Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Economics, Management, and Humanities

Feasibility Study For Power Generation Off-Grid Hybrid System In Rural Area of Ethiopia

Master’s Thesis

Study Program: Electrical Engineering, Power Engineering, and Management

Branch of study: Management of Power Engineering and Electrotechnics

Supervisor: Ing. Martin Benes. Ph.D.

By: Mathewos Erabo Basore

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MASTER‘S THESIS ASSIGNMENT

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Guidelines:

1. Analyze the energy source potential in the selected village.
2. Analyze the consumer load demand for the village.
3. Make a proposal of the hybrid system variants.
4. Evaluate the feasibility of the project from economical point of view.

Bibliography / sources:

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III. Assignment receipt

The student acknowledges that the master’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master’s thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt

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Declaration

I hereby declare that this master’s thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to methodological instruction NO. /2009 –“on maintaining ethical principles when working on the university final project, CTU in Prague”.

Date: ----- --------- signature: ------------------------

Acknowledgment

First, I would like to give glory to God, Psalm 9:1: I will praise you, O LORD, with my whole heart; I will show forth all your marvelous works. I will be glad and rejoice in you: I will sing praise to your name, O you most High.

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Abstract

Access to electricity is crucial for the community’s socioeconomic development; rural electrification is a critical agenda for developing countries to increase the electricity access rate; due to the scarce settlement of rural communities, grid penetration is limited in Ethiopia. GoE planned to reach 35% of the population with off-grid Technologies. This diploma thesis investigates the design and performance evaluation of an off-grid hybrid power generation system adapted to the energy needs of Wagesho village. The research begins with assessing the energy resources potential for solar and wind energy available in the village, providing a foundation for the subsequent system design and analysis. Load consumption patterns specific to Wagesho village are then analyzed to establish the community's energy requirements.

The study comprises two main scenarios: the first scenario involves a hybrid system integrating photovoltaic (PV) panels, a diesel generator (DG), and energy storage batteries, while the second scenario introduces a wind turbine to the mix, forming a PV-DG-Wind-Battery hybrid system, HOMER software is used for optimal components sizing, from the PV-DG hybrid system power generation is achieved with 87% renewable fraction, wind turbine helps to increase renewable fraction to 92.4% by reducing DG operation, and reduces emission which is key for energy sustainability; However, it increases investment cost of the hybrid system because of high initial investment on wind turbine. This paper also studies the calculation of the economic model for both scenarios to see the project's financial feasibility.

Keywords:

Hybrid Power Generation, Renewable Energy, Rural Electrification, Photovoltaic, Wind Turbine, Diesel generator, Battery Storage, Economic Analysis, Load consumption, Energy Sustainability.

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List of Abbreviations

CAPM	Capital asset pricing model
CSA	Central statistical agency
DOD	Depth of discharge
DG	Diesel generator
EAA	Equivalent annual annuity
GIS	Geographical information system
GoE	Government of Ethiopia
GPS	Global positioning system
GTP	Growth and Transformation Plan
HAWT	Horizontal axis wind turbine
HH	Household
IRR	Internal rate of return
MoWIE	Ministry of Water Irrigation and Electricity
MTF	Multi-tier frame
NEP 2.0	National electrification program 2
NASA	National aeronautics and space administration
NPV	Net present value
PV	Photovoltaic
SDG 7	Sustainable Development Goal 7
SNNPR	Southern Nation Nationalities Region
SSA	Sub-Sahara Africa
TDH	Total dynamic head
TSR	Tip speed ratio
VAWT	Vertical axis wind turbine

Chapter One

1 Introduction

Energy plays an essential role in socio-economic development, and access to clean and sustainable energy is essential to achieving sustainable development goals such as poverty reduction, quality education, and access to drinking water. And increase food productivity. According to a World Bank report, a more significant portion of the global population gained access to electricity than ever in the last decade. There are still 759 million people living without access to electricity globally in 2019. At the same time, around one-third of the world's people (2.6 billion) remained without access to clean cooking [1].

In Sub-Saharan African (SSA) countries, the electricity access rate is the lowest globally. Over half of the population lives without electricity, while only one-third uses clean cooking. Despite the progress in rural electrification, more effort is expected to bridge the gap to reach the sustainable development goal (SDG7) by 2030 [2].

The primary access to electricity in SSA is via the national grid, which leaves most of the population living in rural areas without electricity in most SSA countries. There is also the development of decentralized renewable solutions, including mini-grids and off-grid solar home systems, rapidly expanding in East Africa, such as Ethiopia, Kenya, and Uganda. Access to electricity via the national grid will play an essential role in energy access solutions. Yet, a decentralized renewable solution, especially solar, can play an increasing role in expanding the options for remote areas not connected to grids [2].

Implementing off-grid renewable electrification is based on the availability of the source potential, energy independence, lowest operational and maintenance costs, and ease of implementation. However, because of the periodic nature of renewable energy sources, their seasonal fluctuation is the main issue. To improve the source's availability and power quality, system hybridization of solar with wind sources, energy storage, and conventional generators is generally used as backup systems [3].

In this project, power generation from off-grid hybrid solar, wind, batteries, and diesel generators for rural electrification is designed. The Ethiopian government's National Electrification Program 2.0 (NEP) focuses on off-grid electrification to achieve universal energy access by 2025. The country presents many unique investment opportunities to attract the private sector by opening more landscapes for private investment [4]. This project reinforces NEP 2, and the case study is done in the Hadiyya zone, Wagesho village. The study includes both system design and feasibility studies from the investor's point of view.

1.1 Problem statement

Access to energy is crucial for fostering socioeconomic development and improving living standards. It is pivotal in driving economic progress and creating employment opportunities, income, and production. The main constraint to these benefits is the lack of electricity access, which affects over 60 million people, constituting more than 55% of Ethiopia's population. Despite the abundant potential for renewable energy sources in the country, a significant portion of the population relies on firewood and kerosene lamps for their energy needs [16].

Based on a survey by the Central Statistical Agency (CSA) in 2004, access to electricity in urban and rural areas is not proportional. The gap is very high, indicating that about 71.4% of the total HH use kerosene for lighting, followed by firewood at 15.7% and electricity at 12.9%. A higher proportion of urban residents use electricity for lighting, around 75%, while in rural areas, approximately 80% use kerosene and 18.5% use firewood. The primary type of cooking fuel used in all households is firewood [17].

Due to low access to modern energy in rural areas, the excessive dependence on biomass energy involves a trade-off in agricultural productivity. Crop residues and animal wastes are being diverted from the farms, where they supplement soil nutrition. The primary factor in deforestation is cutting down trees for charcoal and firewood. The unavailability of modern energy has also resulted in a need for more opportunities to provide social facilities such as clean water supply, health services, and educational facilities, for which current energy sources are essential.

To change this situation, GoE launched the national electrification plan NEP 2.0, which aims to achieve universal electricity access nationwide by 2025, fast-paced scaling up connectivity to the grid to reach 65 percent, and off-grid access to provide access for rural and deep rural households without grid connectivity [8]. The main constraints for rural energy development in Ethiopia are that most of the power generation capacity is hydropower for the grid-connected area; the main challenge is that during drought time, most of the power plants depend on water from the river, and there is low participation of the private sector in the energy market, which includes generation, transmission, and distribution due to the capital intensity of the industry [17]. One of the options to alleviate this problem is mixing power generation from various sources and making policy reforms to support the private sector.

Because of the deficient consumption level of electricity and the dispersed demand because of scattered settlements, grid electricity penetration into the rural population is very limited. Off-grid power generation is one of the solutions stated under the NEP 2.0 plan to transfer and encourage the gradual shift from traditional to modern energy sources. Depending on the energy tier level and population density, off-grid could be deployed in remote places without grid connection [17]. One of the disadvantages of renewable sources is their intermittent characteristics and high investment in the storage system. This case study focuses on power generation for rural electrification in Wagesho village by a hybrid power system.

1.2 objective

1.2.1 General objective

This study aims to design off-grid hybrid power generation from renewable energy sources and DG for rural electrification in Ethiopia and use HOMER software for optimal component sizing. The project's financial feasibility will be assessed based on the project's economic evaluation criteria.

1.2.2 **Specific objectives**

- To assess the renewable energy source potential, mainly for solar and wind resources, for the case study at Wagesho village in the Hadiya zone, Ethiopia.
- Estimate the load demand of the community in the village.
- Assess the feasibility of a hybrid system to meet the load requirements of the specific village electrification.
- Evaluate the feasibility of the project from an economic point of view.

1.3 Energy situation in Ethiopia

Ethiopia is a country in the SSA, located in the Horn of Africa, and the second-most populous country in Africa. The total estimated population is more than 115 million. Of the total population, over 75% live in rural areas [5]. GoE policy transforms the agricultural lead economy into an industrial lead economy. In the last decade, its economy has been one of the fastest-growing in the region. Energy is vital to achieving the sustainable developmental goal. However, the energy consumption rate is low. Per capita consumption in Ethiopia is 75 kWh, where consumption per capita measures the production of power plants less their use by power plants and losses, then divided by the total population in the country[6].

A multi-tier framework approach, which the World Bank defines, is used to assess the state of energy access. A multi-tier matrix is used to measure the household electricity supply. Categorization of the tier rating is based on the type of appliances used to access electricity and services, reflecting the availability of devices despite poor supply [6].

Table 1.1: Milt-tier matrix for HHs energy consumption capacity [based on data from [6]]

Tier level	Tier criteria	
	Energy consumption ratings [kWh]	Power in [kW]
Tier 0	-	-
Tier 1	> =0.012	> =0.003
Tier 2	> =0.2	> =0.05
Tier 3	> = 1	> =0.2
Tier 4	> =3.4	> =0.8
Tier 5	> =8.2	> =2

Table 1.2: Milt-tier matrix for HHs appliances [based on data from [6]]

Tier level	Tier criteria
Tier 0	-
Tier 1	Lighting and phone charging
Tier 2	Lighting, phone charging, television and fan
Tier 3	Lighting, phone charging, television, fan, and medium size appliances
Tier 4	Tier 3 and any high-power appliances
Tier 5	Tier 4 and very high-power appliances

Of the total population, only around 44.3% have access to electricity. The remaining 55.7% have no access to any electricity source. According to the Energy Sector Management System (ESMS), of those who get electricity, around 12% have access starting from tier 1 based on a multi-tier frame approach [7]. Most HHs connected to electricity use appliances categorized in tier 3, and around 26%, use high-load appliances.

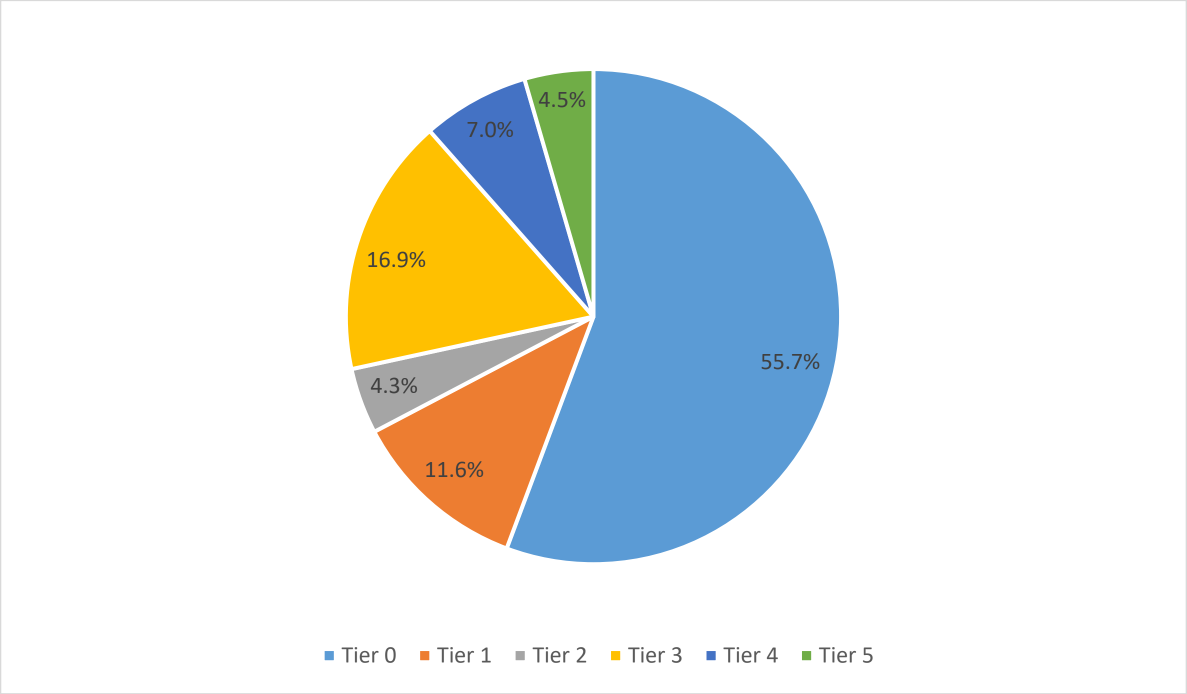

Figure 1.1: Percentage of population with access to electricity categorized in multi-tier [based on data from [7]].

The GoE started a nationwide electrification effort, a comprehensive scheme to improve the current state of the electrification rate. A thorough plan to provide universal access to electricity by 2025 is introduced under NEP 2.0, which employs a coordinated strategy combining off-grid and on-grid options to achieve this, focusing on customer last-mile service delivery [8].

By 2025, the plan will reach 65% of the population through national grid access and the other 35% through off-grid technologies, like stand-alone solar systems and mini-grids. Another crucial focus will be ensuring a reliable electricity supply for schools and health facilities. Utilizing an advanced geographic information system (GIS) will enhance the planning process for off-grid and grid infrastructure [8].

Both GIS and MTF combination is a crucial approach for both off-grid and on-grid electrification, where GIS tools help to identify where and what kind of technologies are needed, and the MTF approach supports the identification of how much service is needed to achieve off-grid and grid connection [8]. The combination of both multi-tier frameworks (MTF) and GIS creates an opportunity to identify:

- Beneficiaries by location,

- Optimal technology solutions by location in the short term, medium term, and long term.

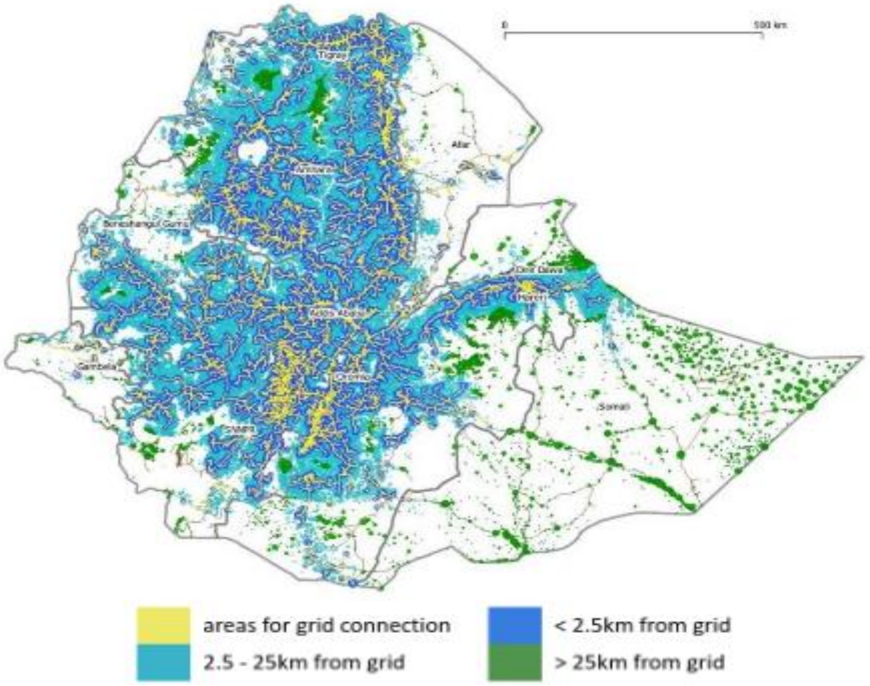

Figure 1.2: - Geo-spatial map of Ethiopia [15].

The comprehensive approach of the Ethiopian national electrification program by 2025 has primary opponents [8].

On-grid access: the target beneficiaries are those living within 2.5 km of the existing national grid system. The plan is to add 8.2 million HHs to reach a cumulative HHs connected to the grid of 15 million, which is 65% of the population by 2025.

Off-grid access: about one million HHs are targeted beneficiaries in remote areas, villages less likely to be served by cost- and time-effective ways by grid connectivity.

1.4 Assessment of energy potential in Ethiopia

Ethiopia has various energy sources, including solar, biomass, wind, hydropower, geothermal, fossil fuels (natural gas and coal reserves), and biofuels (ethanol and biodiesel). From these abundant sources, Ethiopia can generate over 60,000 megawatts (MW) of power [9]. The previous ten years have seen extremely rapid economic expansion, which has led to a steady increase in electricty demand. Ethiopia is facing energy shortages despite of its potential. The nation's installed capacity is about 4200 MW, and some projects are currently being built. Ninety percent of the installed capacity comes from hydropower, with the remaining two percent coming from thermal and eight percent from wind sources. Eighteen power plants under the management of Ethiopian Electric Power produce 4244 megawatts of power for the entire country. Fourteen power plants, among them, are hydroelectric such as Gilgel Gibe III (1870 MW), Beles (460 MW), Gilgel Gibe II (420 MW), Takeze

(300 MW), Gilgel Gibe I (184 MW), Melka Wekena (153 MW), Fincha (134 MW), Amerti Neshi (95 MW), Tis Abay II (73 MW), Koka (43.2 MW), Awash II (32 MW), Awash III (32 MW), Tis Abay I (14.4 MW), and Aba Samuel (6.6 MW) have a total installed capacity of 3814 MW of power [10].

The wind power plant also generates power in Ethiopia, with an installed capacity of 324 MW. Plants that have been generating power are Adama II (153 MW), Adama I (51 MW), and Ashegoda (120 MW). The remaining part of the power plant, 104 MW of power is generated from the diesel generator and the Aluto geothermal plant (7.3 MW) [10].

Because hydropower depends on rainfall to fill the dams, some plants are generating below capacity because of less rain in many Ethiopian regions in recent years. GoE is working to diversify its generation with other solar, wind, and geothermal sources. A plan is to exponentially increase power generation to 17000 MW within the next ten years [9]. One of the megaprojects under construction to achieve the goal is the Grand Ethiopian Renaissance Dam (GERD), with an installed capacity of 5150 MW, which has already started generating with two turbines, each generating 375 MW. To carry out additional solar, wind, and geothermal projects, GoE is also working with the private sector [9].

Table 1.3: - Ethiopia's energy potential [based on data from [13]]

Resources	Unit	Exploitable Potential	Exploited percent
Hydropower	MW	45000	<5
Solar	kWh/m^2	Average 5.5	<1
Wind	GW	1350	<1
Wind speed	m/s	>6.5	
Geothermal	MW	7000	<1
Woody biomass	million tons	1120	50
Agricultural waste	million tons	15-20	50
Natural gas	billion/m^3	113	0
Coal	million tons	300	0

The above table shows the average number of pick sun hours per day in the country at peak sun conditions. kWh /m2/day is the amount of solar energy striking position at a specific time, also known as solar insolation.

1.4.1 Solar energy

The Sun is the primary energy source that sustains all living activity on Earth, including plant photosynthesis, the Earth’s thermal comfort, and the entire biogeochemical system. When the electromagnetic radiation from the Sun reaches the Earth’s surface, it is transformed into different forms of energy and used for various things. And solar energy is available in abundance around the globe [21].

- **Photovoltaic system**

A PV system is a composition of all the technologies that convert solar photons directly into electricity: solar panels, storage units, and regulators; in some cases, the purpose of storage may not be necessary. Among most PV system elements, the solar cell is a crucial component; it contains semiconductors and converts solar radiation into electricity [21].

• Factors that affects the PV module's output power

• The angle of panel orientation

The optimal mounting position for a solar panel depends on the site's latitude; on the north side of the equator, where the Sun is typically in the southern position, the panel orientation should be pointed south, and on the south side, it should be pointed north. Two-axis tracker installation is a more efficient way than a fixed array in terms of energy harvesting. However, fixed array installation is more economical and space-advantageous because it has no moving parts, so there is no extra cost for motors and controllers. The solar altitude angle (γ) varies from $0\text{-}90^0$, and the best absorption of solar radiation on the panel occurs when the striking angle is 90^0. Considering these factors, tilting the solar panel towards the Sun, i.e., at an angle ß relative to the horizontal plane, can increase energy yield [12].

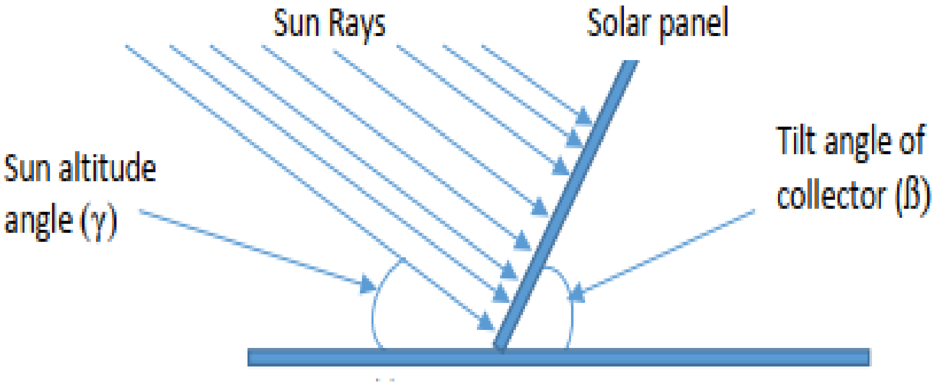

Figure 1.3: - Solar panel installation angle [12]

. Temperature

Increasing the operating temperature affects the output power of the module. An increase in temperature above the reference temperature significantly affects the output voltage; however, the effect on current is not as significant as the voltage.

The effect of temperature on PV power can be expressed quantitatively by expressing effects on voltage and current.

