 for Reyliegh distribution)

C_{PR} = coefficient of performance at the rated wind speed commonly taken as 0.4

CF = Power factor or the plant factor

η_{mR} = transmission efficiency at rated power

η_{gR} = Generator efficiency at rated power

η_o = rated over all efficiency

$\rho =$ Air density which is 1.225 $\frac{kg}{m^3}$ at standard condition

$A =$ Swept area

E_{bw} = Wind Energy stored in the battery (Wh/day)

C_{bnw} = Net capacity of the battery (Ah)

C_{bw} = Commercial capacity of the battery.

η_{cw} = Efficiency of the charge controller.

I_{tw} = The Minimum Discharge current of the controller (A)

P_e = Electrical power out of the wind turbine

H_g = Gross head of the River in [m]

H_{net} = Net head of the river in [m]

h_{hydr} = Hydraulic loss in [m]

n_p = number of identical penstock

$Q =$ Flow rate of the river in [m^3/s]

t_{ave} = average pipe wall thickness of penstock in (mm)

d_p = penstock inner diameter (mm)

$N_t =$ rpm of cross flow turbine

t_t Penstock pipe wall thickness in [mm]

t_b Penstock pipe wall thickness at turbine in (mm)

ρ_w = Density of water in kg/m^3

g = acceleration of gravity in

n : Life time of the system

i : Interest rate

List of Abbreviations and Acronyms

EEPCO	Ethiopian Electric Power Corporation
Genset	Generator Set
ICS	(Grid) Interconnected System

CHAPTER 1
INTRODUCTION

1.1 Problem Statement

Ethiopia, in addition to the persistent drought and famine, is suffering from scarcity of energy. It is known that the development of any country depends on the amount of energy consumed. Energy consumption is proportionally to the level of economic development. The per capital energy consumption in Ethiopia is very low and it is almost biomass. This had a direct impact on deforestation. For lighting systems, in rural areas, kerosene is used which produces and emission of pollutants. Though Ethiopia has a tremendous amount of hydro power potential, because of the high initial cost, it is able to harness only 2 % of its potential so far. Moreover the cyclic drought in the country is causing "Electrical Energy Draught". Using renewable energy technologies like micro hydro power generation, solar photovoltaic and wind turbine rural areas can be electrified. In this project the comparative analysis on feasibility of micro-hydro, solar and wind energy for rural electrification of selected sites of Ethiopia is analyzed.

1.1.1 Objectives

The general objective of this thesis is to analyze the viability of renewable energy technologies for rural electrification in selected sites of Ethiopia.

The Specific Objectives are:

- Assess micro-hydro power resources and get the preliminary data for micro hydro power generation around Dillamo Village.
- Meteorological data collection for the site in consideration (i.e. sunshine duration, wind speed and direction at the anemometer position at the nearest station of the selected site)
- System design for each energy source at the selected site using analytical methods.
- Conduct economic analysis of the three energy consumption methods
- Economic evaluation of the systems and compare their feasibilities

- Make conclusion on the place where micro-hydro, solar (photovoltaic) or wind power generation will be installed in selected sites of rural area of Ethiopia in the future scenario

1.2 Outline of the Report

Chapter two reviews literatures about potential of renewable energy in Ethiopia and techniques of renewable energy technologies such as micro hydro, solar PV and wind. Chapter three presents locations of the selected villages, specific location of micro hydro power generation site, and location of data collection stations and environmental impacts of the three power generation systems. Chapter four describes power generation system design and analysis of the three renewable energy systems. Chapter five presents cost analysis of the three power generation systems. Chapter six presents financial evaluation of the three power generation systems, chapter seven presents conclusion and recommendation

CHAPTER 2

LITERATURE REVIEW

2.1 Rural Electrification in Ethiopia: Potentials

2.1.1 Resource Base

There is a huge energy resource potential in Ethiopia, which, if utilized, could minimize the present energy crisis prevailing in the country and enhance the process of rural electrification. The total exploitable renewable energy that can be derived annually from primary solar radiation, wind, forest biomass, hydropower, animal waste, crop residue and human waste is about $1{,}959\text{x}10^3$ Tcal per year [1]. Out of this, the share of primary solar radiation is about 73.08 percent, and the share of biomass resources is about 12.8 percent [1].

Table 2. 1 An Overview of Renewable Energy Resources in Ethiopia

No	Energy Resources	Energy in 10^2 T cal per year			
		Potential	% share	Exploitation	% share
1	Primary solar Radiation	1,953,550	99.7	1, 954	73.08
2	Wind	4,779	0.24	239	8.94
3	Forest Biomass	800	0.005	240	8.97
4	Hydro Power	552.1	0.03	138.00	5.16
5	Animal West	111.28	0.01	33.73	1.26
6	Crop Residual	81.36	0.0004	40.63	1.52
7	Human Waste	28.18	0.00014	28.18	1.05
Total		**1,959,901.93**	**100.00**	**2673.54**	**100**

Source: CESEN and calculation by EEA (2002)

2.1.2 Status of Solar Photovoltaic Power Generation in Ethiopia

It is estimated that about 1200 kWp PV capacity in about five to six thousands unit are operational in Ethiopia. This is far too low compared to even too low income sub Saharan countries (Tanzania, Burundi, Rwanda, Uganda, and Kenya). As many of these countries are much smaller in area and population computed to Ethiopia, the per-capital renewable energy installed capacity in Ethiopia is probably the least in Africa. For instance, in Rwanda in 1993 the installed capacity of PV lighting systems was about 29 kWp (Karekezi and Ranja, 1997) and the per capital installed capacity was 4.1Wp/1000 people in 1993 compared to 1.5 Wp/10000 people in 2001 for Ethiopia. This is unfortunate considering of the fact that Ethiopia has a large solar energy resource. Application and technology wise, the available information indicates that PV systems of about 850 kWp are being used by the ETC mainly to power repeater and radios in remote areas. PV systems employed for water pumping, refrigeration, school lighting, radios, and home lighting may not exceed 100kWp. As in the case of most developing courtiers, in Ethiopia, PV for water pumping and rural clinics were the main areas of focus, 'Mito' large scale pilot PV systems with 31.5 kWp which was operated by EREDPC [17, 37].

2.1.2.1 Potential of Solar Energy

Studies indicate that for Ethiopia as a whole, the yearly average daily radiation reaching the ground 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 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 values as high as 6.25 kWh/m^2 around Adigrat in the Tigray regional state (northern Ethiopia) and in Afar and Somali Region of Eastern Ethiopia

2.1.3 Status of Wind Power Generation in Ethiopia

Wind energy has been used in a variety of ways for water pumping, flour milling and in the last half of the century for electric generation. The technology of power generation from wind energy is well known [17]. Large electricity generation system by wind turbines are not yet installed in Ethiopia. However, some 100 wind pumps are operating in the country, providing drinking water for cattle and humans. In the Zuway region alone, 67 such wind pumps provide drinking water for more than 120,000 people. In the land-locked Africa country one would not expect a good wind regime, since better wind speeds are normally associated with cost lines and shores. However, taking the meteorological measurements power law for 20m indicates that wind speed above 6 m/s annual average can be obtained in some locations [17].

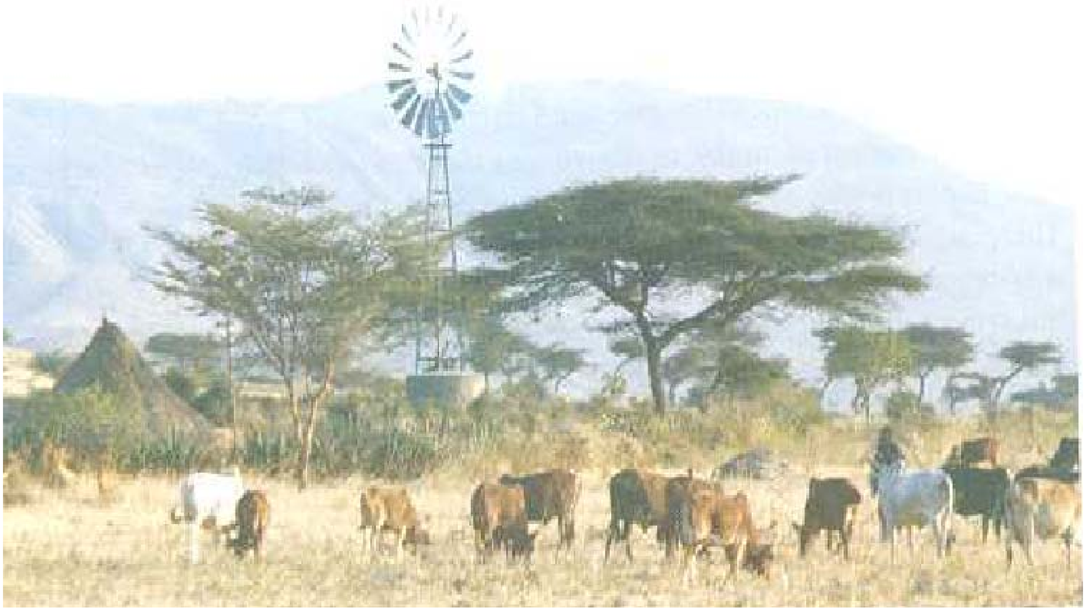

Figure 2. 1 Wind pump in operation near Zuway [6].

2.1.3.1 Potential of Wind Power Generation

In Ethiopia, there are few places with sufficiently high wind speed suitable for power generation. In most part of the country, the average wind speed is in the range of 3.5 to 5.5 m/s. This is not a sufficiently high potential for commercial power production.

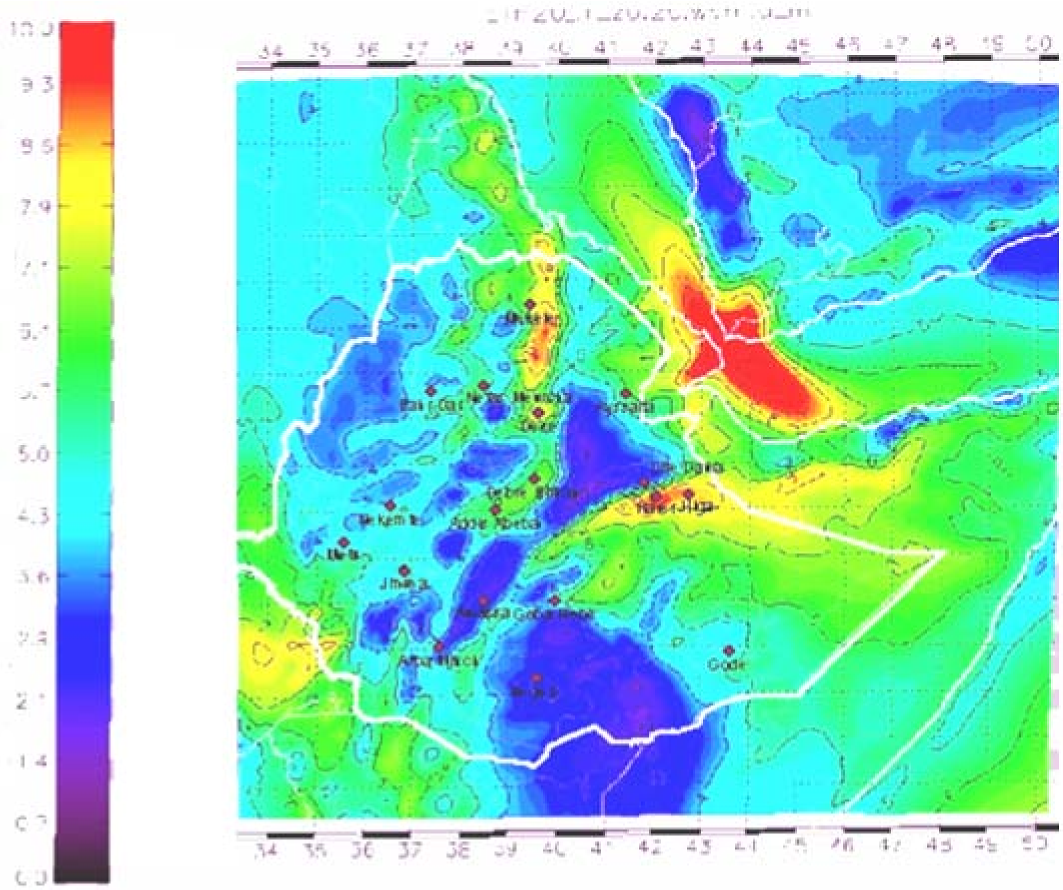

Figure 2. 2 Wind Resource of Ethiopia

2.1.4 Micro Hydro Resources and Existing Experience in Ethiopia [3]

Ethiopia is blessed with large hydro power resources. The gross hydro potential is estimated to be 650 TWh /yr [3]. Out of this gross potential, the economically feasible hydropower potential of Ethiopia has been estimated to be 15,000 MW to 30,000 MW. Of this economically feasible potential, only 10% or 1500MW to 3000MW would be suitable for small scale power generation including Pico and Micro hydropower. The recent baseline survey done for energy access projects reveals that the total theoretical potential for micro hydro development is 100 MW or about 1000 projects of a typical capacity of 100kW.

When the regional distribution is looked up, some parts of Ethiopia have considerable hydro resources while others with semi-arid and arid climate have none. There is also high variability of annual rainfall throughout the country. This indicates the corresponding runoff in the rivers and creeks available for micro hydro development follows the same variability. Pico and micro hydro systems for village application are of the run-of-river type and water availability is the most important aspect. The design flow of the plant must not exceed the minimum dry-season flow of the water resource. Stand-alone hydro schemes without alternative or back-up systems run the risk of insufficient capacity due to lower water. The micro hydro plant (180 kW) of Yaye (Sidama zone), which is recently built, has suffered from such difficulties during the dry season of 2002/03.

2.1.4.1 Regional Distribution of Micro Hydro Power

The Central and Southwestern highlands of the country have an annual water surplus which provides the basis for run-of-river hydro development on small scale.

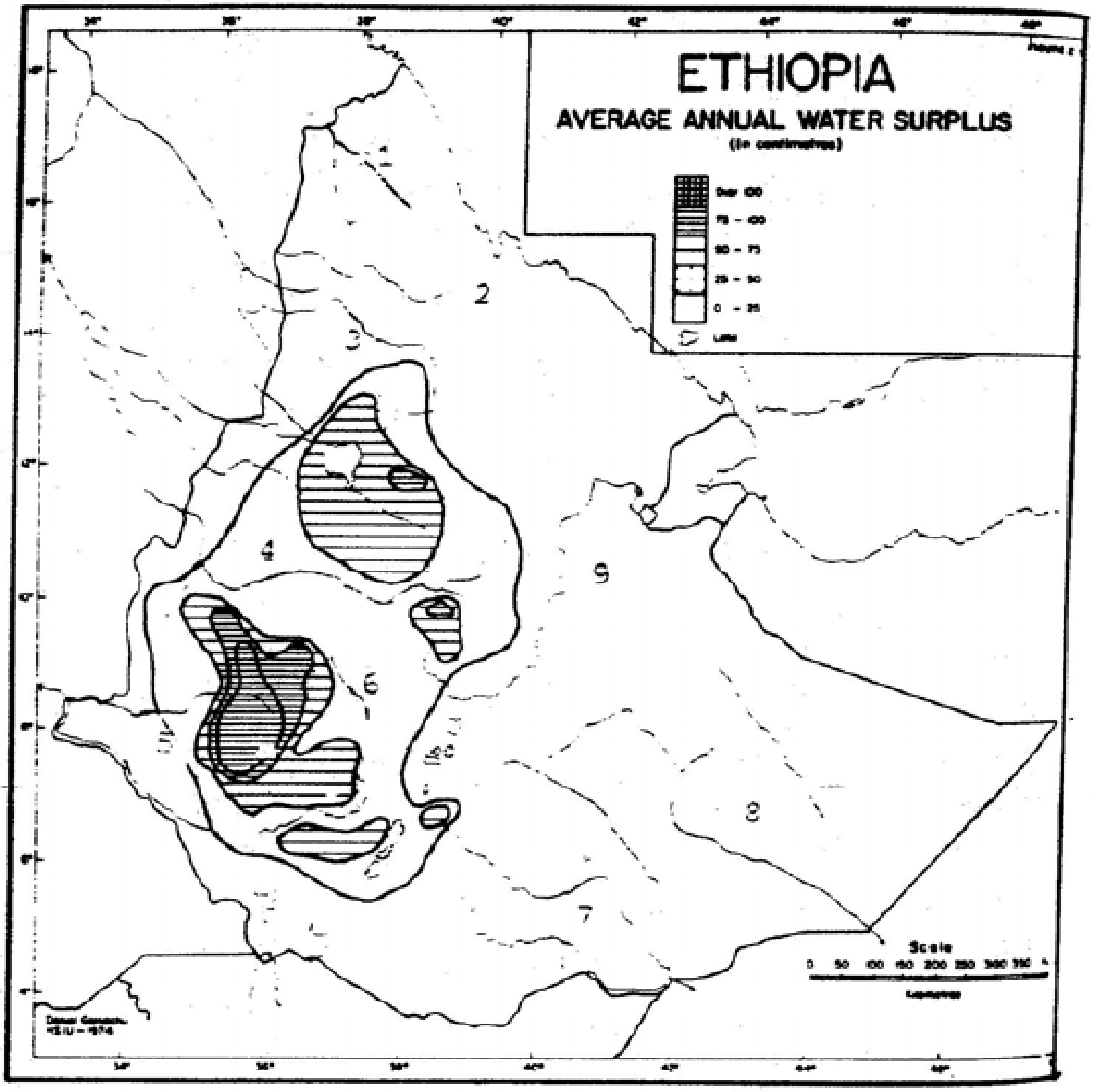

Figure 2. 3 Average annual water surplus regions in Ethiopia [3]

Table 2.2 shows the micro hydro potential (<500 kW) for each region has been estimated as follows:

Table 2. 2 Summary of technical micro hydro potential in Ethiopia per region

Region	Approximate Micro Hydro Potential (technical)
Oromia	35 MW
Amhara	33 MW
Benishangul-Gumuz	12 MW
Gambella	2 MW
SNNP	18 MW

2.1.4.2 EEPCO Micro Hydro Stations [3]

EELPA, the former national utility, used to install and operate a number of small hydropower stations in the micro and mini range. These were used to supply towns as self contained system up to 1990s when demand exceeded their capacity especially during the dry season. The interconnected system (ICS) was brought to these towns and the importance of the micro hydro systems was drastically reduced. As many of these micro/mini hydro systems date back to the 1950s and 1960s, they became unreliable and extremely costly to operate. Today, only one of these micro hydro plants is in regular operation.

The following table provides an overview of the existing EEPCO hydro plants in the micro range (≤ 500kW) and their current status.

Table 2. 3 Small hydro power plants operated by EEPCO [3]

	Name, location	**Head (m)**	**Type of the scheme**	**Installed Capacity (kW)**	**Year of Commissioning**	**Current Status**
1	Yadot, Bale Zone	23	ROR	350	1991	operational
2	Welega, Woliso town	16	ROR	162	1965	Not operational
3	Sotosomere, Jimma	30	ROR	147	1954, new set 1969	Not operational (ceased in 1986)
4	Hulka, Ambo town	40	ROR	150	1954	Not operational (Ceased in 1994)
5	Deneba, Buno Bedele	14	ROR	123	1967	Not operational (ceased in 1990)
6	Gelenmite, Dembi Dollo town	42	ROR	195	1966	Not operational (ceased in 1991)
7	Chemoga, Debre Markos Town	55	ROR	195	1962	Not operational (ceased before 1994)
8	Debre Berhan		ROR	130	1955	Not operational
9	Jibo, Harhar Zone		ROR	420	-	Not operational
	Total Capacity		ROR	1872		
	operational		ROR	350		
	Not operational		ROR	1522		

2.2 Solar Photovoltaic System

To understand the operation of a PV cell, both the nature of the material and the nature of sunlight need to be considered. Solar cells consist of two types of materials, often p-type silicon and n-type silicon. Light of certain wavelength is able to ionize the atoms in the silicon and the internal field produce by the junction separates some of the positive charge (“holes”) from the negative charge (electron) within the photovoltaic device.

The holes are swept into the positive or p-layer and the electron are swept in to the negative or n-layer. Although these opposite charges are attracted to each other, most of them can only recombined by passing through an external circuit outside the material because of the internal potential energy barrier. Therefore, if a circuit is made as is shown in the figure below (2.4). Power can be produce from the cell under illumination, since the free electrons have to pass through the load to recombine with the positive holes.

The amount of power available from a PV device is determined by

- The type and area of the PV material
- The intensity of the sunlight (insolation)
- The wave length of the sunlight

The photovoltaic systems, if designed correctly, can supply energy demand for: illumination, refrigeration, water supply, communications, etc. This technology has been practiced for many years [22].

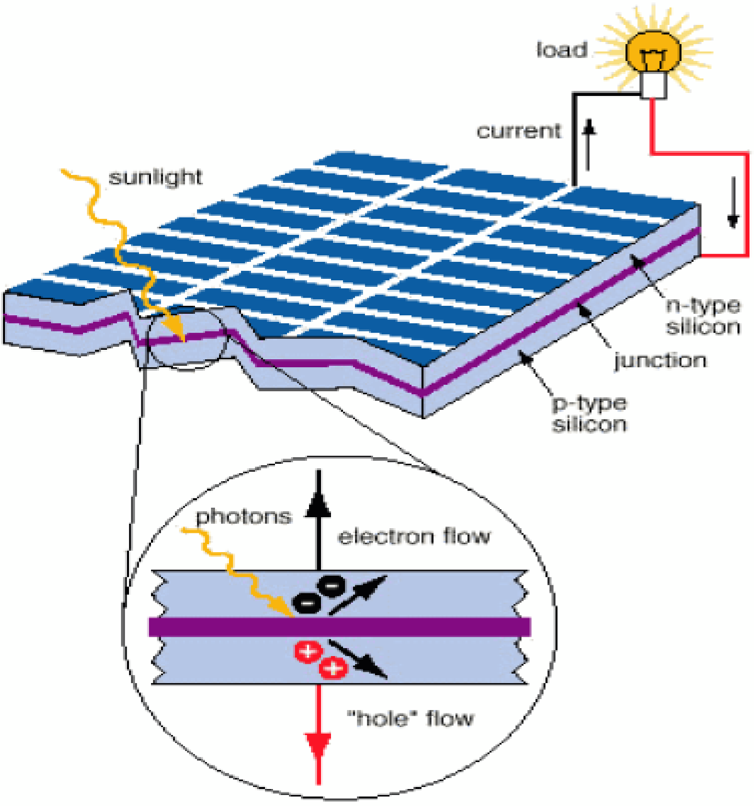

Figure 2. 4 Photovoltaic effect in a solar cell

Depending on the manufacturing process, the modules can be of four types [7].

a. Mono-crystalline Silicon.
b. Polycrystalline Silicon.
c. Amorphous Silicon
d. Ribone silicon

Photovoltaic panels convert solar radiation to electricity with efficiencies in the range of 5% to 20%, depending on the type of the cell.

a*. Mono-*Crystalline Silicon.

Most photovoltaic cells are of single-crystal types. To manufacture the cell, silicon is purified, melted, and crystallized into ingots. The ingots are sliced into thin wafers to make individual cells. The cells have a uniform color, usually blue or blac

*b**. Polycrystalline Silicon**.*

Polycrystalline cells are manufactured and operated in a similar manner. The difference is that lower cost silicon is used. This usually results in slightly lower efficiency, but polycrystalline cell manufacturers assert that the cost benefits outweigh the efficiency losses. The surface of polycrystalline cells has a random pattern of crystal borders instead of the solid color of single crystal cells.

c. Amorphous Silicon

The previous two types of silicon used for photovoltaic cells have a distinct crystal structure. Amorphous silicon has no such structure. Amorphous silicon is sometimes abbreviated "aSi" and is also called thin film silicon.

Amorphous silicon units are made by depositing very thin layers of vaporized silicon in a vacuum onto a support of glass, plastic, or metal. Since they can be made in sizes up to several square yards, they are made up in long rectangular "strip cells." These are connected in series to make up "modules.

d. Ribone Silicon

Ribbon-type photovoltaic cells are made by growing a ribbon from the molten silicon instead of an ingot. These cells operate the same as single and polycrystalline cells.The anti-reflective coating used on most ribbon silicon cells gives them a prismatic rainbow appearance.

2.2.1 Function of the System

The photovoltaic panel receives the sun’s rays (day light) and transforms them into electrical energy. By means of the charge regulator, the energy generated by the panel is conditioned and stored in the battery. The different systems are connected to the charge controller that manages the energy that comes.

A photovoltaic system can supply direct current electricity and in different range of different voltages (12V, 24V, 48V, etc...) a 12 V voltage is often used for the rural electrification, is also possible to get alternative current of 110 or 220 V.

It is possible to convert direct current to alternative current of 220 V, using an inverter 12Vdc/220 Vac which allows utilization of color television, VHS systems, and small electro pumps for water, computers [37].

2.2.2 Components

2.2.2.1 Photovoltaic Panel

A photovoltaic panel is a flat plate, composed by photovoltaic cells that have the property of converting the energy from the sun into electrical energy.

When the temperature of a photovoltaic module is increased, the efficiency drops. This can typically result in an efficiency drop off of 0.5% per °C increase in the cell operating temperature. The operating temperature is increased because a large part of the solar radiation is not converted to electricity but is absorbed by the panel as heat [37, 26]. The voltage and the power of PV cells are very small in order to supply a device. For this reason, many cells are combined together in a PV panel with common electrical output.

One of the main features of the panel is the peak power. The peak power is the power from the photovoltaic when the solar irradiance is 1000 W in every square meter, when the temperature is 25ºC. It is obvious that the power from the panel depends on the area of the panel, the type and its operation temperature. The maximum power is given from the manufacturer [26]. The operating voltage is another important characteristic of the panel. Most photovoltaic today are constructed in a way that they produce power higher than 12 V in order to charge the 12 V batteries. Apart from the voltage, the operating current is another parameter. It is the current which is determined from the maximum power from the panel and the voltage created, for bigger PV systems, panels with operating voltages equal to 24 V or even 48 V are used.

2.2.2.2 Charge Controllers

Charge controllers are used in PV systems to protect the batteries from overcharge and excessive discharge. Most controllers function by sensing battery voltage and then take action based on voltage levels. Other controllers have temperature compensation circuits to account for the effect of temperature on battery voltage and state-of-charge.

2.2.2.3 Battery

The electrical energy is stored to the batteries in order to be provided in intervals with minimum solar irradiance (during nights, cloudy days). Solar energy systems for this research use a *lead-acid deep cycle battery*. This type of battery is different from a conventional car battery, as it is designed to be more tolerant of the kind of ongoing charging and discharging would expect when variable sunshine from one day to the next has [8,29].

Lead-acid deep cycle batteries last longer but it also cost more than a conventional battery. The plate is made of a sponge-like material [26, 10].

2.2.2.4 Inverters

Inverters are the device usually solid state, which change the array DC to AC of suitable voltage, frequency, and phase to lead photovoltaic power generated in to the power local load as the per the requirement [26,29,8] for this research work we use color Television and required alternative current so inverter is required to convert 60W power.

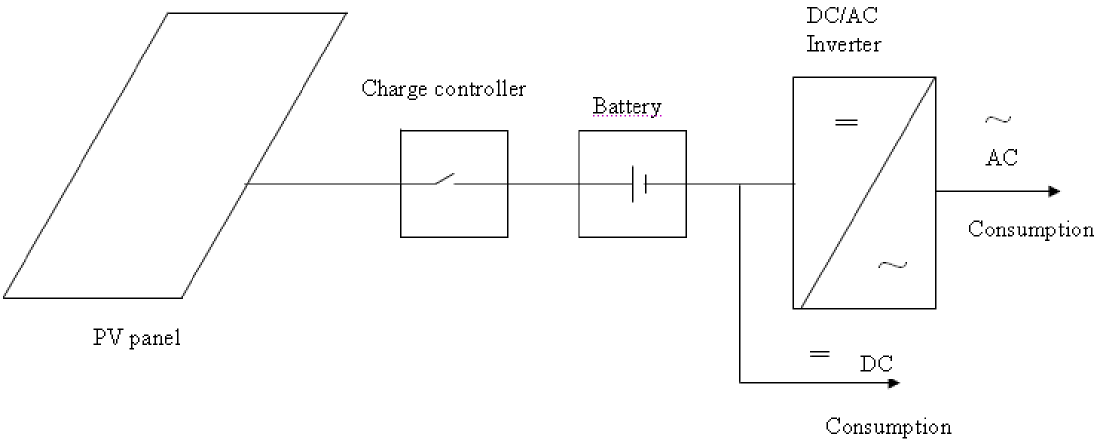

Figure 2. 5 PV electric power generation arrangements

2.2.2.5 Structure

Required to mount or install the PV modules and other components of the power generation.

2.2.2.6 Balance of System Components

Type of Wire and Size: The performance and reliability of a PV system is increased if the correct size and type of wire is chosen. Copper wires are generally used in PV systems. Although aluminum wire is less expensive, it can cause very serious problems to the PV system if used incorrectly. When choosing the type of wire to use, the total current carrying capability of the wire must be considered along with the fuses used to protect the conductors.

Switches and Fuses: Fuses are used in PV systems to provide over current protection when ground faults occur and switches are used to manually interrupt power in case of emergency or maintenance. Since the battery is the major current source of concern in a stand-alone PV system, a fuse has to be connected between the array and the controller.

Connections: Poor connections are responsible for most problems in a stand-alone PV system. Poor connections may result to losses in system efficiency, system failure, and costly troubleshooting and repairs. System connections must be secure and able to with stand extreme weather and temperature. Connections must also be protected from vibration, animal damage and corrosion. To prevent against corrosion, copper conductors should be used for system connections [8, 25].

2.2.3 Advantage and Disadvantage of Photovoltaic Power Generation

Advantage *[30]*

- PV system is lasting longing sources of energy which can be used almost anywhere. They are particularly useful where there is no national grid and also where there are no people such as remote site water pumping or in space. And also it is cost effective solutions to energy problems in places where there is no mains electricity.
- PV systems can also be installed in a distributed fashion, i.e. they don't need large-scale installations it can be installed on roofs, which mean new space may not required and each user can quietly generate their own energy.
- PV systems have no moving parts and no noise or pollution is created from their operation that makes them the safest method of power generation, and requires little maintenance and has a long lifetime.
- The environmental impact of a photovoltaic system is minimal, requiring no water for system cooling and generates no by-products.

Disadvantages *[30]*

- Most types of PV power generation system require large areas of land to achieve average efficiency. The silicon used is also very expensive. Solar energy is currently thought to cost about twice as much as traditional sources (coal, oil etc).

- The problem of nocturnal down times means PV system can only ever generate during the daytime due to the intermittent and variable manner in which the solar energy arrives at the earth's surface.
- At present, the high cost of PV modules and equipment is the primary limiting factor for the technology.

2.3 Wind Power Generation

Wind power, like most sources of energy on earth, originates from the sun. As the earth orbits the sun daily, it receives light and heat. Across the earth there are areas with different temperatures, so that heat transfers from one area to another. These heat differences help to create wind: in warmer regions of the earth, the air is hot and is therefore at a high pressure, compared with the air in colder regions, where it is at a low pressure. Wind is the movement of the air from high pressure to low pressure.

The idea of creating something to capture the power from the wind is not a new idea. Wind turbines have been used for thousands of years for milling grain, pumping water, and other mechanical power applications. Today, there are over one million wind turbines in operation around the world. Most of them are used for water pumping and for generating electricity. Wind energy offers the potential to generate substantial amounts of electricity without the pollution problems of most conventional forms of electricity generation [18, 31].

2.3.1 Working Principle of Wind Turbines

Aerodynamic principle

Air flow over a stationary airfoil produces two forces, a lift force perpendicular to the air flow and the drag force in the direction of air flow. The existence of lift force depends on a laminar flow over the airfoil, which means that the air flows smoothly over both sides of the airfoil. If turbulent flow exists rather than laminar flow, there will be a little or no lift force. The air flowing over the top of the air foil has to speed up because of the greater distance to travel; this increase in speed causes a slight decrease in pressure. This pressure difference across the air foil yields the lift force, which is perpendicular to the direction of air flow

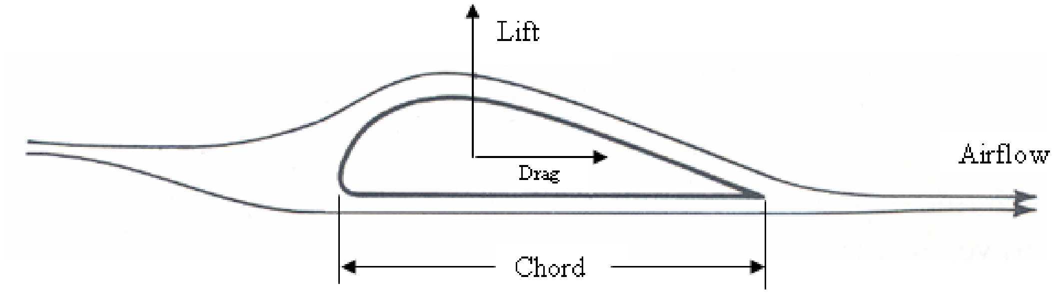

Figure 2. 6 Lift and drag on a stationary airfoil

The air moving over the air foil also produces a drag force in the direction of the air foil. This is a loss term and has to be minimized as much as possible in high performance wind turbines. Both the lift and drag are proportional to the air density, the area of the air foil, and the squire of the wind speed [18].

2.3.2 How Energy has been created by Wind Turbines

So how do wind turbines make electricity? Simply stated, a wind turbine works the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity. Wind turbines below 50 kilowatts, are used for homes, telecommunications dishes, or water pumping [13, 31].

2.3.3 Horizontal and Vertical axis Wind Turbines

Horizontal axis wind turbines generally have either two or three blades or else a large number of blades. Wind turbines with large numbers of blades have what appears to be virtually a solid disc covered as high-solidity devices. In constant, the swept area of wind turbines with few blades is largely void and only a very small fraction appears to be solid. These are referred as low-solidity. Vertical axis wind turbines have an axis of rotation that is vertical, and so unlike the horizontal counterparts, they can harness winds from any direction without the need to repositioning of the rotor when the wind direction changes [18].

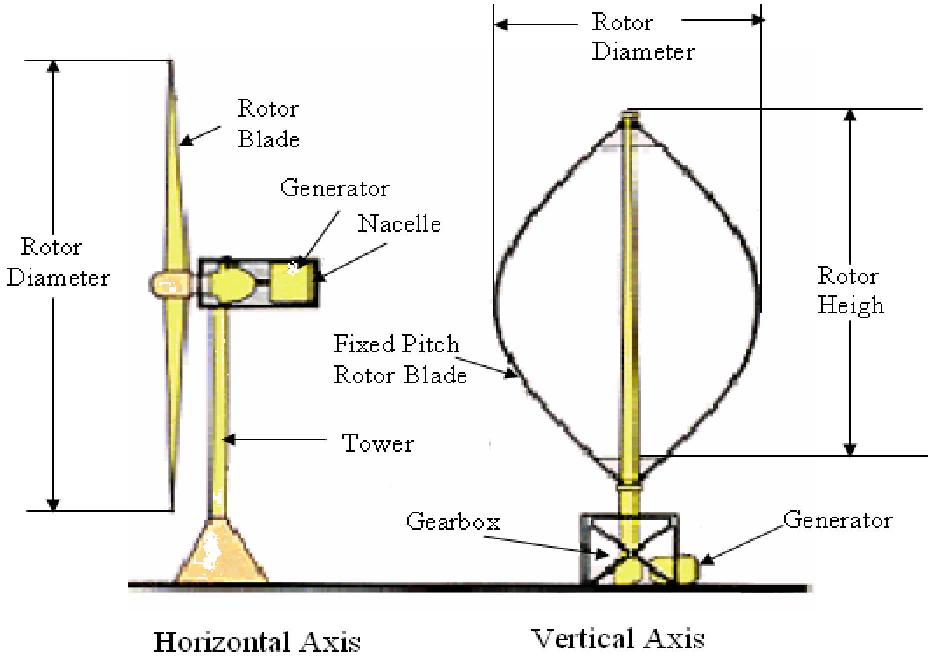

Figure 2. 7 Horizontal and vertical axis wind turbine configuration

2.3.4 Description of Wind Turbine Parts

- ***Hub:*** Hub is the connection point for the rotor blades and the low speed shaft.
- ***Gear box***: Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1200 to 1500 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine and engineers are exploring "direct-drive" generators that operate at lower rotational speeds and don't need gear boxes specially for small scale wind turbines.
- ***Generator:*** The generator is connected to the high-speed shaft and is the component of the system that converts the rotational energy of the shaft into an electrical output.
- ***Tower of wind power generation*****:** The tower is used to support the nacelle and rotor blades and typically made of rolled, tubular steel, and built and shipped in sections because of its size and weight. Common tubular towers incorporate a ladder within the hollow structure to provide maintenance access. Small -scale towers range in height from 24-35m and its weight depends on the material from where it is manufactured.
- ***Nacelle:*** The rotor attaches to the nacelle, which sits top the tower and includes the gear box, low- and high-speed shafts, generator, controller, and brake. A cover

protects the components inside the nacelle. Some nacelles are large enough for a technician to stand inside while working.

- ***Brake:*** A disc brake which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.
- ***Controller:*** The controller starts up the machine at wind speeds of about 3.5 to 7.2 meters per sec (m/s) and shuts off the machine at about 30 m/s.
- ***High-speed shaft:*** Drives the generator.
- ***Low-speed shaft:*** The rotor turns the low-speed shaft at about 30 to 60 RPM
- ***Pitch:*** Blades are turned, or pitched, out of the wind to keep the rotor from turning in winds that are too high or too low to produce electricity.
- ***Rotor:*** The blades and the hub together are called the rotor. ¸ Tower: Towers are made from tubular steel or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.
- ***Yaw drive:*** Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive; the wind blows the rotor downwind.
- ***Yaw motor:*** Powers the yaw drive [21].
- ***Electronic equipment:*** Such as controls, electrical cables, ground support equipment and interconnection equipment [6].

2.3.5 Advantage and Disadvantage of Horizontal and Vertical axis Wind Turbine

2.3.5.1 Vertical axis Wind Turbine

Advantage:-

- You place the generator, gearbox etc. on the ground, and you may not need a tower for the machine.
- You do not need a yaw mechanism to turn the rotor against the wind

Disadvantages:-

- Wind speeds are very low close to ground level, so although you may save a tower, your wind speeds will be very low on the lower part of your rotor
- The overall efficiency of vertical axis machines is not impressive.

- The machine is not self-starting (e.g. a Darrieus machine will need a "push" before it starts. This is only a minor inconvenience for a rid connected turbine, however, since you may use the generator as a motor drawing current from the grid to start the machine).
- The machine may need guy wires to hold it up, but guy wires are impractical in heavily farmed areas.
- Replacing the main bearing for the rotor necessitates removing the rotor on both a horizontal and a vertical axis machine. In the case of the latter, it means tearing the whole machine down.
- The vertical axis wind turbines are still under research and development, hence they are not yet out in the market.

2.3.5.2 Horizontal Axis Wind Turbine

Advantage:-

- High efficiency
- Ability to fuel by turning the rotor (blades) parallel to the wind direction
- Low cut in wind speed
- Generally low cost to power output ratio

Disadvantages:-

- Tail or yaw drive may be required; which adds complexity
- Restricted servicing of generator and gear box

Due to the above reasons horizontal axis wind turbine is commonly used power generation for rural electrification.

2.3.6 Stall and Pitch Control of Wind Power Generation

There are two main methods of controlling the power output from the rotor blades. The angle of the rotor blades can be actively adjusted by the machine control system. This is known as pitch control. The other method is known as stall control. This is sometimes described as passive control, since it is the inherent aerodynamic properties of the blade, which determine power output; there are no moving parts to adjust. The twist and thickness of the rotor blade vary along its length in such a way that turbulence occurs behind the blade whenever the wind speed becomes too high. This turbulence causes some of the wind’s energy to be shed, minimizing power output at higher speeds. Stall control machines also have brakes on the blade tips to bring the rotor to a standstill, if the turbine needs to be stopped for any reason [17].

2.4 General Description about Hydro Power Generation

Hydropower engineering refers to the technology involved in converting the pressure energy and kinetic energy of water into more easily used electrical energy. The prime mover in the case of hydropower is a water wheel or hydraulic turbine which transforms the energy of the water into mechanical energy. Mechanical energy will be converted to electrical energy by using electrical generator [15].

2.4.1 Types of Hydro Power

There are four basic types of hydro power generation

2.4.1.1 Impoundment

An impoundment facility, typically in a large hydropower system, uses a dam to store river water in a reservoir. The water may be released either to meet changing electricity needs or to maintain a constant reservoir level.

2.4.1.2 Run-of-river type

A dam with a short penstock (supply pipe) directs the water to the turbines, using the natural flow of the river with very little alteration to the terrain stream channel at the site and little impoundment of the water.

2.4.1.3 Diversion and Canal type

The water is diverted from the natural channel into a canal or a long penstock, thus hanging the flow of the water in the stream for a considerable distance

2.4.1.4 Pumped Storage Type

When the demand for electricity is low, pumped storage facility stores energy by pumping water from a lower reservoir to an upper reservoir. During periods of high electrical demand, the water is released back to the lower reservoir to generate electricity.

2.4.2 Basic Concepts of Micro-Hydro Power Generation

Micro-hydro schemes are smaller still and usually do not supply electricity to the national grid at all and it is usually refers to hydraulic turbine systems having a capacity of 0.20 kW just enough to provide domestic lighting to a group of houses through a battery charging to 100kW which can be used for small factories and to supply an independent local mini-grid which is not part of the national grid. This small unites have been used for many years, but recent increases in the value of electrical energy and incentive programs have made the construction and development of micro-hydro power plants much more attractive to developers. Similarly small villages and isolated communities in developing nations are finding it beneficial and economical to use micro-hydro power generation [6, 15].

The principles of operation, types of units, and the mathematical equations used in selection of micro-hydro power systems are essentially the same as for conventional hydropower developments. However, there are unique problems and often the costs of the feasibility studies and the expenses of meeting all regulatory requirements make it difficult to justify micro-hydro power developments on an economic basis.

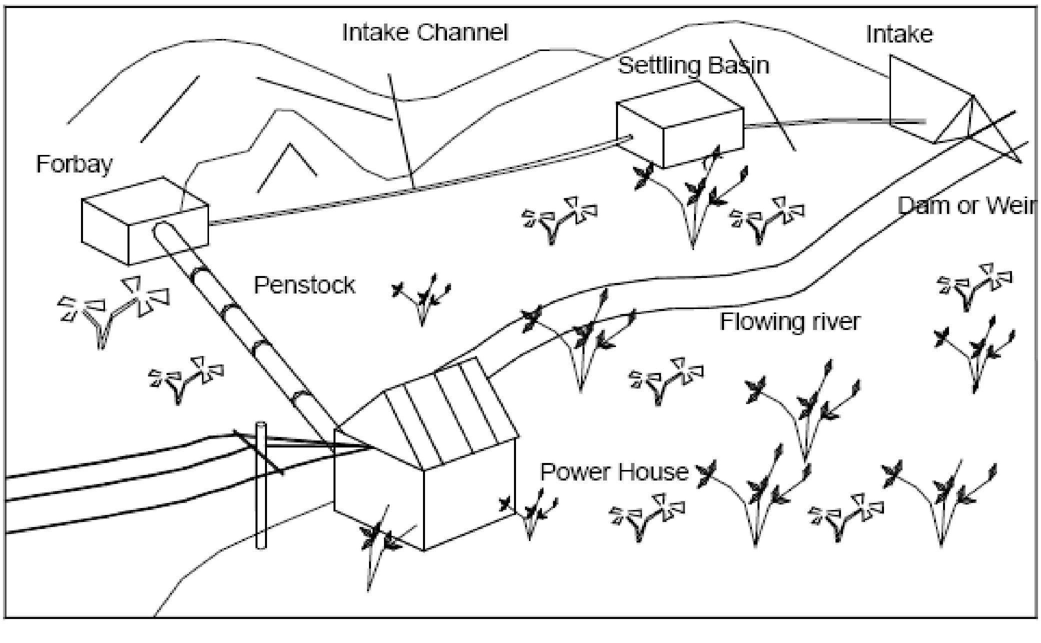

Figure 2. 8 Layout of a typical micro hydro scheme

Components of the Micro Hydro Power Generation can be explained as:

Weir: the weir acts to divert water through an opening in the river side into the open channels

Setting basin: it is used to remove sand particles from water

Channel: this part follows the counter of the hill side so as to preserve the elevation of the divert water

Forebay: the water enters the tank which is called the fore bay tank to feed the water to the penstock. The penstock is connected at a lower elevation to a water wheel which is the turbine.

The choice of the micro hydropower technology serves both local and global objectives.

Some of the advantages are [6]

- It is renewable, non polluting, utilizes indigenous resource;
- Micro hydro schemes permit the energy to be generated near where it to be used, leading to reduced transmission costs;
- It can be easily integrated with irrigation and water supply projects in rural areas;
- Micro hydro schemes permit the generation of mechanical energy to drive agro processing machinery or establish cottage industries in rural areas;
- It is a much more concentrated energy resource than either wind or solar power;
- The energy available is readily predictable;
- No fuel and only limited maintenance are required;

Against these, the main shortcomings are [6]:

- It is a site-specific technology;

2.4.3 Electrical and Mechanical Equipment for Micro-Hydro Power Generation

The primary electrical and mechanical components of a micro - hydro plant are the turbine and generator.

2.4.4 Types of Turbines used in Micro Hydro Power Generation

A hydraulic turbine is a rotating machine that converts the potential energy of the water to mechanical energy. There are two basic types of turbines, denoted as “impulse” and “reaction turbine”. The “impulse turbine” converts the potential energy of water in to kinetic energy in a jet issuing from a nozzle and projected onto the runner buckets or vanes. The “reaction turbine” develops power from the combined action of pressure energy and kinetic energy of the water. The runner is completely submerged and both the pressure and the kinetic energy decrease from the inlet to the outlet

The turbine has vanes, blades or buckets that rotate about an axis by the action of the water. The rotating part of the turbine or water wheel is often referred to as the runner. Rotary action of the water turbine in turn drives an electrical generator that produces electrical energy or could drive other rotating machinery. Impulse turbines are further classified in to Pelton, Turgo and cross flow type, and Reaction turbines are classified as Kaplane, Propeller, and Francis turbines [11].

2.4.4.1 Pelton Turbine

A Pelton turbine consists of a set of specially shaped buckets mounted on a periphery of a circular disc. It is turned by jets of water which are discharged from one or more nozzles and strike the buckets. The buckets are split into two halves so that the central area does not act as a dead spot incapable of deflecting water away from the oncoming jet. The cutaway on the lower lip allows the following bucket to move further before cutting off the jet propelling the bucket ahead of it and also permits a smoother entrance of the bucket into the jet. The Pelton bucket is designed to deflect the jet through 165 degrees which is the maximum angle possible without the return jet interfering with the following bucket for the oncoming jet.

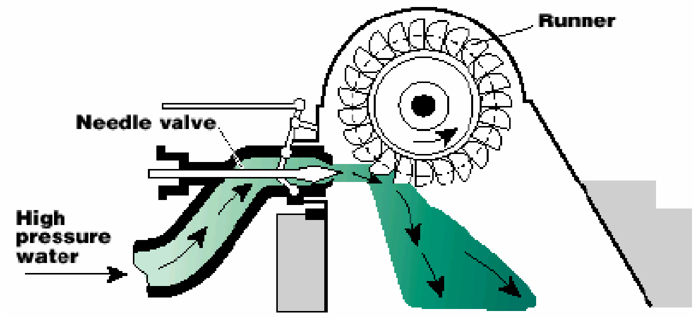

Figure 2. 9 Pelton turbine

2.4.4.2 Turgo Turbine

The Turgo turbine can operate under a head in the range of 30 to 300 meter. Like a pelton it is an impulse turbine, but its bucket are shaped differently and the jet of water strikes the plane of its runner at an angle of 20^o. Water enters the runner through one side of the runner disk and emerges from the other. The higher runner speed of the turgo, due to its smaller diameter compared to other types, make direct coupling of turbine and generator more likely [8].

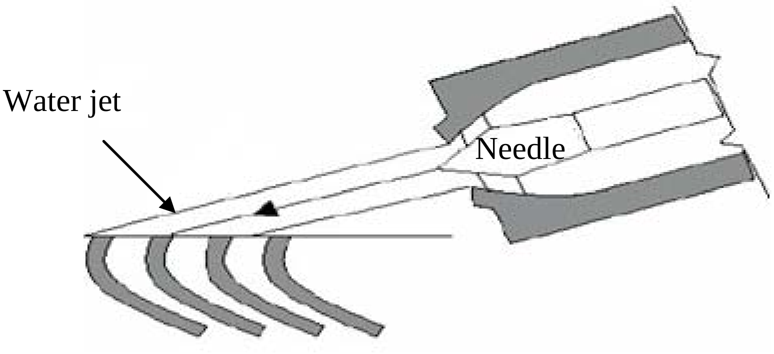

Figure 2. 10 Turgo turbine

2.4.4.3 Cross flow Turbine

Cross flow turbines are also called Banki, Mitchell or Ossberger turbine. A cross flow turbine comprises a drum shaped runner consisting of two parallel disc connected together near their firm by a series of curved blades. A cross flow turbine has its runner shaft horizontal to the ground in all cases.

The cross flow turbine is easy to manufacture in developing countries

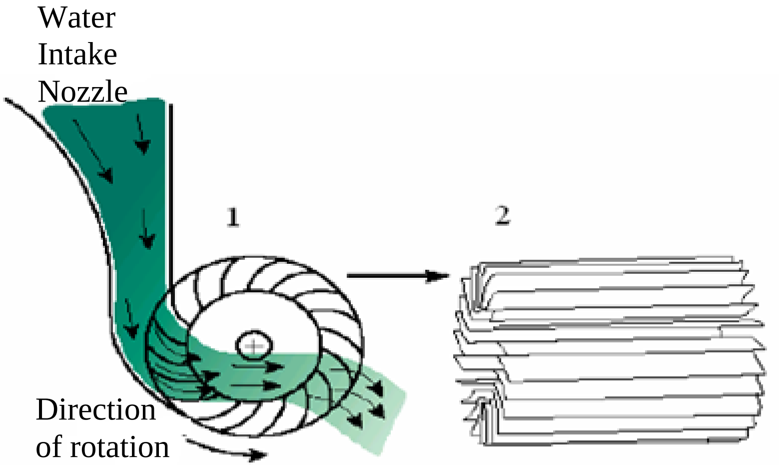

Figure 2. 11 Cross flow turbine (1) cross section through the turbine and (2) arrangements of cross flow turbine blades

2.4.4.4 Kaplan and Propeller Turbines

Kaplan and propeller turbines are axial-flow reaction turbines, generally used for low heads (usually under 16 m). The Kaplan turbine has adjustable runner blades and may or may not have adjustable guide-vanes.

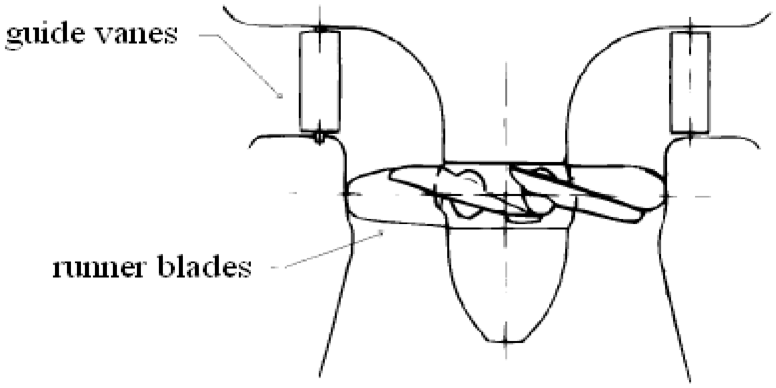

Figure 2. 12 Kaplan turbine

2.4.4.5 Francis Turbines

Francis turbines are radial flow reaction turbines, with fixed runner blades and adjustable guide vanes, used for medium heads. The runner is composed of buckets formed of complex curves. A Francis turbine usually includes a cast iron or steel fabricated scroll casing to distribute the water around the entire perimeter of the runner, and several series of vanes to guide and regulate the flow of water into the runner.

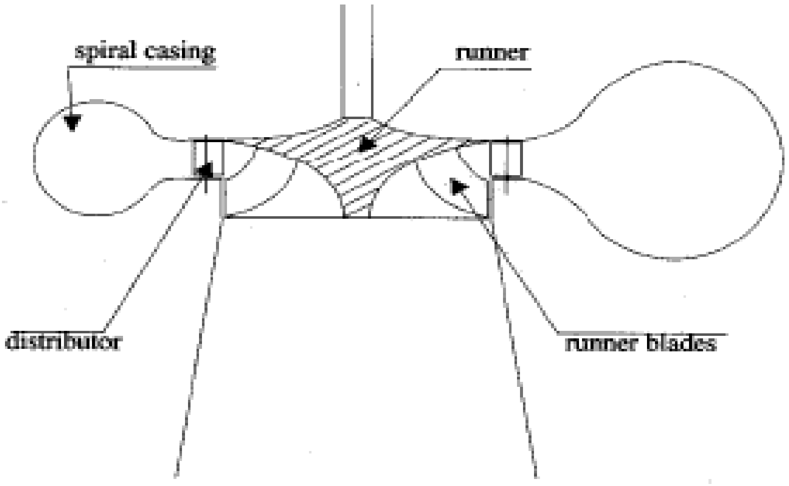

Figure 2. 13 Francis turbine

2.4.4.6 Reverse Pumps as a Turbine (PAT)

Centrifugal pumps can be used as turbines potential advantage is low cost owing to mass production, Local production and availability spare parts and its disadvantages are as yet poorly understood characteristic of turbine performance, lower typical efficiencies, unknown wear characteristics, and poor part flow efficiency, flow rate is fixed for a particular head. This can be overcome at some cost by using two units of different sizes, and switching between them depending on the flow rate. End suction centrifugal pump is suitable for low head micro hydro application. Axial flow pumps are suitable for low head application, small sizes are not commonly available and self priming pumps are not suitable for pump as turbine since they contain a non return valve which prevents reverse flow [14, 8].

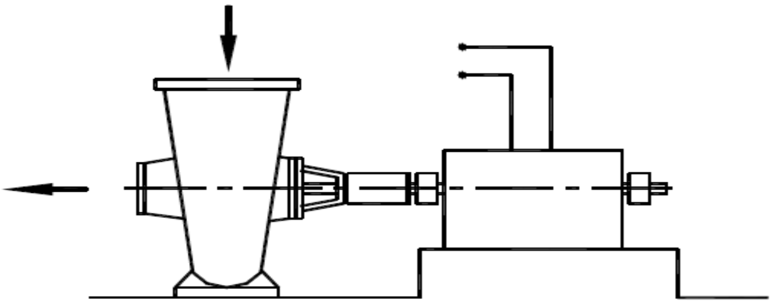

Figure 2. 14 Centrifugal pump used as a turbine

2.4.5 Types of Generator used in Micro Hydro Power Generation

Electrical generators can produce either alternating current (ac) or direct current (dc). In the case of ac current, a voltage cycles sinusoidally with time from positive peak value to negative peak value. Dc current flows in a single direction as a result of a steady voltage.

AC generators: There are two types of generators suitable for use in a micro hydro electricity supply scheme. These are synchronous generators (or ‘alternators’) and induction generators (in which induction motors used as a generator) this machine is simpler or more reliable machine than the synchronous generator. It contains fewer parts, is less expensive, is more easily available from electrical suppliers. It can withstand 200% runway speeds without harm, and has no brush or other parts which require maintenance. These factors all make induction generator an attractive choice for micro hydro power generation than that of synchronous generator [14].

CHAPTER 3

SITE MAPPING, DATA COLLECTION AND ENVIRONMENTAL EFFECTS OF THE SYSTEM

Two sites representing areas of abundant and scarce hydro power potential are identified considering data availability for comparison of rural electrification option. The site with scarce hydro power potential is selected so that it can have wind resources. The two places were selected where comparative analysis is supposed to be done. The first is Dillamo village found in Amhara region specifically in Western Gojjam 19 km from Durbete town and 85 km from regional town that is Bahir Dar. In the village 82 households are found. At this place the three renewable energy generation systems solar photovoltaic, micro-hydro power generation and wind power generation systems are supposed to be compared. The second place is in Somali Region, called village in Gode. The village has 35 households and the geographical location of this place is 7.5^o (latitude of the place). Here two renewable systems have been compared, solar photovoltaic and wind power generation. The source of data for the two systems (i.e. solar and wind power generation) is the Ethiopian Meteorological Station. For Dillamo village, the nearest station is Dangla Meteorological station with geographical location 11^0 16’ 0” latitude and 36^0 $50^{'}$ 0” of longitude. This station is the second class weather station which means all types of weather data are not found. For example only solar data is available and wind data is obtained from the second nearest place for Dillamo village, Bahir Dar weather station with geographical location of 11^0 22’ 12” latitude (North) and 37^0 6’ longitudinal location (east) is considered. For micro hydro data the head is obtained through measurement but the discharge or the flow rate is obtained from research work done on the river during dry season.

3.1 General Description about Kilte River

Kilte River is located 14km from Durbete town on the road to Yismala between Akuri and Dillamo village which is 5km from the selected village. This site is located at 2km up-stream from the road connecting Durbete and Yismala towns and it is suitable for construction. There is a need to build a 2km long access road to the site for transportation of equipment and material. On this site there are 9 (nine) water powered mills operating, which vertical axis arab mill using connected barrels as a penstock.

As it is measured the gross head of the river is around 10m and its flow rate is $0.1627m^3/s$

Figure 3. 1 Pictorial representation of Kilte River

3.1 Environmental Impacts of Wind Power Generation Systems

Wind energy has both positive and negative environmental impacts. One of the positive environmental impacts of wind turbines is that the production of electricity from the wind is clean. Nothing is burned or "used up" to produce wind power. Wind energy does not pollute the air or water, produces no carbon dioxide or any greenhouse gases.

3.1.1 Wind Turbine Noise

Modern wind turbines are quiet and are becoming quieter. The environmental measurements of sound are made in dB (A) which includes a correction for the sensitivity of the human ear. The sound pressure level at a distance of 40m from a typical turbine is 50–60 dB (A); about the same level of conversational speech.

When wind turbines have been designed carefully then they feature a lower noise level. Much effort has been made to create the present quiet machines. A lot of attention has been paid to both the design of the blades and to the mechanical parts of the machine. As a result noise is not an important problem wind turbines, when they are carefully sited. [21, 8]

3.1.2 Electro Magnetic Interference

Any large moving structure can produce electromagnetic interference (EMI). Wind turbines can cause EMI by reflecting signals from the rotor blades. Interference occurs because the reflected signal is delayed due to the difference in path length. EMI is most severe for metallic materials, rather than for wooden blades. Glass reinforced plastic (GRP) used in most blades, can minimize the EMI effect [21, 8].

3.1.3 Visual Impact

One of the more obvious environmental effects of wind turbines is their visual aspects. There is no measurable way of assessing the effect, which is essentially subjective. As with noise, the back ground is also vital important. Experience has been shown that good design and the use of subdued neutral colors “off white” is popular to minimize this effect.

3.1.4 Birds

The need to avoid areas where rare plants or animals are to be found is generally a matter of common sense, but the question of bird is more complicated and has been the subject of several studies. In practice, provided investigations are carried out to ensure that wind installation are not sited too near large concentration of nesting birds, there is a little cause for concern [21,8].

3.2 Solar Photovoltaic Power Generation

3.2.1 Health, Safety and Environmental Aspects [12,26]

Substances that are the subject of health, safety and Environmental assessment and control are (i) toxic and flammable/explosive gases like silane, phosphine, germane, and (ii) toxic metals like cadmium (in CdTe- and CIS-based technologies). The prevention of accidental releases of such hazardous substances is very important for the success of PV power systems. Current environmental control technologies seem to be sufficient to control wastes and emissions in today production facilities. Technologies for recycling of cell materials are being developed presently. Enhanced clarity is however needed regarding costs, energy consumption and environmental aspects of these processes. Depletion of rare materials will probably not pose restrictions if further development towards thinner layers and efficient material reuse is pursued [12, 26].

3.3 Micro Hydro Power Generation

Hydropower is characterized by a variety of potential effects on the environment both positive and negative. First of all, it produces no CO_2 and has little other effect on the atmosphere compared to the conventional power plants. The noise pollution is negligible too.