"

$$I_{sc} = I_o (1 + \alpha.\Delta T) \quad \ldots\ldots 1.1$$

$$Voc = Vo\ (1 - \beta \cdot \Delta T) \quad \ldots\ldots 1.2$$

$$P=Po\ [1 + (\alpha - \beta)\ \Delta T] \quad \ldots\ldots 1.3$$

Where Isc is the short-circuit current of the cell, Voc is the cell's open circuit voltage, Io and Vo are current and voltage at the given operating temperature of the cell, and ΔT is the change in temperature from the operating temperature.

For a single crystal silicon cell, α is about 20x10-6/°C, and β is about 5x10-3/°C. Power is, therefore, given by the following:

$$P=P_o\,[1 + (20\times10^{-6} - 5\times10^{-3})\,\Delta T] \quad P=P_o\,[1-0.005\cdot\Delta T] \quad \ldots\ldots \quad 1.4$$

According to this expression, the silicon cell power output drops by roughly 0.5% for each degree Celsius of the operating temperature rising above the reference temperature. At a higher working temperature, there is a net reduction in power since the rise in current is far smaller than the decrease in voltage.” [21].

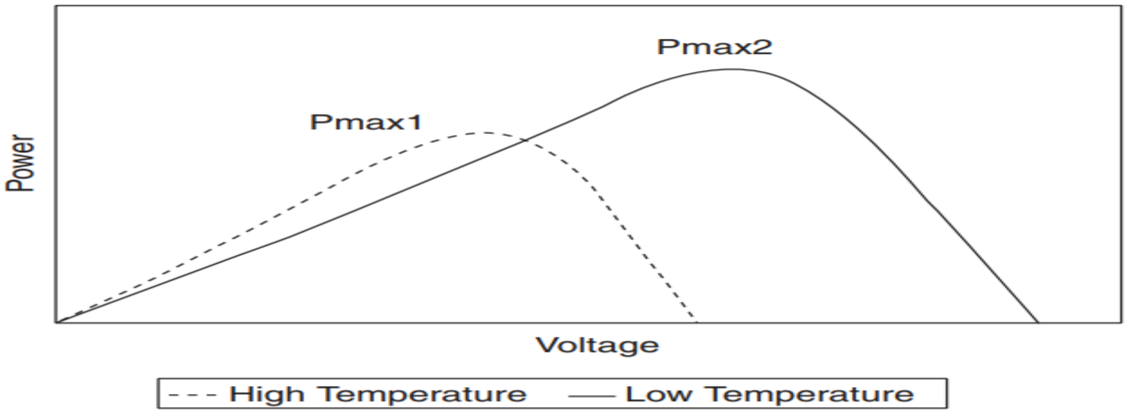

Figure 1.4: - Temperature effect on P-V characteristics [21]

• Shading effect

A module or portion of a shaded module (cell) may only partially or not produce power. If this occurs, it may also result in hot spots heating up. It is always good to see at the PV installation site if there are any possibilities for shading positions. When such objects exist, a minimum distance should be kept. Minimum spacing of the rows of PV modules is also crucial to preventing the possibility of shading of PV modules against each other. The minimum spacing of the module can be done using the Sun's angle.

$$d_{Min} = b.\frac{\sin(\gamma + \beta)}{\sin(\gamma)} \quad \ldots\ldots \quad 1.5$$

Where b is module width, γ is the angle of the sun, and β is the tilt angle of the panel [22].

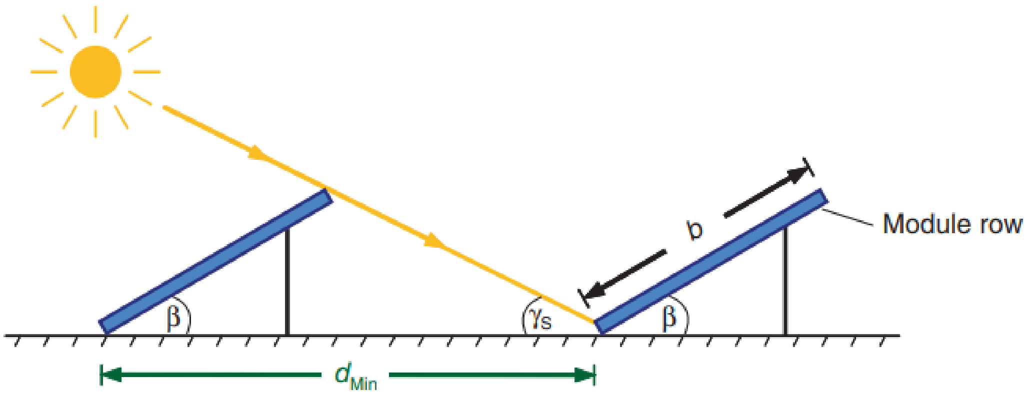

Figure 1.5: - Spacing of the PV module to prevent self-shading effect on [22]

. Solar energy potential assessment of the village

Before load demand estimation and system sizing to meet the demand of the village, the critical step is investigating the solar resource potential of the area. Pvsyst is the most widely used tool for simulating solar energy yield estimation and the optimal design of solar power plants. It runs based on directly imported solar resources from the NASA Surfaces Methodology and Solar Energy database by entering the GPS coordinates. So, the latitude and longitude of the location are 7^0 40' 35" N and 370 44' 35" E.

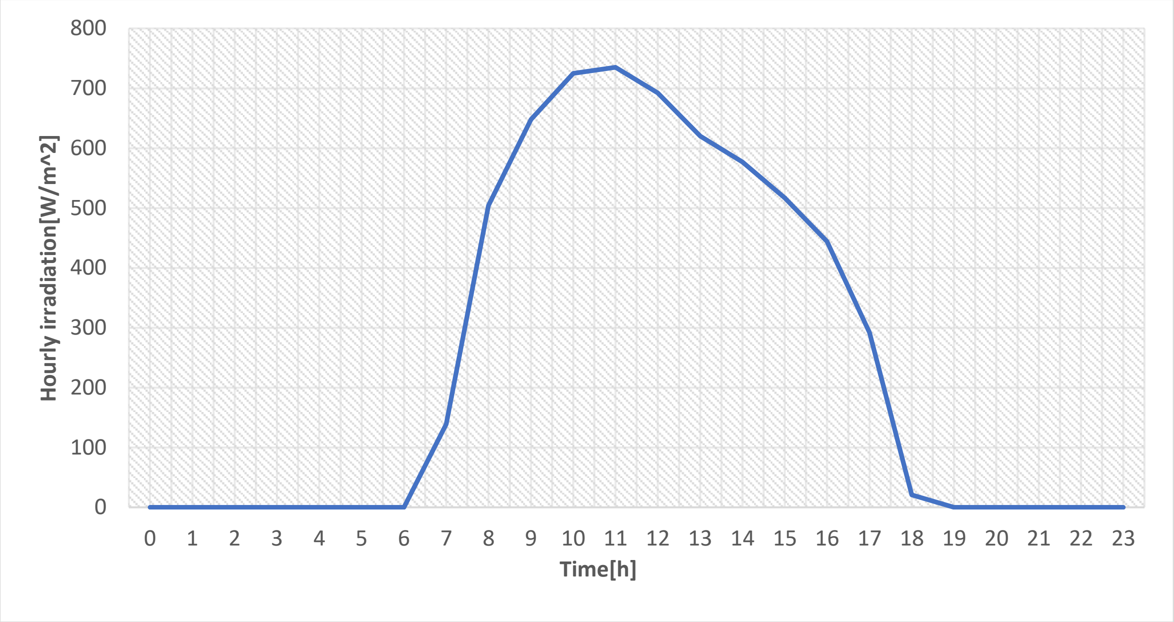

Figure 1. 6: - Hourly solar radiation [W/m^2] of the village in January.

Table 1.4: - Average daily solar radiation for each month for the village.

Months	Average daily radiation[kWh/m^2/day]	Clearness index
January	5.86	0.586
February	6.27	0.604
March	6.26	0.596
April	6.01	0.589
May	5.81	0.602
June	5.24	0.563
July	4.61	0.489
August	4.86	0.490
September	5.55	0.537
October	5.93	0.572
November	6.09	0.603
December	5.97	0.602

The above table shows that the village's monthly average daily global horizontal radiation varies throughout the year. The highest average daily radiation is in February, which is 6.27 kWh/m^2/day, and the lowest solar radiation is during summertime, the rainy season in Ethiopia, with the lowest daily average radiation being 4.61 kWh/m^2/day in July. The average solar radiation of the village is 5.71 kWh/m^2/day. The clearness index measures the clarity of the atmosphere. It is a dimensionless number that varies from 0 to 1, defined as surface radiation divided by extraterrestrial radiation. It has a high value, indicating clear and sunny conditions in the atmosphere, and a low value under cloudy conditions. The average annual number of hours of utilizing the photovoltaic power in the village is 2084 hours.

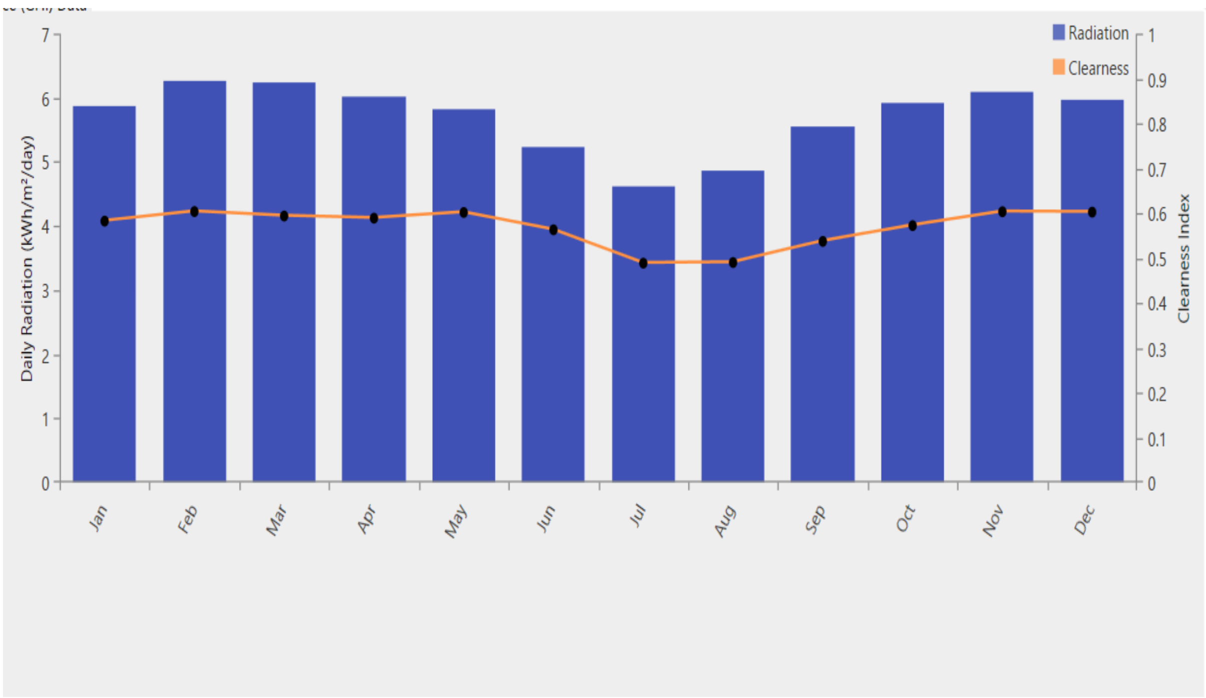

Figure 1.7: - Daily average solar radiation of the village for each months

1.4.2 Wind energy

Due to many emerging civilizations, wind energy is used in many sectors, including transportation and other purposes. The first windmill was built by Professor James Blyth in 1887 in Scotland to generate electricity, and in the USA, the windmill was used to generate electricity in rural areas in 1890. Nowadays, bigger wind turbines are installed in many world regions to provide affordable, clean energy [21]. Wind speeds typically decrease as one moves from higher latitudes toward the equator. Energy transported to higher altitudes becomes stronger with increasing latitude **(**i.e.**,** as the area decreases, the flow of energy density increases). However, the local effects might be significant – geographic structures such as mountains, valleys, and coastal areas may enhance wind speed. Ethiopia is located near the equator; its wind resource potential is minimal. Ethiopia has a few windy regions that show promise: the eastern part, the northeastern escarpment of the nation close to the Tigray regional state, and the East African Rift Valley [11].

. Power extraction principle by wind

When the wind passes over the wind turbine, it slows down the wind from V to V0, and the power extracted by the wind turbine is kinetic power (kinetic energy per second). The mechanical power generated by the differences between the upstream and the downstream velocity is shown in the equation below [14].

$$P_{mech} = \frac{1}{2} m (v^2 - v_o^2) \dots\dots\dots 1.6$$

Where $P_{mech:}$ is mechanical power extracted by the wind turbine (W)

m: - mass flow rate of the air (kg/s)

v: is the upstream wind speed at the entrance of the rotor blade (m/s)

v_O: is the downstream wind speed at the exit of the rotor blade (m/s)

The mass flow of the air will be replaced by the wind speed and air density as follows.

$$M = \rho A \frac{V+V0}{2} \dots\dots\dots 1.7$$

Where: ρ is air density (kg/s) and A is the swept area by the rotor blade in meter square

$$P_{mech} = \frac{1}{2} \rho A v^3 C_p. \dots\dots\dots 1.8$$

Cp is called the power coefficient of the rotor efficiency. It is a dimensionless power coefficient or Betz limit, and it measures the efficiency of the wind turbine when it extracts the kinetic energy of the wind stream to convert it into electrical energy [12, 21]. The maximum theoretical achievable power coefficient is 59.26%; this number will be achieved when the downstream speed equals one-third of the upstream wind speed. However, the practically obtainable value is lower than the theoretical value, around 45%. Not achieving a theoretical limit of power coefficient is caused by the losses and inefficiencies of different configurations like rotor blades, frictions, and turbine designs [19, 21]. Tip speed ratio (TSR) is related to extracting power from a wind turbine. It is the relationship between the rotor tip speed and the wind speed in the free stream, primarily influenced by factors such as wind speed, the radius of the wind turbine blade, and angular velocity.

$$TSR = \frac{\upsilon}{V} = \frac{\omega R}{V} \dots\dots\dots 1.9$$

Where ω is the angular velocity of the rotor in rad/s, which is 2πf, V is the wind speed in m/s, and R is the radius of the rotor blade [19].

- **Wind turbine technology**

The dynamic behavior, strength, qualities of the materials, and complete assembly are all things that must be considered while constructing a wind turbine. And there are different designs of turbines. Based on the position of the rotor shaft, the wind turbine can rotate either on the horizontal axis or the vertical axis [21].

Vertical axis wind turbine (VAWT): The main rotor shaft is positioned vertically. The yaw mechanism is not necessary for VAWTs since they receive wind from any direction. The turbine doesn’t need to be oriented into the wind to be effective, which is a major benefit of this VAWT, especially in areas where wind direction is highly variable [21].

Horizontal-axis wind turbine (HAWT): **-** The main rotor shaft and electrical generator of horizontal-axis wind turbines (HAWT) are located at the top of a tower, and they must face the wind direction The most common turbines currently used in wind farms to produce electric power are usually three-bladed HAWT. The reason for this is stability, and using an uneven number of blades helps to avoid stability problems during the rotation of the blade [23].

The main parts of a modern HAWT are the tower, the rotor, the main prime mover, the nacelle, which houses the generator and gearbox, and the yaw. The tower supports the wind turbine and maintains the blades at the height so that they can effectively harness wind energy. The yaw mechanism turns the wind turbine rotor blades counterclockWise. The gearbox is used to increase the wind turbine rotational speeds to a higher rotational speed that is suited for the electrical generator by connecting the low-speed shaft with the high-speed shaft [21].

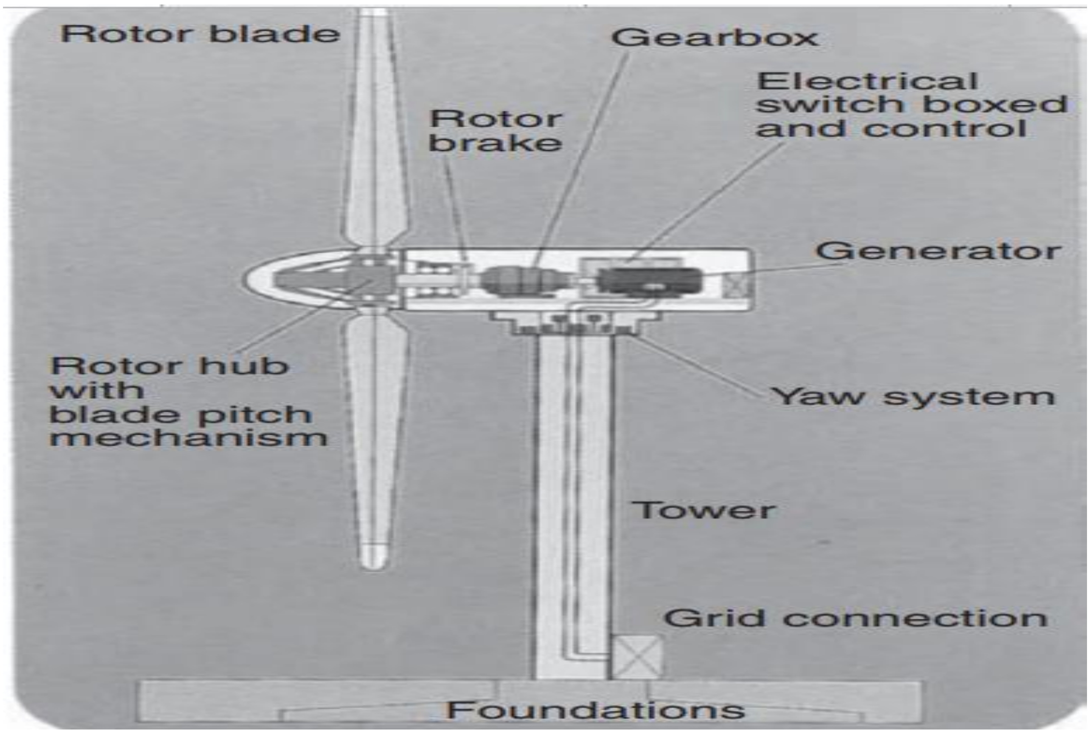

Figure 1.8: Horizontal axis wind turbine with its main component [23].

- **Wind speed distribution**

Wind speed distribution can be used to indicate the annual available wind energy, and these distributions are estimated using measurements, wind maps, and other schemes. The wind is never steady at any site; rather, it is influenced by the weather system, the local land terrain, and its height above the ground. Wind speed varies by minute, hour, day, and season.

The statistical function that describes the wind variation in the best way is the Weibull probability distribution function with two parameters: the shape parameter k and the scale parameter c. Wind speed has the Weibull distribution with shape parameter k=2, specifically known as the Rayleigh distribution and given as follows with wind speed [14, 21].

$$F(v) = \frac{\pi v}{2\nu^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{\nu}\right)^2\right] \quad \ldots\ldots 1.10$$

Where f (v) is the Weibull probability density function of wind speed

v: is instantaneous wind speed (m/s)

$\bar{v}$ Is mean speed (m/s)

- **Wind energy resource**

The different classes of wind resources are categorized into poor, marginal, moderate, good, and excellent based on the mean annual wind speed or corresponding wind power density at different height measurements above ground level. The wind class ranges from poor to excellent wind regimes, identifying the country's land area that falls under this category [11].

Table 1.5: - Categorizing wind resources and its power density into classes [based on [11]].

Wind power class	Description	Wind power density[W/m^2]	Wind speed [m/s]	Wind power density[W/m^2]	Wind speed [m/s]
		At 10 m		At 50 m	
1	Poor class	<100	<4.4	<200	<5.6
2	Marginal	100-150	4.4-5.1	200-300	5.6-6.4
3	Fair	150-200	5.1-5.6	300-400	6.4 -7.0
4	Good	200-250	5.6-6.0	400-500	7.0 -7.5
5	Excellent	250-300	6.0-6.4	500-600	7.5-8.0
6	Outstanding	300-400	6.4-7.0	600-800	8.0-11.9
7	Superb	>400	>7.0	>800	>11.9

Using wind turbines for power generation, an increase in wind speed leads to a considerably more significant increase in power output. Due to its fluctuation, it has an impact on power generation. The minimum wind speed required to rotate most small turbines is 2 m/s, but the minimum speed, also called cut-in speed, for most small wind turbines to start generating power is 3.5 m/s. The wind speed required to generate maximum power varies between 12 m/s to 17 m/s [18].

Ethiopia's total land area falls under the Class 1 wind rating in about 35% of cases. Nearly 50% of the total land area is in low-wind areas. From this, it may be concluded that just 15% of the nation's total land area possesses viable wind resources. Nearly 7% of the overall land area has a moderate-to-excellent wind region, while the actual potential will be smaller due to the exclusion of regions set aside for other uses. The map below displays the distribution of wind resource areas by region [11].