The environmental and related social effects, which hydropower plants produce, are divided in three main categories:

- The hydrological effects meaning water flows, groundwater, and water supply irrigation;
- The landscape effects on the land, its plants and its animals and finally;
- The social effects. Naturally, these three categories of effects are not independent of each other [3].

3.3.1 Hydrological Effect

Hydrological effects will without a doubt be significant for the ecology of a land and for the local community, especially in the case of a large-scale installation. The diversion of a mountain stream into a pipe does not, maybe seriously changes the flow at the valley bottom but it will have a noticeable effect on intermediate levels. Storing part of the water in a reservoir is another problem since it may reduce the final flow as a result of evaporation from a large exposed surface. Furthermore, when groundwater is reduced to a hydropower plant the surrounding countryside might cause suffer a number of changes and impacts which might affect the economy and the ecology [3].

3.3.2 Landscape Effects

A hydropower installation may affect the landscape in many ways. The construction process itself causes disturbance even the building period lasts only a few years. These disturbances are magnified when the construction timetable is not met, as is often the case with large-scale hydropower plant.

3.3.3 Social Effects

It is widely known that an energy power plant has positive and negative effects, sometimes, there are people, who have benefits of this and others pay for this.

The building of dams may have very different consequences on the people immediately affected. The effect of hydropower on human health is the most significant, especially in developing countries where the possibility of spreading of diseases such as malaria. Another category of social effects is the displacement of people living in villages, which are to become water reservoirs. Historically, on a lot of occasions thousands of people were forced to move from their house in order for a hydropower plant to be built [3].

CHAPTER 4

POWER GENERATION SYSTEM DESIGN AND ANALYSIS

4.1 Photovoltaic Power Generation

There are three basic ways that the solar PV can be used:

- On-grid applications: - which cover both central-grid and isolated-grid systems;
- Off-grid applications- which include both stand-alone (PV-battery) systems and hybrid (PV-battery-genset) systems; and
- Water pumping applications: - which include PV-pump systems.

Solar Radiation Data of the Sites:

The Ethiopian Meteorological Service collects only the average sunshine hours for some cities of the country and the solar radiation is calculated from the average sunshine hours. This is due to malfunctioning of the equipments used to measure solar radiation. The average monthly sunshine for Dillamo and village in Gode are given in the figures 4.1 and figure 4.2 respectively.

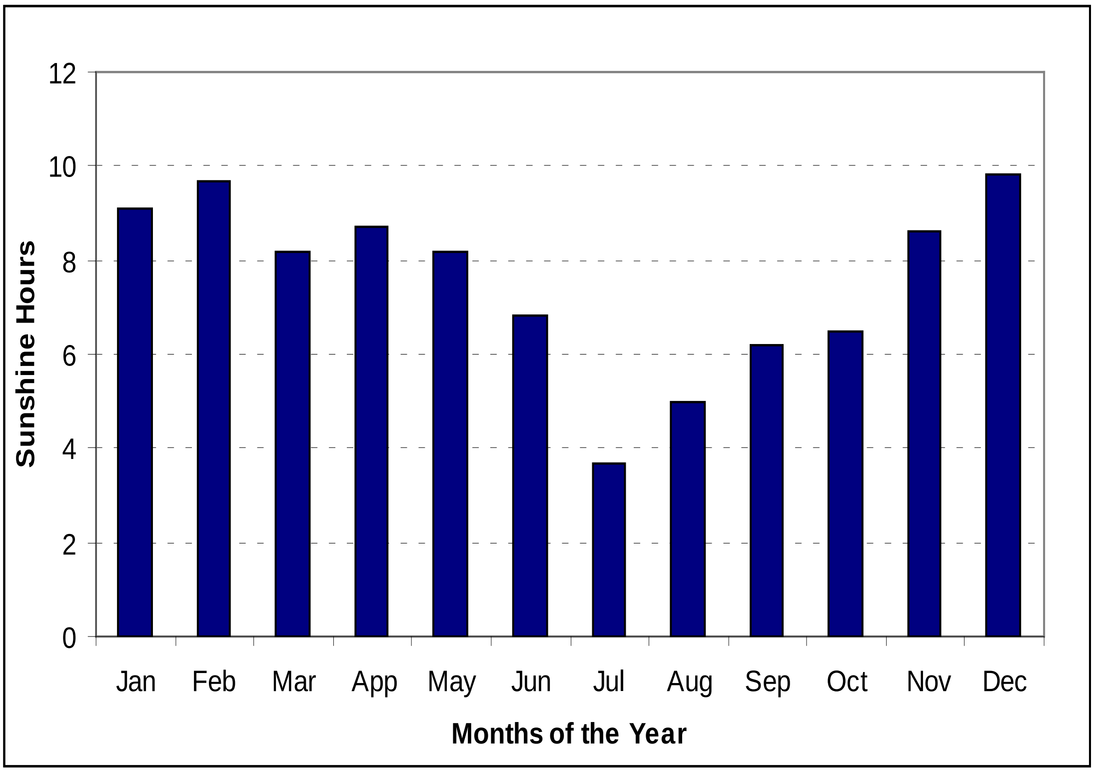

Figure 4. 1 Monthly average sunshine hours for Dillamo village

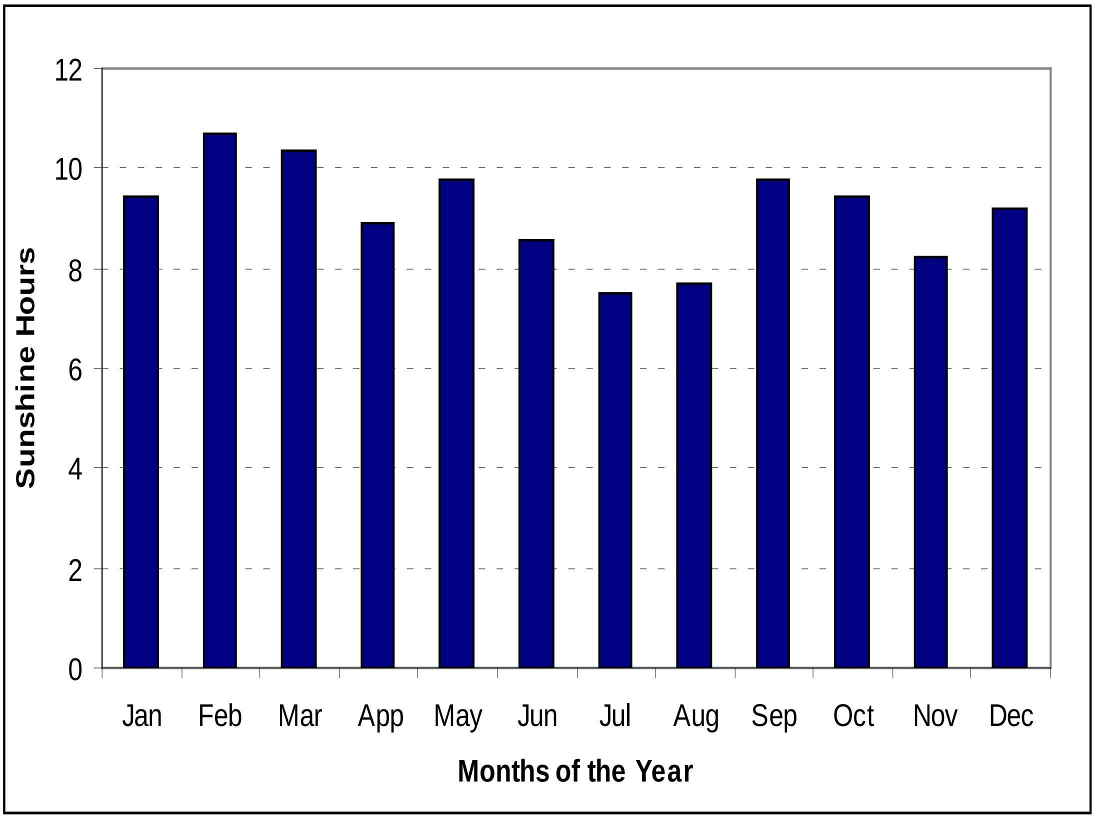

Figure 4. 2 Monthly average sunshine hours for village in Gode

4.1.1 Analysis of Photovoltaic (PV) Power for the Selected Site

4.1.1.1 Declination Angle

The declination is the angular position of the sun at solar noon, with respect to the plane of the equator. Its value in degrees is given by Cooper's equation [11]:

$$\delta = 23.45\sin\left(\frac{360}{365}(284+N)\right) \tag{4.1}$$

4.1.1.2 Solar Hour Angle and Sunset Hour Angle

The solar hour angle is the angular displacement of the sun east or west of the local meridian; morning negative, afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from solar noon.

The sunset hour angle ω_s is the solar hour angle corresponding to the time when the sun sets and it is given by

$$\cos\omega_s = \tan\phi\tan\delta \tag{4.2}$$

4.1.1.3 Extraterrestrial Radiation and Clearness Index

Solar radiation outside the earth’s atmosphere is called extraterrestrial radiation. Daily extraterrestrial radiation on a horizontal surface is given by

$$H_o = \left[\frac{24x3600}{\pi} xI_{sc}\right]\left[1.0 + 0.033\cos\left(\frac{360N}{365}\right)\right]x\left[\cos\phi\cos\delta\sin\omega_s + \frac{\pi}{180}\omega_s\sin\delta\sin\phi\right] \qquad (4.3)$$

4.1.1.4 Prediction of Monthly Average Daily Horizontal Global Radiation from Sunshine Duration

Before reaching the surface of the earth, radiation from the sun is attenuated by the atmosphere and the clouds. The ratio of solar radiation at the surface of the earth to extraterrestrial radiation is called the clearness index. Thus the monthly average clearness index as described by Page and others as [11, 30]:

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_o} = a + b\frac{\bar{n}_s}{\bar{N}_s} \qquad (4.4)$$

Where: -

$$a = -0.110 + 0.235\cos\phi + 0.323\frac{\bar{n}_s}{\bar{N}_s} \qquad (4.4.1)$$

$$b = 1.449 - 0.553\cos\phi - 0.694\frac{\bar{n}_s}{\bar{N}_s} \qquad (4.4.2)$$

4.1.1.5 Tilted Irradiance Calculation

The algorithm used to calculate the radiation on the plane of the PV array will be:

a) Calculate hourly global and diffuse irradiance on a horizontal surface for all hours of an “average day” having the same daily global radiation as the monthly average;

b) Calculate hourly values of global irradiance on the tilted surface for all hours of the day; and then

c) Sum the hourly tilted values to obtain the average daily irradiance in the plane of the PV array.

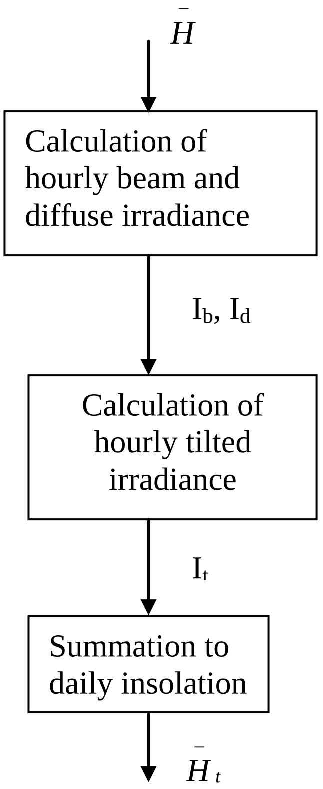

Figure 4. 3 Flow chart for tilted irradiance calculation

4.1.2 Calculation of Hourly Global and Diffuse Irradiance

Solar radiation can be broken down into two components:

a) ***Beam radiation***, which the solar radiation propagating along the line joining the receiving surface and the sun, and

b) ***Diffuse radiation***, the solar radiation scattered by aerosols, dust, and molecules.

The monthly average daily diffuse radiation $\bar{H}_d$ is calculated from the monthly average daily global radiation using the Erbs et al. correlation [5].

$$\frac{\bar{H}_d}{\bar{H}} = 1.391 - 3.560\,\bar{K}_T + 4.189\,\bar{K}_T^2 - 2.137\,\bar{K}_T^3 \tag{4.5}$$

Equation (4.5) is functional when the sunset hour angle for the average day of the month is less than 81.4^0

If the sunset hour angle is greater than 81.4° then equation (4.5) can be written as

$$\frac{\bar{H}_d}{\bar{H}} = 1.311 - 3.022\,\bar{K}_T + 3.42\,\bar{K}_T^2 - 1.82\,\bar{K}_T^3 \tag{4.6}$$

The monthly average hourly global radiation for the representative days of the month on a horizontal surface can be calculated from the monthly average daily global radiation on a horizontal surface by using formulae from Collares-Pereira and Rabl for global irradiance [10, 29].

$$\frac{\bar{I}}{\bar{H}} = r_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\omega_s\cos\omega_s} \tag{4.7}$$

Where: - $a = 0.409 + 0.5016\sin(\omega_s - 60)$ (4.7.1)

$$b = 0.6609 - 0.4767\sin(\omega_s - 60) \tag{4.7.2}$$

$$\omega = (ST - 12)x15^0 \tag{4.7.3}$$

$$\frac{\bar{I}_d}{\bar{H}_d} = r_d = \frac{\pi}{24}\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \tag{4.8}$$

For each hour of the “average day”, global horizontal irradiance *I* and it’s diffuse and beam components I_d and I_b are therefore given by:

$$I = r_t\,\bar{H} \tag{4.9}$$

$$I_d = r_d\,\bar{H}_d \tag{4.10}$$

$$I_b = I - I_d \tag{4.11}$$

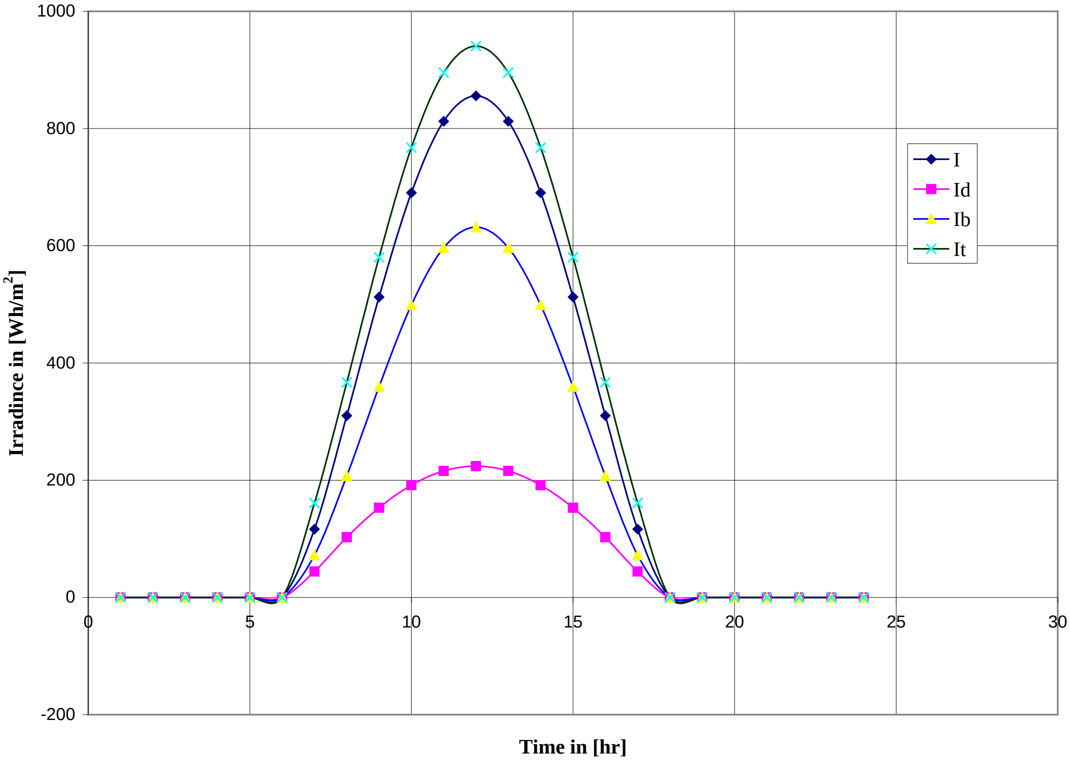

Figure 4. 4 Variation of I, I_d, I_b and I_t for the given time

4.1.3 Calculation of Hourly Irradiance in the Plane of the PV Array

Hourly irradiance in the plane of PV array (I_t) can be calculated as [10]:

$$I_t = I_b R_b + I_d \left(\frac{1+\cos\beta}{2}\right) + I\rho\left(\frac{1-\cos\beta}{2}\right) \qquad (4.12)$$

Where:-

$$R_b = \frac{\cos\theta}{\cos\theta_z} \qquad (4.12.1)$$

$$\cos\theta = \cos(\phi-\beta)\cos\delta\cos\omega + \sin(\phi-\beta)\sin\delta \qquad (4.12.1.1)$$

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \qquad (4.12.1.2)$$

Once tilted irradiances for all hours of the day are computed, the daily total $\bar{H}_t$ is obtained by summing values for individual hours.

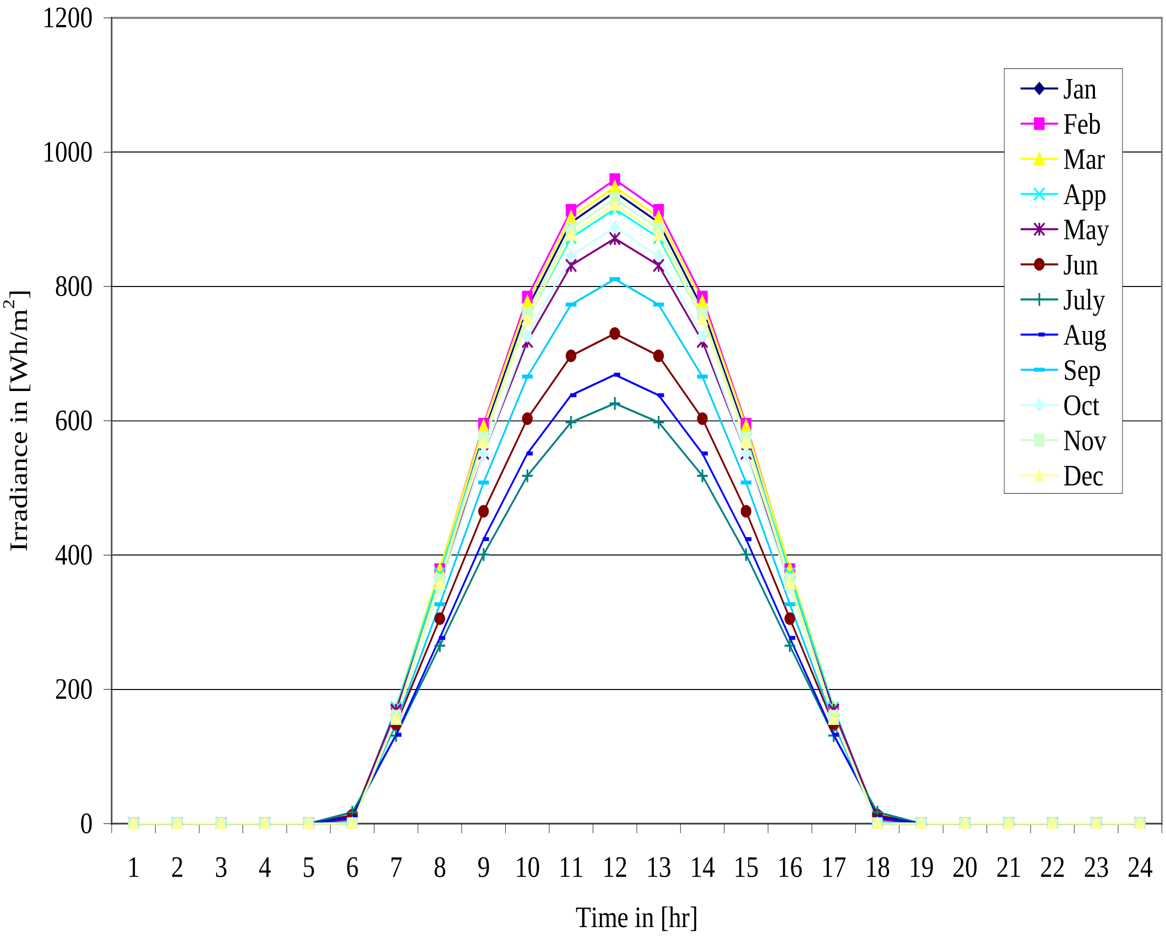

Figure 4. 5 Hourly average irradiance in the plane of PV array for Dillamo village.

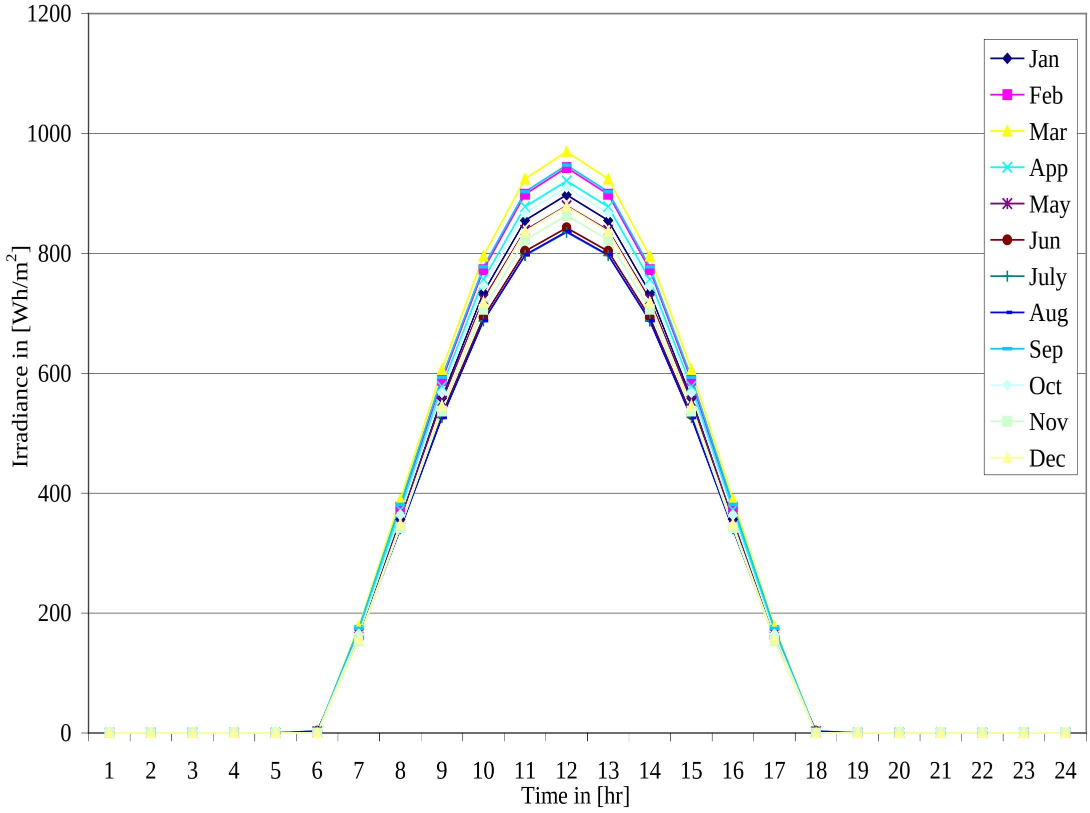

Figure 4. 6 Hourly average irradiance in the plane of PV array for village in Gode

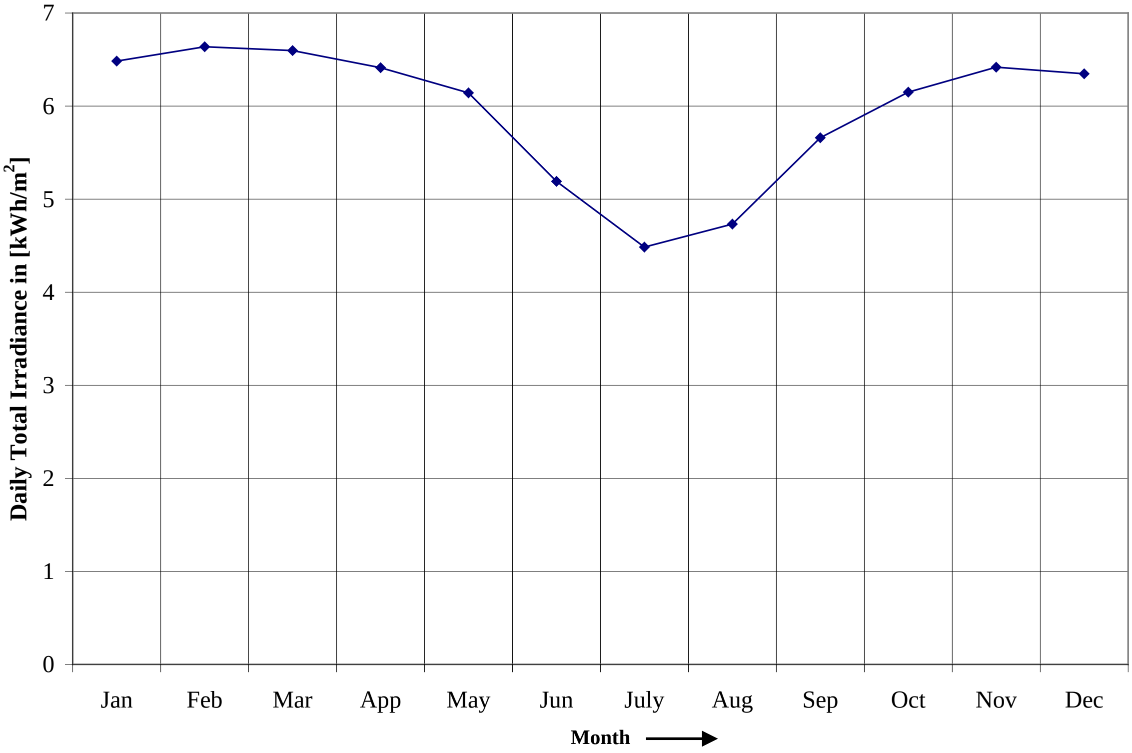

Figure 4. 7 Monthly mean daily solar irradiance in the plane of PV array for Dillamo village

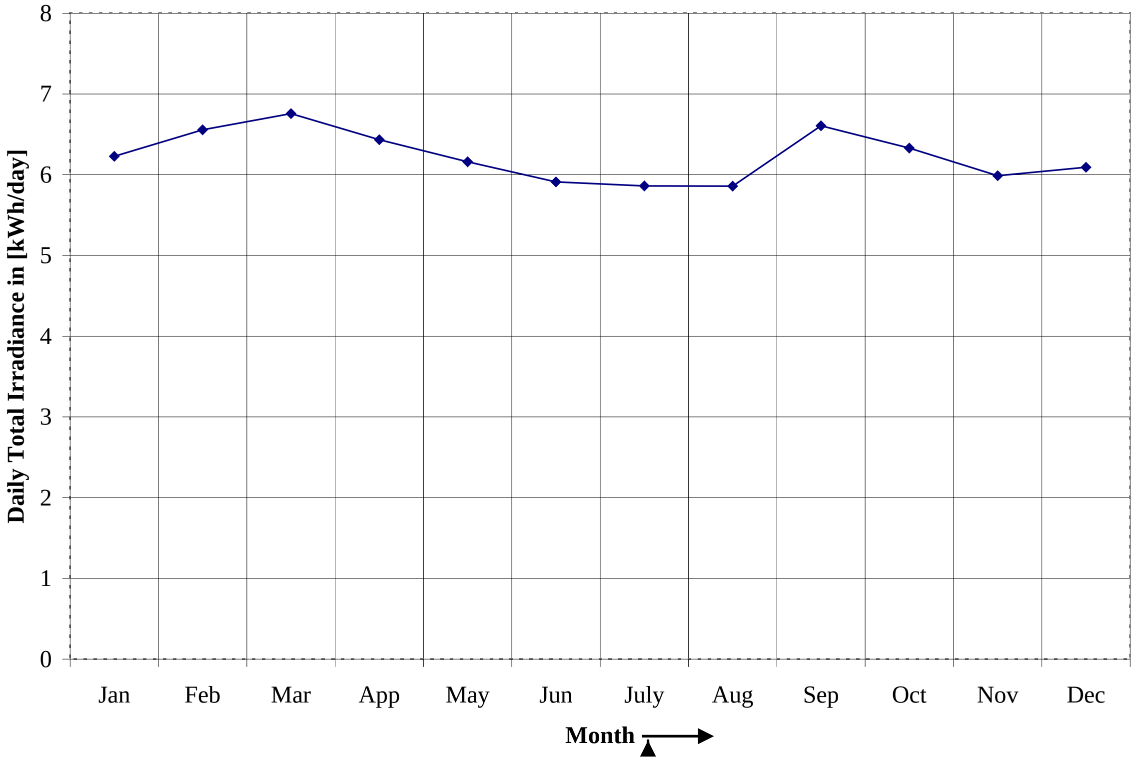

Figure 4. 8 Monthly mean daily average irradiance in the plane of PV array for village in Gode

4.1.4 Calculation of Average Efficiency of PV Module

The array is characterized by its average efficiency, η_p which is a function of average module temperature T_c

$$\eta_p = \eta_r \left[1 - \beta_p \left(T_c - T_r\right)\right] \tag{4.13}$$

The average module temperature (T_c) can be obtained from the mean monthly ambient temperature (T_a) through Evans' formula.

$$T_c - T_a = \left(219 + 832\,\bar{K}_T\right)\frac{NOCT - 20}{800} \tag{4.13.1}$$

Table 4. 1 PV Module Characteristics for Standard Technology

PV module	$\eta_r\,(\%)$	$NOCT\,(^{o}C)$	$\beta_p\,(\%/^{o}C)$
Mono silicon	13.0	45	0.4
Poly silicon	11.0	45	0.4
a-SI (amorphous silicon)	5.0	50	0.11
cdTe (cadmium telluride)	7.0	46	0.24
CIS (copper indium diselenide)	7.5	47	0.46