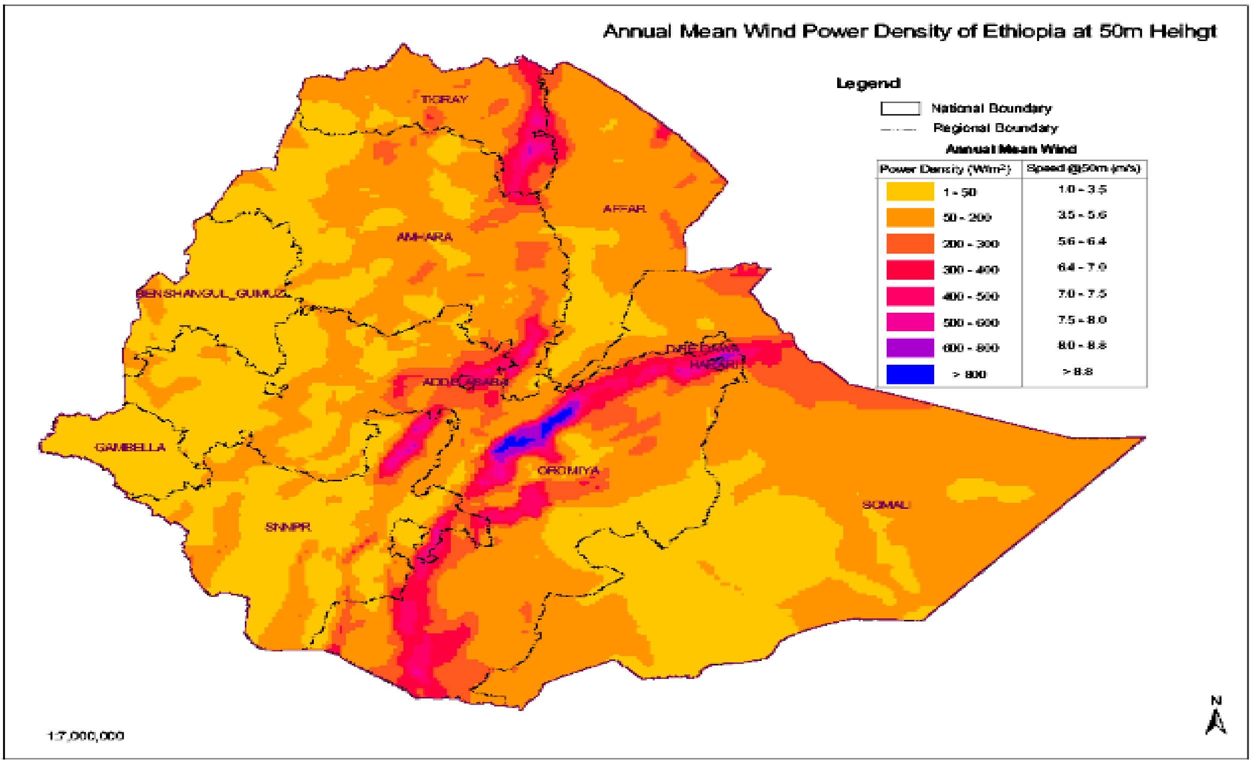

Figure 1.9: -Wind speed and power density of Ethiopia at 50m height [11]

- **Wind energy resource assessment of Wagesho village**

This study investigates the potential of renewable energy resource in a selected village by analyzing wind speed data obtained from NASA. The organization provides comprehensive meteorological data that includes wind speed measurements at different heights for specific locations. Wind speed data was collected at a height of 10m, and the data spans five years, from 2017 to 2021, as presented in the table below. The data collected from NASA is a valuable resource for renewable energy research, and it allows us to accurately assess the feasibility of wind energy projects in the selected village. By utilizing this data, we can better understand the wind energy potential of the area.

Table 1.6: - Wind speed (m/s) [34]

year	2017	2018	2019	2020	2021	Average from 2017-2021
Jan	2.82	2.0	2.91	2.09	2.38	2.44
Feb	2.15	2.09	2.27	2.43	1.96	2.18
Mar	1.99	2.07	1.74	1.84	2.8	2.09
Apr	2.66	1.41	1.77	1.95	2.09	1.98
May	1.77	1.88	1.88	1.73	1.56	1.76
Jun	1.84	1.92	1.81	1.97	1.88	1.88
Jul	2.13	2.11	2.09	2.2	2.4	2.19
Aug	2.1	2.08	1.98	2.1	2.02	2.06
Sep	1.91	2.0	1.91	1.8	1.95	1.91
Oct	2.23	2.12	2.45	2.2	2.37	2.27
Nov	2.38	2.53	2.16	2.45	2.57	2.41
Dec	2.42	2.43	2.12	2.52	2.47	2.39

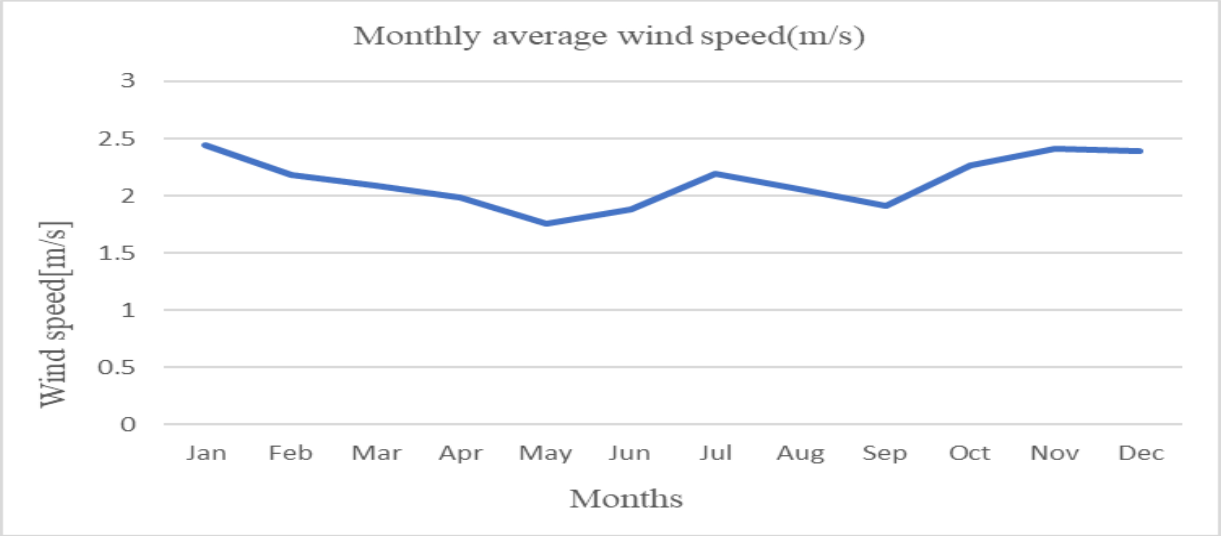

Figure 1.10: -Monthly average wind speed (m/s) at a height of 10 m for Wagesho village [34].

According to the above figure in the Wagesho village, the maximum estimated mean wind speed at 10m height is 2.44 m/s, which can be observed in January. In comparison, the minimum speed can be observed in May, with a mean speed of 1.76 m/s. The average wind speed is 2.13 m/s. The average speed obtained at a height of 10 meters for the selected village falls under the poor class. It suggests that the wind speeds recorded may not be suitable for installing a wind turbine at this height.

However, considering the potential benefits of harnessing wind energy in the area, a small-scale wind turbine with a minimum startup wind speed of 2 m/s could be considered. To assess the feasibility of this approach, it would be practical to recalculate the wind speed at higher elevations, where wind speeds tend to be higher. By collecting wind speed data at higher heights, such as 30 or 50 meters, it may be possible to determine if the average wind speed exceeds the minimum startup wind speed required for a small-scale wind turbine.

[35] To calculate wind speed at different elevations, The Hellmann exponential law, widely employed in practice, provides a simple yet effective correlation between the wind speeds measured at two different heights:

$$\frac{V2}{V1} = \left(\frac{H2}{H1}\right)^{\alpha}$$

Where v_2 is wind speed at height H_2 and, v_1 wind speed at height H1 and α is friction coefficients, varies for different landscapes.

Table 1.7: Friction coefficient α for a different landscape [based on data from [35]]

Landscape	α
Lakes, ocean, and smooth hard ground	0.1
Grasslands (ground level)	0.15
Tall crops, hedges, and shrubs	0.2
Heavily forested land	0.25
Small town with some trees and shrubs	0.3
City areas with high-rise buildings	0.4

Using the above formula, wind speed is extrapolated for different turbine hub heights, using coefficient factor α is taken as 0.2. The result is shown in the table below:

Table 1.8: - Extrapolated wind speed at the height of 36m

year	2027	2018	2019	2020	2021	Average from 2017-2021
Jan	3.64	2.58	3.76	2.70	2.07	3.15
Feb	2.78	2.70	2.93	3.14	2.53	2.82
Mar	2.57	2.67	2.24	2.37	3.62	2.70
Apr	3.44	1.82	2.28	2.52	2.70	2.55
May	2.28	2.42	2.43	2.23	2.02	2.28
Jun	2.37	2.48	2.34	2.54	2.43	2.43
Jul	2.75	2.73	2.70	2.84	3.10	2.83
Aug	2.71	2.68	2.56	2.71	2.61	2.65
Sep	2.46	2.58	2.47	2.33	2.52	2.47
Oct	2.88	2.74	2.3.16	2.84	3.06	2.94
Nov	3.07	3.27	2.80	3.16	3.32	3.12
Dec	3.12	3.14	2.74	3.26	3.20	3.09

- **Wind power density for the village**

The power the wind transfers to the rotor of a wind turbine is proportional to the density of the air, the rotor area, and the cube of the wind speed [21]. Power available P in the wind speed v for the area of the rotor A is.

$P/A = \frac{1}{2} \rho . v^3$ …………………….…………………………………………………..………1.11

The following correlation is used to estimate air density at various elevation levels [23].

$\rho = 1.225 – (1.194 \times 10^{-4}). z$

Where z is the elevation of the wind speed measurement, for this case study wind speed data at 10 meters is taken from NASA at the elevation of 1925 meters, therefore air density is calculated.

$\rho = 1.225 – (1.194 * 10^{-4}). 1925 = 1$ kg/s

Table 1.9: Wind power density for the village.

Months	Wind speed(m/s) at 10-meter	Power density [W/m^2]	Wind speed(m/s) at 36-meter	Power density [W/m^2]
January	2.44	7.26	3.15	15.63
February	2.18	5.18	2.82	11.22
March	2.09	4.56	2.70	9.85
April	1.98	3.88	2.55	8.30
May	1.76	2.73	2.28	6.00
June	1.88	3.32	2.43	7.20
July	2.19	5.25	2.83	11.33
August	2.06	4.37	2.65	9.30
September	1.91	3.48	2.47	7.54
October	2.27	5.85	2.94	12.70
November	2.41	7.00	3.12	15.18
December	2.39	6.83	3.09	14.75
Yearly Average	2.13	4.83	2.75	10.40

Chapter Two

2.1 Literature review

Many studies on hybrid stand-alone power generation have been conducted worldwide, including in Ethiopia. Various articles used different technological approaches and methods to assess different renewable energy resource configurations, including solar energy, wind energy, small hydropower, and hybrid designs. According to the findings of numerous investigations, many publications have been published for various purposes; some of the research papers are reviewed below.

For his doctoral dissertation, Bekele G researched solar-wind hybrid energy sources. The study aimed to investigate how to provide electric energy from solar-wind hybrid resources to the rural population and those moved by the government from overpopulated, dry areas to more productive, fertile areas to combat poverty. A hybrid standalone supply system was meant to provide energy for a community of 200 households. Electric load is used for lighting, water pumping, a radio receiver, and certain medical equipment for health centers. He used HOMER software to conduct the analysis. The expenses of the viable hybrid set-ups obtained in this study are high, ranging from 30 to 40 cents per kilowatt hour, and numerous alternate feasible hybrid systems with various degrees of contribution outcomes were found. He claimed that while the hybrid system’s energy costs are considerably high, they are still preferable given the country’s power constraint and efforts to preserve the country’s timber and nature [23]. This study was conducted in 2009 and covers most technical optimization; however, sensitivity analysis from an economic point of view is not discussed.

The article by Ouman C. studies power generation from hybrid energy sources, which include wind turbines, diesel generators, and batteries for off-grid rural electrification in Kenya, to provide electricity for a community of 500 households, one school, one medical center, and an irrigation system. He also simulated the Hybrid system using the Homer software tool, analyzed the result, and made a sensitivity analysis for the height of the turbine hub and the price of diesel USD per liter. He analyzed that optimal production is at a hub height of 40m and 1.2 USD/liter of diesel, which gives more than 15% production than the actual demand, and connecting to the national grid is viable when generating more than demand. The author did not discuss the price of electricity. [24].

Mandefro, Y. conducted a Study in 2017 on the feasibility of off-grid power generation from a small Hydro/PV/Wind hybrid system to supply people without access to electricity in a rural area of Ethiopia. This paper also prefers to disregard wind turbine from a hybrid system based on technical evaluation; wind power generation covers only 5% of the load because of the low wind speed, and as mentioned here, a Small Hydro-PV-battery hybrid system is the least cost of power generation which is 0.049$/kWh [14].

The study by Gebrehiwot, K., Mondal, M. A. H., Ringler, C., & Gebremeskel, A. G. (2019). Discusses the potential of hybrid mini-grids for electrifying remote villages in Ethiopia and concludes that using a combination of wind, solar, batteries, and diesel generators is the least expensive way to solve the problem of access to electricity in remote areas. The paper’s strength is the sensitivity analysis done to demonstrate how variations in solar radiation, wind speed, and diesel price affect the best system designs and costs. On the other hand, the article does not discuss the effect of the source of financing the project by doing sensitivity on loan, the effect of discount rate on Net Present Value (NPV), and how affordable the minimum price of electricity from the mini-grid (cost of power generation is: $0.207/kWh) is compared to the price of electricity from the national grid. [25].

Research conducted by Tamrat B. (2007) [26]. In evaluating the viability of rural electrification through solar PV, wind, and micro-hydro power generation in chosen Ethiopian rural locations, this study primarily compares the three renewable energy sources by examining the monthly payments per household associated with each system. The calculation is based on the energy consumption assumption by each household with and without some home appliances like TVs. Based on the paper from the given energy sources in both conditions, meaning with and without considering power consumption by TV in each household, Hydropower generation is preferable or least cost among the others, which are 5.53 Ethiopian Birr/kWh without TV and 9.58 Birr/kWh if there is a TV set, followed by power generation by wind turbine and solar PV power generation is more expensive than the other two. However, in most areas of the country where there is no river to generate hydropower and wind speed is not feasible, solar PV systems remain the only option. This paper also didn't discuss the hybrid systems to see the effect on the minimum price of power generation and technical optimization.

Most of the authors before me focused on hybrid systems using PV/Wind/small hydropower/diesel and batteries to electrify rural areas. Each author designs a hybrid system based on different load demands, study areas, and climatic data used to analyze the hybrid system setups in different ways. All the above authors also focused their paper on the optimization of the technical parameter.

This paper focuses on a feasibility study of power generation from the hybrid system of solar PV/Wind/diesel/batteries system for rural electrification in Wagesho village in the southern part of Ethiopia, in the Hadiya zone, focusing on mere coverage of the household load profile, a few public centers mainly school and health post and churches, and power consumption for water pumping and analyze technical optimization using Homer software and the main addition from the previous papers is a calculation of proper discount rate which is the expected return from the investment by investors and evaluating a project using project evaluation criteria like NPV, EAA and Internal rate of return to see economic feasibility of the project from an investor point of view.

2.2 Load estimation

One of the critical considerations in designing such off-grids to power local communities is the estimate of load demand. Accurately assessing demand increases the likelihood of developing a f feasible project by avoiding wasteful investment caused by overestimation.

Since it significantly impacts the technical and financial viability of renewable energy projects, it is essential to use caution when estimating the load demand for communities connecting to electricity for the first time. The rural load profile forecast is vital to its financial viability in this context. This study's baseline for measuring HHs energy use is the multi-tier framework.

2.2.1 Study site description

The selected village for the case study is in the southern part of Ethiopia, in the SNNP region, in the Hadiya zone, specifically in Gibe Woreda. The village's name is Wagesho, which is geographically located at the latitude and longitude of 70 40' 35" N and 370 44' 35" E. This village has 215 households; the community is made up of smallholder farmers, and their primary economic sources are livestock and agriculture. Since there is no access to electricity, the main energy sources of the community in the village are firewood, biomass combustion, candles, and kerosene light lamps (Kuraz) for cooking and lighting..

Figure 2.1; Image of the Wagesho village, taken from Google Earth.

2.2.2 Load profile estimation for the Wagesho village

The consumption profile will be calculated so that the community daily load curve can be created. In cases where there are already electricity consumers, this information can be obtained by measuring the amount of electricity used, but in the case of this project, there is no grid connection and no electric power supply, so the household's electricity consumption will depend on the proposed type of appliances they use and their period of electricity use needs for each consumption unit, which can be added together to get daily consumption for the community.

Before calculating the load, HHs in the village are divided into different groups based on their income levels, such as low-income, middle-income, and high-income. Thirty-eight (38) HHs are high-income, 75 of the HHs are middle-income, and 102 HHs are low-income.

The proposed appliance's wattage and number of appliances for each categorization based on HHs income are explained in the table below.

Table 2.1: Proposed HHs appliances and their wattage.

		Low-income HH	Middle-income HH	High-income HH
Appliances	Power[W]	Number of appliances	Number of appliances	Number of appliances
Light bulbs	10	2	3	3
Radio/tape	5	1	1	1
Mobile phone	5	1	2	2
Television	60	1	1	1
Refrigerator	300	1	1	1

The tables below show information about the wattage of the proposed appliance and the number of appliances proposed for other community institutions. These institutions include two churches, one school, and one health post.

Table 2.2: Proposed appliances and their wattage for community institutions in the village

Estimated appliances and their load for churches.			
Appliances	Power[W]	Quantity	Total load[W]
Light bulbs	10	16	160
Fan	70	8	560
Microphone, and keyboard	20	2	40
Proposed appliances and their load for school			
Appliances	Power[W]	Quantity	Total load[W]
Light bulbs	10	12	120
Radio/tape	5	1	5
Computer	180	3	540
Fan	70	22	1540
Proposed appliances and their load for health post			
Appliances	Power[W]	Quantity	Total load[W]
Light bulbs	10	4	40
Vaccine refrigerator	400	1	400
Fan	70	3	210
TV	60	1	60
Computer	180	1	180
Proposed street light load			
Streetlight	25	30	750

To conduct this study, it was necessary to make certain assumptions regarding the ownership of household appliances. This assumption is based on the findings of a market assessment conducted by the USAID Power Africa project in Ethiopia, and Power Africa load profile estimation [27,36], which provided valuable insights into the ownership of appliances in Ethiopian households.

Table 2.3: Household appliance ownership.

	Low-income HHs	Medium income HHs	High-income HHs
Appliances	Ownership	Ownership	Ownership
Lights	100%	100%	100%
Mobile phone	37%	62%	78%
Radio	3%	15%	76%
Television (TV)	16%	45%	82%
Refrigerator	1%	4%	17%

For the HHs appliance's consumption, the following table, adapted from the power Africa load profile estimation [36], is used to calculate consumption in each hour of the day.

Table 2.4: - Assumed hourly percentage (%) of appliance usage by households

Hours	Light Bulb	Radio	Charger	TV	Refrigerator
0:00	0	0	0	0	1
1:00	0	0	0	0	1
2:00	0	0	0	0	1
3:00	0	0	0	0	1
4:00	0	0	0	0	1
5:00	0	0	0	0	1
6:00	0	0	0.1	0	1
7:00	0	0	0.1	0	1
8:00	0	0.25	0.1	0	1
9:00	0	0.25	0.1	0	1
10:00	0	0.25	0.1	0	1
11:00	0	0.25	0.25	0	1
12:00	0	0.5	0.25	0	1
13:00	0	0.5	0.25	0	1
14:00	0	0.5	0.25	0	1
15:00	0	0.25	0	0	1
16:00	0	0.25	0	0	1
17:00	0	0	0.25	0	1
18:00	0.75	0	0.5	0.3	1
19:00	1	0	0.5	1	1
20:00	1	0	0.5	1	1
21:00	1	0	0.5	1	1
22:00	1	0	0.25	0.6	1
23:00	0.25	0	0	0.1	1
Total hours in the day	5	3	4	4	24

Consumption for refrigerator is 0.35 x 24 =8.4 hours, where 0.35 is for 35% of the duty cycle in every hour.

Table 2.5: Consumption hours for community institutions

Appliances	School (1) Load consumption time(h)	Health-post(1) Load consumption time(h)	Churches (2) Load consumption time(h)	Street light Load consumption time(h)
Light bulb	18:00-21:00	8:00-18:00	18:00-21:00	19:00-6:00
Fan	11:00-14:00	11:00-14:00	11:00-14:00	-
Computer	9:00-14:00	8:00-18:00	-	-
Refrigerator	-	0:00-23:00	-	-
Microphone	-	-	8:00-13:00,18:00-21:00	-
Radio	9:00-14:00	-	-	-
TV	-	8:00-18:00	-	-

An estimate of the daily energy consumption has been calculated based on the proposed household appliances, resulting in a figure of around 72 kWh per day. Additionally, the daily consumption of other crucial facilities, including churches, schools, health posts, and streetlights, has been calculated to be approximately 26 kWh per day.

- **Load estimation to supply clean water**

Estimation of consumption to supply clean water for community water demand involves determining the amount of water needed to meet the daily demand of the community. According to the Ethiopian Rural Socioeconomic Survey (ERSS) of 2013 [29], the average household size in the rural part of the SNNPR is 5.3 individuals. To fulfill the goals of the MoWIE's GTP-2 strategy, which aims to offer clean water to rural areas, a minimum daily water consumption of 25 liters per person per day has been established [28]. Based on this information, the village's daily water consumption is 28,488 liters.

According to a study conducted in the Hadiya zone, HHs with higher incomes own an average of 7 cattle and 4 sheep. In comparison, HHS with medium and low incomes own 5 cattle and 3 sheep, and 2 cattle and 2 sheep, respectively [30]. It should be noted that the water consumption of livestock is influenced by their size and seasonal variations; however, for this project, water consumption is assumed to be uniform throughout the year. A study on water resources for livestock in Ethiopia [31] has been adapted for this project. The assumed water consumption of the livestock is explained in the table below.

Table 2.6: Average daily water consumption by livestock.

Livestock	The average number of livestock for lower-income HHs have	The average number of livestock medium-income HHs have	The average number of livestock higher income HHs have	Estimated Average daily water consumption per head
Cattle	2	5	7	25 liters
Sheep	2	3	4	5 liters
Donkey	0	0	1	15 liters
Total consumption per day				24,600 liters

According to the estimated water demand for the community, the total water requirement per day is 53,100 liters, equivalent to 53.1 cubic meters (1 m3 = 1000 liters). I assumed that the pumping operation would run for 12 hours per day and that the flow rate required for the pump would be 4.45 cubic meters per hour.

It is necessary to consider the total dynamic head (TDH), the sum of the perpendicular distance from the water surface level to the water supply end, and the total friction losses. For this study, the TDH has been determined to be 122 meters.

The energy required per day (kWh) is [32]

$$E = \rho . V . g . TDH \quad \text{……………………………..……………………………………} \quad 2.1$$

Where ρ -is supply water density (1000 kg/m3).

g -is acceleration due to gravity (9.81 m/s^2).

TDH- is the total pumping head in meters.

V- is the volume of water required per day which is 53.1 m^3/day.

$$E = (1000\ kg/m^3 \times 53.1\ m^3/day \times 122m \times 9.81\ m/s2)$$

$$=63551142\ J$$

$$=63.6MJ$$

1 kWh =3.6 MJ; therefore, the energy required is 18 kWh. However, pumps are not 100% efficient, and there are energy losses due to friction and other factors. The efficiency of motor pumping is about 40–60%, considering the optimum efficiency of the motor is about 85% and the pump is about 70% [33]. For this project, 60% efficiency for water pumping is taken.

Using this efficiency factor, calculate the total energy needed to supply water. It divides the required energy of 18 kWh by the efficiency of 0.6, resulting in a total energy requirement of 30 kWh per day.

The village’s estimated daily load demand amounts to around 125 kWh on weekdays, while it decreases to approximately 122 kWh on weekends. The daily consumption for the village between weekdays and weekends has a few variations. Consumption during the weekdays is higher than on weekends, and the difference is around 3 kWh, which is insignificant. The daily load curve is shown in the figure below.

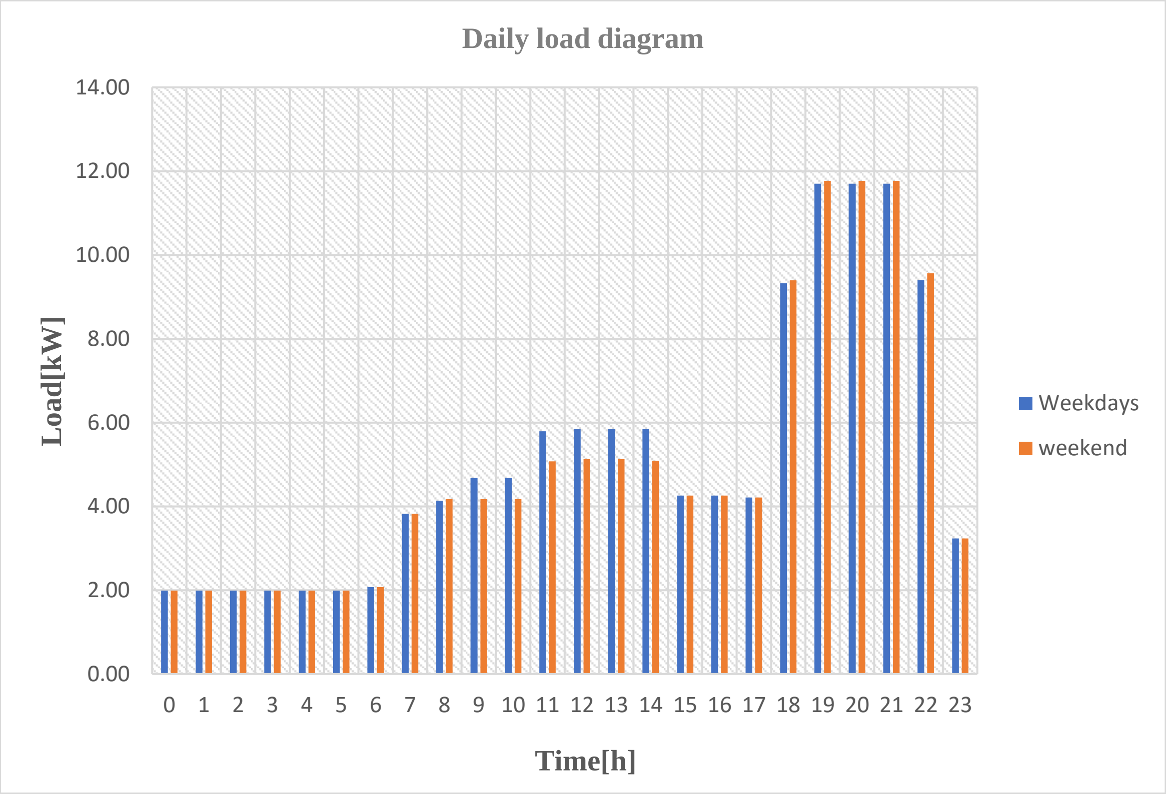

Figure 2.2: Estimated daily load profile of the village between weekdays and weekends.

The daily load profile in the figure shows that demand in the village varies during the day. The load is constant between midnight and morning because only a few appliances, like refrigerators and street lights, consume power during this time. Peak demand time is between 7:00 p.m. and 9:00 p.m. During this time, almost all people are at home, and most appliances consume power.

Monthly energy consumption can be divided into three parts, and the first part is from December to April; these months are the winter season with high temperatures, so these months are the peak consumption months. In May, June, September, October, and November, Fan will not be used for cooling, so the consumption difference from the peak months is by 2.5%; for July and August, the school will be closed, and there will be no cooling, so the consumption decreases further from the peak months by 5.5%. The pattern of consumption is described in the figure below.

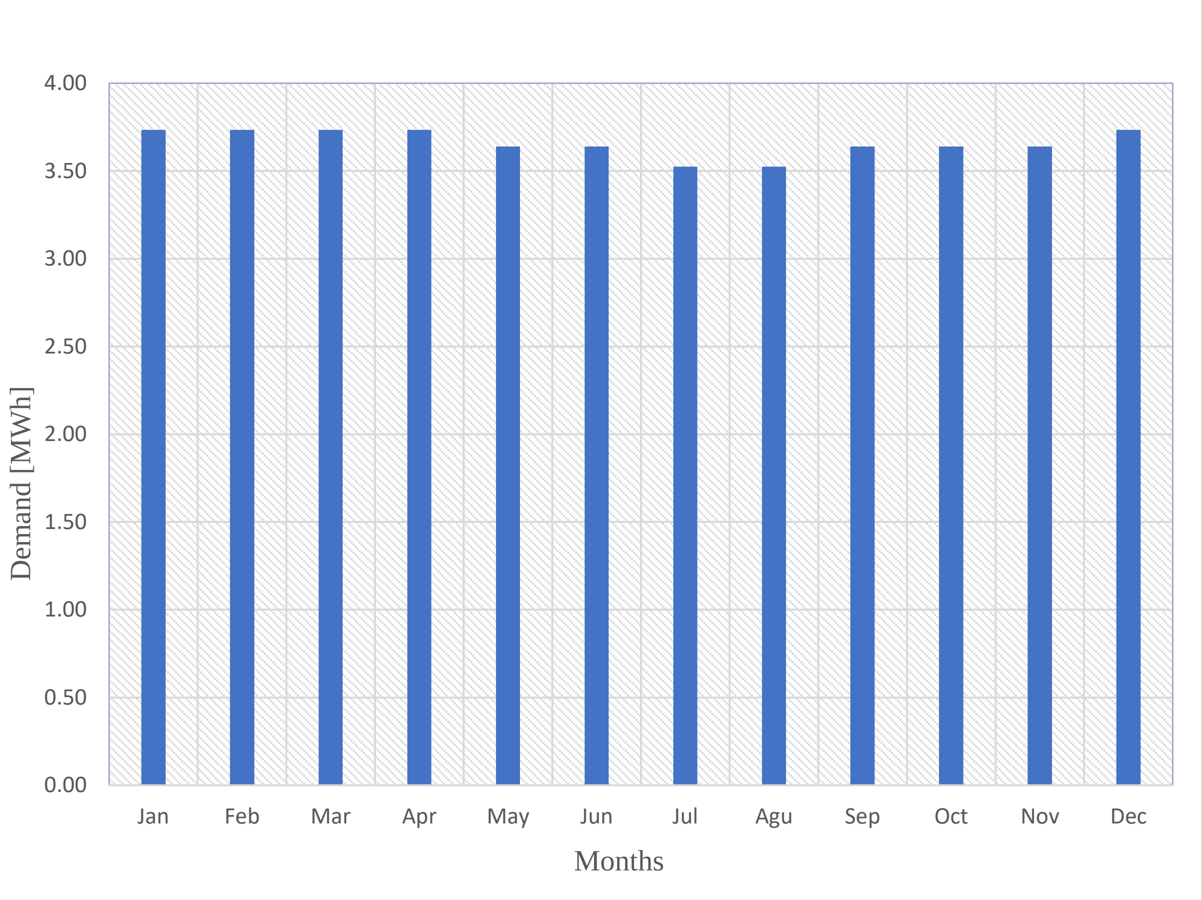

Figure 2.3: - Monthly energy consumption graph for the Wagesho village

Chapter Three

3 Power production and system component size

The hybrid system combines solar and wind with a diesel generator and a battery bank for backup, and converters are also included in the supply system. A solar-wind hybrid system has the potential to provide numerous benefits. One benefit is better reliability; when solar and wind power production resources are combined, the system's service is enhanced along with increased reliability. This means that if one type of source is unavailable, another will be available to carry out the service, which helps reduce the dependence on the back system. The hybrid system's operational concept is that renewable resources are the first choice for supplying the load, and any excess energy produced is stored in the battery. The diesel generator is a backup energy source when there is insufficient storage to meet demand [23.24].

Hybrid renewable systems can deliver better quality and more reliability for customers than a system based on one resource. For instance, winter typically has relatively strong winds, while summer has greater solar radiation and stream flow. The hybrid system reduces the output's reliance on seasonal fluctuations and provides stable power output from the resources. In addition, it maximizes the utilization of the various renewable energy sources that are accessible [23]. Due to pressing environmental concerns and the skyrocketing price of oil and natural gas, renewable energy options have increasingly become the preferred option for power generation because they provide clean, efficient power.

3.1 HOMER software

HOMER is a hybrid optimization model for electric renewable energy, which is computer-based software provided by the Midwest Research Institute in the National Renewable Energy Laboratory (NREL) operated by the USA Department of Energy. It is mainly used for optimization and decision analysis of hybrid renewable projects for grid-connected and off-grid systems. HOMER helps to simulate the system's operation by calculating the energy balance between demand and production for each of the hours in a year, by comparing the demands in each hour to the energy the system is capable of providing in that time frame, and by calculating the energy flow to and from each component of the system for the system that has a battery bank. HOMER also decides how to operate the generator and when to discharge and charge batteries. To do this simulation, HOMER needs a model with inputs that describe technology options and resource availability. Then, it takes input to simulate system configurations or combinations of the components. Its fundamental capability is to size the system setup optimally such that there is no capacity deficit, and it considers the system feasible when the produced power adequately serves the hourly electric load demand; if not, it considers the system infeasible [37].

Table 3.1: Inputs of HOMER simulation software [based on [37]]

Load profile	• The HOMER software feature allows to enter daily load profiles for weekdays and weekends for each month.
Resources	• Input data for solar radiation, wind speed, and temperature.
System design	• Components settings ○ PV, Wind turbine, Battery, Generator, and DC-AC converter.

3.2 System component

3.2.1 Photovoltaic module

Selecting the photovoltaic (PV) modules is essential in developing a solar power system, as it impacts the project's financial and technical viability. The two most common varieties of silicon solar cells used in PV modules are polycrystalline and monocrystalline, and each has a unique set of advantages and characteristics [22].

The monocrystalline solar cell has higher efficiency than the polycrystalline cell; this solar cell also performs better in high heat and warm weather conditions. A polycrystalline silicon solar cell is less efficient than a monocrystalline one but more cost-friendly. For the proposed system, polycrystalline cell PV modules with 300 Wp manufactured by Jinko Solar are selected based on cost and technical performance, and their price is $0.3/watt [38].

Figure 3.1: - Eagle PERC 60 300 model solar panel [38]

HOMER software models a PV array as a device that produces DC electricity directly proportional to the global solar irradiation incident upon it. HOMER uses the following equation to determine the amount of power generated by the PV array [37].

$$P_{pv} = f_{pv}.\ Y_{pv}.\frac{It}{Is}\ .[1- \alpha_p.\Delta T]\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\quad 3.1$$

Where P_{pv}: -is the output power of the PV array,

f_{pv}: - is the derating factor which includes dust, shading, and panel degradation which deviate PV power output,

Y_{pv}: -is the rated capacity of the PV array in (kW) at the standard test condition,

I_t: - is the global solar irradiation (both diffuse and beam) in kW/m^2,

I_s: - is $1kW/m^2$.

$\alpha_{p:\ -}$ is the temperature coefficient of the power [$0.39\%/^0C$][38], and

ΔT: - is the temperature difference between the PV cell under standard test conditions and the PV cell in the current time step[^0C].

3.2.2 Storage system

The storage system is a crucial component in off-grid renewable power generation systems to keep load demand and power supply in balance by storing the excess energy produced from RES for later use. Because of their intermittent nature, RES are not always available. During the daytime, due to high solar radiation, excess power is generated more than the load demand for non-business consumers. Maximum demand is at night, during which there will be no power generation from PV. In this case, demand should be supplied from the backup system, which includes a battery bank and diesel generator [23].

Different battery technologies can be used in off-grid renewable energy systems; in optimizing the system, the lifetime of batteries, DOD, and price are the main issues that should be addressed. Lead-acid batteries and Li-ion batteries are the most widely used. Lion batteries have a longer cycle life, higher energy efficiency, and lower operating and maintenance costs than lead-acid batteries. They also have better performance with daily charge and discharge at deep cycles. Operation conditions for batteries in 10^0C to 30^0C are the most applicable; higher temperatures can influence aging speed. Lead-acid batteries are also widely used because of their compelling cost advantage over Li-ion batteries [39].

For the proposed system, a 6-FM-250 lead acid battery with a nominal capacity of 250 ah and a nominal voltage of 12 V, manufactured by Yangtze Battery, is chosen with a cost price of $200 and a designed life span of the battery with the operation of 10 years with a maintenance-free operation [40].

Figure 3.2: 6-FM-250 lead acid battery [40]

The battery bank's capacity to supply total load demand can be calculated by taking into account the energy demand, DoD, and number of autonomous days [12].

$$Bc = \frac{E.Ad}{DoD.\eta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.2$$

Where Bc is the battery bank capacity (kWh)

E: - is the total daily energy use (kWh)

DoD- is the maximum depth of discharge of the battery [%]

η - is battery efficiency [%]

Ad -is the number of autonomous days.

3.2.3 Wind turbine

Based on the wind resource potential assessment for the village, the mean wind speed is 2.75 m/s, which is very poor, so to generate power to supply the load demand, installing a wind turbine with a minimum starting speed should be below the mean speed of the village. The main parameters for selecting wind turbines are their life span, cut-in speed, rotor diameter, and the turbine's cost.

For this paper, the chosen turbine model is the Ryse Energy E-10 wind turbine, which Ryse Energy makes. It has a 10 kW rated power, a 9 m/s rated wind speed, and a 2 m/s minimum starting speed, all favorable for the village's prospective wind resource. The chosen wind turbine has a 20-year lifespan, costs $45,000, and is intended to run in the -20^0 to 50^0 C temperature range [41].

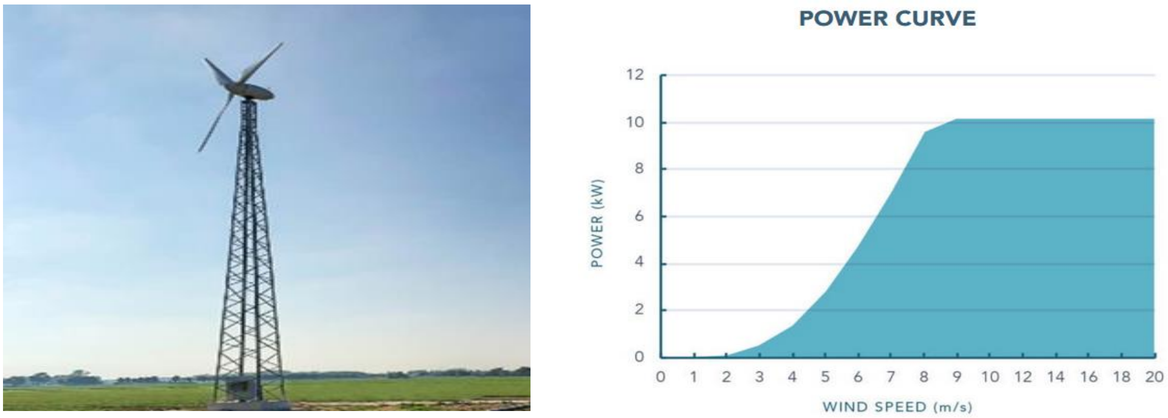

Figure 3.3: Ryse Energy E-10 10 kW wind turbine, and its power curve [41].

3.2.4 Inverter

A device that converts direct current into rotating current is known as an inverter. Most electronics and appliances operate on alternating current, whereas some RES power sources only produce direct current. As a result, this is significant. Due to the development of environmentally friendly power sources like sunlight-based cells and some wind turbines, which primarily provide direct current, inverters have recently gained popularity [23].

To decide the proper size of the inverter, which needs to have the ability to deal with all the power that the system is producing, this paper proposes an inverter made and provided by Schneider. Its rated power is 6.8 kW, with an efficiency of 95% and a life range of 10 years with guarantee. The selected inverter costs $3990 per unit, and its scalable future enables the creation of additional systems up to 34 kilowatts [42]. For this paper, two inverters will be associated with 13.6 kW, which assists with providing peak load.

Figure 3.4: - Schneider Conext XW 6848 inverter [42]

3.2.5 Diesel generator

When there is not enough storage on the battery bank, and it cannot supply the load, diesel generators are used to provide the load. The problem with a diesel generator is that its operating and maintenance costs are very high because it requires a continuous fuel supply. During the engine's operating life, it shall be regularly maintained and inspected. Diesel generators are most effective when they operate at their maximum output, but their efficiency will considerably decline when their load is lower as well [43].

When selecting a diesel generator, its output power should be sufficient to meet the needs of the system in case there is no power supply from other sources; fuel efficiency is also an important consideration; selecting a fuel-efficient generator leads to a lower operational cost of the system, lifetime of the generator is its operation hours, so generator should be reliable for long time operation without failure, to manage the efficient operation of the generator require regular maintenance. The size and brand of the diesel generator are the two factors that have the biggest impact on price. [43].

For this paper, the generator selected is the Generac Protector series automatic standby diesel generator-RD02025; its fuel is diesel oil, the rated power is 15 kW, the price of the select generator is $13500, and its life span is 15000 hours [44].

Figure 3.5: - Generac protector series 15 kW diesel generator-RD02025 [44]

3.2.6 Power production from PV/DG

The photovoltaic (PV) and DG are the systems that produce power to supply load. Optimized modeling involves determining the appropriate size of the system components that provide the necessary power supply to meet the demands of the village with zero unmet load. The system schematic structure is described in the figure below.

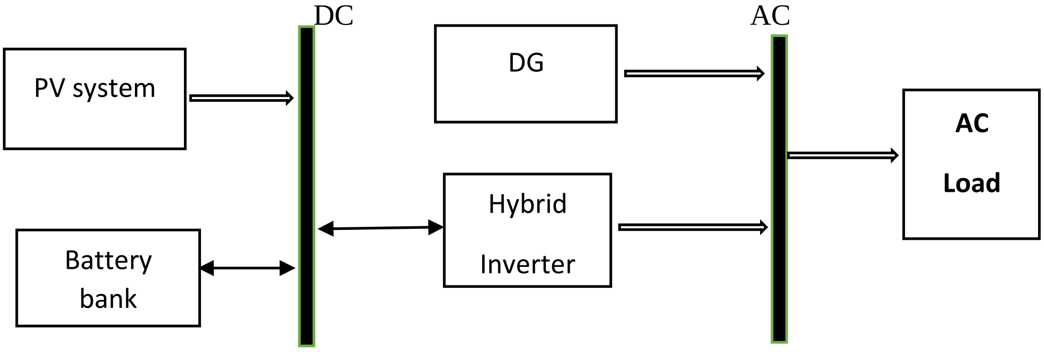

Figure 3.6: Schematic diagram of power generation model on HOMER software from PV/DG.

The HOMER optimization software study is made for component sizing of a PV system combined with a diesel generator, battery, and inverter for power generation to supply load demand.

Factors considered in operation include a derating factor of 98% applied to the PV system, accounting for factors such as shading and dust and the PV panel annual degradation of 0.45% from the third year onwards, and the battery must maintain a minimum state of charge of 30%. The projected project lifespan is 25 years.

HOMER software calculates hourly energy production throughout the year, and based on the calculation, the proposed size for each component is described in the table below.

Table 3.2: - Size of the component used for power production by PV/DG

Component	Size	Energy produced by PV&DG	Renewable fraction %
• PV	22 kW	42.8MWh/yr	87
• Diesel Generator	15 kW	6.4 MWh/yr	13
• Batteries	168 kWh		
• Hybrid inverter	13.6 kW		

PV system covers around 87% of production, and DG produces the remaining 13%. The total energy produced is approximately 49 MWh/year; from this, about 44 MWh/year will be consumed. The energy produced exceeds consumption by 5 MWh; HOMER also considers loss on the storage and converter.

From hourly production for the year, the following figure shows the load demand served, Generator output, PV output, and storage system charge and discharge for a day.