Equation (4.13.1) is valid when the array's tilt is optimal which is latitude minus declination. If the angle differs from the optimum, the right side of equation (4.13.1) has to be multiplied by a correction factor C_f defined by:

$$C_f = 1 - 1.17x10^{-4}(Z_M - \beta)^2 \tag{4.13.2}$$

$$Z_m = \phi - \delta \tag{4.13.2}$$

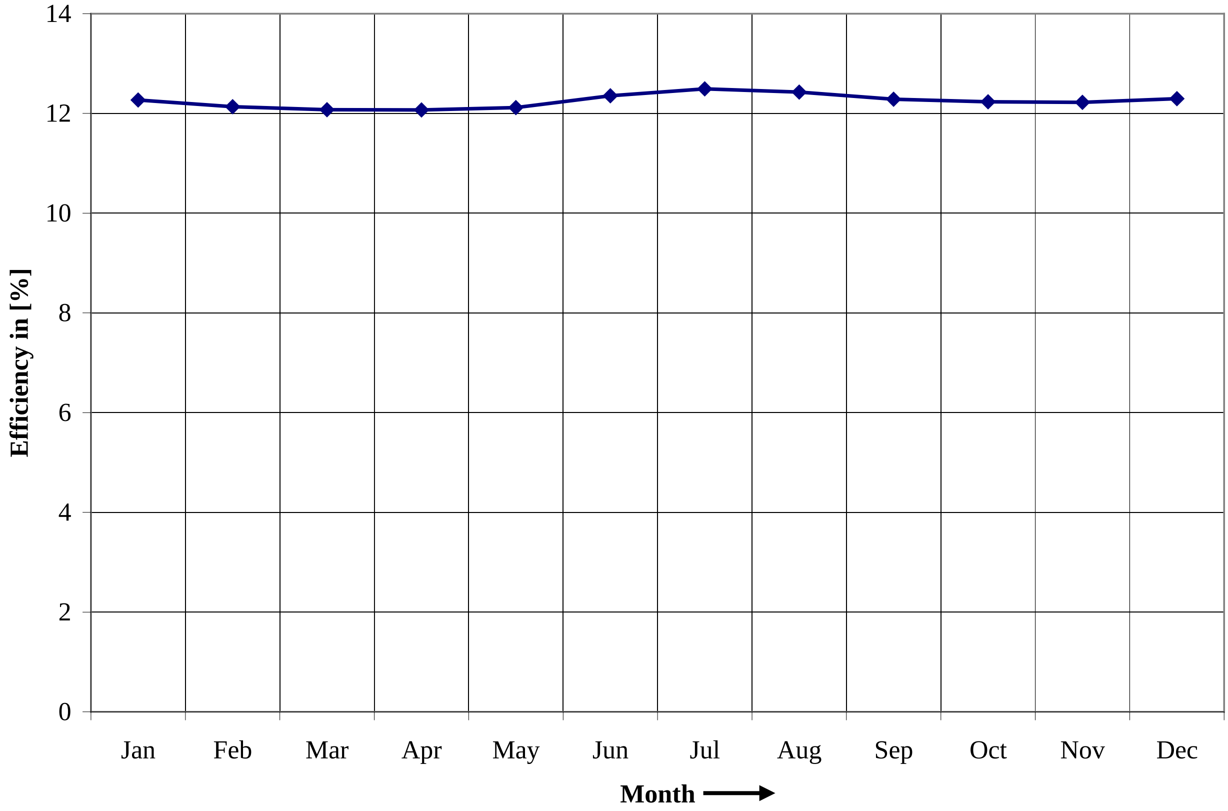

Figure 4. 9 Variation of average module efficiency with time for Dillamo village

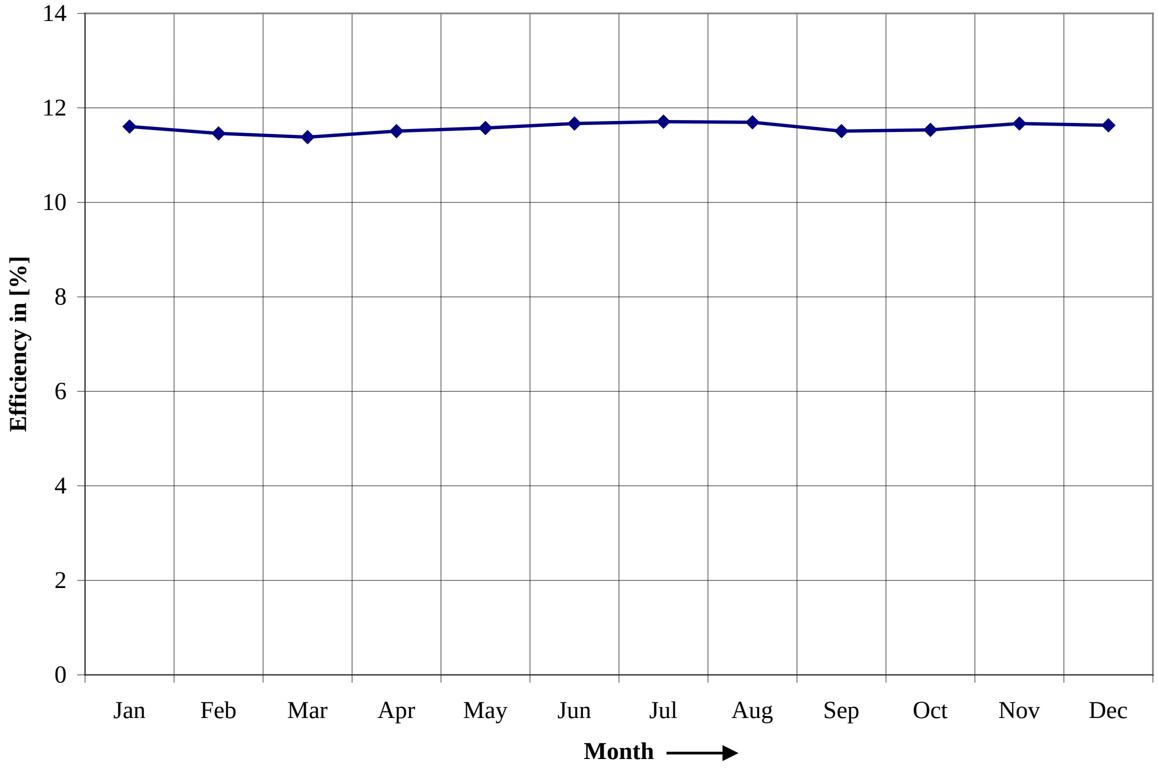

Figure 4. 10 Variation of average module efficiency with time for village in Gode

4.1.5 Energy of the PV Array

The power delivered by the PV array (E_p) can be calculated as:

$$E_p = A_p \eta_p \bar{H}_t \tag{4.14}$$

The array energy available to the load and the battery (E_A) can be obtained by the following relations:

$$E_A = E_p(1-\lambda_p)(1-\lambda_c) \tag{4.15}$$

Where:-

λ_p: Miscellaneous loss like dust cover on the PV array commonly taken as 4%

λ_c: Power conditioning losses commonly taken as 10%

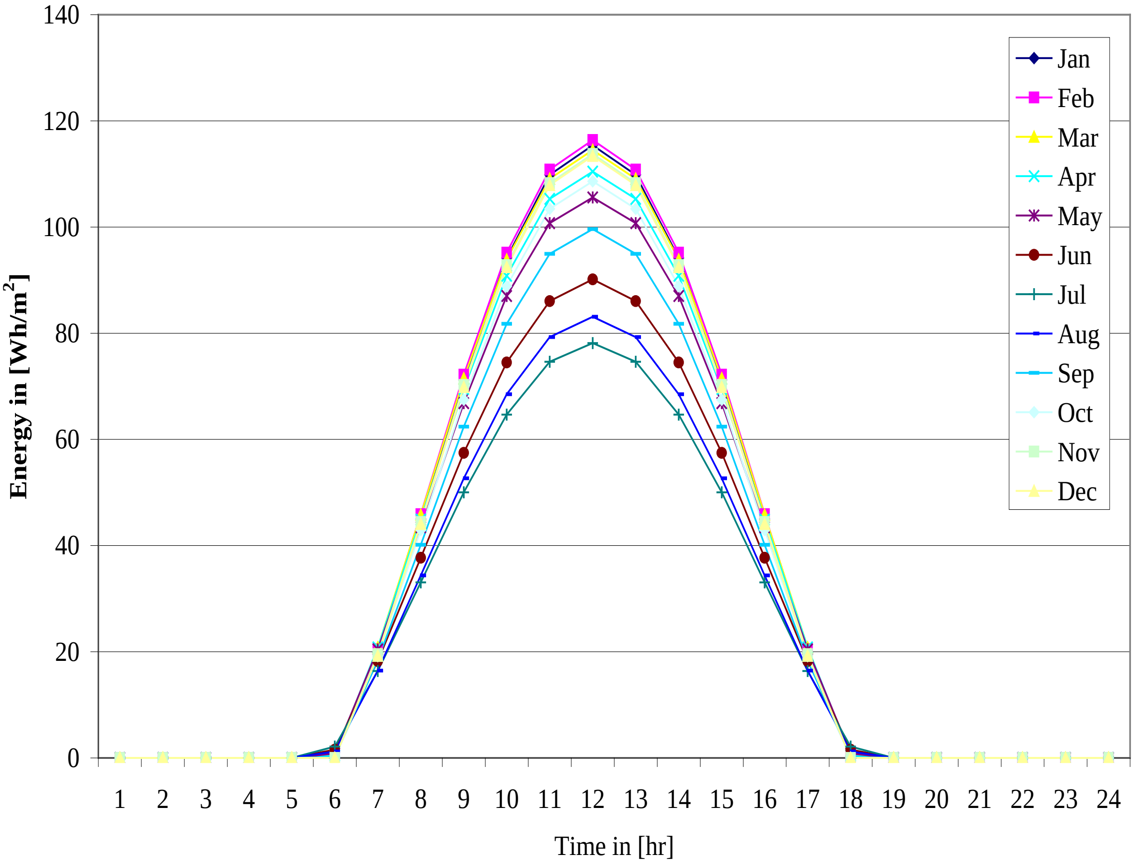

Figure 4. 11 Hourly average total energy delivered by the PV array for Dillamo village

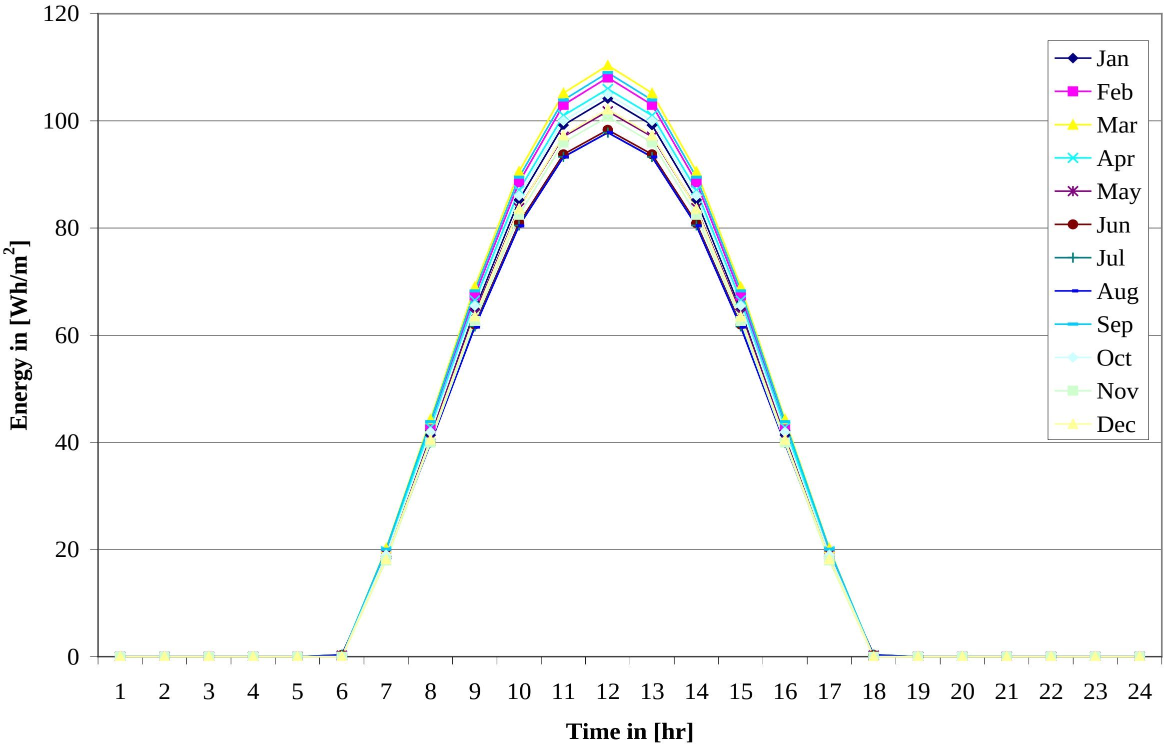

Figure 4. 12 Hourly average total energy delivered by the PV array for village in Gode

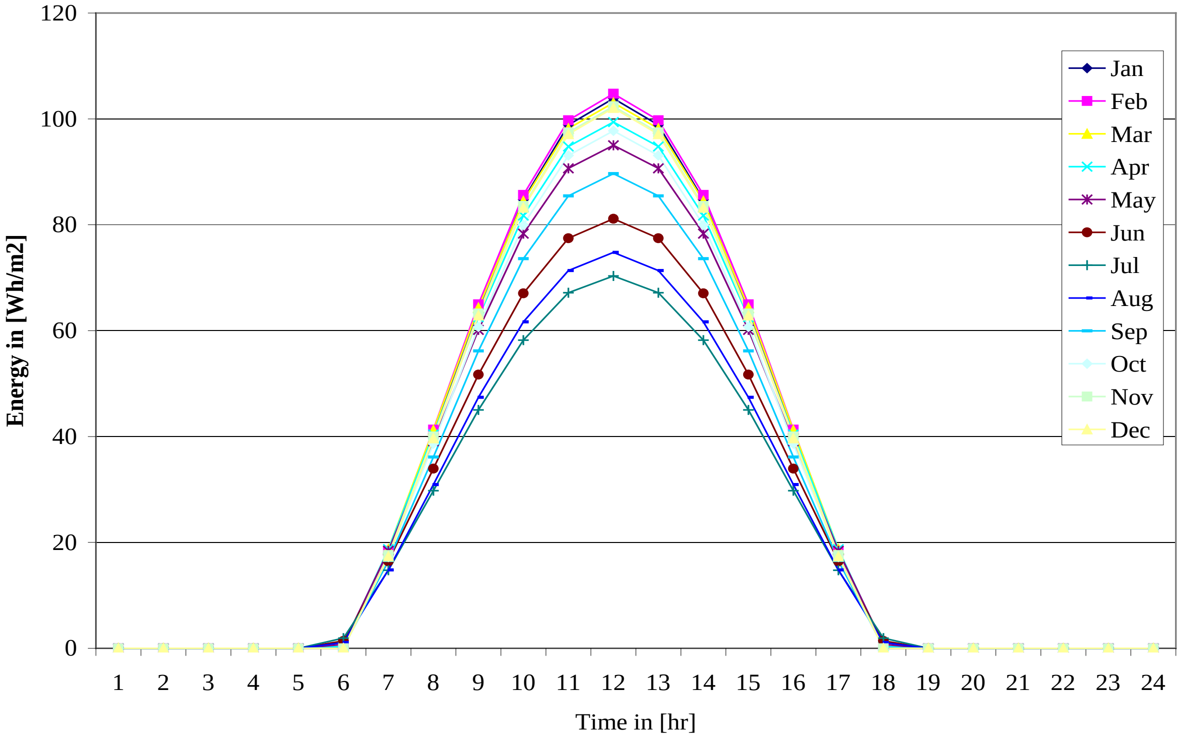

Figure 4. 13 Hourly array energy available to the load and battery for Dillamo village

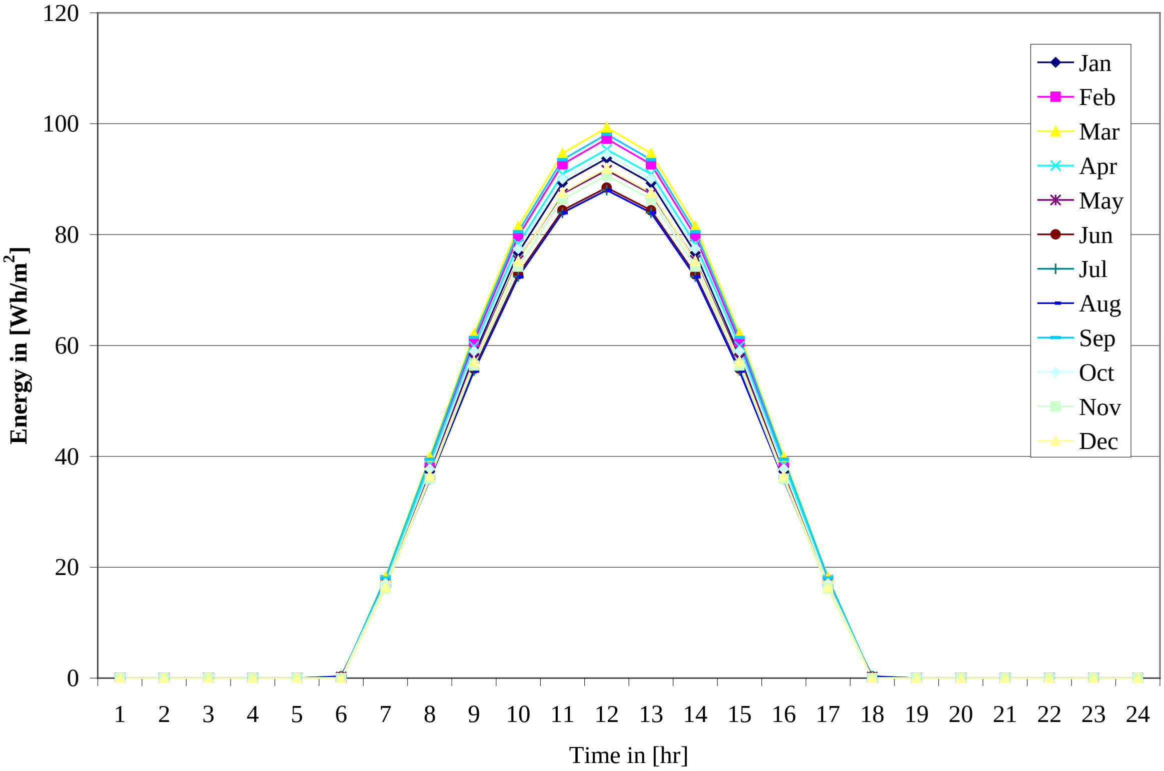

Figure 4. 14 Hourly array energy available to the load and battery for village in Gode

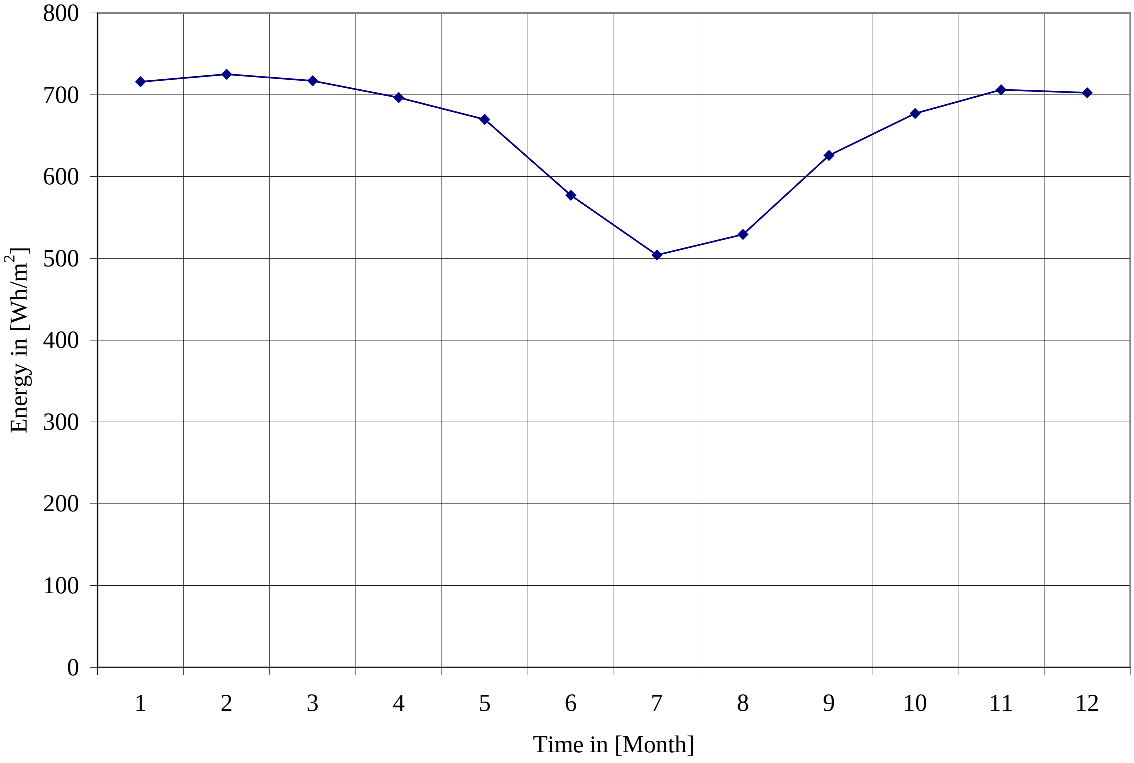

Figure 4. 15 Monthly mean daily average energy available to the load or battery for Dillamo village

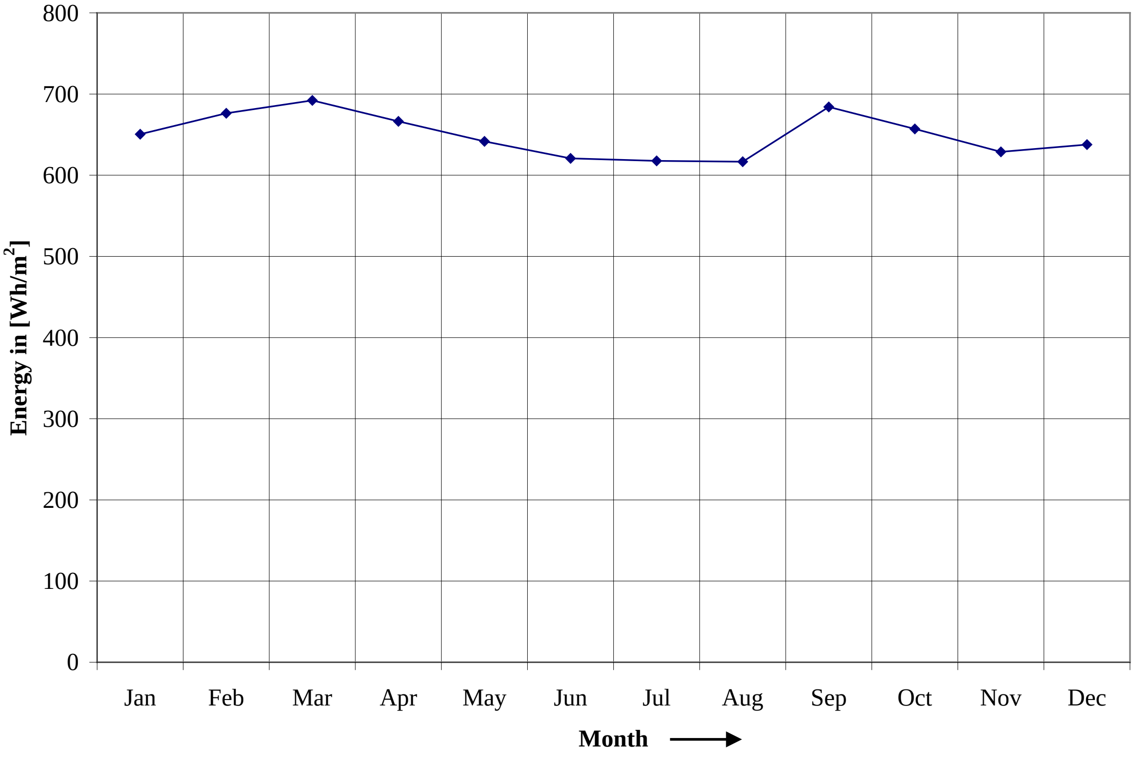

Figure 4. 16 Monthly mean daily average energy available to the load or battery for village in Gode

The overall array efficiency is defined as:

$$\eta_A = \frac{E_A}{A_p \bar{H}_t} \tag{4.16}$$

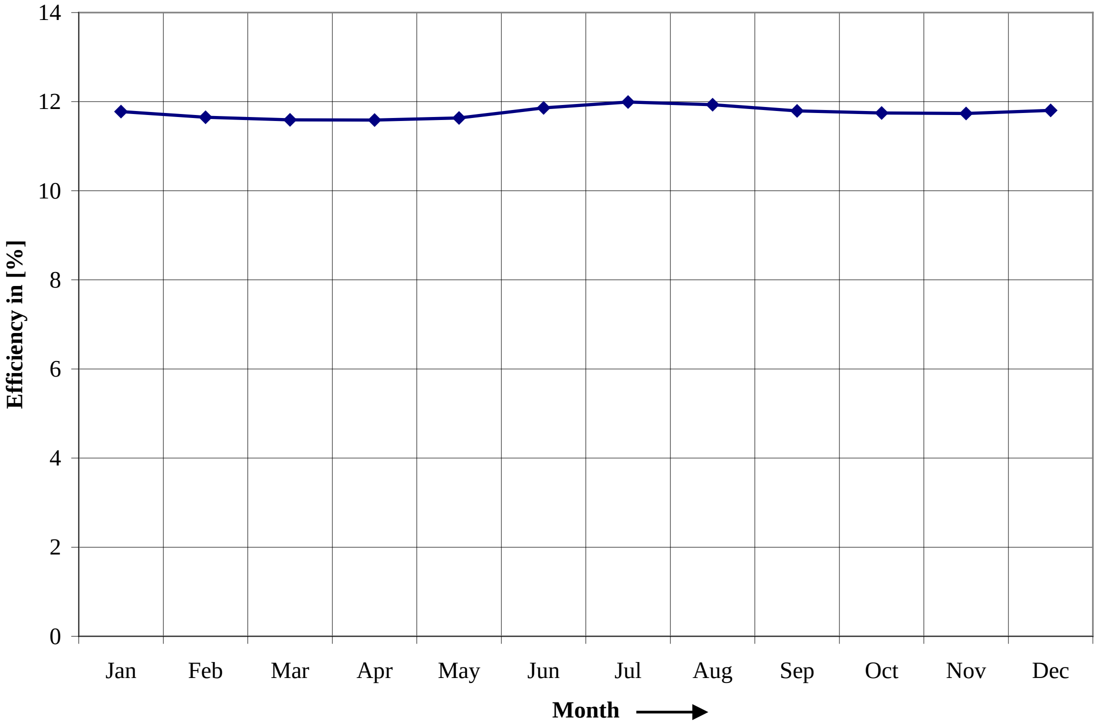

Figure 4. 17 Variation of overall array efficiency with time for Dillamo village

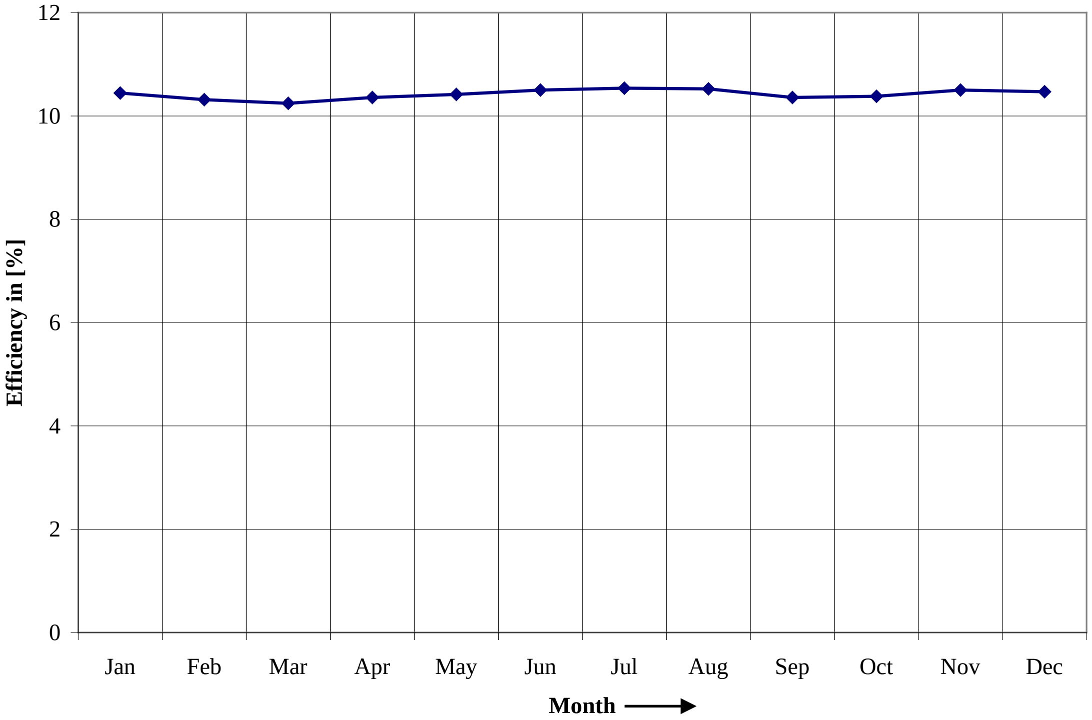

Figure 4. 18 Variation of overall module efficiency with time for village in Gode

4.1.6 The Off-Grid Model of the PV Array

The off-grid model represents stand-alone systems with a battery backup, with or without an additional power generation. Energy from the PV array is either used directly by the load, or goes through the battery before being delivered to the load. The flow chart is as follows:

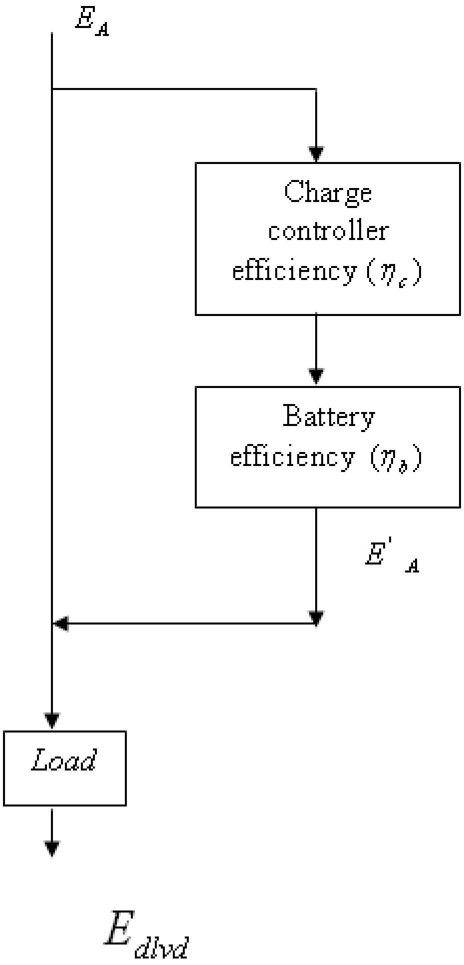

Figure 4. 19 Flow chart for off grid model of PV power generation

4.1.7 Household Energy Demand for the Two Cases and Two Conditions

Table 4. 2 Household Daily Energy Demand if there is color TV

No	Appliance	Watt (W)	Daily use/hour	Daily Energy
1	Lamp 1 (Salon)	11	3	33
2	Lamp 2 (Kitchen room)	11	2	22
3	Lamp 3 (Bed room)	11	2	22
4	Radio / Caste player	8	3	24
5	21’’ color Television	60	2	120
	Total	**101**		221 **Wh/day**

Table 4. 3 Household Daily energy Demand if there is no color TV

No	Appliance	Watt (W)	Daily use/hour	Daily Energy
1	Lamp 1 (Salon)	11	3	33
2	Lamp 2 (Kitchen room)	11	2	22
3	Lamp 3 (Bed room)	11	2	22
4	Radio / Tap Recorder.	8	3	24
	Total	**41**		101**Wh/day**

4.1.8 Sizing of PV System for the Two Cases and Two Conditions

Case 1: Dillamo Village

Condition 1: If there is TV set

a) Battery

The minimum energy that can be stored by the battery is given by:

$$E_b = \frac{E_u}{\eta_b} = 245.56 Wh/day$$ (Assuming efficiency of battery to be 90%)

Assuming that the working voltage for direct current is 12V, then, the net capacity that the battery can store in Ah/day will be

$$C_{bn} = \frac{E_b}{V_{cc}} = 20.46 Ah/day$$

The net capacity of the battery depends on the depth of the discharge of the battery (DDP), and the depth of discharge determines the life cycle of the battery. Deep cycle lead acid battery can store 30% to 80% depth taking an assumption of DDP = 30% then the total commercial capacity of the of the battery is calculated as

$$C_b = \frac{C_{bn}}{DDP} = 68.2\, Ah$$

This value is correct, if only if there aren't cloudy days. Considering cloudy days, let us assume the battery have energy demand of two days.

$$C_b = 68.2 Ah\, x2 = 136.42 Ah$$

Hence, the capacity of the battery is taken as 140Ah.

b) ***Charge controller***

The power output required per household if all appliances are functional at the same time is 101W and the voltage required for the solar home system is usually 12V. So, the charge controller must work at a maximum current of

$$I_T = \frac{Power\ out\ put}{V_{cc}} = 8.4\, A$$

c) Area of the solar panel

The PV panel of the solar home system must be sized with the annual minimum of daily available PV electric energy (E_h). In Dillamo village, it occurs in month of July (with a value of 503.99Wh/m^2) as determined in table (A. 7).