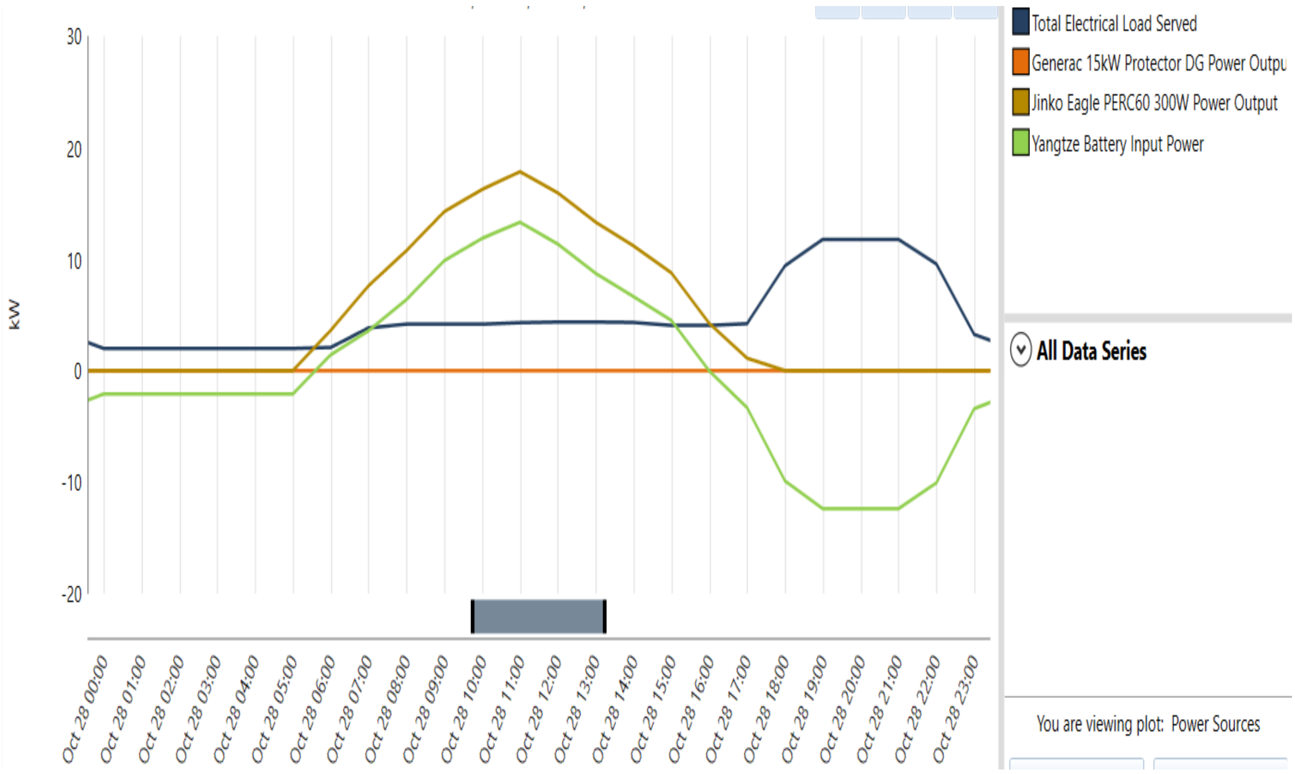

Figure 3.7: Hourly power production and consumption from PV/DG/Battery storage, October 28

3.2.7 Power production from PV/DG/wind

The proposed hybrid system predominantly harnesses renewable energy sources, specifically photovoltaic (PV) and wind power, complemented by a backup system consisting of Diesel generators and batteries. An essential component is the inverter, which converts the generated direct-current power into alternating-current power to serve the load.

Integrating wind power into the system is pivotal in achieving energy sustainability, mainly by reducing the dependence on the backup system during nighttime hours when PV production is inactive. The system configuration is visually represented in the figure below.

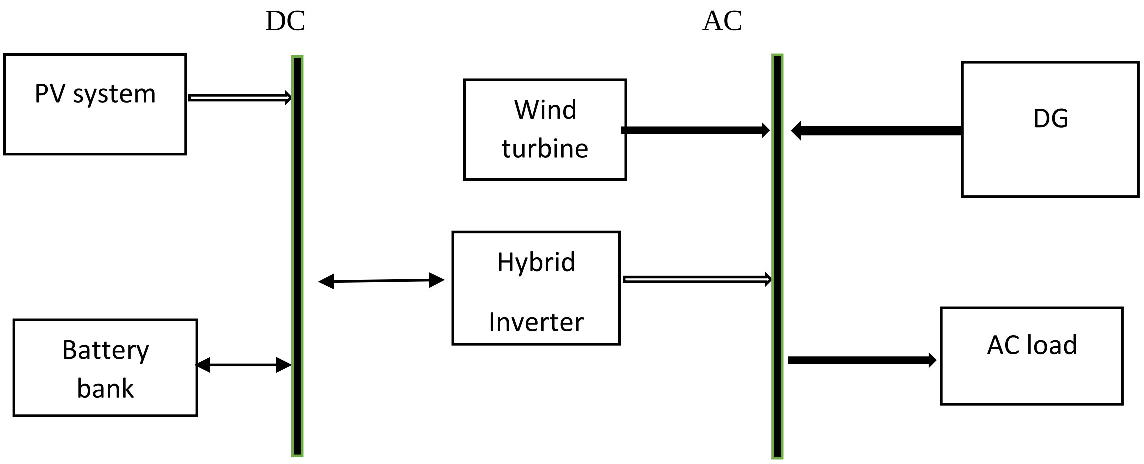

Figure 3.8: Schematic diagram of power generation model on HOMER software from PV/DG/wind.

In this scenario, the wind turbine is included, which could reduce the power generation from the diesel generator by increasing the renewable fraction. The projected lifetime of the project is 20 years. HOMER software calculated hourly power production for each hour in the year, and the feasible combination of the component sizes proposed by HOMER is shown in the table below.

Table 3.3: - Size of the component used for power production by PV/DG/Wind

Component	Size	Energy produced by PV&DG	Renewable fraction %
• PV system	22 kW	42.8 MWh/yr	92.4
• Wind turbine	10 kW	4.2MWh/yr	
• Diesel Generator	15 kW	3.9 MWh/yr	7.6
• Batteries	180 kWh		
• Hybrid inverter	13.6 kW		

PV and wind hybrid systems cover around 92.4% of production, and diesel generators produce the remaining 7.6%. The total energy produced is 50.9 MWh/yr; from this, around 44 MWh/year will be consumed. Adding wind power production helps increase the renewable fraction from 87% on the previous PV/DG system to 92.4% by reducing DG output.

Figure 21 shows daily consumption and production for a specific day, October 28; during the night, the load is supplied by both the battery and wind turbine, while during the daytime, there is power production from both wind and PV to supply the load and charge battery storage. The diesel generator will not operate because there is sufficient power to satisfy load demand from PV, wind, and battery.

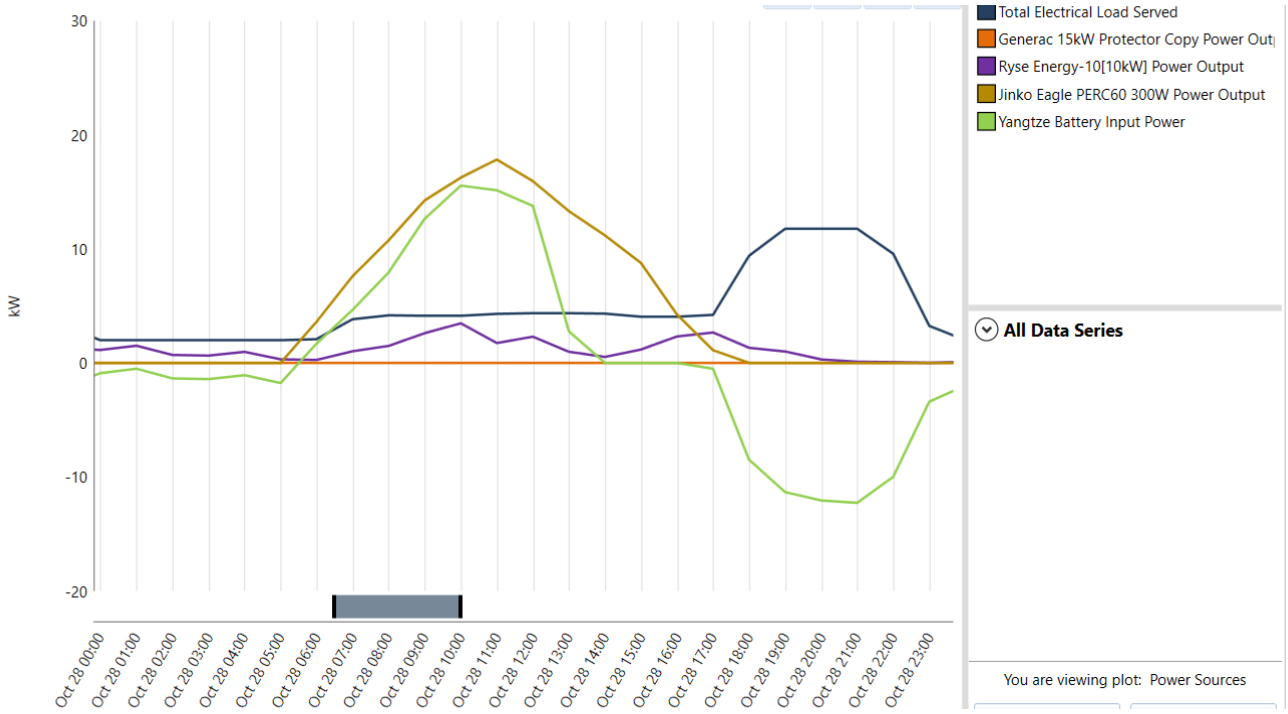

Figure 3.9: Hourly power production and consumption from PV/Wind/DG/Battery storage for the village on October 28.

3.2.8 Fuel Cconsumption calculation for DG

To analyze the technical and economic indicator of the generator, it is necessary to evaluate the fuel consumption dependency of the diesel generator on the degree of its load, using the linear relationship of fuel consumption characteristics with power generation for a diesel generator engine the following approximate formula can be used to determine specific fuel consumption for generating 1 kWh [56].

$$Q = K_{idle} . Qn + (1 - K_{idle}). Q.\frac{Pout}{Prated} \ [g/kWh] \ldots\ldots\ldots\ldots \quad 3.3$$

Pout -is the actual power produced by the generator.

Prated- is the rated capacity of the DG.

K_{idle}- is the no-load fuel consumption coefficient of a diesel engine it can be approximated to 0.3 [56]

Q and Qn -are the actual and the nominal fuel consumption rates. Most engines' nominal fuel consumption is (Qn= 250 g/kWh) [56].

The fuel consumption for the corresponding volume of energy generated by the DG over the given period can be calculated by

$$M = Q. E_{gen}$$

M: - is annual fuel consumption, and Q: - is specific fuel consumption, which can be calculated by the above formula. E_{gen} is energy generated by diesel generators to supply the village's load demand when RE generation and battery storage are insufficient. Egen by DG for both PV-DG and PV-DG-Wind systems is 6.4 MWh and 3.9 MWh, respectively. Based on the above two formulas and information on the energy generated in both scenarios, fuel consumption is calculated as

M = 1358 kg for PV-DG hybrid system and,

M = 828 kg for PV-DG-Wind hybrid system.

3.2.9 Emission calculation

The annual emission of carbon dioxide (CO2) is a critical parameter in assessing the environmental impact of energy consumption, particularly in the context of fossil fuel combustion. As a primary greenhouse gas, CO2 contributes significantly to climate change. [53]. For CO2 emissions from fuel consumption for energy generation, the following formula may be used for the calculation: [54].

$$CO_2 = M. K_1 . Ncv. K_2 . \frac{44}{12} \ldots\ldots\ldots\ldots \quad 3.4$$

CO2- is annual emissions in (tons/year)

M- is fuel consumption per year (tons/year)

K_1-is coefficient of carbon oxidation in fuel (shows the proportion of burned carbon) =0.99

Ncv- net calorific value (J/ton) = 43.02

K_2- carbon emission factor (tons/J) =19.98

$\frac{44}{12}$ -is the conversion factor of carbon into carbon dioxide

Using the above formula and fuel consumption for both the PV-DG and the PV-DG-Wind hybrid system, I calculated the amount of CO_2 emission as follows.

Annual CO_2 emission by DG on PV-DG system:

CO_2 = (1.358). (0.9). (43.02). (19.98). (44/12) =3852 tons.

Annual CO_2 emission by DG on PV-DG-Wind system:

CO_2 = (0.828). (0.9). (43.02). (19.98). (44/12) =2348 tons.

Chapter Four

4 Project evaluation with economic parameters.

4.1 Evaluation criteria

Project evaluation is an essential process that helps determine the effectiveness of the project and provides necessary data and information for decision-making by assessing the feasibility and economic viability of the project by analyzing cash flows and potential return on investment. NPV, IRR, and payback period are valuable tools for project evaluation [20].

•Net Present Value (NPV)

The investor favors projects that offer greater value than their costs and evaluates them using NPV, representing the current worth of a project's cash inflows when weighed against its expected lifetime cash outflows [45].. If the NPV is positive, it indicates that the project is profitable, increases investor value, and is attractive to invest in. Zero NPV suggests the return on the investment is the same as the expected rate of return or discount rate, and the project may still be acceptable; however, if NPV is less than zero, it is not acceptable to invest [20].

[20] Net Present value can be calculated using the formula: -

$$\text{NPV}= \mathrm{C}_0 + \sum_{t=1}^{T} \mathrm{C}_\mathrm{t} \,.\, (1 + \mathrm{r})^{-\mathrm{t}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 4.1$$

Where C_0 is the initial investment

T is the lifetime of the project,

r is discount rate,

C_t is cash flow at t year.

• Internal Rate of Return (IRR)

IRR is a financial indicator used to assess the profitability of potential projects. It is the discount rate required to achieve zero net present value for an investment. When considering a possible project, IRR is compared with a required rate of return (discount rate); the IRR rule is to accept investment on the project if the discount rate is less than the IRR and to reject if the discount rate is greater than the IRR [20].

Calculating IRR:

$$\text{NPV} = \frac{\mathrm{C1}}{1+\mathrm{IRR}} + \cdots + \frac{\mathrm{Ct}}{(1+\mathrm{IRR})^{\mathrm{T}}} + \mathrm{C}_0 = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 4.2$$

NPV: - Net Present Value

IRR: - internal rate of return

T: -project lifetime

C_{0}: - initial investment

C1… Ct: - is cash flows at t years.

- **Equivalent Annual Annuity(EAA)**

An Equivalent Annual Annuity (EAA) is a financial metric used to evaluate the cost-effectiveness of investment projects or assets with varying lifespans. It represents the equal annual cash flow received or paid over the asset's life, which would result in the same present value as the cash flows of the investment being evaluated. The EAA calculation is practical when comparing projects or investments with different durations, making it easier to assess their relative profitability on an annual basis. EAA can be calculated using the formula [20].

$$EAA = NPV.\ a_{T} \quad \text{………………………………………………………} \quad 4.3$$

NPV is the net present value of the cash flows.

$$a_{T} = \frac{(1+r)^{T}.\ r}{(1+r)^{T}-1}$$

a_{T}: - is the annuity factor, T is project lifetime, and r is the discount rate.

4.1.1 Input parameter for evaluation criteria

It is essential to take into account all significant input parameters when calculating the evaluation criteria, including the discount rate, inflation, expenditure (which includes the project's initial investment), and operating expense (which includes fuel costs, maintenance costs, loan interest if the project is financed by a loan), as well as personal and environmental costs related to CO2 emissions.

- **Discount rate**

[20] A discount rate is the rate of return an investor wants from investing in a specific project. I used CAPM to estimate the required rate of return on investment. The formula to calculate the discount rate is

$$r = rf + \beta.\ (rm - rf) \quad \text{……………………………………………..} \quad 4.4$$

Where rf is a risk-free return on risk-free investments, β is the systematic risk of the investment, and (rm - rf) is the risk premium investors require for investing in risky businesses.

[46] According to the Development Bank of Ethiopia, for long-term bonds interest rate payment is 6%; therefore, the risk-free return is 6%. Since Ethiopia has no stock market exchange, it is impossible to have sufficient historical data to estimate a reasonable risk premium. I decided to use the risk premium for the mature market and add the country's risk premium.

[47] To calculate the mature market risk premium, the S&P 500 historical data for 10 years shows that the market return is 8.5%, and the US 10-year government bond is 3.5%. So, the risk premium for a mature market is 5%. To calculate the equity risk premium (ERP) for Ethiopia, Moody's rating for credit is Caa2.

ERP = Risk premium of mature market + country risk premium

[47] Country default spread provides an important step to measure country risk premium, but it only measures premium for default risk; country risk premium (CRP) on equity can be calculated based on the formula below to scale the default spread up to reflect higher equity risk in the market.

CRP= (country default spread). (Average relative Volatility Multiplier)

[47] credit default spread for Ethiopia is 9.63%, and the average relative volatility multiplier is 1.42.

ERP= 5% + (9.63%). (1.42) = 18.67%

Estimating beta for a firm that does not have publicly traded stock can be done by using a comparable firm's unlevered beta and adjusting for the levered beta for the specific company; adjusting both levered and unlevered beta can be done by using the following formula [60].

$$\beta_l = \beta_u . (1 + (1-t) . \frac{D}{E})) \ldots\ldots\ldots\ldots\ldots\ldots \quad 4.5$$

β_{l}: - levered beta

β_{u}: - unlevered beta, since there is no publicly traded company in the power sector in Ethiopia, I took unlevered beta for the power sector for the emerging market ($\beta_u = 0.53$) [48].

1-t: -is a tax shield and, the tax rate in Ethiopia is 30% [50].

$\frac{D}{E}$: - is debt to equity ratio, I assumed the debt-to-equity ratio is 50%

Based on the above information I calculated $\beta_l = 0.715$

The discount rate for the project is r = 19.34%

- **Inflation**

Inflation is an increase in the price of services and goods over time; inflation decreases the purchasing power of money, and future cash flow needs to be inflation-adjusted because of the current global economic situation, including covid-2019 impact and mainly internal political unrest and security situations, are the main reasons for sharp inflation rate rise in Ethiopia from 2019 to 2022 [55]. The historical inflation rate recorded in Ethiopia by the Ethiopian Statistical Agency is shown in the figure below [49].

Table 4.1: -Historical inflation rate in Ethiopia [49]

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Inflation %	13.9	8.1	7.7	9.7	7.0	14.4	12.6	19.9	20.1	33.7	32.6

From this historical inflation rate, the average value of the inflation rate is 16.3%.

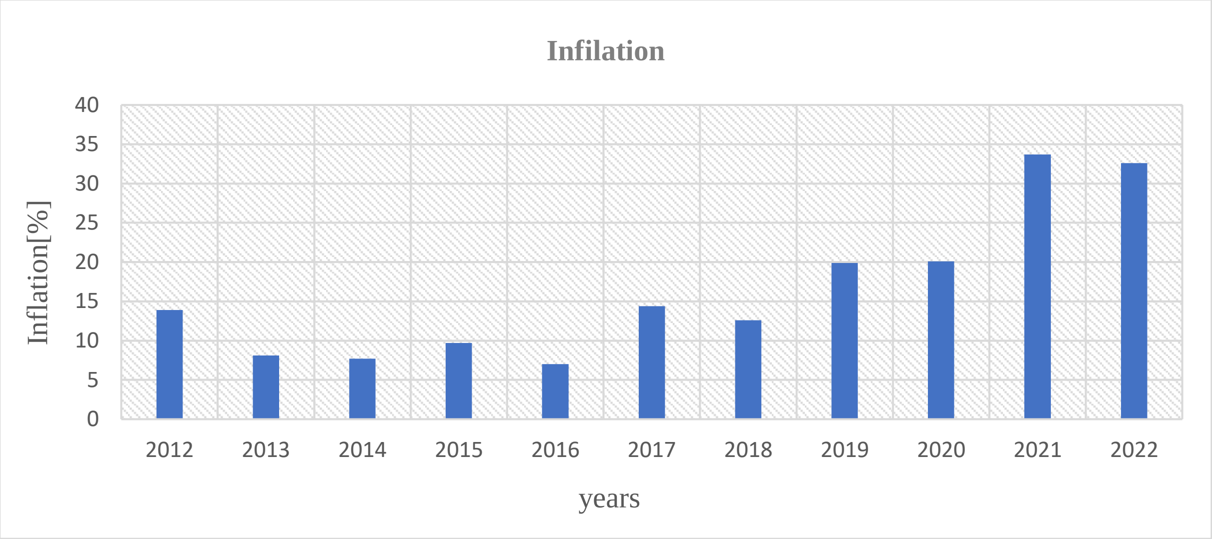

Figure 4.1: Historical inflation rate in Ethiopia [49].

- **Escalation rate**

The escalation rate indicates the change in the cost of specific goods or services in the specified period. According to the Ethiopian Statistical Agency, the escalation rate of electricity and fuel consumption in Ethiopia has sharply increased for the last four years [49]. The historical escalation rate is described in the table below.

Table 4.2: -Historical Escalation rate for electricity and fuel in Ethiopia [49]

Year	2012	2013	2014	2015	2016	2017	2018	2019	220	2021	2022
Inflation %	15	10.6	8	8	7.4	15.8	12	15.8	16.4	25	33.8

From this historical escalation, the average value of escalation is 15.25%; I will use the average escalation rate for the escalation of fuel cost and electricity price in the cash flow model.

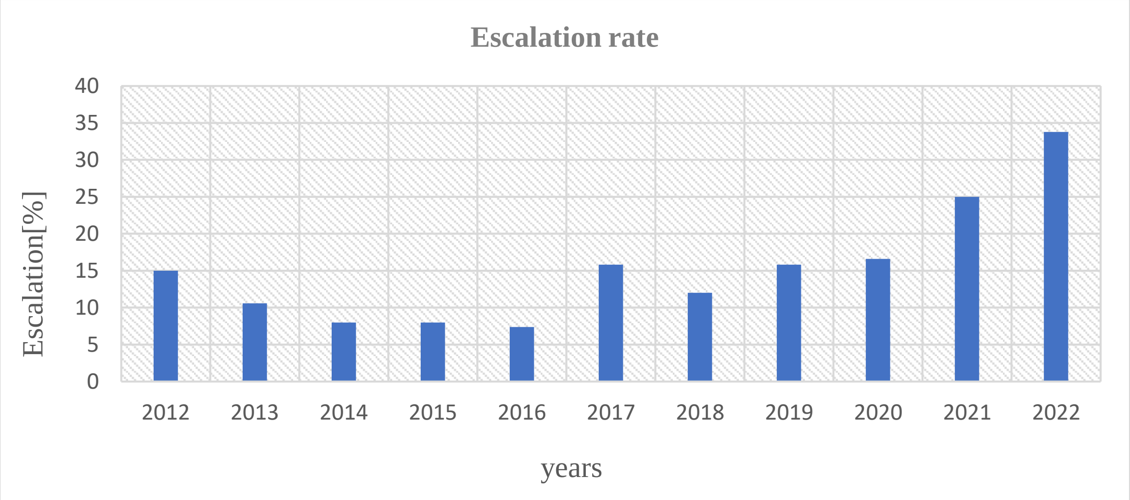

Figure 4.2: Historical escalation rate in Ethiopia on fuel.