Thus, the net energy to the load from the battery per unit area is

$$E_{net} = E_h \eta_b \eta_c = 408.23Wh/day.$$

The maximum daily energy consumption per household if all the appliances operate at the same time is 221Wh/day. Hence the required PV panel area will be

$$A_p = \frac{daily\ Energy\ demand}{E_{net}} = \frac{221}{408.23} = 0.541m^2$$

From this, the energy available to the load and battery from the PV panel can be determined by:

$$E_p = E_h x A_p = 503.99x0.541 = 272.66Wh/day$$

In order to select PV panel in the market, the panel has to be specified in peak watts, which is the power obtained with irradiation of 1000W/m^2 at the cell temperature of 25°C. The monthly global irradiance ranges from 4.84 KWh/day in July to 6.72 KWh/day in April. Hence, the effective hours with peak radiation (1000W/m^2) for the minimum case is 4.84 hours that gives the same energy per day.

As the temperature of the PV panel is not constant, a given correction factor (f_t) is taken as 0.89 [11]. From this, the peak power for a given PV panel from the daily available electrical energy of the panel can be obtained as follows:

$$P_p = \frac{E_p}{EEHxf_t} = \frac{272.66}{4.84\,x\,0.51} = 63.3\ W_p$$

The standard size of solar module which fits this size is 65W$_p$ Kyocera Solar PV Module (KC65T)

d) Electrical Accessories

Installation of PV panel requires the following accessory parts:

- Wire from solar panel – charge controller;
- Wire from charge controller – battery;
- Wire from charge regulator - charges: Lights, radio, etc;
- Key of charges control;
- Switches and Radio connections.

Condition 2: If there is no TV

Using similar assumptions and formula as condition 1:

a) Battery

$$E_b = 112.2 Wh/day$$

$$C_b = 65\, Ah$$

b) Charge controller

$$I_t = 3.42 A$$

c) Area of the solar panel

The daily available PV electrical energy (E_h) is minimum in July (503.99Wh/m^2). Then, net energy to the load from the battery per day is

$$E_{net} = E_h \eta_b \eta_c = 408.23 Wh/m^2 .$$

The maximum daily energy consumption per household if all the appliances operate at the same time is 101 Wh/day. Hence, the required PV panel area will be

$$A_p = \frac{daily\, energy\, demand}{E_{net}} = \frac{101}{408.23} = 0.247 m^2$$

The energy available to the load and battery from the PV panel is computed as follows:

$$E_p = E_h x A_p = 503.99 x 0.247 = 124.49 Wh/day$$

Like condition one, the peak power for a given PV panel from the daily available electrical energy of the panel is found as follows:

$$P_p = \frac{E_p}{EEHxf_t} = \frac{124.49}{4.84x0.89} = 28.9\ W_p$$

The standard size of solar module which fits this size is 30 W_p AEE Solar PV Modules (AE-37G)

Case 2: Village in Gode

Condition 1: If there is TV set

Using assumptions in the same manner of case 1 of condition 1, different values can be determined as follows:

a) Battery

$$E_b = 245.56 Wh/day$$

$$C_b = 68.2x2 = 136.4 Ah$$

To be safer the best battery size will be 140Ah

b) Charge controller

$I_T = 8.4$ A

c) Area of the Solar Panel

Size of solar PV panel for the solar home system (SHS) at the minimum daily PV electric energy available (E_h) in village in Gode occurs in August (616.66 Wh/m^2) as shown in table (B. 7). (Assuming the efficiency of battery and charge controller be 0.9)

The net energy to the load from the battery is:

$$E_{net} = E_h \, x \eta_b \, x \eta_c = 499.5 Wh/day/m^2$$

The daily energy consumption per household if all the appliances are functional at the same time is 221Wh/day, and then the required area of the solar panel will be

$$A_p = \frac{daily\,energy\,demand}{E_{net}} = \frac{221}{499.5} = 0.442 m^2,$$

The energy delivered by this size of the PV panel can be calculated as follows:

$$E_p = E_h x A_p = 616.66 x 0.442 = 272.84 Wh/\text{day}$$

In order to select PV panel in the market, the panel has to be specified in peak watts, which is the power obtained with irradiation of 1000W/m^2 at the cell temperature of 25ºC. The monthly global irradiance ranges from 5.54 KWh/day to 6.74 KWh/day. Hence, the effective hours with peak radiation (1000W/m^2) for the minimum case is 5.54 hours that gives the same energy per day.

The peak PV power in W_P is obtained by dividing energy supply by the PV pane by the effective equivalent hours and considering power variation with all temperature.

$$P_p = \frac{E_p}{EEHxf_t} = \frac{272.84}{5.54\,x\,0.89} = 55.34\ W_p$$

The standard size of solar module which fits this size is 60 W_p Siemens Solar Module (SW-60)

Condition 2: If there is no TV set

Like case 1 of condition 2:

a) Battery

$$E_b = 112.2 Wh/day$$

$$C_b = 31.2x2 = 62.4Ah$$

To be safer, the best battery to covers this need will be 65Ah

b) Charge controller

The maximum current charge controller must work is

$$I_T = 3.42A$$

c) Area of the solar panel

The annual minimum of daily available PV electrical energy (E_h) is in August (616.66 Wh/m^2). Then, net energy to the load from the battery per day is

$$E_{\text{net}} = E_h \text{ x } \eta_b x \eta_c = 499.5\text{Wh/day /m}^2$$

The maximum daily energy consumption per household if all the appliances operate at the same time is 101 Wh/day. Hence, the required PV panel area will be

$$A_p = \frac{daily\,Energy\,demand}{E_{net}} = \frac{101}{499.5} = 0.202m^2$$

The energy available to the load and battery from the PV panel is calculated as:

$$E_p = E_h x A_p = 616.66x0.2022 = 124.69\ W_p$$

As in condition one, the peak power for a given PV panel from the daily available electrical energy of the panel can be determined as follows:

$$P_p = \frac{E_p}{EEHxf_t} = \frac{124.69}{5.54x0.89} = 25.32\ W_p$$

The standard size of solar module which fits this size is 30 W$_p$ AEE Solar PV Modules (AE-37G)

4.2 Wind Power Generation

4.2.1 Wind System Energy Productivity

The fraction of power extracted from a practical wind turbine is usually given the symbol Cp, standing for the coefficient of performance.

$$P_m = C_p\left(\frac{1}{2}\rho A u^3\right) = C_p P_w \qquad (4.17)$$

The coefficient of performance is not a constant, but varies with wind speed, the turbine rotational speed, and turbine blade parameters (like angle of attack and pitch angle). For practical wind turbine, the maximum C_p value is in the range of 0.2 to 0.45. The pitch is varied to hold C_p at its largest possible value up to the rated speed u_R of the turbine, and then is varied to reduce C_p while P_w continues to increase with wind speed, in order to maintain output power at its rated value [18].

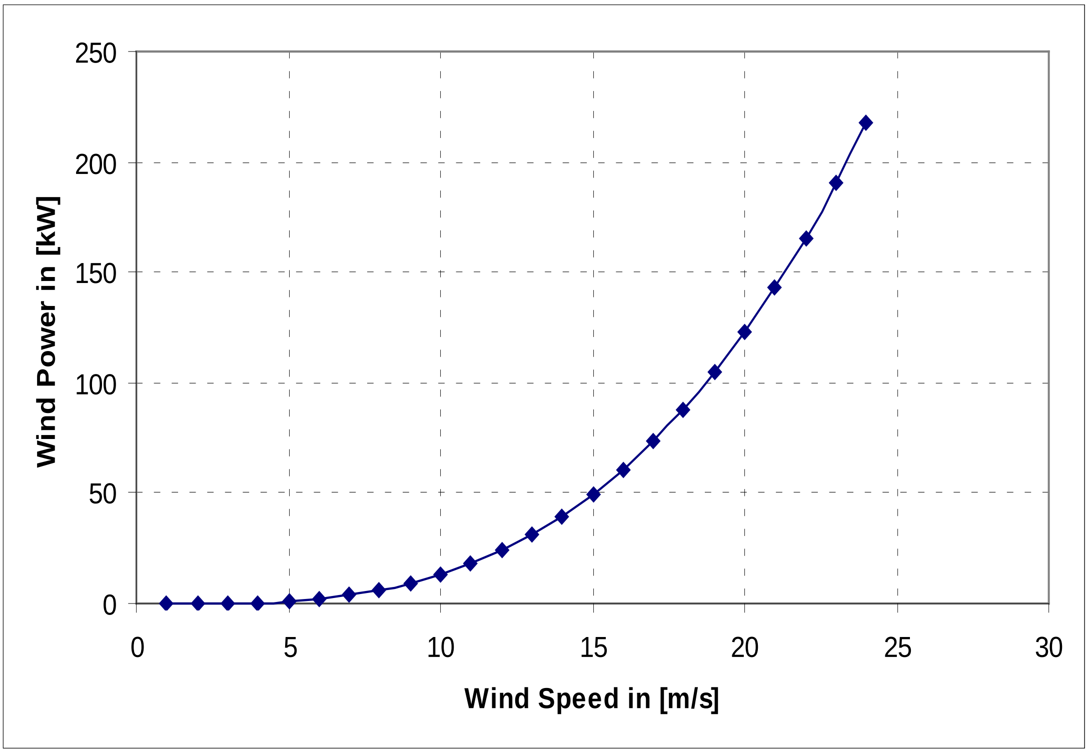

Figure 4. 20 Wind power vs. wind speed for both villages

4.2.2 Wind Speed Frequency

The wind speed is constantly changing and it is influenced by so many factors that make it impossible to model exactly. The annual average wind speed gives an indication about the potential power that can be developed from a particular site, through on a shorter time basis, the distribution of wind speeds around the mean is extremely important [8].

Wind speed distribution is calculated as a Weibull probability density function (the Rayleigh wind speed distribution, which is a special case of the Weibull distribution, where the shape factor is equal to 2). It conforms well to the observed long-term distribution of mean wind speeds for different sites.

$$f(x) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left[-\left(\frac{u}{c}\right)^{k}\right] \tag{4.18}$$

Where: - $k > 1, x \geq 0$ and $C > 0$

$$C = \frac{2}{\sqrt{\pi}} v_{ave} \tag{4.18.1}$$

v_{ave} = average wind speed = 4.76m/s

From equation (4.18), plot of the yearly wind speed distribution is shown in figure (4.21) and figure (4.22):

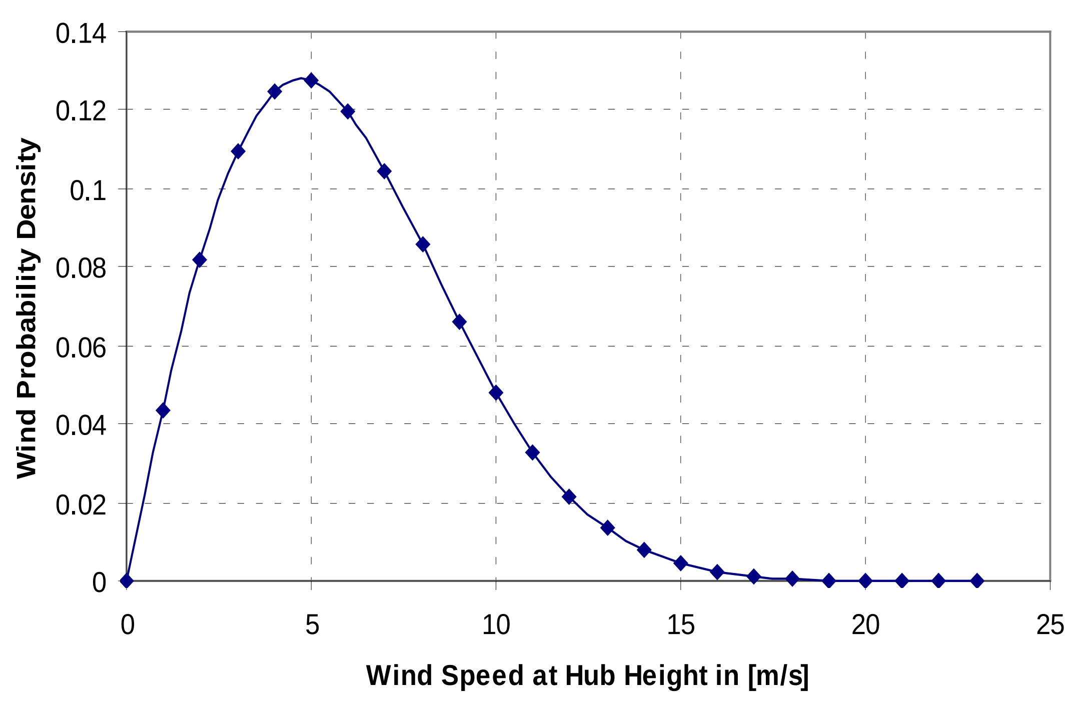

Figure 4. 21 Probability density vs. wind speed at hub height in Dillamo village

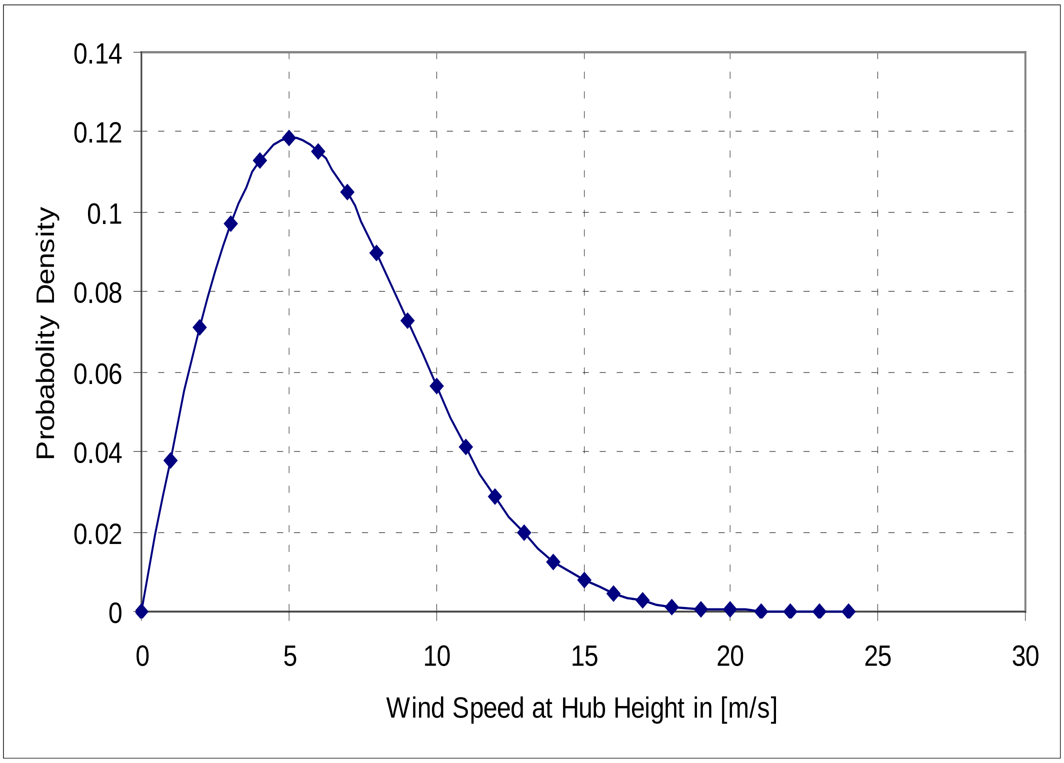

Figure 4. 22 Probability density vs. wind speed at hub height for village in Gode

4.2.3 Sizing of Main Components of Wind Power Generation

Case 1: Dillamo village

Condition 1: If there is TV set

The average wind speed at hub height can be computed as:

$$\frac{V_{avh}}{V_{ava}} = \left(\frac{H}{H_o}\right)^{\alpha} \tag{4.21}$$

$$V_{avh} = 5.93 m/s \tag{4.21.1}$$

The scale parameter can be calculated as:

$$C = \frac{2}{\sqrt{\pi}} v_{aveh} = 6.69 m/s \tag{4.22}$$

The optimum design of energy production is a rated wind speed of which is about 1.8 times the mean speed at hub height [10].

$$u_R = 1.8 \ x \ u_{avh} = 11 m/s \tag{4.23}$$

The wind must contain enough power at the cut-in speed to overcome all the system losses. It would be expected, then, u_c would almost always lie in the range from 0.25 to 0.5 of rated wind speed [10].

$$u_c = 0.25 \ x \ u_R = 2.75 m/s \tag{4.24}$$

A furling speed (u_f) is approximately twice that of the rated speed (u_R). This means the turbine control system is able to maintain a constant power output over an eight to one range of wind power input.

$$u_f = 2 x u_R = 22 m/s \tag{4.25}$$

Sizing of the wind turbine is dependent up on the total power (101W x 82 = 8.282 kW) required for the village at the rated speed. So, diameter of the rotor will be 6.10m [30].

4.2.4 Generator Efficiencies

The shaft power output is not normally used directly, but it is usually coupled to a load through a transmission however, for small turbines the shaft power is directly coupled with the load. To generate electricity the load is the electrical generator and the basic system of electric generation using wind turbine is as shown in figure 4.23.

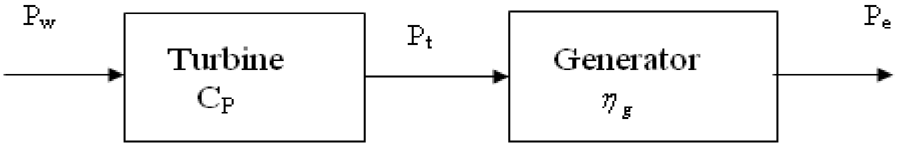

Figure 4. 23 **Wind electric systems**

The electric power output from the wind turbine can be obtained as:

$$P_e = C_p \eta_g P_w \qquad (4.26)$$

Where:-

$$P_W = \frac{1}{2}\rho A u^3 \qquad (4.27.1)$$

The generator losses may be considered in three categories: hysteresis and eddy current losses (functions of the operating voltage and frequency), windage and bearing friction losses (varies with rotational speed), and copper losses (vary as the square of the load or output current) [5].

The rated power will be calculated from:

$$P_{eR} = C_{pR} \eta_{gR} \frac{\rho}{2} A u_R^3 \qquad (4.28)$$

$$= \left\{ \left[0.4 \; x \, 0.87 \, x \frac{1.225}{2} x \left(\frac{\pi}{4} x \, 6.1^2 \; x 11^3 \right) \right] / 1000 \right\} = 8.291 kW$$

Good quality generators may have full load efficiency of 0.87. The rated overall efficiency of the turbine is found as:

$$\eta_o = C_{pR} \eta_{gR} = 0.348 \qquad (4.29)$$

Plot of electrical power output for wind speed at hub height is indicated in figure 4.24.

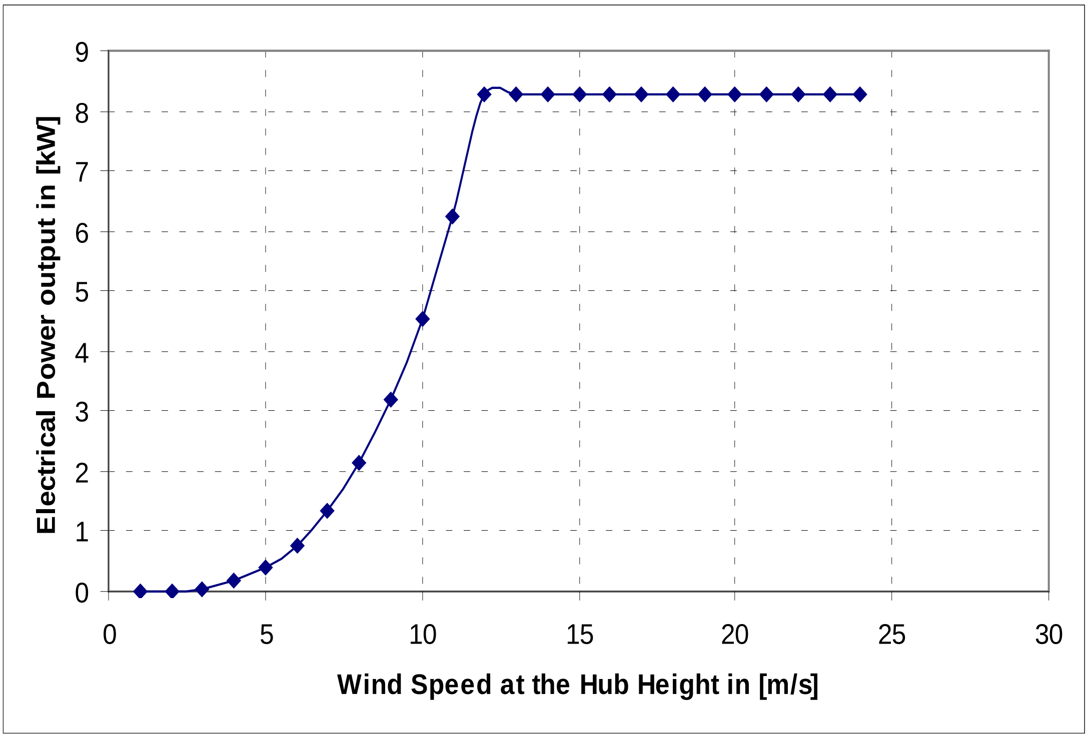

Figure 4. 24 Electrical power output vs. wind speed at hub height for Dillamo village

4.2.5 Energy Production and Capacity Factor

As it has been seen earlier, the electrical power output of a wind turbine is a function of the wind speed, turbine angular velocity, and efficiencies of each component in the electrical generator.

The average power output of a turbine is a very important parameter of a wind energy system since it determines the total energy production and the total income. It can be obtained by multiplying the power produced at each wind speed and the fraction of the time that wind speed has been experienced, integrated overall wind speeds [6].

For a wind turbine, the electrical power output will vary with the wind speed and it can be obtained as:

$$\begin{aligned} P_e &= 0 && (u < u_c) \\ P_e &= a + bu^k && (u_c \le u \le u_R) \\ P_e &= 0 && (u > u_F) \end{aligned} \tag{4.30}$$

The furling wind speed is the wind speed at which the turbine is shut down to prevent structural damage.

The coefficient a and b can be described as

$$a = \frac{P_{eR} u_c^k}{u_c^k - u_R^k} \tag{4.30.1}$$

$$b = \frac{P_{eR}}{u_R^k - u_c^k} \tag{4.30.2}$$

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left[-\left(\frac{u}{c}\right)^k\right] \tag{4.32}$$

$$P_{e,ave} = \int_0^\infty P_e f(u)du \tag{4.33}$$

The average power output can be obtained by substituting equation (4.30) and equation (4.32) to equation (4.33). This provides (4.34)

$$P_{e,ave} = \int (a + bu^k) f(u)du + P_{eR} \int_{uR}^{uf} f(u)du \tag{4.34}$$

Integrating equation (4.34) the average power will be computed as

$$P_{e,ave} = P_{eR} \left\{ \frac{\exp\left[-\left(\frac{u_c}{c}\right)^k\right] - \exp\left[-\left(\frac{u_R}{c}\right)^k\right]}{\left(\frac{u_R}{c}\right)^k - \left(\frac{u_c}{c}\right)^k} - \exp\left[-\left(\frac{u_F}{c}\right)^k\right] \right\} \tag{4.35}$$

$$= P_{eR} CF$$

$$CF = \left\{ \frac{\exp\left[-\left(\frac{2.75}{6.69}\right)^k\right] - \exp\left[-\left(\frac{11}{6.69}\right)^k\right]}{\left(\frac{11}{6.69}\right)^k - \left(\frac{2.75}{6.69}\right)^k} - \exp\left[-\left(\frac{22}{6.69}\right)^k\right] \right\} = 0.30678$$

$$P_{e,ave} = 0.30678 * 8.291 = 2.5435 kW$$

The energy production with in a year is determined as follows:

$$E = P_{e,ave}(time) = (CF)P_{eR}(8760) \text{ kWh } = 22.281 MWh/year$$

$$\text{Re}\, quired\ energy = 221\frac{Wh}{day}\ x\,30\frac{day}{month}\ x\,12\frac{months}{year}\ x\,82\, households\ =\ 6.524\, MWh/year$$

Hence, 15.76 MWh/year is excess energy and the resident may use for other purpose.

Condition 2: If there is no TV set

The total power required to cover the village for condition two is 3.362 kW at rated speed in the village. So, diameter of the rotor will be 3.92m [30].

4.2.6 Rated Power output for Condition Two

Good quality generators may have full load efficiencies of 0.853 for 3.36 kW.
The rated power will be

$$P_{eR} = \left\{\left[0.4\ x 0.853 x \frac{1.225}{2} x (\frac{\pi}{4} x 3.923^2\ x 11^3)\right]/1000\right\} = 3.362\,kW$$

The rated overall efficiency of the turbine can be computed as:

$$\eta_o = C_{pR}\eta_{gR} \quad = 0.3412$$

4.2.7 Energy Production and Capacity Factor

As in condition one, we can get average power of the wind turbine

$$P_{e,\ ave} = P_{eR} CF$$

$$CF = \left\{ \frac{\exp\left[-\left(\frac{2.75}{6.69}\right)^k\right] - \exp\left[-\left(\frac{11}{6.69}\right)^k\right]}{\left(\frac{11}{6.69}\right)^k - \left(\frac{2.75}{6.69}\right)^k} - \exp\left[-\left(\frac{22}{6.69}\right)^k\right] \right\} = 0.30678$$

$$P_{e,ave} = 0.30678 * 3.362 = 1.0314 kW$$

The total energy production with in a year will be determined

$$E = P_{e,ave}(time) = (CF)P_{eR}(8760)\ \text{kWh} = 9.035\ MWh/year$$

$$\text{Re}\,quired\ \ energy = 101\frac{Wh}{day}\ x 30\frac{day}{month}\ x 12\frac{months}{year}\ x 82\,households\ =\ 2.982\,MWh/year$$

Case 2: village in Gode

Condition 1: If there is TV set

Similar to case 1:

$$V_{avh} = 6.398\text{m/s}$$

$$c = 7.22 m/s$$

$$u_R = 12\ \text{m/s}$$

$$u_c = 3 m/s$$

$$u_{f\,R} = 24m/s$$

For sizing of wind turbine of the total power 3.54kW to cover the village, the corresponding diameter the rotor will be 3.53m [32].

As it has been seen in case 1, generator efficiency is 0.854 which is by interpolation.

$$P_{eR} = C_{pR}\eta_{gR}\frac{\rho}{2}Au_R^3 \tag{4.37}$$

$$= \left\{\left[0.4x0.854\ x\frac{1.225}{2}x(\frac{\pi}{4}x3.528^2\ x12^3)\right]/1000\right\} = 3.535kW$$

The rated overall efficiency of the turbine

$$\eta_o = C_{pR}\eta_{gR} = 0.3416$$

The average power of the wind turbine can be calculated as:

$$P_{e,ave} = P_{eR}\left\{\frac{\exp\left[-\left(\frac{u_c}{c}\right)^k\right] - \exp\left[-\left(\frac{u_R}{c}\right)^k\right]}{\left(\frac{u_R}{c}\right)^k - \left(\frac{u_c}{c}\right)^k} - \exp\left[-\left(\frac{u_F}{c}\right)^k\right]\right\} \tag{4.38}$$

$$= P_{eR}CF$$

$$CF = \left\{\frac{\exp\left[-\left(\frac{3}{7.22}\right)^2\right] - \exp\left[-\left(\frac{12}{7.22}\right)^k\right]}{\left(\frac{12}{7.22}\right)^2 - \left(\frac{3}{7.22}\right)^2} - \exp\left[-\left(\frac{24}{7.22}\right)^k\right]\right\} = 0.3005$$

$$P_{e,ave} = 0.3005 * 3.535 = 1.0623KW$$

The total energy production with in a year will be

$$E = P_{e,ave}(time) = (CF)P_{eR}(8760)\ \text{kWh} = 9.3055MWh/year$$

$$\text{Required energy} = 221\frac{Wh}{day}\ x30\frac{day}{month}\ x12\frac{months}{year}\ x35\,households = 2.785\,MWh/year$$

Hence, 6.521MWh/year is excess energy and the resident may use for other purpose.