- **Corporate tax rate**

The corporate tax rate is the percentage of the income generated by businesses required to be paid as a tax to the government. Tax is levied on the profits earned by the company after deducting allowable business expenses; the corporate tax rate varies from country to country; some nations impose high rates, and the corporate income tax (tax on profit) in Ethiopia is 30 percent [50].

- **Depreciation**

Deprecation is used to allocate the cost of an asset over its useful life. It reflects the decrease in the value of an asset over time due to wear and other factors, and it is used as a tax shield. Different methods can be used to calculate the asset's depreciation, such as straight-line and accelerated methods [51]. The formula to calculate depreciation is as follows.

2) Straight line deprecation method

$$\text{Depreciation at year 1} = \frac{1}{T} \cdot \text{Capex}$$

where Capex is for capital expenditure on the asset, and T useful life of the depreciable asset.

3) Accelerated depreciation method.

$$\text{Depreciation at year 1} = \frac{1}{T}$$

$$\text{Depreciation at year t} = \frac{2.\ (T-t+1)}{T^2} \cdot \text{Capex}$$

According to Ethiopian income tax regulation, Taxpayers choose from the straight line and accelerated depreciation and use the same method of deprecation in the financial account and for all depreciable assets [52].

- **Land rent expense**

[57] As per the Federal Democratic Republic of Ethiopia's constitution, land is the property of the state and the people of Ethiopia. Both urban and rural land is available for investment on a leasehold and rental basis. The value of the land for rent in the SNNPR, Hadiya zone, is 103 Ethiopian Birr per hectare per year [57]. Since the rent value is so small that it will not be significant in the cash flow calculation, I decided not to consider rent expenses.

- **Installation and Transportation cost**

All the components are selected from the manufacturer’s websites, and their costs also include the shipping cost. The installation cost and transportation of the component to the project site are very uncertain and depend on different factors, including the location of the site, the technician, and the person selected to transport the component. By considering all these factors, I assumed 10% of the initial investment for installation and transportation costs.

. Initial investment for the power generation components

The initial investment for the first scenario includes costs for the components, which include the costs of the PV panels, inverters, battery bank, and diesel generator, as well as transportation and installation. The initial investment costs for each component are described in the following tables below. Using the USD ($) and Ethiopian Birr, the exchange rate from USD to Ethiopian Birr is 56.7 based on Commercial Bank of Ethiopia exchange rate information [61].

Table 4.3; - Components cost for PV-DG hybrid system.

System	Size	Cost in USD ($)	Cost in Ethiopian birr (Birr)
PV panels	22 kW	7,260	411,642
Inverter	13.6 kW	8,778	497,712
Diesel generator	15 kW	14,850	841,995
Battery bank	168 kWh	12,320	698,544

The total initial investment of the power generation components is $ 43,208 (2,449,893 Birr). The lifespan of the battery and inverter is 10 years, and since the project life is 25 years, both components will be purchased at the 10th and 20th years and replaced at 11 and 21 years, respectively. The diesel generator's expected service life is 13 years, and the replacement cost of the components will be calculated using the inflation factor on the current component price as follows:

$$Rc = Ic.\ (1+ Inf)^{T}$$

Rc – is the replacement cost of the components, Inf- is the inflation rate, I_C -is the initial cost of the components, and T-is the year where the component was purchased.

The replacement cost for the battery is:

For the first replacement = $(698{,}544).\ (1+ 0.163)^{10} =$ 3,162,211 Birr.

Second-time replacement = $(698{,}544).\ (1+ 0.163)^{20} =$ 14,314,891 Birr

Since the life span of the battery is 10 years, there will be a salvage value after the second replacement of the battery. The salvage value can be calculated as follows:

Salvage value = cost of the asset minus accumulated depreciation (I used the straight-line depreciation method).

$$= 14{,}314{,}891 – (\frac{14{,}314{,}891}{10}).5 = 7{,}157{,}445 \text{ Birr}$$

The replacement cost for the inverter is:

First-time replacement = $(497{,}712).\ (1+ 0.163)^{10} =$ 2,253,072 Birr.

Second-time replacement = $(497{,}712).\ (1+ 0.163)^{20} =$ 10,199,347 Birr

Salvage value of Invertor = 10,199, 347 - $(\frac{10,199,347}{10})$.5 = 5,099,674 Birr

The replacement cost for the DG= (841,995). (1+ 0.163)^{13} = 5,995,781 Birr.

Salvage value of the DG= 5,995,781 - $(\frac{5,995,781}{13})$ .12 = 461,214 Birr

The initial investment for the second scenario includes costs for the wind turbine, inverters, battery bank, diesel generator, and PV panels.

Table 4.4; - components cost for PV-DG-Wind hybrid system.

System	Size	Cost in USD ($)	Cost in Ethiopian birr (Birr)
PV panels	22 kW	7,260	411,642
Inverter	13.6 kW	8,778	497,712
Diesel generator	15 kW	14,850	841,995
Battery bank	180 kWh	13,200	748,440
Wind turbine	10 kW	49,500	2,806,650

The total initial investment in the power generation components is $93,588 (5,306,439 Birr). The life span of the project is 20 years, and the battery and inverter will be replaced in the 11th year. The life span of the DG is 13 years. The DG will be purchased in the 13th year and replaced in the 14th year.

The replacement cost for the Inverter= (497,1712). (1+ 0.163)^{10} = 2,253,072 Birr.

The replacement cost for the battery = (748,440). (1+ 0.163)^{10} = 3,388,083 Birr.

The replacement cost for DG= (841,995). (1+ 0.163)^{13} = 5,995,781 Birr.

salvage value of the DG= 5,995,781 - $(\frac{5,995,781}{13})$ .7 = 2,767,283 Birr

- **Distribution system cost**

Since there is no national grid transmission and distribution line in the village, the generated power from the off-grid hybrid system will be distributed through the distribution line. According to [68], for the low-voltage off-gird, the main components in the distribution line are conductor cables, poles, insulators, and surge protectors. The distribution transformer can also be used to increase the system's efficiency if the mini-grids cover a large area. The proper conductor size should be selected to reduce the voltage drop, and the maximum voltage drop should not be higher than 5% for the feeder (distribution) line. The pole height from the earth should not be lower than 6 meters, and the minimum distance between the two poles could be in the range of 30–50 meters.

For this project, the generation site location is assumed to be at the center of the village, a single-phase 220V two-wire feeder line is taken from the generation site to the consumer, and the total length of the distribution line is assumed to be 2.5 km. A wooden pole is considered to support the distribution line, and 30 meters between the two poles is considered. A distribution transformer will not be used.

The price of a bare copper wire conductor with a cross-sectional area of 29 mm2 is \$0.95 per meter [69], the price of a spool insulator is \$3 per piece [70], and by considering the local availability of the trees, I considered \$20 per piece for a wooden pole. According to [71], the service life of distribution facilities is 30 years.

Table 4.5: Distribution system component cost.

	Quantity	Unit cost (\$)	Total cost (\$)	Total cost (Birr)
Bare copper conductor (29 mm^2)	5000meter	0.95 per meter	4750	269,325
Wooden pole 6-meter	84	20	1680	95,256
Spool insulator	168	3	504	28,576
Other cost (20%)			1387	78,642
Total cost			8321	471,800

For the transportation and installation of the distribution system, I considered 10% of the total cost of \$832 (47,180 Birr). The total estimated cost for the distribution line is \$9,153 (518,975 Birr). This cost is only for the main distribution line; I assumed the cost of the connection for each consumer from the distribution line would be covered by the consumer during the connection.

- **Operating and maintenance cost**

Maintenance costs for RES depend on different factors, like the location of the project site, system types, system component size, and environmental conditions. Main maintenance activities include cleaning and inspecting all equipment, checking the cabling system, and inspecting battery connections and inverter settings [58]. I considered 2% of the initial investment for the operation and maintenance cost of PV panels yearly; the battery and inverter are considered maintenance-free.

Operating and maintenance costs for wind can be measured annually based on capacity based on \$/kW/yr. Wind turbine operating and maintenance cost estimates vary widely. For small wind turbine capacities of 1–10 kW, operating and maintenance energy costs are between \$2 and \$4/kW, and annual costs can go up to \$75/year [58]. Maintenance costs for diesel generators depend on the operating time. When the operating time is shorter, the maintenance cost is smaller, and the operational lifetime increases. The maintenance schedule varies on a daily, weekly, monthly, and yearly basis. The typical maintenance cost is 0.02\$/kWh [62]. I assumed 2% of the initial cost for the maintenance of the distribution system.

- **Financing of the project**

This project can be financed using investor equity, or part of the investment can be financed by a loan from the government bank. For financing by loan, the Commercial Bank of Ethiopia provides term loans, which are loans for working capital or project financing. These can be short-term for up to one year, medium-term for up to five years, and long-term for over five years. The interest rate differs for each term; I considered a long-term loan, which is 16.5% [63].

- **Fuel expense**

For the proposed hybrid PV-DG and PV-DG-Wind systems, DG generates 6.4 MWh and 3.9 MWh yearly, and the annual fuel consumption for the generated power is calculated at 1358 kg and 828 kg, respectively.

According to [64], the density of the diesel fuel is 0.873 kg/l. Based on this information, annual fuel consumption is 1556 liters for the PV-DG system and 948 liters for the PV-DG-Wind system.

[65] The diesel fuel price in Ethiopia is 79.75 birr per litter. Using all the inputs, fuel expenses are calculated for the first year in both scenarios as follows:

The fuel expense for the PV-DG system = (79.75). (1556) = 124,091 Birr.

The fuel expense for the PV-DG-Wind system =(79.75). (948) = 75,603 Bir.

The above expense will be recalculated with an escalation rate from the second year to the project's lifespan.

- **Personal expense**

For the proposed system, I assumed 2 electricians to monitor the operating conditions of the system, and according to [66], the average monthly salary expenditure for employees working in the energy sector in Ethiopia is $100 (5,670 Birr). Employers are required to contribute 11% of their salary to social security [67].

Personal expense = (2). (5,670). (1+0.11). (12) = 151,048 Birr

For the following year, T, the personal expenses will be recalculated using the inflation rate as follows:

Personal expenses = 151,048. $(1+\text{inf})^{T}$, inf is the inflation rate.

- **Revenue from selling electricity.**

Revenue generated from electricity sales can be calculated using currently existing electricity prices in Ethiopia. According to the Ethiopian Electricity Utility, electricity tariffs are classified into business and household tariffs; for households, the tariff is also classified into a different block; for consumption up to 300 kWh per month, the tariff is 2 Ethiopian Birr per kWh [59]. Since the proposed power consumption for the village is very low, this tariff is used to calculate the revenue.

$$\text{Revenue} = \text{Econ}.\ 2\ \text{Birr/kWh}$$

Econ is the village's yearly energy consumption [44,000 kWh/year].

Revenue = 44000 kWh. 2 Birr/kWh = 88,000 Birr; this value will change annually with the escalation rate, as follows:

Revenue in a year t =88,000. $(1+\text{escalation})^{t}$ Birr

The above result is based on the Ethiopian electricity utility tariff. In the next economic model, I will also calculate the minimum price for selling electricity to investors and compare it with the current existing tariff.

4.2 The economic model calculation result

I did a cash flow model on an Excel sheet and calculated the NPV and EAA for both scenarios. On the cash flow model, for cash inflow, I used the existing electricity price to sell electricity to the village consumers, and for cash outflows, I included all the expenses related to the project, which I discussed in the above section. Based on the cash flow calculation, both projects have negative net present values. Since the project lifetimes for both scenarios are different, I used EAA to compare which project is better. The calculation results for both projects are shown in the following table below.

Table 4.6: - Economic model calculation result

	Scenario 1	Scenario2
• NPV	-8,619,831 Birr	-9,456,841 Birr
• EAA	-1,667,076 Birr	-1,883,821 Birr

Based on EAA value, the PV-DG-Battery system is better than the PV-DG-Wind-Battery system.

Since investors do not prefer to invest in a project with a negative NPV, I calculated the minimum price for both variants, which means the investor would sell at a minimum price to get the return, which is equal to the discount rate.

The calculated minimum price is: -

- $ 0.267/kWh (15.18 Birr/kWh) for PV-DG-Battery, and
- $ 0.333/kWh (18.92 Birr/kWh) for PV-DG-Wind-Battery system projects.

The minimum selling price calculated for both variants, 15.18 Birr/kWh and 18.92 Birr/kWh, are significantly higher than the current electricity price, which is 2 Birr/kWh for low block consumption.

The electricity tariffs in Ethiopia are currently noted to be among the lowest in sub-Saharan Africa, falling below the actual cost of generation. The data from the Ethiopian Electric Utility (EEU) indicates that the current tariff falls significantly short of covering the actual expenses, with a substantial subsidy for low-block consumers relative to the generation cost. This considerable subsidy underscores a financial gap between the tariffs collected from consumers and the true costs associated with electricity generation, posing challenges to sustaining the sector's economic viability. Addressing this difference is crucial for ensuring the long-term financial sustainability of the energy infrastructure and fostering continued growth in the Ethiopian electricity sector [73].

4.3 Sensitivity Analysis

Sensitivity analysis is used to investigate the effect that a change in the value of various variables would have on the particular NPV. Finding the factors that affect the project and identifying the critical variable that affects the project the most are helpful [72].

Sensitivity analysis will be performed to see the effect of changes in the NPV when the following parameters change:

- discount rate,
- bank loan,
- electricity price
- fuel prices.

Before going to sensitivity analysis, it is necessary to see the NPV calculation formula and the relationship with each component.

NPV= $\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$ from this formula, C_t is cash flow at year t, and r is the discount rate [20].

The detailed formula to calculate cash flow is explained as follows:

$$C_t = (R_{se,t} - N_{ovc,t} - N_{ofc,t} - D_{ep,t} - I_{ntr,t}).(1-Tax) + D_{ep,t} - L_{p,t} - N_{inv,t}$$

Where $R_{se,t}$ is revenue from selling electricity, $N_{ovc,t}$ is operating variable costs, $N_{ofc,t}$ is operating fixed costs, $D_{ep,t}$ is depreciation, $I_{ntr,t}$ is interest on bank loan, $L_{p,t}$ amortization on loan, and $N_{inv,t}$ is investment cost including initial investment and replacement costs. Based on the above formulas it could be possible to see the effect of change in input parameters on the NPV.

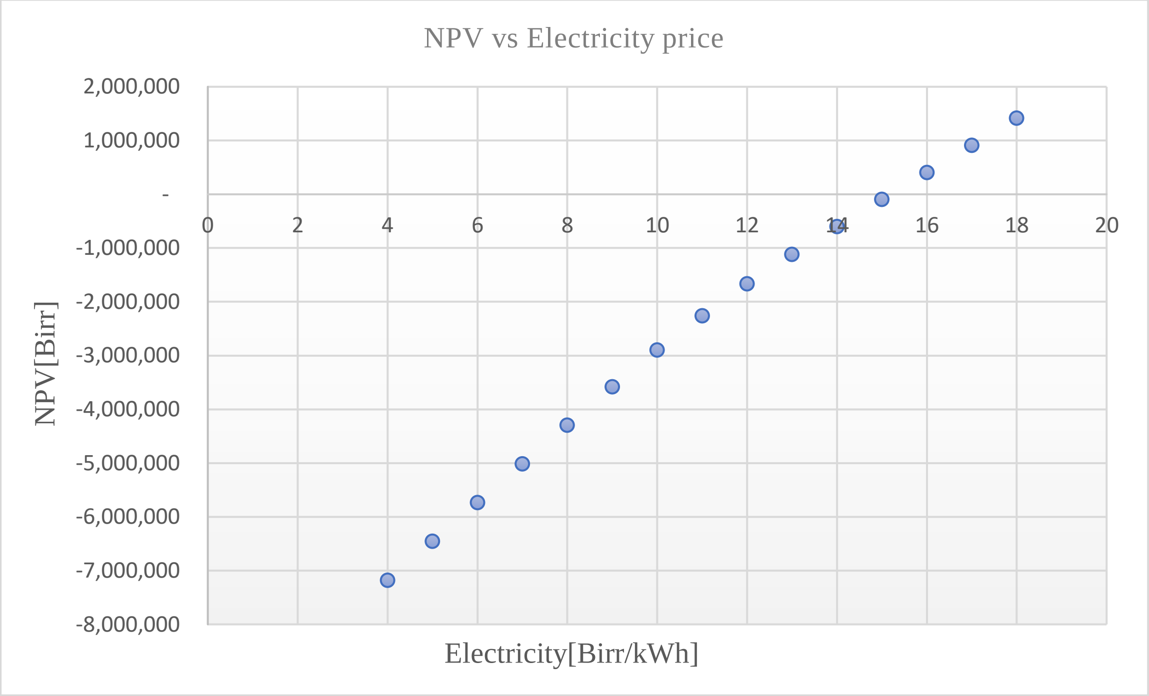

Figure 4.3: Effect of electricity selling price on NPV

The above figure shows the direct relationship between the selling price of electricity and NPV. As calculated above, the breakeven point for investors to sell electricity to the village is \$0.267/kWh (15.18 Birr/kWh). Selling below this value will make the NPV value negative, which investors would not like to do, and any price above the minimum price will also make the NPV positive.

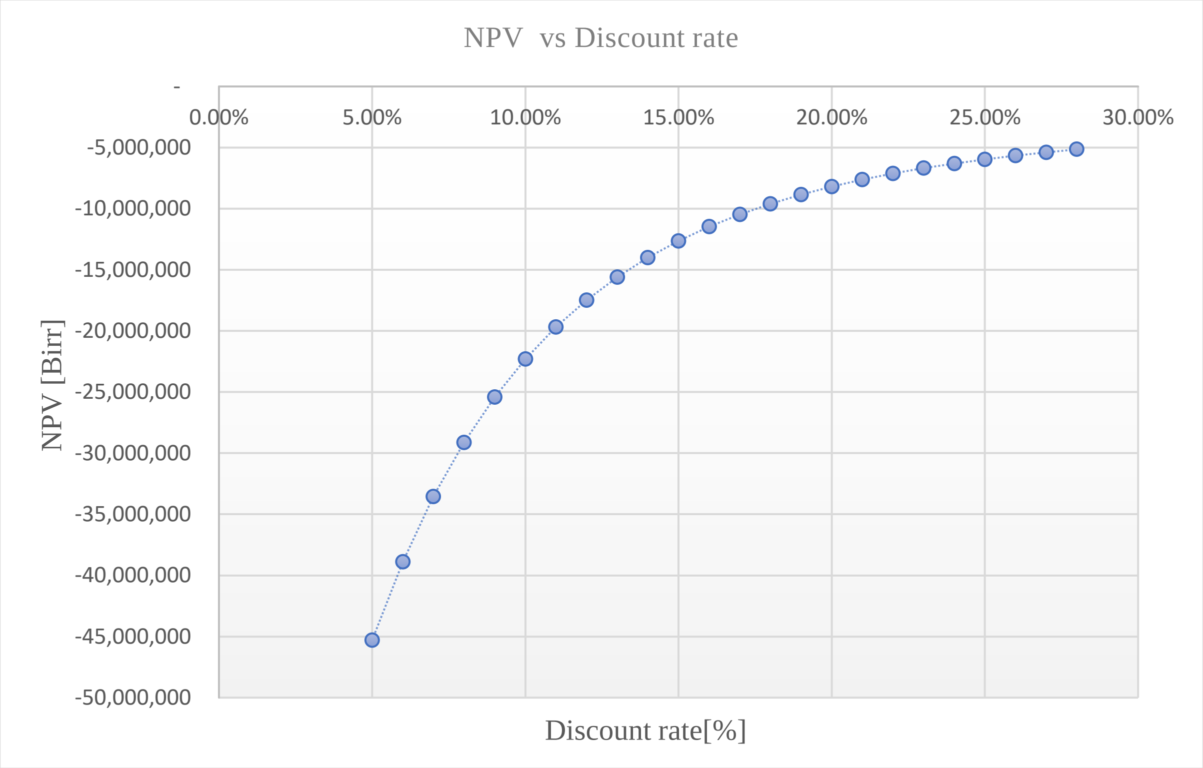

Figure 4.4: - Effect of changing discount rate on NPV

There is an inverse relationship between NPV and discount rate; the higher the discount rate, the lower the NPV. This is because future cash flows reduce in value when discounted at a higher rate. The above figure shows that NPV is increasing with an increasing discount rate, which is because of the negative cash flow.

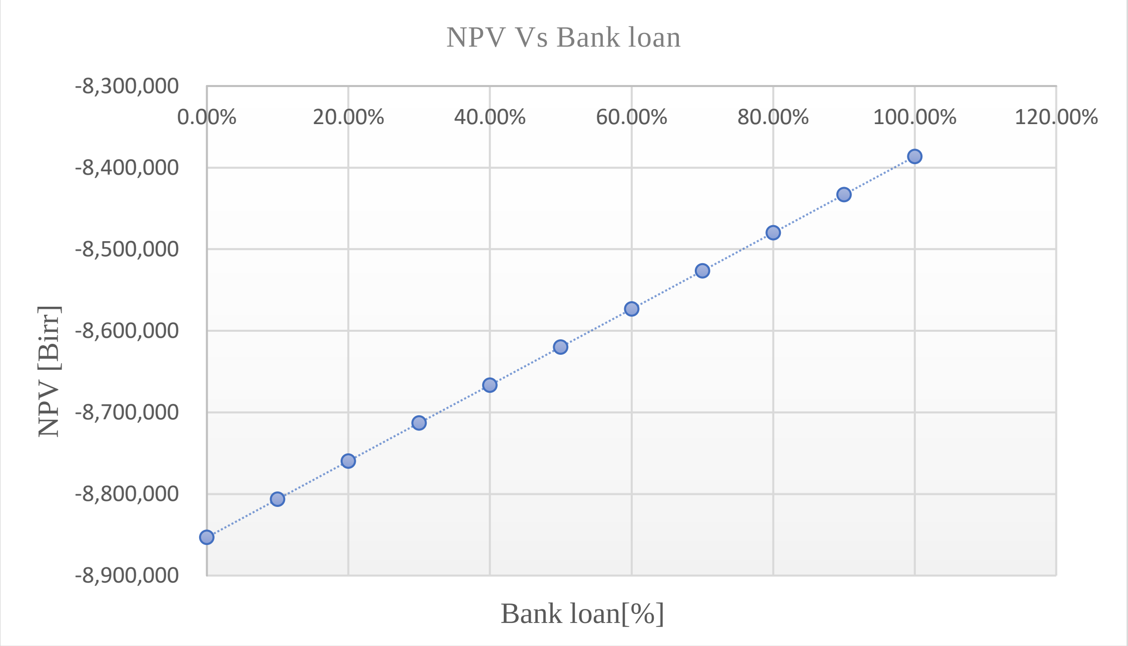

Figure 4.5: Effect of changing project financing by loan on NPV

From the NPV and bank loan relationship in the above figure, the financing method of the project has a direct effect on the NPV. Investing in a project by loan helps the project investor spread the investment cost over the project duration.

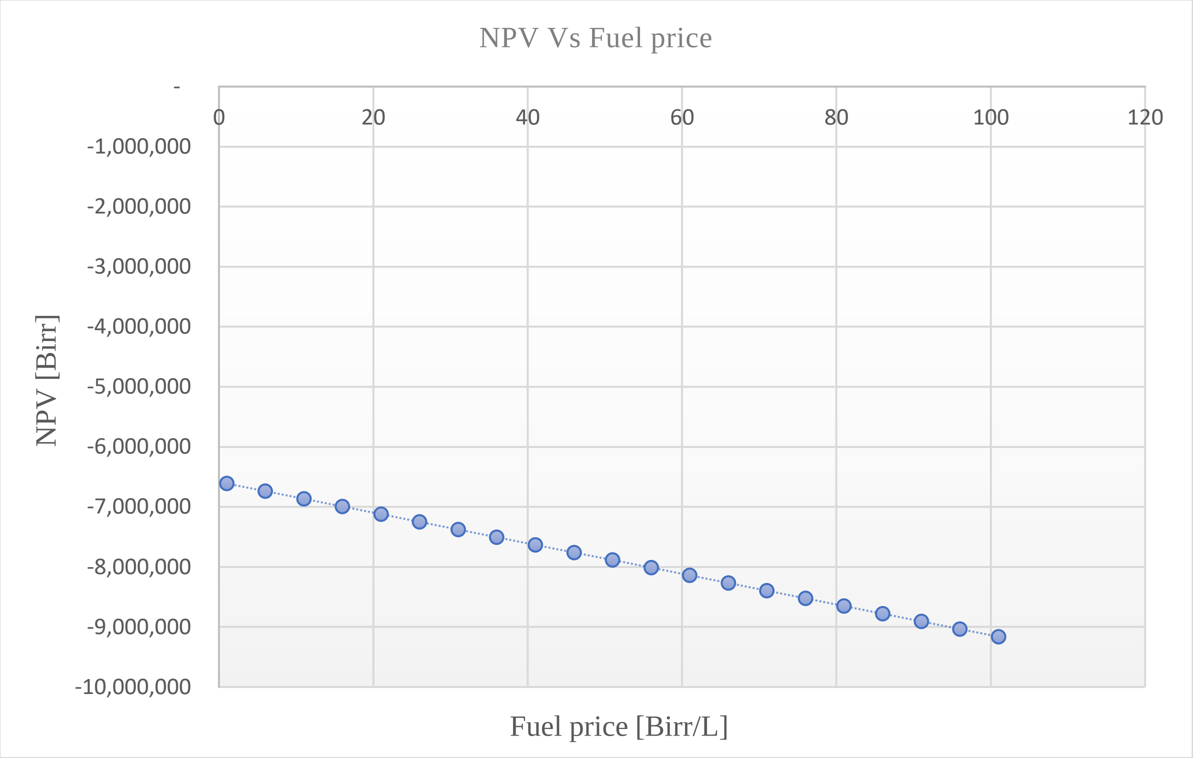

Figure 4.6: Effect of fuel price on NPV

Fuel cost is the operating cost of the project, which means operating costs have an inverse relationship with the NPV because they increase cash outflow. The above figure shows the effect of the diesel fuel price change on the NPV.

Chapter Five

5 Conclusion and recommendation

5.1 Conclusion

This paper focused on the feasibility study of power generation from a hybrid power system to supply electricity to Wagesho village, which has no access to electricity. Firstly, the energy resource potential for both wind energy and solar energy was assessed for the village. From the result of the energy resource potential assessment, solar energy potential is 5.71 kWh/m2, which is higher than the average exploitable potential in Ethiopia, which is 5.5 kWh/m2 [13]. For wind energy potential, the wind speed for the village based on five years (2017–2021) of average data from NASA at the height of 10m is 2.13 m/s. The extrapolated average wind speed at the height of 36m is 2.75 m/s, which can be classified as a poor class with a very low power density. Based on the energy potential assessment, an off-grid hybrid electric power supply system is conducted for 215 households in the village.

Since both solar and wind energy sources are not reliable because of their intermittent nature, I decided to design a hybrid system combining solar, wind, and a backup system that includes DG and batteries. For the hybrid system, I considered two scenarios. The first scenario is combining the PV-DG battery system with a system size of 22 kW PV, 15 kW DG, and 168 kWh battery capacity. For the second scenario, I designed the PV-DG-Wind-Battery system with a system size of 22 kW PV, 15 kW DG, 10 kW wind turbine, and 180 kWh battery capacity. In the first scenario, the renewable fraction is 87%, the remaining 13% is covered by DG, and the annual CO_2 emission is 3852 tons. In the second scenario, the renewable fraction is 92.4%, and the rest 7.6% is generated by DG, with annual CO2 emissions of 2348 tons.

Economic analysis is conducted for both PV-DG-battery hybrid power supply systems and PV-DG-wind-battery hybrid power supply systems. Using the cash flow model, the NPV is calculated using the current electricity price in Ethiopia, which is 2 Birr/kWh, and the NPV result is -8,619,831 Birr (-$152,025) for the first scenario and -9,456,841 Birr (-$166,787) for the second scenario. Investors would not invest in the project with a negative NPV, so the minimum electricity selling price is also calculated for the external investor to invest in this project to get the return, which is the same as the discount rate, and the result is 15.18 Birr/kWh ($ 0.267/kWh) for the first scenario and 18.92 Birr/kWh ($ 0.333/kWh) for the second scenario. In both cases, there is a big difference when compared with the current electricity price in Ethiopia.

Sensitivity analysis is also conducted to see the effect of different variables on NPV. The effect of changing the discount rate, loan, and fuel price on NPV is also examined, and increasing financing by loan has a positive effect on NPV. However, an increase in the discount rate, and fuel price has a negative relationship with NPV.

5.2 Recommendation

The risk for investors to invest in this type of project is consumer-side risk. This risk will impact the investor's ability to finance the project. The potential problem regarding the end-user risk is rural HHs lack of ability to pay the bill due to the economic conditions and lack of finance for appliances and connection fees. The comparison of the subsidized grid electricity price with the investor's selling price will also reduce the social acceptance of the mini-grid projects. To address these concerns, the GoE should consider implementing measures to enhance the financial capacity of rural HHs, such as targeted subsidies or financial assistance programs. Additionally, raising the current electricity tariff and another effort to reduce the minimum selling price for an investor including a reduction in the cost of financing, tax exemptions, and operational subsidy to power generation (green bonus).

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Appendices

Appendix A: Technical specification

Technical data for Ryse Energy E-10 10KW wind turbine

Generator	• Type	Permanent magnet
	• Rated power	10 kW
Rotor	• Configuration	Horizontal
	• No of blades	3
	• Blade length	4.5 m
	• Rotor diameter	9.8 m
	• Swept area	75.8 m^2
Wind	• Cut-in speed	2 m/s
	• Rated speed	9 m/5
	• Cut-out speed	30 m/s
Tower	• Lattice tower	15-36 m
Design parameters	• Life span	20 years

Technical data for Eagle PERC 60 300 model solar panel

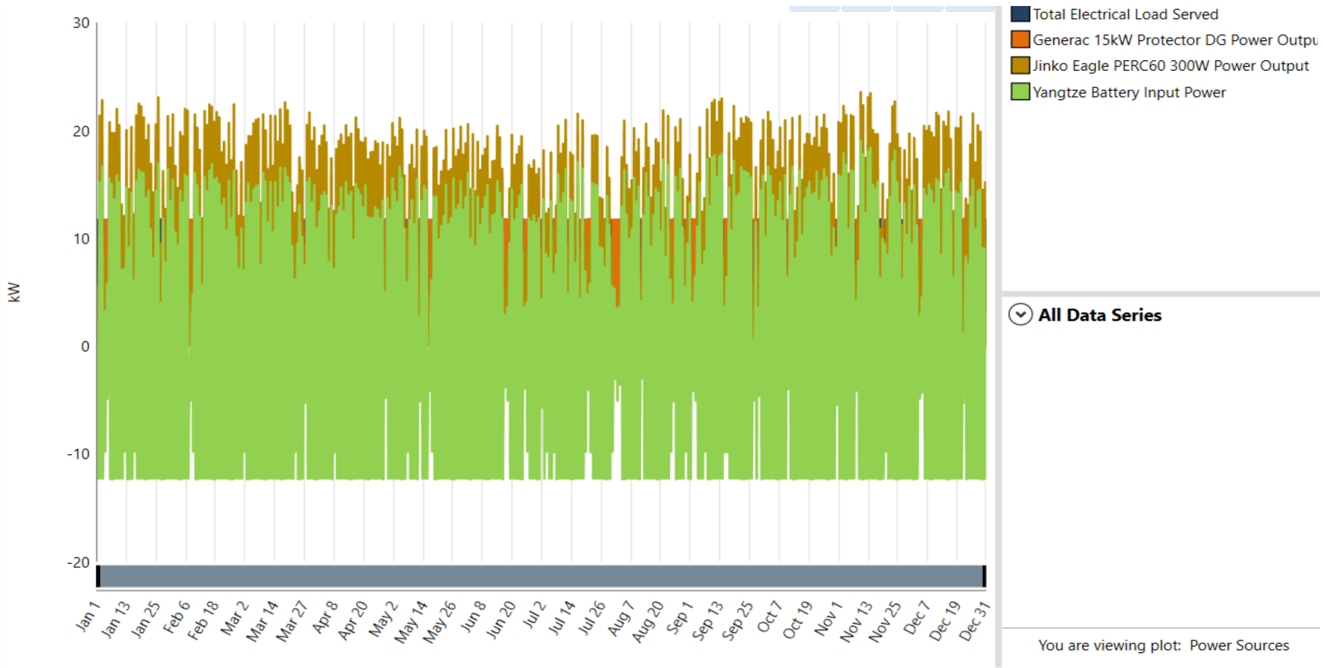
Electrical data at STC	• Maximum power(Pmax)	300 Wp
	• Voltage at maximum power	32.6 V
	• Current at maximum power	9.21 A
	• Voc	40.1 V
	• Isc	9.71 A
	• Panel efficiency	18.3%
Thermal ratings	• Operating temperature	-40 to 85 ^{0}C
	• Temperature coefficient of Pmax	-0.39 %/°C
	• Temperature Coefficient of Voc	-0.29 %/°C
	• Temperature Coefficient of Isc	0.05 %/°C
Panel dimension	• Length, width and height	1650x992x40 mm
Design parameter	• Life span	25 years

Technical data for 6-FM-250 lead acid storage battery

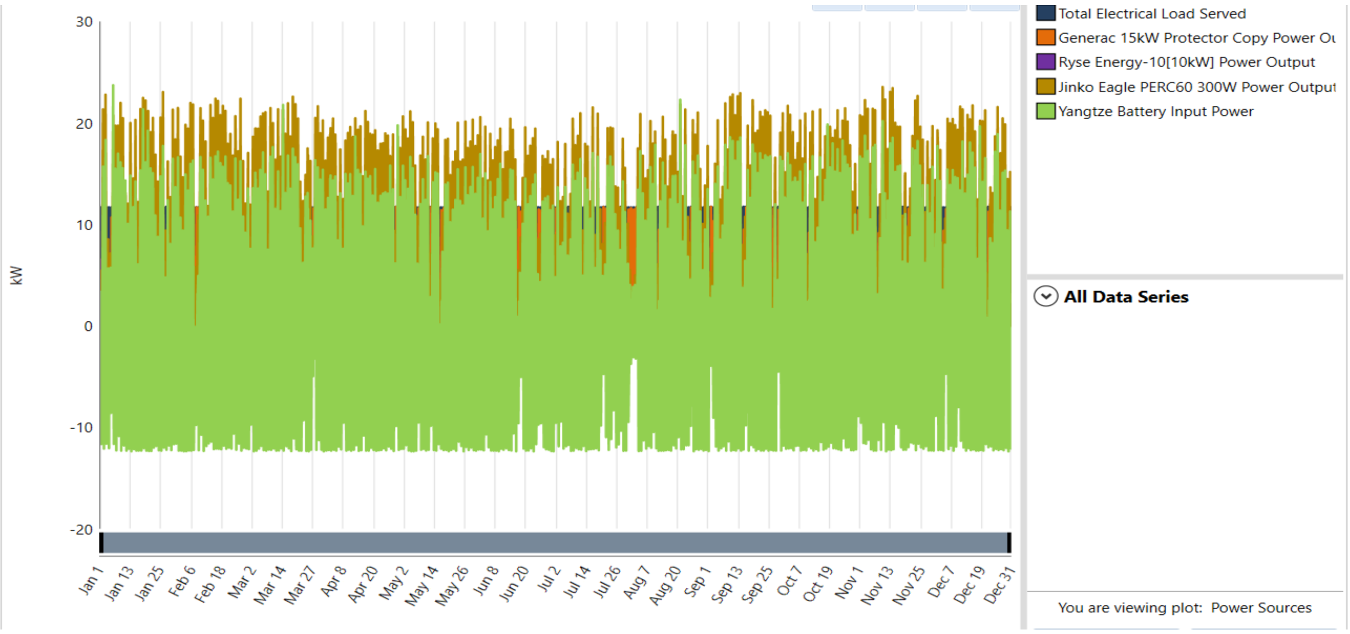
Functional parameters	• Nominal Voltage	12 V
	• Nominal Capacity	250 A.h
	• Number of Cells	6 cells
	• Internal resistance	2 mOhom
	• Maximum Discharge Current	3750A (5s)
	• Maximum charging current	62.5 A
Environment temperature	• charge temperature	0-50 ^{0}C
	• discharge temperature	-20-60 ^{0}C
	• storage temperature	-20-60 ^{0}C
dimension	• Length, width and height	520x269x225 mm
Wight	• weight	68 kg
Design parameter	• Life span	10 years

Appendix B: HOMER simulation result

Power production and consumption form PV/DG/Battery hybrid system

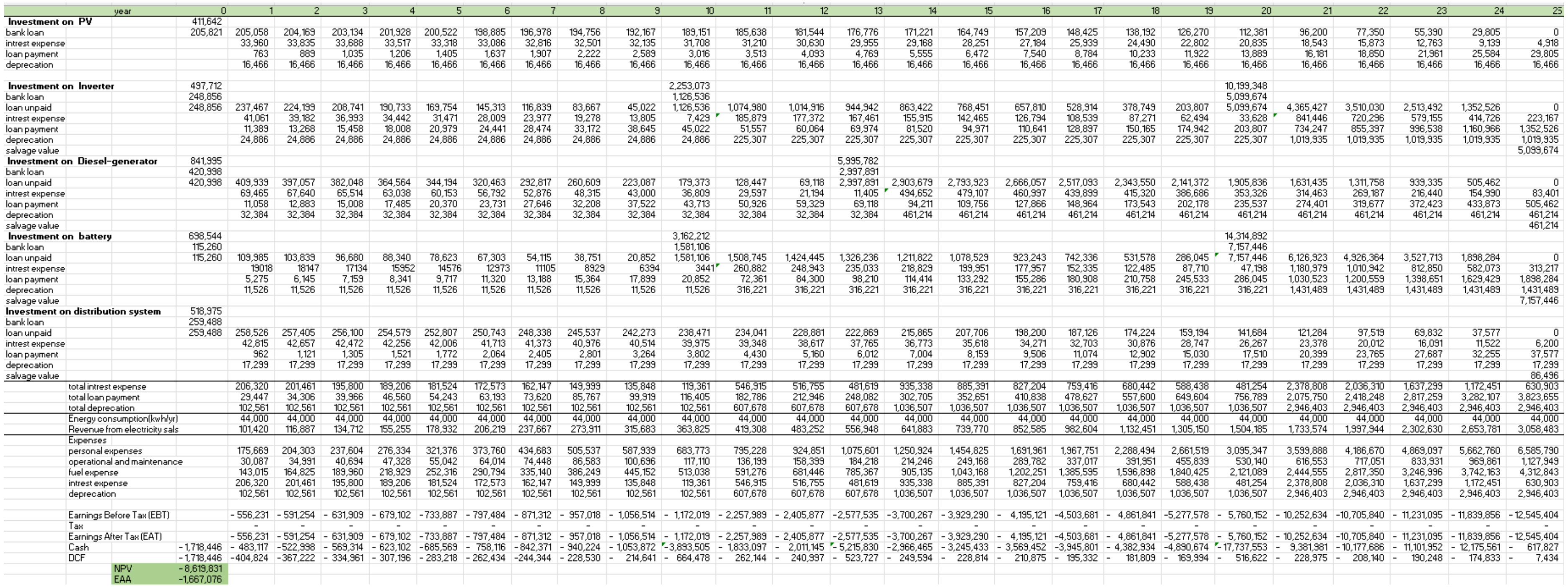


Power production and consumption form PV/DG/Wind/Battery hybrid system



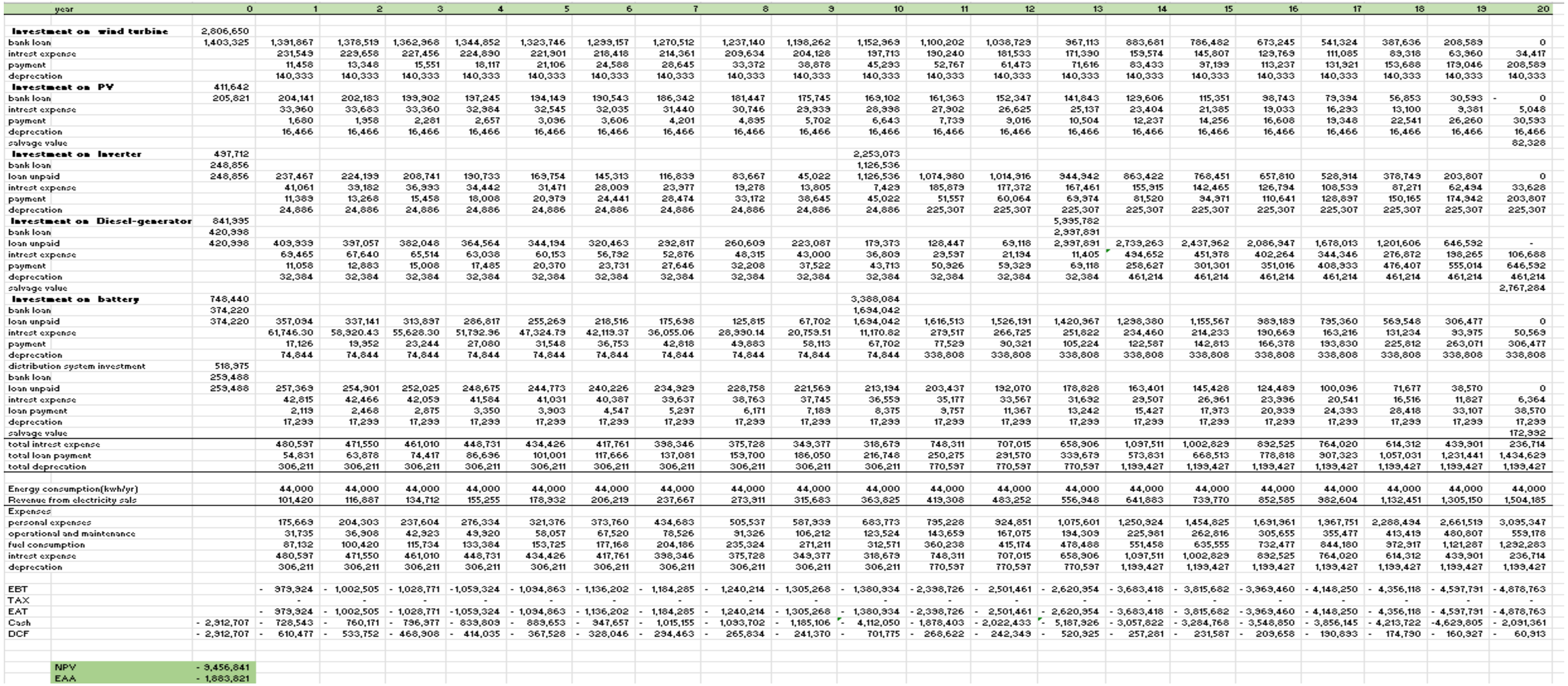
Appendix C: -Cash flow model calculation results