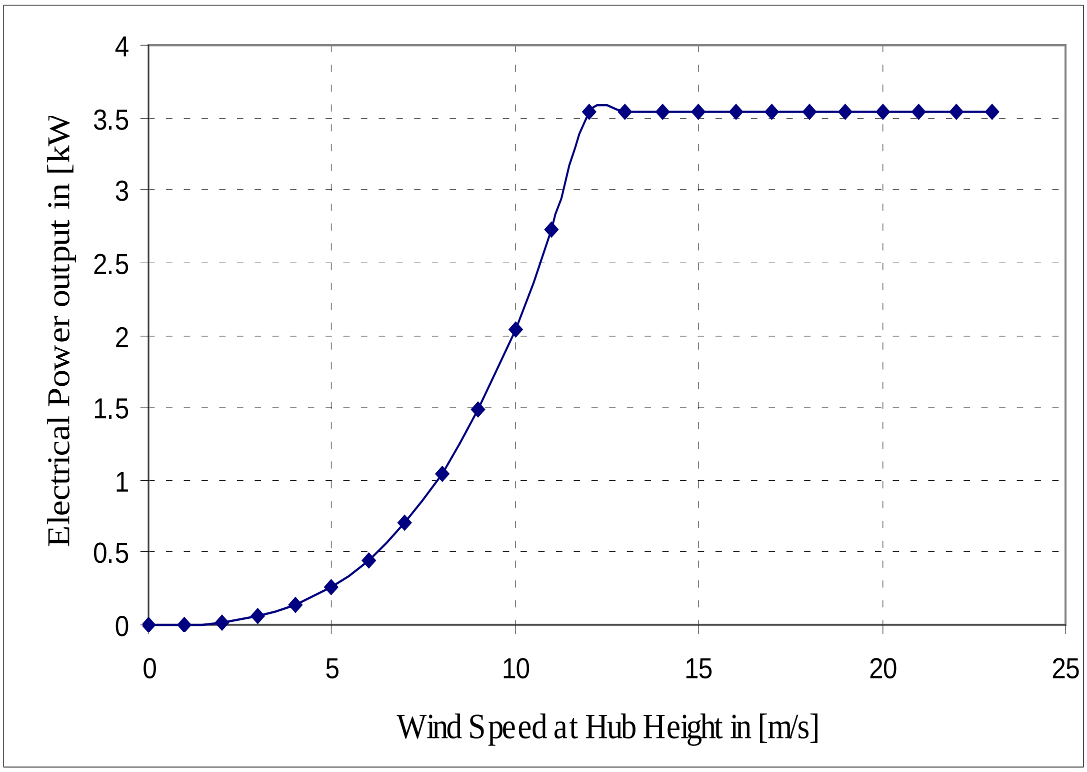

Figure 4. 25 Variation of electrical power output with wind speed at hub height for village in Gode

Condition 2: If there is no TV set

The total power required to cover the village if there is no TV set is 1.435kW. So, diameter of the rotor will be 2.251m [30]. Assume generator efficiency is 0.850, then, rated power output can be calculated as:

$$P_{eR} = C_{pR}\eta_{gR}\frac{\rho}{2}Au_R^3$$

$$P_{eR} = \left\{\left[0.4\,x\,0.850\,x\frac{1.225}{2}x\left(\frac{\pi}{4}x\,2.251^2\,x12^3\right)\right]/1000\right\} = 1.432\,kW$$

The rated overall efficiency of the turbine can be computed as:

$$\eta_o = C_{pR}\eta_{gR} = 0.340$$

$$CF = \left\{\frac{\exp\left[-\left(\frac{3}{7.22}\right)^2\right] - \exp\left[-\left(\frac{12}{7.22}\right)^k\right]}{\left(\frac{12}{7.22}\right)^2 - \left(\frac{3}{7.22}\right)^2} - \exp\left[-\left(\frac{24}{7.22}\right)^k\right]\right\} = 0.3005$$

$$P_{e,ave} = 0.3005*1.432 = 0.4303\,kW$$

The total energy production with in a year

$$E = P_{e,ave}(time) = (CF)P_{eR}(8760)\ \text{ kWh } = 3.7696\,MWh/year$$

$$\text{Re}\,quired\ \ energy = 101\frac{Wh}{day}\ x30\frac{day}{month}\ x12\frac{months}{year}\ x35\,households\ = 1.273\,MWh/year$$

4.1.1 Sizing of Balance of Wind Power Generation System

Case 1: Dillamo Village

Using similar as that of sizing of PV system for this case:

Condition 1: If there is TV set

a) Battery

$$E_{bw} = \frac{E_u}{\eta_b} = \frac{221}{0.9} = 245.56\,Wh/day$$

$$C_{bnw} = \frac{E_{bw}}{V_{cc}} \quad = \frac{245.56}{12} = 20.46\,Ah/day$$

$$C_{bw} = \frac{C_{bn}}{DDP} \quad = \quad \frac{20.46}{0.3} = 68.2\,Ah$$

This value is correct, if we suppose that every day will be sufficient wind speed and every day, the forecasted energy is consumed. It is necessary to take into account that there are calm days and let the number such days be two, then

$$C_{bw} = 68.2\,x\,2 = 136.42\,Ah$$

To be safer, the best battery size will be 140Ah and the total battery bank required to cover the village is 11480Ah

b) Charge controller

The power output required per household is 101W and the voltage required is usually 12V. So, the charge controller must work at a maximum current of

$$I_T = \frac{Power\,out\ put}{V_{cc}} = 8.4\,A$$

Total capacity of the charge controller to cover the village is 688.8 A

c) Inverter size

In the system we are required inverter to use color television and the size of inverter required is 60W and total size will be 4.92 kW.

Condition 2: If there is no TV set

a) Battery

$$E_{bw} = \frac{E_u}{\eta_b} = \frac{101}{0.9} = 112.22\,Wh/day$$

$$C_{bnw} = \frac{E_{bw}}{V_{cc}} = \frac{112.22}{12} = 9.352\,Ah/day$$ `

$$C_{bw} = \frac{C_{bnw}}{DDP} = 31.17\,Ah$$

Considering calm days, let as assume the battery have energy demand of two days.

$$C_{bw} = 31.17x2 = 62.33\,Ah$$

To be safer the best battery size will be 65 Ah and total battery bank required is 5330Ah

b) Charge controller

The maximum current charge controller must work is:

$$I_t = \frac{Power\ out\ put}{\mathrm{V_{cc}}} = \frac{41W}{12V} = 3.42A$$

Total capacity of the charge controller to cover the Dillamo Village is 280.44 A.

Case 2: village in Gode

Condition 1: If there is TV set

a) Battery

$$E_{bw} = \frac{E_u}{\eta_b} = 245.56Wh/day$$

$$C_{bnw} = \frac{E_{bw}}{V_{cc}} = \frac{245.56}{12} = 20.46Ah/day$$

$$C_{bw} = \frac{C_{bn}}{DDP} = 68.2Ah$$

Accounting for calm days, the battery capacity will be

$$C_{bw} = 68.2x2 = 136.4Ah$$

To be safer the best battery size will be 140Ah and the total battery bank required to cover the village is 4900Ah

b) Charge controller

$$I_t = \frac{power\ output}{Vcc} = \frac{101}{12} = 8.4\,A$$

Total capacity of the charge controller to cover the village is 294 A

c) Inverter sizing

In the system we are required inverter for television and the size of inverter is 60W per household and total size will be 2.1 kW

Condition 2: If there is no TV set

a) Battery

$$E_{bw} = \frac{E_u}{\eta_b} = \frac{101}{0.9} = 112.2Wh/day$$

$$C_{bnw} = \frac{E_{bw}}{V_{cc}} = 9.35\ Ah/day$$

$$C_{bw} = \frac{C_{bnw}}{DDP} = 31.2Ah$$

Considering cloudy days, let as assume the battery have energy demand of two days.

$$C_b = 31.2x2 = 62.4Ah$$

To be safer, the best battery to covers this need will be 65Ah and the total battery bank required to cover the village is 2275Ah

b) Charge Controller

The power required per household if all the appliances are working at the same time is 41W. From this the charge controller must work at a minimum current of

$$I_t = \frac{power\ outpu}{Vcc} = 3.42\,A$$

Total capacity of the charge controller to cover the Village is 109.44 A

4.2 Micro Hydro Power Generation

Actual power P available from the micro hydro plant at any given flow value Q and gross head Hg can be obtained.

4.2.1 Typical Scheme Layout of Micro Hydro Power Generation[15]

Micro-hydro power generation is a very site-specific technology and scheme configurations that varies from site to site. The flow of water in a river may be regulated by means of a small dam or weir. The weir also slightly raises the water level of the river and diverts sufficient water into the conveyance system. The water is channeled to a forebay tank where it is stored until required and it forms the connection between the channel and the penstock. The penstock carries the water under pressure from forebay to the turbine. The penstock is a very important part of a hydro project as it can affect the overall cost and capacity of a scheme. The penstock connects to the hydraulic turbine, which is located within the powerhouse [15].

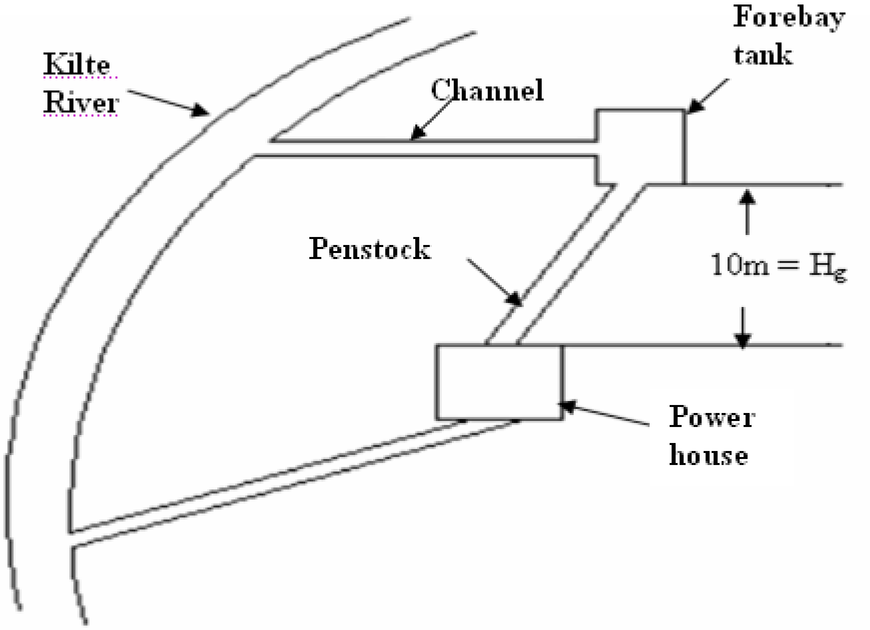

Figure 4. 26 Micro hydro power generation system layouts of Kilte River

4.2.2 Turbine Selection

A turbine converts energy in the form of falling water in a rotating shaft power. The selection of best turbine for a particular micro hydro site depends on the site characteristics, the dominant factor is the head available and the power required. Selection also depends on the speed at which it is desired to run the generator or other devices loading the generator [15]. From table (5.3), a turbine type suitable for this site is impulse turbine typically cross flow type [15, 6].

Table 4. 4 Classification of micro hydro turbines according to head, flow rate and power output [15, 6]

Classification	Turbine Name	Head Range(m)	Flow Range (m^3/s)	Power output (kW)
Impulse	Pelton	50 - 1,000	0.2 - 3	50 - 15,000
	Turgo	30 - 200	0.2 - 5	20 - 5000
	Cross Flow	2 - 50	0.01 - 2	0.1 - 600
Reaction	Kaplan	3 - 40	3 - 20	50 - 5000
	Propeller	3 - 40	3 - 20	50 - 500
	Francis Radial- Flow	40 - 200	1 - 20	500 - 15000
	Francis-Mixed -Flow	10 - 40	0.7 - 10	100 - 5000

4.2.3 Sizing of Cross Flow Turbine

Conditions 1: when the customers use TV

For sizing of cross flow turbine, the dimension of interest is the runner length (L_{runner}), diameter (D_{runner}) and jet thickness (t_{jet}). Assuming gear ratio 2 and alternator speed 1500 rpm,

$$D_{runner} = \frac{41\sqrt{H_{net}}}{N_t}$$

Where:-

Turbine speed (N_t) = $\frac{alternator\ rpm}{gear\ ratio} = \frac{1500}{2} = 750\ rpm$

$H_{net} = H_g - h_{hydr}$, h_{hydr} is usually 2 to 7% of H_g

$$= H_g - 7\% \; of \; H_g = 9.3m$$

$$D_{runner} = \frac{41\sqrt{9.3}}{750} = 0.167\,m$$

The jet thickness is usually one tenth of the runner diameter

$$t_{jet} = 0.1 \; x \, D_{runner} = 16.67\,mm$$

Having t_{jet}, the approximate runner length (L_{runner}) can be obtained from the orifice discharge equation. The runner length will be equivalent to the jet width

$$Q = A_{nozzle}\sqrt{2gH_{net}} = t_{jet} \; x \, L_{runner} \; x\sqrt{2gH_{net}}$$, for Q = 0.1627 m^3/s

$$L_{runner} = 0.723\,m$$

4.2.4 Turbine Efficiency

For this condition, it is assumed that the three parameters design flow (Q_d), flow at any time (Q) and peak flow (Q_p) be equal [15].

$$e_t = 0.79 - 0.15\frac{(Q_d - Q)}{Q_p} - 1.37\left(\frac{Q_d - Q}{Q_p}\right)^{14}$$

Hence, turbine efficiency will be 0.79 or it is possible to read from figures (4.31) approximately equal to the calculated value.

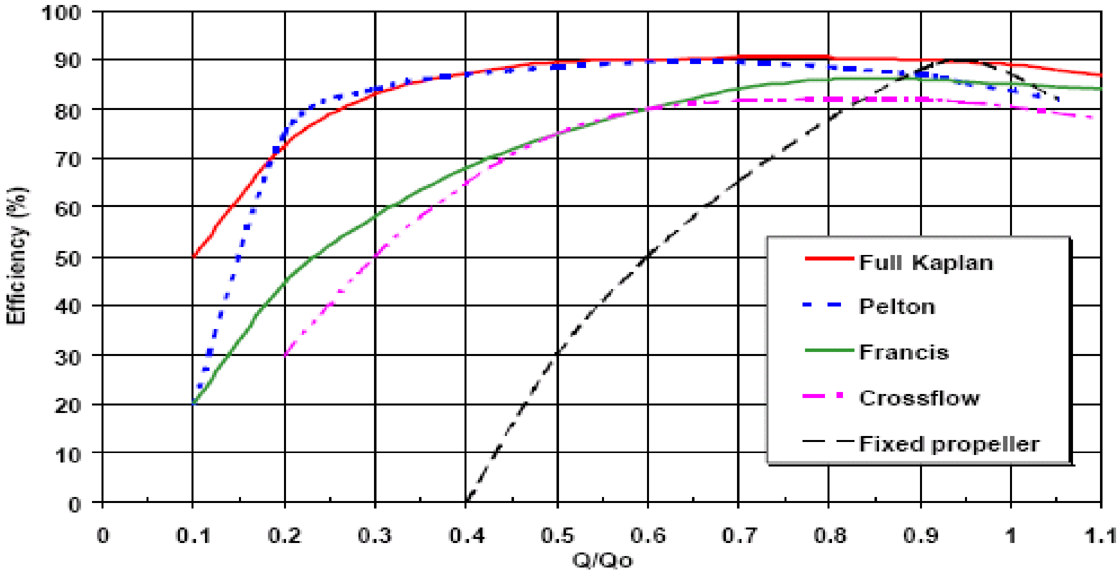

Figure 4. 27 Relative efficiency of turbines for micro-hydro power generation [15].

4.2.5 Sizing of Penstock

Diameter of penstock can be calculated from discharge and head of the river

$$d_p = \frac{\left(\frac{Q_d}{n_p}\right)^{0.46}}{H_g^{0.14}} = 0.314\,m$$

Length of the penstock can be approximated from the layout of the scheme

$L_p = 24$m

Total weight of penstock is important to estimate its cost and can be calculated as

$$W = \frac{\pi\, l_p}{4}\rho_p\left(d_o^2 - d_p^2\right)$$

Where:-

$$d_{o\,p} = d_p + 2t_{ave}$$

$$t_{ave} = 0.5(t_t + t_b) \text{ if} t_b \geq t_t, \qquad t_{ave} = t_t \text{ if } t_b < t_t$$

$$t_t = d_p^{1.3} + 6 = 6.222mm$$

$$t_b = 0.0375\,x\,d_p\;x\,H_g = 0.118\,mm$$

From this, it can be concluded that $t_{ave} = 6.222\ mm$ and d_{op} = 0.3264 m

Mass of the penstock will be then:

$$W = \frac{\pi\, l_p}{4}\rho_p\left(d_o^2 - d_p^2\right) = 1167.53\ kg$$

4.2.6 Power available from Kilte River

Power input = power output + losses

The power input, or the total power absorbed by the hydro scheme is the gross power and the power usually delivered is the net power. The overall efficiency of the scheme is termed as e_o.

$$P_{net} = \rho g h_{gross}\, Q\;\; e_o$$

Where:-

$$e_o = e_{chanal}\ x\ e_{penstock}\,x\,e_{turbine}\,x\,e_{generatore}\,x\,e_{line} = \ 0.95\,x\,0.9\,x\,0.79\,x\,0.85\,x\,0.9 = 0.52$$

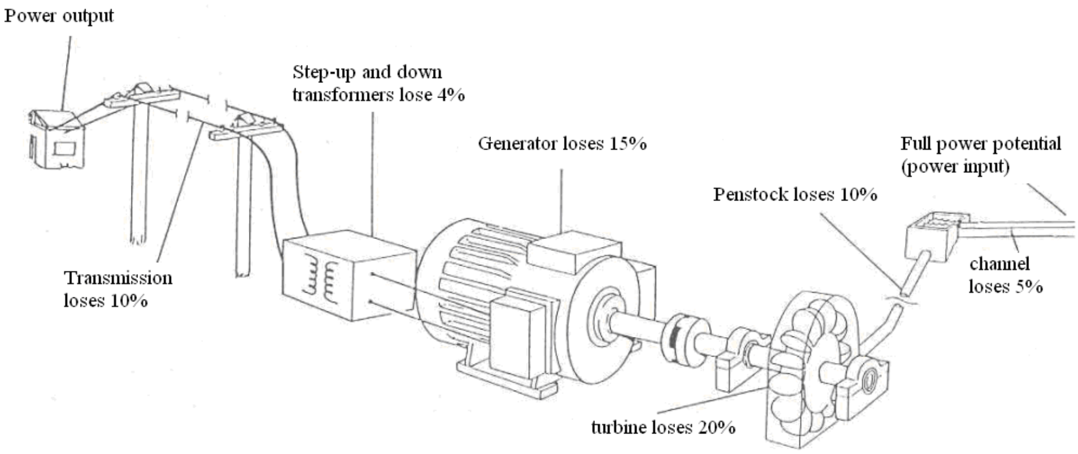

Figure 4. 28 Typical system efficiency of micro- hydro power generation [15]

Hence, the actual power i.e. P_{net} available from Kilte River micro hydro power generation is 8.3 kW.

4.2.7 Capacity Factor or Plant Factor

As it has been explained before, in Kilte River, there are nine traditional Arab Mills that are functional in the day time and the river is functional for the village in night time only. So, the plant capacity factor can be calculated by taking these factors in consideration. There are three lamps taking 11W power and functional one for three hours and two lamps for two hours each, radio/tape recorder taking 8W power functional for three hours, and 21” color television taking 60W power which is functional for three hours.

$$Capacity\ \ or\ plant\ \ factor = \frac{energy\ used}{energy\,available}$$

$$C.F = \frac{[0.011x3 + 0.011x2\ + 0.011x2\ + 0.008x3 + 0.06x2]x82\,(kWhr)}{8.3x12\,(kWh)} = 0.182$$

Annual energy production becomes 8.3kW x 8760 x 0.182 = 13.23 MWh/year

The annual energy consumption of the village can be calculated as:

$$\text{Re}\,quired\ \ energy = 221\frac{Wh}{day}\ x30\frac{day}{month}\ x12\frac{months}{year}\ x82\,households\ =\ 6.524\,MWh\,/\,year$$

Hence, 6.71 MWh/year is extra energy and the residents may use this energy for other works.

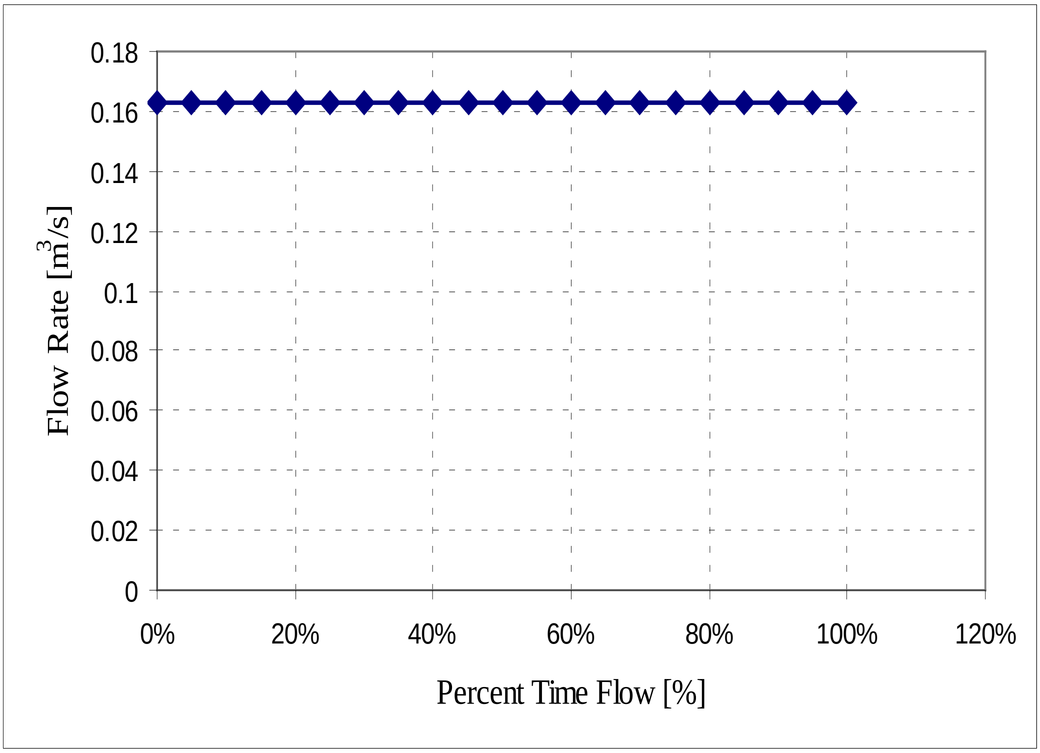

Figure 4. 29 Variation of design flow with percent time flow

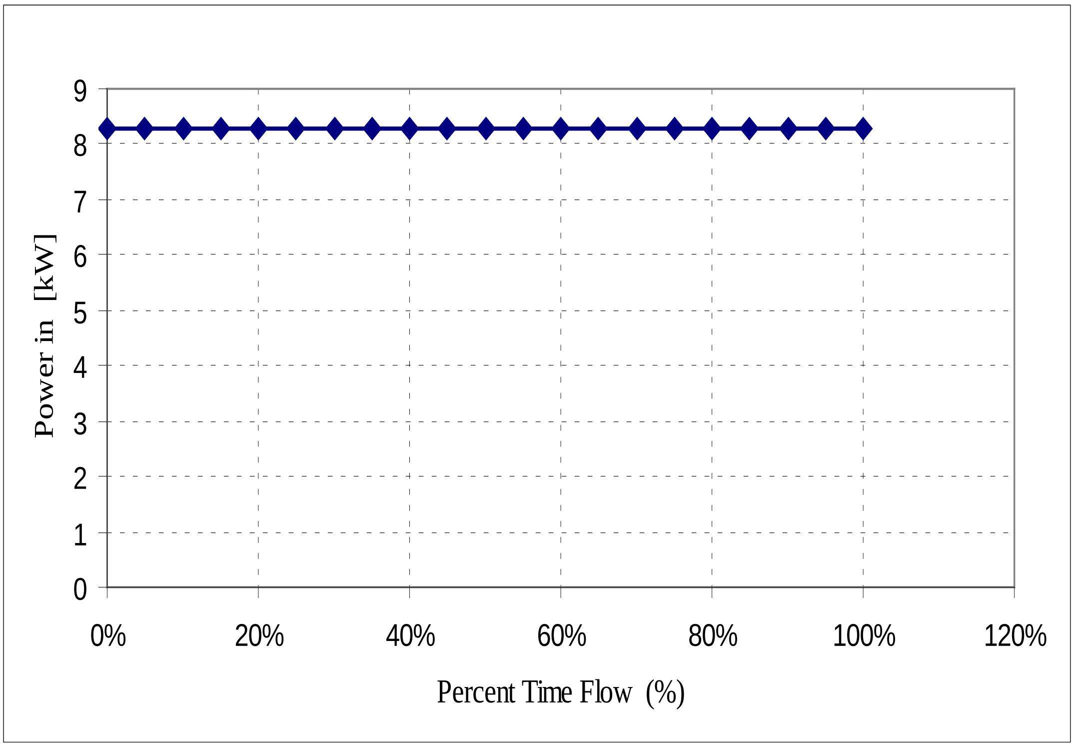

Figure 4. 30 Power Generated for the given flow rate and head with percent time flow

Condition2: when there is no TV

4.2.8 Turbine Sizing

As it has been described in condition one, turbine speed, gear ration, net head of the river is not changed.

$$D_{runner} = \frac{41\sqrt{H_{net}}}{N_P} = 0.167m$$

$$t_{jet} = 0.1\ x\ D_{runner} = 16.67\ mm$$

$$Q = A_{nozzle}\sqrt{2gH_{net}} = t_{jet}\ x\ L_{runner}\ x\sqrt{2gH_{net}}$$

$L_{runner} = 0.2927\,m$, for Q = 0.0659m^3/s

4.2.9 Turbine Efficiency

Turbine efficiency is approximately the same as condition one which is 0.79

4.2.10 Sizing of Penstock

Similar to condition 1:

$$d_p = 0.207\,m$$

L_P = 24 m

$$t_{ave} = 6.13\ mm$$

$d_o = d_p + 2t_{ave}$ = 0.2196 m

$$W = \frac{\pi\, l_p}{4}\rho\left(d_o^2 - d_p^2\right) = 769.58\ kg$$

4.2.11 Power available from the River

$P_{net} = \rho g h_{gross}\ Q\ e_o$ = 3.362 kW

4.2.12 Capacity Factor or Plant Factor

$$Capacity\ or\ plant\ factor = \frac{energy\ used}{energy\ available}$$

C.F = $\dfrac{[0.011x3 + 0.011x2 + 0.011x2 + 0.008x3]x82\,(kWhr)}{3.362x12\,(kWh)}$ = 0.205

The annual energy consumption is 3.362kW x 8760 x 0.2053 = 6.046 MWh/year

The total energy required per year is 2.98 MWh/year and 3.064 MWh/year is extra

CHAPTER 5

COST ANALYSIS OF THE OPTIONS

5.1 Cost Evaluation of Solar Photovoltaic Power Generation

It is believed in rural households of Ethiopia electric energy demand is limited to lighting and radio/cassette player at minimum and addition of color television at maximum. For lighting purpose, energy saving lamps of compact fluorescent type with 11W DC or 11W AC current is recommended. The households are assumed to have a salon, bed room and kitchen

CASE 1: DILLAMO VILLAGE

The cost data was collected from importer of solar PV system and the average cost of the PV panel per peak watt was found to be Birr 68. Table (5.1) indicates investment cost break down of solar PV system for Dillamo village with 21" TV.

Table 5. 1 Cost break down of solar PV system for Dillamo village with 21" TV

No	**Description**	**Quantity**	**Unit rice [Birr]**	**Total Price [Birr]**
1	Module (65Wp)	1	68.00/W_P	4420.00
2	Battery (140) deep cycle	1	2097.01	2097.01
3	Charge Regulator (8.4A)	1	742.00	742.00
4	DC-AC inverter for 21" color TV	1	750.00	750.00
5	DC lamps (11w)	3	96.76	290.28
6	Cabling, Switch, Holder, plug, Divider and PV panel support structure cost			300.00
Direct Cost of the Equipment				**8599.29**
7	Repair and Maintenance cost of direct cost of the equipment mainly battery replacement			2097.00
8	Installation cost (7%)			593.86
Total System Cost				**11, 290.15**

The total cost of the solar PV for Solar Home System (SHS) for each household of Dillamo village is Birr 11290.15. When it is added 5% of the retail margin, interested rural household can have a system at a cost of Birr 11, 854.66 (US $ 1314.26).

- When TV set is excluded and the total power required per household will fall to 41W and the daily energy consumption becomes 101Wh per day. For this case, the required system and its cost are given in Table 6.2.

Table 5. 2 Cost break down of solar PV system for Dillamo village without color TV

No	Description	Quantity	Unit Price [Birr]	Total Price [Birr]
1	Module (29Wp)	1	68.00/W$_P$	2040.00
2	Battery (65 Ah) deep cycle	1	974.95	974.95
3	Charge Regulator (3.5A)	1	309.60	309.60
4	DC lamps (11w) (energy saving lamps)	3	96.76	290.28
5	Cabling, Switch, Holder, Plug, Divider and PV panel support structure cost			252.28
Direct cost of the equipment				**3914.83**
6	Repair and maintenance cost through out its life			975.00
7	Installation cost (7%) of the direct cost of the equipment			274.04
Total System Cost				**5163.82**

The total cost of the solar PV system for Solar Home System (SHS) is Birr 5, 694.25 and considering 5% of the retail margin, interested rural household can incur a cost of Birr 5, 422.01 (US $ 601.11).

CASE 2: village in Gode

For a village in Gode, the required system and its cost for the case with color TV is given in Table 6.3.

Table 5. 3 Cost break down of solar PV for village in Gode with color TV

No	**Description**	**Quantity**	**Unit Price [Birr]**	**Total Price [Birr]**
1	Module (60 Wp)	1	68.00/W_P	4080.00
2	Battery (140) deep cycle	1	2097.1	2097.1
3	Charge Regulator (8.4A)	1	742.00	742.00
4	DC-AC inverter for 21" color TV	1	750.00	750.00
5	DC lamps (11w) (energy saving lamps)	3	96.76	290.28
6	Cabling, Switch, Holder, Plug, Divider and PV panel support structure cost			300.00
Direct cost of the equipment				**8259.38**
7	Repair and Maintenance cost through out its life			2097.10
8	Installation cost (7%) of direct cost of the equipment			555.98
Total System Cost				**10912.46**

Taking similar assumption as case 1, total system cost per household is Birr 11, 458.08 (US $ 1270.30)

Like case 1, total power required per household and daily energy consumption are 41 W and 101Wh respectively excluding color TV set. Its cost breakdown is shown in table 6.4

Table 5. 4 Cost break down of solar PV system for Village in Gode when 21” TV excluded

No	Description	Quantity	Unit Price [Birr]	Total Price [Birr]
1	Module (30 Wp)	1	$68.00/W_P$	2040.00
2	Battery (65 Ah) deep cycle	1	974.95	974.95
3	Charge Regulator (3.5A)	1	309.60	309.60
4	DC lamps (11w) (energy saving lamps)	3	96.76	290.28
5	Cabling, Switch, Holder, Plug, Divider and PV panel support structure cost			300.00
Direct cost of the equipment				**3914.83**
6	Repair and Maintenance cost through out its life			974.95
7	Installation cost (7%) of direct cost of the equipment			251.76
Total System Cost				**4823.30**

The total cost will be Birr 5, 422.01 (US $ 601.11) including 5% of retail margin.

5.2 Cost Evaluation of Wind Power Generation

A wind generator consists of several components. At the top of the tower of a horizontal axis turbine, there are the rotors, gear box (for small wind power generation no need), generator (Brushless, Direct Drive, Permanent Magnet type), bedplate, enclosure and various sensors, controls, couplings, a brake, and a lighting protection. At the bottom of the tower, there are switchgears, protection relays, necessary instrumentation, and controllers. The distribution line connects the wind generator to the mini grid. Land, an access road construction is also required to have a working system. But the capital cost of distribution line, land and access road can vary with respect to site location. This cost would be minimized by placing the wind generator along with an existing road and the cost per kilowatt of maximum power output various with the size of wind turbine. Cost of component per unit size tend to decrease as size increases [29].

Case 1: Dillamo village

The American Wind Energy Association (AWEA) says a typical home wind system costs approximately $50,000 (10 kW) and it can be approximated that the cost of 8.3 kW power generations is $ 41,500. This cost includes tower, batteries, and inverter costs [35]. Taking in consideration an inflation rate of 25% of the equipment cost, transportation cost of 10% and taxation cost of 30% and it will become Birr 611,481.75 (US $ 68, 475.00).

Table 5. 5 Cost of Balance of wind power generation system with TV set for Dillamo village

No	Component Description	Unit Price [Birr]	Total Price [Birr]
1	Lead Acid Deep Cycle Battery 140Ah of 82pcs. totally 11,480Ah	2097.1	171, 962.2
2	Charge regulator 8.4Ar and 82 pcs.(688.8A)	742.00	60,844.00
3	DC-AC inverter for 21” TV 60W 82 pcs	750.00	61,500.00
4	Compacted type fluorescent 3 per household for 82 households	96.76/HH	23,802.96
Total Cost			**318,109.2**

To calculate the cost of each component of the wind power generation system, inverter and charge controller costs have to be disregarded from the total cost of the wind power generation. Hence, other components cost excluding cost balance system will be Birr 317,176.00 or US $35, 517.98.

Table 5. 6 Wind generator component cost excluding balance of system cost with TV for Dillamo village [36]

Component Description	Component Cost (%)	Component Unit Price [Birr]	Component Total Price [Birr]
Blades	21.45	68034.25	68034.25
Hub	9.30	29497.37	29497.37
Pitch mechanisms and bearings	5.12	16239.41	16239.41
Shaft (main shaft)	2.97	9420.13	9420.13
Main shaft bearing and block	1.68	5328.56	5328.56
Electrometric mounting system	0.39	1236.99	1236.99
Generator isolation mount	0.13	412.33	412.33
Support structure	4.91	15573.34	15573.34
Generator cooling system	0.39	1236.99	1236.99
Brake system hydraulics	0.78	2473.97	2473.97
Coupling	0.39	1236.99	1236.99
Nacelle cover	2.45	7770.81	7770.81
Generator	8.66	27467.44	27467.44
Cables (wire)	2.58	8183.14	8183.14
Switch gear	1.81	5740.89	5740.89
Yaw derive and bearings	2.33	7390.20	7390.20
Control and safety system	1.03	3266.91	3266.91
Tower	26.61	84400.53	84400.53
Foundation	6.98	22138.88	22138.88
Total Cost			**317, 176.00**

Source: Alternative Design Study Report: Wind PACT Advanced Wind Turbine Drive Train Study

The total cost of the wind generator excluding the maintenance and operation cost will be Birr 635,285.16 (US $ 71,140).

❖ Operation and Maintenance Cost

Lifetime of wind generator varies most of the time, but usually manufacturers estimated design lifetime of turbines has been used in economic assessment as the life time of the systems and the suggested design life time of wind turbine is 20 years.

A ‘block’ approach for operation and maintenance cost estimate has been used [2]

- For year 1 the (O & M) cost is estimated as 2% of the total turbine cost;
- The operation and maintenance cost for each year in the year 2 – 5 ‘block’ is given as 2% of the turbine cost + 1% of the O&M cost for the previous year;
- For 6 – 10 years it is given as 2% of the turbine cost + 2% of the O&M cost for the previous year;
- For 11 – 15 years it is given as 2% of the turbine cost + 3% of the O&M cost for the previous year; and
- For 16 – 20 years it is given as 2% of the turbine cost + 4% of the O&M cost for the previous year.

Hence, the operation and maintenance cost thought out its life will be Birr 260, 522.00.

Hence, life cycle cost of wind power generation system becomes Birr 895, 807.2 (US $ 99, 313.44).

For individual household the total cost of the wind power generation if there is TV set becomes Birr 10, 924.48

If the customers do not have color TV, the power requirement from wind generator reduces to 3.362 kW. The American Wind Energy Association (AWEA) [3] says a typical home wind system costs approximately US $15,000 for 3kW rated power. Hence, the cost of 3.362kW rated power generator becomes $16,810 and when inflation rate, transportation and taxation costs are included, the cost rises to Birr 247,686.95 (US $ 27,736.50)

Table 5. 7 Cost of balance of wind power generation for the village without TV for Dillamo village

No	Component Description	Unit Price [Birr]	Total Price [Birr]
1	Lead Acid Deep Cycle Battery 65Ah of 82pcs.totally 5330Ah	974.95	79, 945.9
2	Charge regulator 3.42A and 82pcs.(208.44A)	309.60	25, 387.2
3	Compacted type fluorescent 3 per household	96.76/HH	23, 802.96
Total Cost			**129, 136.06**

As battery and inverter costs are subtracted from the total cost of the wind power generation, other components cost of 3.362 kW rated power wind generator will be around Birr 142, 353.85 (US $15, 941.08).

Table 5. 8 Wind generator component cost without TV set for Dillamo village [36]

Component Description	Component Cost (%)	Component Unit Price [Birr]	Component Total Price [Birr]
Blades	21.45	30534.91	30534.91
Hub	9.30	13238.91	13238.91
Pitch mechanisms and bearings	5.12	7288.52	7288.52
Shaft (main shaft)	2.97	4227.91	4227.91
Main shaft bearing and block	1.68	2391.55	2391.55
Electrometric mounting system	0.39	555.18	555.18
Generator isolation mount	0.13	185.06	185.06
Support structure	4.91	6989.58	6989.58
Generator cooling system	0.39	555.18	555.18
Brake system hydraulics	0.78	1110.36	1110.36
Coupling	0.39	555.18	555.18
Nacelle cover	2.45	3487.67	3487.67
Generator	8.66	12327.85	12327.85
Cables (wire)	2.58	3672.73	3672.73
Switch gear	1.81	2576.61	2576.61
Yaw derive and bearings	2.33	3316.85	3316.85
Control and safety system	1.03	1466.25	1466.25
Tower	26.61	37880.37	37880.37
Foundation and installation	6.98	9936.30	9936.30
Total Cost			**142, 353.9**

Source: Alternative Design Study Report: Wind PACT Advanced Wind Turbine Drive Train Study

Total cost of the wind generator disregarding of the maintenance and operation cost falls to Birr 271, 489.96 (US $ 30, 402.01).

The life of the wind generator is taken as 20 years and the operation and maintenance cost will be Birr 111, 276.10.

Hence, life cycle cost of the wind power generation system will be Birr 382, 766.06 (US $ 42, 435.26).

For individual household, the total cost without TV will be Birr 4, 667.88

Case 2: village in Gode

The power of wind generator for household with color TV becomes 3.54 kW. The equipment cost is extrapolated from the previous cost to US $ 17, 700. Acounting inflation rate, transportation and custom taxes, the cost becomes US $ 29, 205 or Birr 260, 800.63).

Table 5. 9 Cost of balance of wind power generation with TV set for village in Gode

No	Component Description	Unit Price [Birr]	Total Price [Birr]
1	Lead Acid Deep Cycle Battery 140 Ah 35pcs.totally 4900Ah	2097.1	73,398.5
2	Charge regulator 8.4Ar and 35 pcs.(294A)	750	26,250.00
3	DC-AC inverter for color 21"TV per HH	642.96	22,503.60
4	Compacted type fluorescent 3 per HH for 35 households	96.76/HH	10, 159.80
Total			**132, 311.9**

Similar to the previous case, the wind generator cost becomes Birr 138, 648.53 and balance of system Birr 132, 311.9

Table 5. 10 Cost break down of wind power generation for village in Gode with TV set for village in Gode

Component Description	Component Cost (%)	Component Unit Price [Birr]	Component Total Price [Birr]
Blades (three)	21.45	29, 740.11	29, 740.11
Hub	9.30	12, 894.31	12, 894.31
Pitch mechanisms and bearings	5.12	7, 098.8	7, 098.8
Main shaft	2.97	4, 117.86	4, 117.86
Main shaft bearing and block	1.68	2, 329.3	2, 329.3
Electrometric mounting system	0.39	540.73	540.73
Generator isolation mount	0.13	180.24	180.24
Support structure	4.91	6, 807.64	6, 807.64
Generator cooling system	0.39	540.73	540.73
Brake system hydraulics	0.78	1, 081.46	1, 081.46
Coupling	0.39	540.73	540.73
Nacelle cover	2.45	3, 396.89	3, 396.89
Generator	8.66	12, 006.96	12, 006.96
Cable	2.58	3, 577.13	3, 577.13
Switch gear	1.81	2, 509.54	2, 509.54
Yaw derive and bearings	2.33	3, 230.51	3, 230.51
Control and safety system	1.03	1, 428.08	1, 428.08
Tower	26.61	36, 894.37	36, 894.37
Foundation	6.98	9, 677.67	9, 677.67
Total Cost			**138, 648.53**

The total cost of the wind generator excluding maintenance and operation cost will be Birr 270,960.43 (US $ 30,342.71).

The maintenance and operation cost becomes Birr 111, 117.30 for 20 years life.

Hence, the total cost of wind power generation cost to cover the village will be Birr 382, 077.70 (US $37, 947.78).

For individual household total cost if there is TV is Birr 10, 916.51.

In a village in Gode if the residents have no color TV, the amount of power required is 1.432 kW. According to the American Wind Energy Association (AWEA) [3], a 1.5kW rated power will costs approximately US $7680. When it is extrapolate, the cost for 1.432 kW rated power generation becomes $7331.84 and including inflation rate, transportation cost and taxation cost, it results the capital cost of Birr 108, 031.00 or US $12,097.54

Table 5. 11 Cost of balance of wind power generation without TV set for village in Gode

No	Component Description	Unit Price [Birr]	Total Price [Birr]
1	Lead Acid Deep Cycle Battery 65Ah of 35 pcs. totally 2275Ah	974.95	34, 123.25
2	Charge regulator 3.42Ar and 35 pcs.(208.44A)	309.60	10, 836.00
3	Compacted type fluorescent 3 per household	96.76/HH	10,159.8
Total Cost			**55,119.05**

Similar to the previous cases, the wind generator cost becomes Birr 63,071.75 or US $7,062.91 and balance of the system is Birr 55, 119.05

Table 5. 12 Cost break down of wind power generation without TV set for village in Gode

Component Description	Component Cost (%)	Component Unit Price [Birr]	Component Total Price [Birr]
Blades (three)	21.45	13528.89	13528.89
Hub	9.30	5865.67	5865.67
Pitch mechanisms and bearings	5.12	3229.27	3229.27
Main shaft	2.97	1873.23	1873.23
Main shaft bearing and block	1.68	1059.61	1059.61
Electrometric mounting system	0.39	245.98	245.98
Generator isolation mount	0.13	81.99	81.99
Support structure	4.91	3096.82	3096.82
Generator cooling system	0.39	245.98	245.98
Brake system hydraulics	0.78	491.96	491.96
Coupling	0.39	245.98	245.98
Nacelle cover	2.45	1545.26	1545.26
Generator	8.66	5462.01	5462.01
Cable	2.58	1627.25	1627.25
Switch gear	1.81	1141.6	1141.6
Yaw derive and bearings	2.33	1469.57	1469.57
Control and safety system	1.03	649.64	649.64
Tower	26.61	16783.39	16783.39
Foundation	6.98	4402.41	4402.41
Total Cost			**63, 071.75**

The total cost of the wind generator excluding the maintenance and operation cost will be Birr 118, 190.8 or US $ 13, 235.25.

The maintenance cost will be Birr 46, 104.65 for 20 years life span.

Hence, total cost of the wind power generation cost if there is no TV set is Birr 164, 295.5 (US $16, 747.75)

For individual household the total cost of the wind power generation for the village if there is no TV set becomes Birr 4, 694.16.

5.3 Cost Evaluation of Micro-Hydro Power Generation

5.3.1 Cost Calculation of Penstock [15]

The cost of penstock is determined after determining its weight. As it has been calculated earlier, the mass of penstock is 1167.53 kg and cost of the penstock per kg is Birr 18.00. Which means the total cost of the penstock becomes Birr 21, 015.57. In addition, pipe flanges and bolts are required. The standard length of penstock is 2m and 11 joints are required. Cost of flanges and bolts for each joint is Birr 540.57 or US $ 59.93 per joint, and then total costs for all joints will be Birr 5886.73 or US $ 659.21. Hence, the total penstock cost for Kilte River micro hydro power generation reaches to Birr 26,902.3 or US $ 2982.52.

5.3.2 Turbine (Cross Flow) Cost

The cost of various types of turbine is given in references [15] which are given in range with respect to the shaft power and the shaft power is calculated as 10.78 kW. Hence, it is possible to get the cost of turbine for shaft power which is (US $ 5,000). Considering the inflation rate, transportation cost and taxation, the total cost rises to Birr 73, 672.5 or US $ 8250.00.

5.3.3 Cost of Induction Generator

Rating for induction motors tend to cost less than synchronous generator up to 25kW capacity. Larger size of induction motor costs more than asynchronous generator of the same size [15]. To choose a motor to act as a generator, simply dividing the generator rating that the power generation system requires by a derating factor of 0.8. The power demand of 6kW; from this, it is possible to get the generator size that is sufficient for this power. After the generator, there is power loss in the transmission line, transformer, and generators itself, so, the generator rating will be 8.17kW. To use the induction motor as induction generator, it is better to divide by derating factor and the power of induction motor becomes 10.2kW. From standard tables, the size of the motor will be 11kW with D160M frame size and the current will be 22.5A with the voltage of 380V [15]. The approximate cost of induction generator, electronic load and voltage controller is given in references. Adding inflation rate (25%), transportation cost (10%) and taxation (30%), the cost of the induction generator becomes Birr 7, 514.6, and frequency and voltage controller becomes Birr 17, 534.06 and Birr 15, 029.2 respectively.

5.3.4 Civil Work

The cost of civil works varies depending on the general layout of the scheme, and it includes channel work, forebay tank, tail race, and power house. The civil work is estimated to be Birr 25,000.

5.3.5 Transmission Line

The best approximate cost of transmission line including poles and cables will be [28]:-

Transmission line cost = $0.0011\ x\ D\ x\ P\, x\ l_T^{0.95}\ x\ V\ x 10^6$

Where:

D: Transmission line installation difficulty 1 to 2;

P: Reflect cost of wood vs. steel tower construction 0.85 if v < 69, 1.0 if v $\geq$ 69;

V: Transmission line voltage (kV) which is 380V (0.38kV);

l_t : Length of transmission line in (km).

$Transmission\ line\ \cos t = 0.0011 x 1 x 1 x 0.85\, x\, (5)^{0.95}\, x\, 0.38\, x 10^6 =$ US $1639.14 with considering inflation, transportation and taxation it becomes Birr 24, 151.95 or US **$** 2704.59

5.3.6 Installation Cost

Installation cost of the micro hydro power generation is approximated as 20% of the total cost of the equipment [28]. Hence, it becomes Birr 32, 053.62

Table 5. 13 Summarized cost of micro hydro power generation with TV set

No	Component Description	Unit Price [Birr]	Total Price [Birr]	Total Price [US $]
1	penstock	26,902.3	26,902.3	2982.52
2	Turbine (cross flow)	73, 672.5	73, 672.5	8250
3	Motor as generator	7, 514.6	7, 514.6	841.5
4	Frequency control	17, 534.06	17, 534.06	1963.5
	Voltage Control	15, 029.2	15, 029.2	1683.00
5	Transmission line	24, 151.95	24, 151.95	2704.59
	Total cost of the equipment		**164, 804.6**	**17,947.16**
6	Civil work		25, 000.00	2771.62
7	Miscellaneous cost (8%) of direct cost		13,184.37	1461.68
8	Installation cost(20% of total equipment cost)	32, 960.92	32, 960.92	3654.20
9	Compacted type fluorescent 3 per HH 82 households	96.76/HH	23, 802.96	2665.51
Total Cost of the System			**259, 752.9**	**28, 797.43**

The total costs for individual household will be Birr 3167.72.

Following the same steps as that of the system with color television, cost break down of the system without color TV can be determined as follows:

Table 5. 14 summarized cost of micro hydro power generation without TV

No	Component Description	Unit Price [Birr]	Total Price [Birr]	Total Price [US $]
1	penstock	17, 284.36	17, 284.36	1, 916.23
2	Turbine (cross flow)	58, 938.00	58, 938.00	6, 600.00
3	Motor as generator	5, 643.3	5, 643.3	631.95
4	Frequency control	13, 157.91	13, 157.91	1, 473.45
	Voltage Control	11, 271.89	11, 271.89	1, 262.25
5	Transmission line	24, 151.95	24, 151.95	2, 704.59
6	**Total cost of the equipment**		**130, 447.41**	**14, 607.77**
7	Civil work		20,000.00	2, 217.29
8	Miscellaneous cost (8%) of direct cost		10,435.79	1, 156.96
8	Installation cost(20% of total equipment cost)	26, 089.48	26, 089.48	2, 892.40
9	Compacted type fluorescent 3 per HH 82households	96.76/HH	23, 802.96	2, 665.51
Total Cost of the System			**210, 775.64**	**23, 367.6**

For individual household, the total cost for this micro hydro power generation will be Birr 2570.43.

CHAPTER 6

FINANCIAL EVALUATION

The economy feasibility of the different option of rural electrification having different life span can not be compared using common feasibility indicators such as internal rate of return, net present value and pay-back . Hence, the method used in this study the different option is using the electricity service cost either in monthly or unit energy basis. The monthly energy cost which hast to be beard by the user is calculated from the annual cost of the investment and annual operating cost which is mainly maintenance cost. Similarly, the unit energy cost can be calculated by dividing the total annual cost by the energy generated per annum.

$$C_A = \frac{C_I}{\frac{(1+i)^n - 1}{i(1+i)^n}} + C_m$$

Where:-

C_A = Annual payment

C_I = Capital cost

C_M = maintenance cost

n = life span

i = interest rate

The unit energy cost (price) is determined by dividing the total annual cost by the total of electrical energy generated per year.

For solar power generation system

$$p_e = \frac{C_A}{365 * E_d}$$

For micro hydro power generation and wind generator

$$p_e = \frac{C_A}{365 * E_d * Total\ number\ of\ households}$$

Where:-

P_e = unit energy cost

E_d = daily energy consumption

The analysis was conducted for a single household for solar home system as each household has it's own self-contained system. For micro-hydro power and wind generator, each household gets electricity from the mini-grid. Hence, the analysis is conducted for the village as a whole

6.1 Monthly Payment of the Systems

To evaluate the system, an assumption of 10% interest rate is taken in to consideration [36].

Case 1: Dillamo Village

6.1.1 Solar PV System

a) When customer uses 21" color TV

The initial capital cost (C) of the PV system when the customers use TV set is Birr 9757.66. Then, the annual payment will be [15, 19]:

$$C_A = \frac{C_I}{\frac{(1+i)^n - 1}{i(1+i)^n}} + C_m = \frac{9757.66}{\frac{(1+0.1)^{25} - 1}{0.1(1+0.1)^{25}}} + 88.88 = 1163.87\,Birr$$

Monthly payment (MP) = $\frac{1163.87}{12} = Birr\ 96.99$

The unit energy cost will be:

$$p_e = \frac{C_A}{365 * E_d} = 14.43 \text{ Birr/kWh}$$

b) When color TV has been excluded

Similar to condition a, annual payment (A) is calculated as:

$$C_A = \frac{C}{\frac{(1+i)^n - 1}{i(1+i)^n}} + C_m = \frac{4447.06}{\frac{(1+0.1)^{25} - 1}{0.1(1+0.1)^{25}}} + 39.00 = Birr\,528.92$$

Monthly payment $= \frac{528.92}{12} = Birr\,42.80$

$$p_e = \frac{C_A}{365 * E_d} = 14.35 \text{ Birr/kWh}$$

6.1.2 Wind Power Generation

a) When Customer uses 21” TV

Like the PV system:

C = Birr 635, 285.2

$$C_A = \frac{C_I}{\dfrac{(1+i)^n - 1}{i(1+i)^n}} + C_m = \frac{635,285.2}{\dfrac{(1+0.1)^{20} - 1}{0.1(1+0.1)^{20}}} + 13,026.10 = Birr\ 87,646.49$$

MP per household $= \dfrac{87,646.49}{12\,x\,82} = Birr\ 89.07$

$$p_e = \frac{C_A}{365 * 82 * E_d} = 13.25 \text{ Birr/kWh}$$

b) When color TV is excluded

C_I = Birr 271, 489.96

The total maintenance cost thought out the life of the wind power generation if there is no TV set was Birr 111, 276.10. And, the annual maintenance cost (assuming constant through out its life) is Birr 5563.81. Hence, monthly electricity bill becomes:

Then, $C_A = \dfrac{C_I}{\dfrac{(1+i)^n - 1}{i(1+i)^n}} + C_m = \dfrac{271,489.96}{\dfrac{(1+0.1)^{20} - 1}{0.1(1+0.1)^{20}}} + 5563.81 = Birr\ 37,452.93$

MP per household = $\dfrac{37,\ 452.93}{12\,x\,82} = Birr\ 38.06$

$$p_e = \frac{C_A}{365 * 82 * E_d} = 12.56 \text{ Birr/kWh}$$

6.1.3 Micro Hydro Power Generation

a) When Customer uses 21"color TV

The initial capital cost of Kilte River micro hydro power generation system is Birr 259, 752.86 according to this situation.

The annual maintenance cost of micro hydro power generation is usually taken as 2% of the initial investment cost of the system. Hence, annual maintenance cost will be Birr 5, 195.06

$$C_A = \frac{C_I}{\frac{(1+i)^n - 1}{i(1+i)^n}} + C_m = \frac{259,752.86}{\frac{(1+0.1)^{20} - 1}{0.1x(1+0.1)^{20}}} + 5,195.06 = Birr\ 35,705.53$$

MP per household = $\frac{35,705.53}{12\,x82} = Birr\,36.29$

$$p_e = \frac{C_A}{365*82*E_d} = 5.53\ \text{Birr/kWh}$$

b) When color TV has been excluded

From table (5.14), the capital cost (C_I) for this condition is Birr 210, 775.64

Then, $C_A = \frac{C_I}{\frac{(1+i)^n - 1}{i(1+i)^n}} + C_m = \frac{210,775.64}{\frac{(1+0.1)^{20} - 1}{0.1x(1+0.1)^{20}}} + 4,215.51 = Birr\ 28,973.14$

MP per household = $\frac{28,973.14}{12\,x82} = Birr\ 29.44$

$$p_e = \frac{C_A}{365*82*E_d} = 9.58\ \text{Birr/kWh}$$

Case: 2 Villages in Gode

In this village it is supposed to compare wind and solar PV power generation system. The same assumptions are considered like case 1:

6.1.4 Solar PV system

a) when customer uses 21" color TV

C_I = Birr 9028.26

The total maintenance cost throughout its life of solar photovoltaic system for village in Gode is Birr 2097.10. Hence, the annual maintenance cost is Birr 83.88 and the monthly electricity bill becomes:

Then, $C_A = \dfrac{C_I}{\dfrac{(1+i)^n - 1}{i(1+i)^n}} + C_m = \dfrac{9028.26}{\dfrac{(1+0.1)^{25} - 1}{0.1x(1+0.1)^{25}}} + 83.88 = Birr\, 1078.51$

MP per household = $\dfrac{1078.51}{12} = Birr\ 89.88$

$$p_e = \frac{C_A}{365 * E_d} = 13.37 \text{ Birr/kWh}$$

b) when color TV has been excluded

C_I = Birr 4089.52.

$$C_A = \frac{C_I}{\dfrac{(1+i)^n - 1}{i(1+i)^n}} + C_m = \frac{4089.52}{\dfrac{(1+0.1)^{25} - 1}{0.1x(1+0.1)^{25}}} + 39.00 = Birr\ 489.54$$

MP per household = $\dfrac{489.54}{12} = Birr\ 40.80$

$$p_e = \frac{C_A}{365 * E_d} = 13.28 \text{ Birr/kWh}$$

6.1.5 Wind Power Generation

a) when there is color TV

C_I = Birr 270, 960.43

The total maintenance cost of wind power generation for village in Gode with TV set thought out its life is Birr 111, 117.30. For 20 years life span, the annual maintenance cost becomes Birr 5, 555.86.

Then, $C_A = \dfrac{C_I}{\dfrac{(1+i)^n - 1}{i(1+i)^n}} + C_m = \dfrac{270{,}960.43}{\dfrac{(1+0.1)^{20} - 1}{0.1(1+0.1)^{20}}} + 5{,}555.86 = Birr\ 37{,}385.78$

MP per household $= \dfrac{37{,}385.78}{12x35} = Birr\ 89.01$

$$p_e = \frac{C_A}{365*35*E_d} \quad 13.24 \text{ Birr/kWh}$$

b) when color TV is excluded

C_I = Birr 118, 190.8

The total maintenance cost through out its life is Birr 46, 104.65. Hence, the annual maintenance cost is Birr 2, 305.23.

$$\text{Then, } C_A = \frac{C_I}{\frac{(1+i)^n - 1}{i(1+i)^n}} + C_m = \frac{118{,}190.8}{\frac{(1+0.1)^{20} - 1}{0.1(1+0.1)^{20}}} + 2305.23 = Birr\ 16{,}187.88$$

$$\text{MP per household} = \frac{13{,}882.65 + 2{,}305.23}{12\, x 35} = Birr\, 38.54$$

$$p_e = \frac{C_A}{365*35*E_d} = 12.55 \text{ Birr/kWh}$$

CHAPTER 7

CONCLUSION AND RECOMMENDATION

7.1 Conclusion

Case 1: DILLAMO VILLAGE

As it has been analyzed in earlier chapter, the best system to compare the three renewable power generation is the monthly payment.

In Dillamo village, the three renewable energy systems were compared and the monthly payment per household of each system has been calculated based on two conditions.

Condition 1: If there is TV set

- Solar PV power generation: 96.99 Birr/Month or 14.43 Birr/kWh
- Wind power generation : 89.07 Birr/Month or 13.25 Birr/kWh
- Micro hydro power generation : 36.29Birr/Month or 5.53 Birr/kWh

Condition 2: If there is no TV set

- Solar PV power generation: 42.80Birr/Month or 14.35 Birr/kWh
- Wind power generation : 38.06 Birr/Month or 12.56 Birr/kWh
- Micro hydro power generation : 29.44 Birr/Month or 9.58 Birr/kWh

Hence, from the above result, micro hydro power generation is preferable than the two systems and wind power generation is the second if it is considered cost wise in the two conditions. But in most areas where the wind is below 5m/s and no stream or river is available, PV system will remain the best alone.

Conditions that make PV system preferable are:

1) *When micro hydro power generation is considered*

- ➢ It is really a site-specific technology;
- ➢ There is always a maximum useful power output available from a given hydro power site, which limits the level of expansion of activities which make use of the power;

- River flows often vary considerably with the seasons, especially where there are monsoon-type climates, and this can limit the total power output to quite a small fraction of the possible peak output.
- There can be conflicts with fisheries and with irrigation users.

2) Wind Power Generation

- It is a site-specific technology and often an excellent supplement to other renewable sources;
- The cost of wind power generation is approximately equal to that of solar PV power generation systems for moderate wind speeds.
- PV system i.e. for solar home system is independent of each other and requires less maintenance.

These conditions will make solar PV system the future glorious energy generation system for most remote areas of Rural Ethiopia.

Case 2: village in Gode

In the village in Gode, the two systems (solar PV power generation and wind power generation) are compared and the monthly payment for each system is:

Condition 1: If there is TV

- Solar PV power generation: 89.88 Birr/Month or 13.37 Birr/kWh
- Wind power generation: 89.01 Birr/Month or 13.24 Birr/kWh

Condition 2: If there is no TV set

- Solar PV power generation: 40.80 Birr/Month or 13.28 Birr/kWh
- Wind power generation: 38.54 Birr/Month or 12.55 Birr/kWh

From cost point of view, wind power generation for a village in Gode is a little bit smaller than that of solar PV system. However, the operation of wind power generation is complex compared to solar home systems and requires maintenance. In addition, it is not modular. Considering these ease of operation, maintenance and installation, solar PV system is recommended for a village in Gode. But, for areas in semiarid and arid zones with average wind speed greater than 6.5 m/s, wind generators can the viable renewable energy option for village electrification.

7.2 Recommendation

- From this research work, it has seen that Ethiopia has a huge potential for rural electrification through the off grid system. There are, however, formidable challenges like low purchasing power of the rural people, unfavorable public attitude towards the private sector and unfair regulations that work against development and distribution of renewable energy technologies. It is thus recommended that the government, non-governmental organizations and the public make combined efforts to overcome these challenges by using more flexible approaches to improve the current terrible state of rural electrification in Ethiopia.

- Since the government cannot simply afford to electrify rural areas of Ethiopia where 85% of the total population reside, maximum effort must be exerted to change the prevailing attitude towards the private investors and help the private sector in all possible ways beyond designing policies.

- This study shows only two selected sites of Ethiopia and it doesn’t represent all areas of the country. So, the future researchers should expand this research work in other sites and make the rural people beneficial.

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ANNEX

Solar PV energy calculation result tables

Case 1: Dillamo Village

Table A. 1 from sunshine duration to daily energy available to the load or battery

Months of the year	Average Sunshine Duration in (hr.)	Daily Ave. Global Irradiance on a horizontal plane in (kWh/m^2)	Daily Ave. Diffuse Irradiance in kWh/m^2).	Daily Ave. Beam irradiance In (kWh/m^2)	Daily Average Irradiance on the plane of PV array (It) in (kWh/m^2)	Mean temperature In (°C) In Dillamo Village	Average Array Efficiency in (%)	Daily Average Energy Delivered in (Wh/m^2)	Overall Array Efficiency in (%)	Daily Ave. Energy available to the load or battery in (wh/m^2)
January	9.7	5.739714	1.639086	4.100628	6.48303	15.68	12.26882	795.3872	11.7778	715.848
February	9	6.157794	1.807466	4.350328	6.63792	17.92	12.13552	805.5582	11.6503	725.002
March	8.45	6.464855	1.984298	4.480557	6.59672	19.27	12.07561	796.5983	11.5929	716.938
April	8.55	6.67548	2.00487	4.67061	6.41277	20	12.07034	773.951	11.5874	696.556
May	9.3	6.718656	2.040551	4.678106	6.14228	19.97	12.11664	744.2126	11.6337	669.791
Jun	5.9	5.745756	2.153426	3.59233	5.19064	18.1	12.3533	641.1899	11.8597	577.071
July	4.9	4.834849	2.376437	2.458412	4.48487	17.27	12.49273	559.988	11.9927	503.989
August	4.35	4.973177	2.242732	2.730445	4.73177	17.47	12.42843	588.0594	11.9313	529.253
September	5.9	5.681779	2.139002	3.542777	5.65976	17.48	12.28489	695.2892	11.7935	625.76
October	7.4	5.829586	1.915216	3.91437	6.14955	17.07	12.23447	752.329	11.7462	677.096
November	8.8	5.760084	1.69287	4.067214	6.41831	16.62	12.22324	784.5213	11.7347	706.069
December	9	5.546902	1.590251	3.956651	6.34705	15.43	12.2962	780.4525	11.8046	702.407

Table A. 2 Hourly Global Radiation in (Wh/m^2)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	18.62921	37.31362	39.31113	30.30779	19.83197	3.785212	0	0	0
116.5153	140.5812	166.5047	190.7147	206.345	182.1515	151.1483	146.7143	152.8604	138.7899	120.8122	108.4546
310.0881	342.1793	370.6711	392.4142	401.9076	346.426	290.4915	294.5932	329.3684	327.399	313.5653	297.1276
512.4883	551.2102	580.304	597.4465	599.1364	511.4886	430.7339	444.4024	509.8814	522.3249	514.6598	494.8911
690.46	734.1066	762.6575	774.7149	768.8294	653.18	551.2431	573.654	666.5269	692.5491	691.2527	669.0362
812.4122	859.082	886.8451	895.0145	883.6615	748.9339	632.7312	661.2608	773.0585	808.7366	812.1706	788.4636
855.7866	903.4748	930.8902	937.6115	924.269	782.7736	661.5375	692.264	810.8175	849.9868	855.1626	830.9555
812.4122	859.082	886.8451	895.0145	883.6615	748.9339	632.7312	661.2608	773.0585	808.7366	812.1706	788.4636
690.46	734.1066	762.6575	774.7149	768.8294	653.18	551.2431	573.654	666.5269	692.5491	691.2527	669.0362
512.4883	551.2102	580.304	597.4465	599.1364	511.4886	430.7339	444.4024	509.8814	522.3249	514.6598	494.8911
310.0881	342.1793	370.6711	392.4142	401.9076	346.426	290.4915	294.5932	329.3684	327.399	313.5653	297.1276
116.5153	140.5812	166.5047	190.7147	206.345	182.1515	151.1483	146.7143	152.8604	138.7899	120.8122	108.4546
0	0	0	18.62921	37.31362	39.31113	30.30779	19.83197	3.785212	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
5739.714	**6157.794**	**6464.855**	**6675.48**	**6718.656**	**5745.756**	**4834.849**	**4973.177**	**5681.779**	**5829.586**	**5760.084**	**5546.902**

Table A. 3 Hourly Diffuse Irradiation in (Wh/m^2)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	8.240022	16.32913	21.01476	21.34429	13.04715	2.134496	0	0	0
44.32554	54.27567	66.2283	72.90427	78.62598	85.0822	92.86465	83.68698	74.07371	59.67827	47.14091	41.57617
102.8086	115.7516	130.0077	133.1618	136.6774	144.7835	159.511	149.5128	141.1104	123.6084	106.7827	99.11497
153.0291	168.5422	184.7762	184.906	186.5273	196.0503	216.7416	206.0388	198.6761	178.5064	157.9983	148.5247
191.5647	209.0498	226.8017	224.6108	224.7785	235.3886	260.6561	249.4126	242.8478	220.6312	197.2973	186.438
215.7892	234.514	253.2199	249.5703	248.8241	260.1177	288.2619	276.6786	270.6153	247.1119	222.0018	210.2714
224.0517	243.1994	262.2307	258.0835	257.0257	268.5523	297.6777	285.9785	280.0863	256.144	230.428	218.4005
215.7892	234.514	253.2199	249.5703	248.8241	260.1177	288.2619	276.6786	270.6153	247.1119	222.0018	210.2714
191.5647	209.0498	226.8017	224.6108	224.7785	235.3886	260.6561	249.4126	242.8478	220.6312	197.2973	186.438
153.0291	168.5422	184.7762	184.906	186.5273	196.0503	216.7416	206.0388	198.6761	178.5064	157.9983	148.5247
102.8086	115.7516	130.0077	133.1618	136.6774	144.7835	159.511	149.5128	141.1104	123.6084	106.7827	99.11497
44.32554	54.27567	66.2283	72.90427	78.62598	85.0822	92.86465	83.68698	74.07371	59.67827	47.14091	41.57617
0	0	0	8.240022	16.32913	21.01476	21.34429	13.04715	2.134496	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
1639.086	**1807.466**	**1984.298**	**2004.87**	**2040.551**	**2153.426**	**2376.437**	2242.73	**2139.002**	**1915.216**	**1692.87**	**1590.251**

Table A. 4 Hourly Beam radiation in (Wh/m^2)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	10.38919	20.98448	18.29637	8.963498	6.784818	1.650717	0	0	0
72.1898	86.30557	100.2764	117.8105	127.719	97.06933	58.28363	63.02731	78.78673	79.11159	73.67127	66.87847
207.2795	226.4277	240.6635	259.2525	265.2302	201.6425	130.9805	145.0804	188.258	203.7906	206.7826	198.0126
359.4591	382.668	395.5277	412.5405	412.6091	315.4383	213.9924	238.3637	311.2053	343.8185	356.6615	346.3664
498.8953	525.0568	535.8558	550.1041	544.051	417.7914	290.587	324.2413	423.679	471.918	493.9554	482.5982
596.623	624.568	633.6251	645.4443	634.8374	488.8162	344.4693	384.5822	502.4432	561.6247	590.1689	578.1921
631.7349	660.2754	668.6595	679.5281	667.2433	514.2213	363.8597	406.2855	530.7312	593.8429	624.7346	612.5551
596.623	624.568	633.6251	645.4443	634.8374	488.8162	344.4693	384.5822	502.4432	561.6247	590.1689	578.1921
498.8953	525.0568	535.8558	550.1041	544.051	417.7914	290.587	324.2413	423.679	471.918	493.9554	482.5982
359.4591	382.668	395.5277	412.5405	412.6091	315.4383	213.9924	238.3637	311.2053	343.8185	356.6615	346.3664
207.2795	226.4277	240.6635	259.2525	265.2302	201.6425	130.9805	145.0804	188.258	203.7906	206.7826	198.0126
72.1898	86.30557	100.2764	117.8105	127.719	97.06933	58.28363	63.02731	78.78673	79.11159	73.67127	66.87847
0	0	0	10.38919	20.98448	18.29637	8.963498	6.784818	1.650717	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
4100.628	4350.328	4480.557	4670.61	4678.106	3592.33	2458.412	2730.445	3542.777	3914.37	4067.214	3956.651

Table A. 5 Hourly Total Irradiation on the Plane of the PV Array (Wh/m^2)

Jan	Feb	Mar	App	May	Jun	July	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	3.512485	6.785302429	12.58506	17.03775	9.8371128	1.37014332	0	0	0
161.1312	168.666	172.31	172.4169	168.8560829	147.6445	131.2304	132.25439	149.92464	156.6975	160.024261	156.518
366.8813	378.313	379.315	371.9613	358.666308	305.2881	264.9053	276.55717	326.681036	350.9619	363.66381	358.339
580.453	594.968	592.064	575.7712	551.5326546	465.1308	400.6864	423.74609	507.978902	551.3949	574.807889	568.095
767.4445	784.159	777.233	752.4953	718.2404577	603.1138	518.027	551.26933	665.584601	726.2527	759.551985	751.885
895.2658	913.289	903.379	872.6278	831.3569477	696.6685	597.6365	637.91523	772.879027	845.5342	885.789553	877.571
940.6771	959.133	948.125	915.1987	871.4077614	729.7815	625.822	668.61287	810.926338	887.8717	930.630517	922.233
895.2658	913.289	903.379	872.6278	831.3569477	696.6685	597.6365	637.91523	772.879027	845.5342	885.789553	877.571
767.4445	784.159	777.233	752.4953	718.2404577	603.1138	518.027	551.26933	665.584601	726.2527	759.551985	751.885
580.453	594.968	592.064	575.7712	551.5326546	465.1308	400.6864	423.74609	507.978902	551.3949	574.807889	568.095
366.8813	378.313	379.315	371.9613	358.666308	305.2881	264.9053	276.55717	326.681036	350.9619	363.66381	358.339
161.1312	168.666	172.31	172.4169	168.8560829	147.6445	131.2304	132.25439	149.92464	156.6975	160.024261	156.518
0	0	0	3.512485	6.785302429	12.58506	17.03775	9.8371128	1.37014332	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
6483	**6638**	**6597**	**6412.8**	**6142.28327**	**5190.6**	**4484.9**	**4731.8**	**5659.763**	**6149.6**	**6418.31**	**6347**

Table A. 6 Average Total Energy Delivered by the PV array (Wh/m^2)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.424068	0.822234105	1.554873	2.129778	1.2226549	0.16832356	0	0	0
19.76877	20.4689	20.8075	20.80893	20.4590476	18.2384	16.38717	16.436501	18.4179074	19.17006	19.5600451	19.246
45.01177	45.911	45.8049	44.89169	43.45682926	37.7117	33.07704	34.370249	40.1320318	42.93619	44.4512875	44.0624
71.21438	72.2035	71.4956	69.48925	66.82489824	57.45664	50.02993	52.662685	62.404066	67.45698	70.2598229	69.8547
94.15593	95.1631	93.856	90.81787	87.02354708	74.50132	64.68045	68.511099	81.7655714	88.84892	92.8414392	92.454
109.838	110.834	109.089	105.3165	100.7289662	86.05788	74.62006	79.279334	94.9464502	103.4417	108.271693	107.909
115.4094	116.397	114.492	110.4543	105.5816025	90.14824	78.13916	83.094395	99.6204767	108.6213	113.752688	113.401
109.838	110.834	109.089	105.3165	100.7289662	86.05788	74.62006	79.279334	94.9464502	103.4417	108.271693	107.909
94.15593	95.1631	93.856	90.81787	87.02354708	74.50132	64.68045	68.511099	81.7655714	88.84892	92.8414392	92.454
71.21438	72.2035	71.4956	69.48925	66.82489824	57.45664	50.02993	52.662685	62.404066	67.45698	70.2598229	69.8547
45.01177	45.911	45.8049	44.89169	43.45682926	37.7117	33.07704	34.370249	40.1320318	42.93619	44.4512875	44.0624
19.76877	20.4689	20.8075	20.80893	20.4590476	18.2384	16.38717	16.436501	18.4179074	19.17006	19.5600451	19.246
0	0	0	0.424068	0.822234105	1.554873	2.129778	1.2226549	0.16832356	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
795.39	**805.6**	**796.6**	**773.95**	**744.212647**	**641.19**	**559.99**	**588.06**	**695.2892**	**752.33**	**784.521**	**780.5**

Table A. 7 Average daily total energy available to the load and battery (Wh/m^2)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.381661	0.740010694	1.399386	1.9168	1.1003894	0.1514912	0	0	0
17.7919	18.422	18.7268	18.72804	18.41314284	16.41456	14.74846	14.792851	16.5761166	17.25305	17.6040406	17.3214
40.5106	41.3199	41.2244	40.40252	39.11114634	33.94053	29.76934	30.933224	36.1188286	38.64257	40.0061587	39.6562
64.09294	64.9831	64.3461	62.54033	60.14240842	51.71098	45.02694	47.396417	56.1636594	60.71128	63.2338406	62.8692
84.74033	85.6468	84.4704	81.73608	78.32119237	67.05119	58.2124	61.65999	73.5890142	79.96403	83.5572953	83.2086
98.85421	99.7505	98.1801	94.78486	90.65606957	77.4521	67.15806	71.3514	85.4518051	93.09755	97.4445239	97.1179
103.8685	104.758	103.043	99.40891	95.02344229	81.13342	70.32524	74.784956	89.658429	97.75913	102.377419	102.06
98.85421	99.7505	98.1801	94.78486	90.65606957	77.4521	67.15806	71.3514	85.4518051	93.09755	97.4445239	97.1179
84.74033	85.6468	84.4704	81.73608	78.32119237	67.05119	58.2124	61.65999	73.5890142	79.96403	83.5572953	83.2086
64.09294	64.9831	64.3461	62.54033	60.14240842	51.71098	45.02694	47.396417	56.1636594	60.71128	63.2338406	62.8692
40.5106	41.3199	41.2244	40.40252	39.11114634	33.94053	29.76934	30.933224	36.1188286	38.64257	40.0061587	39.6562
17.7919	18.422	18.7268	18.72804	18.41314284	16.41456	14.74846	14.792851	16.5761166	17.25305	17.6040406	17.3214
0	0	0	0.381661	0.740010694	1.399386	1.9168	1.1003894	0.1514912	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
715.85	**725**	**716.9**	**696.56**	**669.791383**	**577.07**	**503.99**	**529.25**	**625.7603**	**677.1**	**706.069**	**702.4**

Case 2: Village in Gode

Table B. 1 from Sunshine Duration to Daily Energy Available to the Load or Battery

Months of the year	Average Sunshine Duration in (hr.)	Daily Ave. total Irradiance on a horizontal plane in (kWh/m^2)	Daily Ave. Diffuse Irradiance in KWh/m^2).	Daily Ave. Beam irradiance In Wh/m^2)	Daily Ave. Irradiance on the plane of PV array (It) in (kWh/m^2)	Mean temperature in (^{o}C) in Gode Village	Average Array Efficiency in (%)	Daily Average Energy Delivered in (Wh/m^2)	Overall array Efficiency in (%)	Daily Ave. Energy available to the load or battery in (Wh/m^2)
January	9.76	5.715184	1.639284	4.0759	6.228113	28.5125	11.60	722.7144	10.4	650.4437
February	10.67	6.220933	1.775484	4.445449	6.556422	30.7	11.46	751.4215	10.37	676.2793
March	10.4	6.679706	1.902703	4.777003	6.756376	32.05	11.38	769.0027	10.25	692.1024
April	8.46	6.66427	2.045743	4.618527	6.433269	30.825	11.5	740.3439	10.37	666.3094
May	9.11	6.737544	2.017635	4.719909	6.160413	30.325	11.57	713.0272	10.42	641.7244
Jun	8.23	6.477778	2.041246	4.436532	5.911374	29.55	11.67	689.7666	10.5	620.7897
July	7.72	6.361291	2.071511	4.28978	5.861189	28.775	11.71	686.2927	10.54	617.6635
August	6.98	6.153329	2.127426	4.025904	5.858954	28.725	11.69	685.1732	10.53	616.6558
September	9.39	6.649484	1.940119	4.709365	6.605455	29.95	11.51	760.1738	10.36	684.1563
October	8.45	6.096238	1.866241	4.229996	6.329397	29.7875	11.53	730.0732	10.38	657.0658
November	7.87	5.560554	1.735386	3.825168	5.987533	27.83125	11.67	698.6757	10.50	628.8081
December	*9.54*	*5.537568*	*1.594645*	*3.942924*	*6.091694*	*28.22813*	*11.63*	*708.5171*	*10.47*	637.6653

Table B. 2 **Hourly Global Radiation in (Wh/m^2)**

Jan	Feb	Mar	App	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	12.42522	25.2616	30.10563	27.01409	16.47874	2.925195	0	0	0
128.4315	149.7156	173.466	185.5674	197.5176	194.4138	188.9425	175.256	177.7092	150.5708	127.3122	121.8783
316.3411	350.3506	383.8478	389.4004	398.5043	385.3193	377.4374	361.4565	384.8816	345.6574	309.2138	304.9506
511.4111	557.5265	599.7072	597.1492	602.2534	578.3518	568.2514	550.7945	596.8911	546.6784	497.7807	495.2913
682.2124	738.3555	787.3959	777.0562	778.1166	744.7016	732.8056	714.526	780.9402	721.9132	662.7502	662.1032
798.9701	861.745	915.1849	899.2609	897.346	857.3771	844.3111	825.6518	906.1367	841.3989	775.4676	776.1928
840.4514	905.5463	960.5022	942.5512	939.5449	897.2394	883.7669	865.0025	950.5159	883.8002	815.5048	816.7358
798.9701	861.745	915.1849	899.2609	897.346	857.3771	844.3111	825.6518	906.1367	841.3989	775.4676	776.1928
682.2124	738.3555	787.3959	777.0562	778.1166	744.7016	732.8056	714.526	780.9402	721.9132	662.7502	662.1032
511.4111	557.5265	599.7072	597.1492	602.2534	578.3518	568.2514	550.7945	596.8911	546.6784	497.7807	495.2913
316.3411	350.3506	383.8478	389.4004	398.5043	385.3193	377.4374	361.4565	384.8816	345.6574	309.2138	304.9506
128.4315	149.7156	173.466	185.5674	197.5176	194.4138	188.9425	175.256	177.7092	150.5708	127.3122	121.8783
0	0	0	12.42522	25.2616	30.10563	27.01409	16.47874	2.925195	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
5715.184	6220.933	6679.706	6664.27	6737.544	6477.778	6361.291	6153.329	6649.484	6096.238	5560.554	5537.568

Table B. 3 Hourly diffuse radiation in (Wh/m^2)

Jan	Feb	Mar	App	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	5.658896	11.05678	13.76753	12.80704	8.39822	1.280732	0	0	0
48.54152	55.85196	63.96195	72.8592	74.90827	77.22277	77.71902	77.16838	66.82138	60.05629	52.24399	46.35565
104.6793	114.823	124.8634	135.4799	134.4084	136.3536	138.2074	141.252	127.8955	121.2879	111.1941	101.4474
152.8858	165.4625	177.1606	189.2535	185.5023	187.1305	190.1499	196.2818	180.3411	173.8686	161.8158	148.7558
189.876	204.3196	217.2897	230.5155	224.708	226.0929	230.0068	238.5077	220.584	214.2152	200.6591	185.0568
213.1291	228.7462	242.5159	256.4538	249.3538	250.5857	255.0619	265.052	245.8818	239.5782	225.0771	207.8766
221.0602	237.0776	251.1201	265.3009	257.76	258.9398	263.6077	274.1057	254.5103	248.229	233.4056	215.66
213.1291	228.7462	242.5159	256.4538	249.3538	250.5857	255.0619	265.052	245.8818	239.5782	225.0771	207.8766
189.876	204.3196	217.2897	230.5155	224.708	226.0929	230.0068	238.5077	220.584	214.2152	200.6591	185.0568
152.8858	165.4625	177.1606	189.2535	185.5023	187.1305	190.1499	196.2818	180.3411	173.8686	161.8158	148.7558
104.6793	114.823	124.8634	135.4799	134.4084	136.3536	138.2074	141.252	127.8955	121.2879	111.1941	101.4474
48.54152	55.85196	63.96195	72.8592	74.90827	77.22277	77.71902	77.16838	66.82138	60.05629	52.24399	46.35565
0	0	0	5.658896	11.05678	13.76753	12.80704	8.39822	1.280732	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
1639.284	1775.484	1902.703	2045.743	2017.635	2041.246	2071.511	2127.426	1940.119	1866.241	1735.386	1594.645

Table B. 4 hourly beam radiation in (Wh/m^2)

Jan	Feb	Mar	App	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	6.766322	14.20482	16.3381	14.20705	8.080522	1.644463	0	0	0
79.88993	93.86366	109.504	112.7082	122.6094	117.191	111.2235	98.08761	110.8878	90.51446	75.06822	75.52262
211.6619	235.5276	258.9844	253.9204	264.096	248.9656	239.23	220.2045	256.9861	224.3696	198.0197	203.5032
358.5253	392.064	422.5466	407.8957	416.7511	391.2214	378.1015	354.5127	416.55	372.8098	335.9649	346.5355
492.3364	534.0359	570.1062	546.5407	553.4085	518.6087	502.7989	476.0183	560.3562	507.698	462.0911	477.0464
585.8411	632.9988	672.669	642.8071	647.9922	606.7914	589.2492	560.5998	660.255	601.8207	550.3905	568.3162
619.3912	668.4686	709.3821	677.2502	681.7849	638.2996	620.1593	590.8968	696.0056	635.5712	582.0992	601.0758
585.8411	632.9988	672.669	642.8071	647.9922	606.7914	589.2492	560.5998	660.255	601.8207	550.3905	568.3162
492.3364	534.0359	570.1062	546.5407	553.4085	518.6087	502.7989	476.0183	560.3562	507.698	462.0911	477.0464
358.5253	392.064	422.5466	407.8957	416.7511	391.2214	378.1015	354.5127	416.55	372.8098	335.9649	346.5355
211.6619	235.5276	258.9844	253.9204	264.096	248.9656	239.23	220.2045	256.9861	224.3696	198.0197	203.5032
79.88993	93.86366	109.504	112.7082	122.6094	117.191	111.2235	98.08761	110.8878	90.51446	75.06822	75.52262
0	0	0	6.766322	14.20482	16.3381	14.20705	8.080522	1.644463	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
4075.9	4445.449	4777.003	4618.527	4719.909	4436.532	4289.78	4025.904	4709.365	4229.996	3825.168	3942.924

Table B. 5 Hourly Total Irradiation on the Plane of the PV Array in (Wh/m^2)

Jan	Feb	Mar	App	May	Jun	July	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1.10323	2.023353	2.766341	3.232866	2.942170392	0.174436	0	0	0
160.7538	170.7473	177.6333724	171.0426	165.306	159.5766	158.348	157.3728862	174.3151	164.9001	153.8312	156.7628
356.4376	376.4445	389.3520397	372.1954	357.5815	343.7658	340.7632	339.7969068	381.2052	363.6053	342.3925	348.2739
558.4246	588.2175	606.6116085	577.877	553.5812	531.2393	526.5637	526.1028626	593.2166	567.9735	536.91	546.0983
734.6849	772.7303	795.5325144	756.3444	723.3295	693.4541	687.401	687.6398333	777.4201	745.9271	706.5908	718.8013
854.9414	898.5052	924.166426	877.7094	838.6401	803.5882	796.6275	797.4448636	902.7817	867.1886	822.3344	836.6603
897.628	943.1324	969.7842489	920.7248	879.4892	842.5939	835.3163	836.3554338	947.2292	910.2074	863.4151	878.5006
854.9414	898.5052	924.166426	877.7094	838.6401	803.5882	796.6275	797.4448636	902.7817	867.1886	822.3344	836.6603
734.6849	772.7303	795.5325144	756.3444	723.3295	693.4541	687.401	687.6398333	777.4201	745.9271	706.5908	718.8013
558.4246	588.2175	606.6116085	577.877	553.5812	531.2393	526.5637	526.1028626	593.2166	567.9735	536.91	546.0983
356.4376	376.4445	389.3520397	372.1954	357.5815	343.7658	340.7632	339.7969068	381.2052	363.6053	342.3925	348.2739
160.7538	170.7473	177.6333724	171.0426	165.306	159.5766	158.348	157.3728862	174.3151	164.9001	153.8312	156.7628
0	0	0	1.10323	2.023353	2.766341	3.232866	2.942170392	0.174436	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
6228.113	**6556.422**	**6756.376171**	**6433.269**	**6160.413**	**5911.374**	**5861.189**	**5858.95448**	**6605.455**	**6329.397**	**5987.533**	**6091.694**

Table B. 6 Average Total Energy Delivered by the PV array in (Wh/m^2)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.12696	0.23419	0.322789	0.37854	0.34407094	0.020075	0	0	0
18.654	19.56908	20.21801728	19.68367	19.13308	18.62013	18.54113	18.40390923	20.06065	19.02063	17.95032	18.23288
41.3613	43.14373	44.31558193	42.83243	41.3877	40.11217	39.90032	39.73741335	43.87012	41.94057	39.95323	40.50728
64.80004	67.4147	69.04380535	66.50237	64.07337	61.98745	61.6559	61.52488883	68.26896	65.5137	62.65117	63.51598
85.25342	88.56144	90.54655615	87.04049	83.72062	80.91541	80.4885	80.41576525	89.4676	86.04	82.45095	83.60285
99.20809	102.9763	105.1875136	101.0072	97.06706	93.76637	93.27795	93.25687059	103.8946	100.0271	95.95688	97.31088
104.1615	108.091	110.3796795	105.9575	101.7951	98.31773	97.80806	97.80725167	109.0097	104.9891	100.7505	102.1773
99.20809	102.9763	105.1875136	101.0072	97.06706	93.76637	93.27795	93.25687059	103.8946	100.0271	95.95688	97.31088
85.25342	88.56144	90.54655615	87.04049	83.72062	80.91541	80.4885	80.41576525	89.4676	86.04	82.45095	83.60285
64.80004	67.4147	69.04380535	66.50237	64.07337	61.98745	61.6559	61.52488883	68.26896	65.5137	62.65117	63.51598
41.3613	43.14373	44.31558193	42.83243	41.3877	40.11217	39.90032	39.73741335	43.87012	41.94057	39.95323	40.50728
18.654	19.56908	20.21801728	19.68367	19.13308	18.62013	18.54113	18.40390923	20.06065	19.02063	17.95032	18.23288
0	0	0	0.12696	0.23419	0.322789	0.37854	0.34407094	0.020075	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
722.7152	**751.4215**	**769.0026281**	**740.3438**	**713.0271**	**689.7664**	**686.2927**	**685.173088**	**760.1736**	**730.0731**	**698.6756**	**708.517**

Table B. 7 Average daily total energy available to the load and battery in (Wh/m^2)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0.114264	0.210771	0.29051	0.340686	0.309663846	0.018067	0	0	0
16.7886	17.61217	18.19621555	17.7153	17.21977	16.75812	16.68702	16.56351831	18.05459	17.11856	16.15529	16.40959
37.22517	38.82936	39.88402374	38.54919	37.24893	36.10095	35.91029	35.76367201	39.48311	37.74651	35.95791	36.45655
58.32004	60.67323	62.13942481	59.85213	57.66603	55.7887	55.49031	55.37239994	61.44207	58.96233	56.38606	57.16438
76.72808	79.7053	81.49190054	78.33645	75.34856	72.82387	72.43965	72.37418872	80.52084	77.436	74.20585	75.24256
89.28728	92.67868	94.66876224	90.90652	87.36035	84.38973	83.95015	83.93118353	93.5051	90.02437	86.36119	87.57979
93.74532	97.28186	99.34171153	95.36173	91.61556	88.48596	88.02725	88.0265265	98.10873	94.49023	90.67547	91.95954
89.28728	92.67868	94.66876224	90.90652	87.36035	84.38973	83.95015	83.93118353	93.5051	90.02437	86.36119	87.57979
76.72808	79.7053	81.49190054	78.33645	75.34856	72.82387	72.43965	72.37418872	80.52084	77.436	74.20585	75.24256
58.32004	60.67323	62.13942481	59.85213	57.66603	55.7887	55.49031	55.37239994	61.44207	58.96233	56.38606	57.16438
37.22517	38.82936	39.88402374	38.54919	37.24893	36.10095	35.91029	35.76367201	39.48311	37.74651	35.95791	36.45655
16.7886	17.61217	18.19621555	17.7153	17.21977	16.75812	16.68702	16.56351831	18.05459	17.11856	16.15529	16.40959
0	0	0	0.114264	0.210771	0.29051	0.340686	0.309663846	0.018067	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
650.4437	**676.2793**	**692.1023653**	**666.3094**	**641.7244**	**620.7897**	**617.6635**	**616.6557792**	**684.1563**	**657.0658**	**628.8081**	**637.6653**