Cash flow calculation model for PV-DG -Battery hybrid system



year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Investment on PV	411,642																									
bank loan	205,821	205,058	204,169	203,134	201,928	200,522	198,885	196,978	194,756	192,167	189,151	185,638	181,544	176,776	171,221	164,749	157,209	148,425	138,192	126,270	112,381	96,200	77,350	55,390	29,805	0
intrest expense		33,960	33,835	33,688	33,517	33,318	33,086	32,816	32,501	32,135	31,708	31,210	30,630	29,955	29,168	28,251	27,184	25,939	24,490	22,802	20,835	18,543	15,873	12,763	9,139	4,918
loan payment		763	889	1,035	1,206	1,405	1,637	1,907	2,222	2,589	3,016	3,513	4,093	4,769	5,555	6,472	7,540	8,784	10,233	11,922	13,889	16,181	18,850	21,961	25,584	29,805
deprecation		16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466
Investment on Inverter	497,712										2,253,073										10,199,348					
bank loan	248,856										1,126,536										5,099,674					
loan unpaid	248,856	237,467	224,199	208,741	190,733	169,754	145,313	116,839	83,667	45,022	1,126,536	1,074,980	1,014,916	944,942	863,422	768,451	657,810	528,914	378,749	203,807	5,099,674	4,365,427	3,510,030	2,513,492	1,352,526	0
intrest expense		41,061	39,182	36,993	34,442	31,471	28,009	23,977	19,278	13,805	7,429	185,879	177,372	167,461	155,915	142,465	126,794	108,539	87,271	62,494	33,628	841,446	720,296	579,155	414,726	223,167
loan payment		11,389	13,268	15,458	18,008	20,979	24,441	28,474	33,172	38,645	45,022	51,557	60,064	69,974	81,520	94,971	110,641	128,897	150,165	174,942	203,807	734,247	855,397	996,538	1,160,966	1,352,526
deprecation		24,886	24,886	24,886	24,886	24,886	24,886	24,886	24,886	24,886	24,886	225,307	225,307	225,307	225,307	225,307	225,307	225,307	225,307	225,307	225,307	1,019,935	1,019,935	1,019,935	1,019,935	1,019,935
salvage value																										5,099,674
Investment on Diesel-generator	841,995													5,995,782												
bank loan	420,998													2,997,891												
loan unpaid	420,998	409,939	397,057	382,048	364,564	344,194	320,463	292,817	260,609	223,087	179,373	128,447	69,118	2,997,891	2,903,679	2,793,923	2,666,057	2,517,093	2,343,550	2,141,372	1,905,836	1,631,435	1,311,758	939,335	505,462	0
intrest expense		69,465	67,640	65,514	63,038	60,153	56,792	52,876	48,315	43,000	36,809	29,597	21,194	11,405	494,652	479,107	460,997	439,899	415,320	386,686	353,326	314,463	269,187	216,440	154,990	83,401
loan payment		11,058	12,883	15,008	17,485	20,370	23,731	27,646	32,208	37,522	43,713	50,926	59,329	69,118	94,211	109,756	127,866	148,964	173,543	202,178	235,537	274,401	319,677	372,423	433,873	505,462
deprecation		32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	461,214	461,214	461,214	461,214	461,214	461,214	461,214	461,214	461,214	461,214	461,214	461,214
salvage value																										461,214
Investment on battery	698,544										3,162,212										14,314,892					
bank loan	115,260										1,581,106										7,157,446					
loan unpaid	115,260	109,985	103,839	96,680	88,340	78,623	67,303	54,115	38,751	20,852	1,581,106	1,508,745	1,424,445	1,326,236	1,211,822	1,078,529	923,243	742,336	531,578	286,045	7,157,446	6,126,923	4,926,364	3,527,713	1,898,284	0
intrest expense		19018	18147	17134	15952	14576	12973	11105	8929	6394	3441	260,882	248,943	235,033	218,829	199,951	177,957	152,335	122,485	87,710	47,198	1,180,979	1,010,942	812,850	582,073	313,217
loan payment		5,275	6,145	7,159	8,341	9,717	11,320	13,188	15,364	17,899	20,852	72,361	84,300	98,210	114,414	133,292	155,286	180,908	210,758	245,533	286,045	1,030,523	1,200,559	1,398,651	1,629,429	1,898,284
deprecation		11,526	11,526	11,526	11,526	11,526	11,526	11,526	11,526	11,526	11,526	316,221	316,221	316,221	316,221	316,221	316,221	316,221	316,221	316,221	316,221	1,431,489	1,431,489	1,431,489	1,431,489	1,431,489
salvage value																										7,157,446
Investment on distribution system	518,975																									
bank loan	259,488																									
loan unpaid	259,488	258,526	257,405	256,100	254,579	252,807	250,743	248,338	245,537	242,273	238,471	234,041	228,881	222,869	215,865	207,706	198,200	187,126	174,224	159,194	141,684	121,284	97,519	69,832	37,577	0
intrest expense		42,815	42,657	42,472	42,256	42,006	41,713	41,373	40,976	40,514	39,975	39,348	38,617	37,765	36,773	35,618	34,271	32,703	30,876	28,747	26,267	23,378	20,012	16,091	11,522	6,200
loan payment		962	1,121	1,305	1,521	1,772	2,064	2,405	2,801	3,264	3,802	4,430	5,160	6,012	7,004	8,159	9,506	11,074	12,902	15,030	17,510	20,399	23,765	27,687	32,255	37,577
deprecation		17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299
salvage value																										86,496
total intrest expense		206,320	201,461	195,800	189,206	181,524	172,573	162,147	149,999	135,848	119,361	546,915	516,755	481,619	935,338	885,391	827,204	759,416	680,442	588,438	481,254	2,378,808	2,036,310	1,637,299	1,172,451	630,903
total loan payment		29,447	34,306	39,966	46,560	54,243	63,193	73,620	85,767	99,919	116,405	182,786	212,946	248,082	302,705	352,651	410,838	478,627	557,600	649,604	756,789	2,075,750	2,418,248	2,817,259	3,282,107	3,823,655
total deprecation		102,561	102,561	102,561	102,561	102,561	102,561	102,561	102,561	102,561	102,561	607,678	607,678	607,678	1,036,507	1,036,507	1,036,507	1,036,507	1,036,507	1,036,507	1,036,507	2,946,403	2,946,403	2,946,403	2,946,403	2,946,403
Energy consumption(kwh/yr)		44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000
Revenue from electricity sals		101,420	116,887	134,712	155,255	178,932	206,219	237,667	273,911	315,683	363,825	419,308	483,252	556,948	641,883	739,770	852,585	982,604	1,132,451	1,305,150	1,504,185	1,733,574	1,997,944	2,302,630	2,653,781	3,058,483
Expenses																										
personal expenses		175,669	204,303	237,604	276,334	321,376	373,760	434,683	505,537	587,939	683,773	795,228	924,851	1,075,601	1,250,924	1,454,825	1,691,961	1,967,751	2,288,494	2,661,519	3,095,347	3,599,888	4,186,670	4,869,097	5,662,760	6,585,790
operational and maintenance		30,087	34,991	40,694	47,328	55,042	64,014	74,448	86,583	100,696	117,110	136,199	158,399	184,218	214,246	249,168	289,782	337,017	391,951	455,839	530,140	616,553	717,051	833,931	969,861	1,127,949
fuel expense		143,015	164,825	189,960	218,929	252,316	290,794	335,140	386,249	445,152	513,038	591,276	681,446	785,367	905,135	1,043,168	1,202,251	1,385,595	1,596,898	1,840,425	2,121,089	2,444,555	2,817,350	3,246,996	3,742,163	4,312,843
intrest expense		206,320	201,461	195,800	189,206	181,524	172,573	162,147	149,999	135,848	119,361	546,915	516,755	481,619	935,338	885,391	827,204	759,416	680,442	588,438	481,254	2,378,808	2,036,310	1,637,299	1,172,451	630,903
deprecation		102,561	102,561	102,561	102,561	102,561	102,561	102,561	102,561	102,561	102,561	607,678	607,678	607,678	1,036,507	1,036,507	1,036,507	1,036,507	1,036,507	1,036,507	1,036,507	2,946,403	2,946,403	2,946,403	2,946,403	2,946,403
Earnings Before Tax (EBT)		- 556,231	- 591,254	- 631,909	- 679,102	-733,887	- 797,484	- 871,312	- 957,018	- 1,056,514	- 1,172,019	- 2,257,989	- 2,405,877	-2,577,535	-3,700,267	- 3,929,290	- 4,195,121	-4,503,681	- 4,861,841	-5,277,578	- 5,760,152	- 10,252,634	-10,705,840	- 11,231,095	- 11,839,856	- 12,545,404
Tax		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Earnings After Tax (EAT)		- 556,231	- 591,254	- 631,909	- 679,102	-733,887	- 797,484	- 871,312	- 957,018	- 1,056,514	- 1,172,019	- 2,257,989	- 2,405,877	-2,577,535	-3,700,267	- 3,929,290	- 4,195,121	-4,503,681	- 4,861,841	-5,277,578	- 5,760,152	- 10,252,634	-10,705,840	- 11,231,095	- 11,839,856	- 12,545,404
Cash	- 1,718,446	- 483,117	-522,998	- 569,314	- 623,102	-685,569	- 758,116	-842,371	- 940,224	- 1,053,872	-3,893,505	- 1,833,097	- 2,011,145	- 5,215,830	-2,966,465	- 3,245,433	- 3,569,452	-3,945,801	- 4,382,934	-4,890,674	- 17,737,553	- 9,381,981	- 10,177,686	- 11,101,952	- 12,175,561	- 617,827
DCF	- 1,718,446	-404,824	-367,222	- 334,961	- 307,196	- 283,218	- 262,434	-244,344	- 228,530	- 214,641	- 664,478	- 262,144	- 240,997	- 523,727	- 249,594	- 228,814	- 210,875	- 195,332	- 181,809	- 169,994	- 516,622	- 228,975	- 208,140	- 190,248	- 174,833	- 7,434
NPV	- 8,619,831																									
EAA	-1,667,076																									

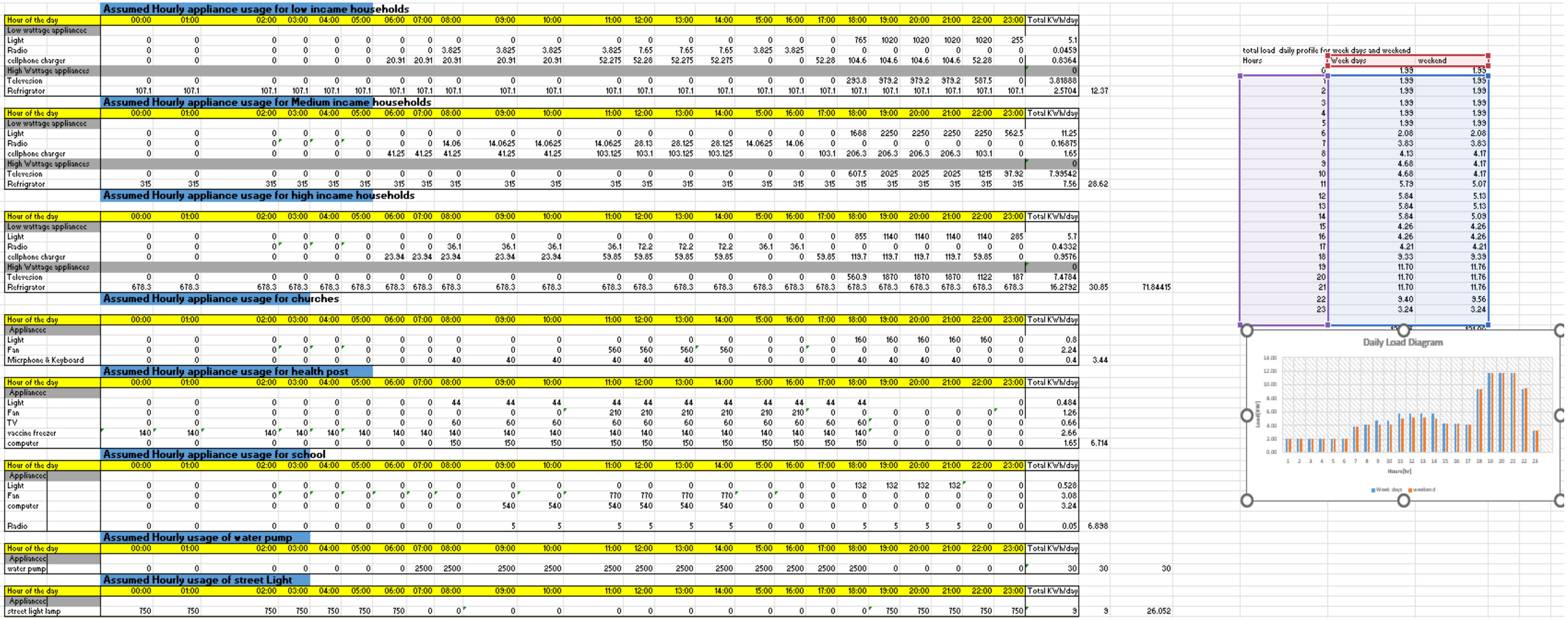
Cash flow model for PV-DG-Wind -Battery hybrid system



year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Investment on wind turbine	2,806,650																				
bank loan	1,403,325	1,391,867	1,378,519	1,362,968	1,344,852	1,323,746	1,299,157	1,270,512	1,237,140	1,198,262	1,152,969	1,100,202	1,038,729	967,113	883,681	786,482	673,245	541,324	387,636	208,589	0
intrest expense		231,549	229,658	227,456	224,890	221,901	218,418	214,361	209,634	204,128	197,713	190,240	181,533	171,390	159,574	145,807	129,769	111,085	89,318	63,960	34,417
payment		11,458	13,348	15,551	18,117	21,106	24,588	28,645	33,372	38,878	45,293	52,767	61,473	71,616	83,433	97,199	113,237	131,921	153,688	179,046	208,589
deprecation		140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333	140,333
Investment on PV	411,642																				
bank loan	205,821	204,141	202,183	199,902	197,245	194,149	190,543	186,342	181,447	175,745	169,102	161,363	152,347	141,843	129,606	115,351	98,743	79,394	56,853	30,593	- 0
intrest expense		33,960	33,683	33,360	32,984	32,545	32,035	31,440	30,746	29,939	28,998	27,902	26,625	25,137	23,404	21,385	19,033	16,293	13,100	9,381	5,048
payment		1,680	1,958	2,281	2,657	3,096	3,606	4,201	4,895	5,702	6,643	7,739	9,016	10,504	12,237	14,256	16,608	19,348	22,541	26,260	30,593
deprecation		16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466	16,466
salvage value																					82,328
Investment on Inverter	497,712										2,253,073										
bank loan	248,856										1,126,536										
loan unpaid	248,856	237,467	224,199	208,741	190,733	169,754	145,313	116,839	83,667	45,022	1,126,536	1,074,980	1,014,916	944,942	863,422	768,451	657,810	528,914	378,749	203,807	0
intrest expense		41,061	39,182	36,993	34,442	31,471	28,009	23,977	19,278	13,805	7,429	185,879	177,372	167,461	155,915	142,465	126,794	108,539	87,271	62,494	33,628
payment		11,389	13,268	15,458	18,008	20,979	24,441	28,474	33,172	38,645	45,022	51,557	60,064	69,974	81,520	94,971	110,641	128,897	150,165	174,942	203,807
deprecation		24,886	24,886	24,886	24,886	24,886	24,886	24,886	24,886	24,886	24,886	225,307	225,307	225,307	225,307	225,307	225,307	225,307	225,307	225,307	225,307
Investment on Diesel-generator	841,995													5,995,782							
bank loan	420,998													2,997,891							
loan unpaid	420,998	409,939	397,057	382,048	364,564	344,194	320,463	292,817	260,609	223,087	179,373	128,447	69,118	2,997,891	2,739,263	2,437,962	2,086,947	1,678,013	1,201,606	646,592	-
intrest expense		69,465	67,640	65,514	63,038	60,153	56,792	52,876	48,315	43,000	36,809	29,597	21,194	11,405	494,652	451,978	402,264	344,346	276,872	198,265	106,688
payment		11,058	12,883	15,008	17,485	20,370	23,731	27,646	32,208	37,522	43,713	50,926	59,329	69,118	258,627	301,301	351,016	408,933	476,407	555,014	646,592
deprecation		32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	32,384	461,214	461,214	461,214	461,214	461,214	461,214	461,214
salvage value																					2,767,284
Investment on battery	748,440										3,388,084										
bank loan	374,220										1,694,042										
loan unpaid	374,220	357,094	337,141	313,897	286,817	255,269	218,516	175,698	125,815	67,702	1,694,042	1,616,513	1,526,191	1,420,967	1,298,380	1,155,567	989,189	795,360	569,548	306,477	0
intrest expense		61,746.30	58,920.43	55,628.30	51,792.96	47,324.79	42,119.37	36,055.06	28,990.14	20,759.51	11,170.82	279,517	266,725	251,822	234,460	214,233	190,669	163,216	131,234	93,975	50,569
payment		17,126	19,952	23,244	27,080	31,548	36,753	42,818	49,883	58,113	67,702	77,529	90,321	105,224	122,587	142,813	166,378	193,830	225,812	263,071	306,477
deprecation		74,844	74,844	74,844	74,844	74,844	74,844	74,844	74,844	74,844	74,844	338,808	338,808	338,808	338,808	338,808	338,808	338,808	338,808	338,808	338,808
distribution system investment	518,975																				
bank loan	259,488																				
loan unpaid	259,488	257,369	254,901	252,025	248,675	244,773	240,226	234,929	228,758	221,569	213,194	203,437	192,070	178,828	163,401	145,428	124,489	100,096	71,677	38,570	0
intrest expense		42,815	42,466	42,059	41,584	41,031	40,387	39,637	38,763	37,745	36,559	35,177	33,567	31,692	29,507	26,961	23,996	20,541	16,516	11,827	6,364
loan payment		2,119	2,468	2,875	3,350	3,903	4,547	5,297	6,171	7,189	8,375	9,757	11,367	13,242	15,427	17,973	20,939	24,393	28,418	33,107	38,570
deprecation		17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299	17,299
salvage value																					172,992
total intrest expense		480,597	471,550	461,010	448,731	434,426	417,761	398,346	375,728	349,377	318,679	748,311	707,015	658,906	1,097,511	1,002,829	892,525	764,020	614,312	439,901	236,714
total loan payment		54,831	63,878	74,417	86,696	101,001	117,666	137,081	159,700	186,050	216,748	250,275	291,570	339,679	573,831	668,513	778,818	907,323	1,057,031	1,231,441	1,434,629
total deprecation		306,211	306,211	306,211	306,211	306,211	306,211	306,211	306,211	306,211	306,211	770,597	770,597	770,597	1,199,427	1,199,427	1,199,427	1,199,427	1,199,427	1,199,427	1,199,427
Energy consumption(kwh/yr)		44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000	44,000
Revenue from electricity sals		101,420	116,887	134,712	155,255	178,932	206,219	237,667	273,911	315,683	363,825	419,308	483,252	556,948	641,883	739,770	852,585	982,604	1,132,451	1,305,150	1,504,185
Expenses																					
personal expenses		175,669	204,303	237,604	276,334	321,376	373,760	434,683	505,537	587,939	683,773	795,228	924,851	1,075,601	1,250,924	1,454,825	1,691,961	1,967,751	2,288,494	2,661,519	3,095,347
operational and maintenance		31,735	36,908	42,923	49,920	58,057	67,520	78,526	91,326	106,212	123,524	143,659	167,075	194,309	225,981	262,816	305,655	355,477	413,419	480,807	559,178
fuel consumption		87,132	100,420	115,734	133,384	153,725	177,168	204,186	235,324	271,211	312,571	360,238	415,174	478,488	551,458	635,555	732,477	844,180	972,917	1,121,287	1,292,283
intrest expense		480,597	471,550	461,010	448,731	434,426	417,761	398,346	375,728	349,377	318,679	748,311	707,015	658,906	1,097,511	1,002,829	892,525	764,020	614,312	439,901	236,714
deprecation		306,211	306,211	306,211	306,211	306,211	306,211	306,211	306,211	306,211	306,211	770,597	770,597	770,597	1,199,427	1,199,427	1,199,427	1,199,427	1,199,427	1,199,427	1,199,427
EBT		- 979,924	- 1,002,505	- 1,028,771	-1,059,324	- 1,094,863	- 1,136,202	- 1,184,285	- 1,240,214	- 1,305,268	- 1,380,934	- 2,398,726	- 2,501,461	- 2,620,954	- 3,683,418	- 3,815,682	- 3,969,460	- 4,148,250	- 4,356,118	- 4,597,791	- 4,878,763
TAX		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
EAT		- 979,924	- 1,002,505	- 1,028,771	-1,059,324	- 1,094,863	- 1,136,202	- 1,184,285	- 1,240,214	- 1,305,268	- 1,380,934	- 2,398,726	- 2,501,461	- 2,620,954	- 3,683,418	- 3,815,682	- 3,969,460	- 4,148,250	- 4,356,118	- 4,597,791	- 4,878,763
Cash	- 2,912,707	- 728,543	- 760,171	- 796,977	- 839,809	- 889,653	- 947,657	- 1,015,155	- 1,093,702	- 1,185,106	- 4,112,050	- 1,878,403	- 2,022,433	- 5,187,926	- 3,057,822	- 3,284,768	- 3,548,850	- 3,856,145	- 4,213,722	-4,629,805	- 2,091,361
DCF	- 2,912,707	- 610,477	- 533,752	- 468,908	- 414,035	- 367,528	- 328,046	- 294,463	- 265,834	- 241,370	- 701,775	- 268,622	- 242,349	- 520,925	- 257,281	- 231,587	- 209,658	- 190,893	- 174,790	- 160,927	- 60,913
NPV	- 9,456,841																				
EAA	- 1,883,821																				

Appendix D: Hourly load profile

Hourly load profile



Assumed Hourly appliance usage for low incame households

Hour of the day	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total KWh/day		
Low wattage appliancec																											
Light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	765	1020	1020	1020	1020	255	5.1		
Radio	0	0	0	0	0	0	0	0	3.825	3.825	3.825	3.825	7.65	7.65	7.65	3.825	3.825	0	0	0	0	0	0	0	0.0459		
cellphone charger	0	0	0	0	0	0	20.91	20.91	20.91	20.91	20.91	52.275	52.28	52.275	52.275	0	0	52.28	104.6	104.6	104.6	104.6	52.28	0	0.8364		
High Wattage appliances																									0		
Televesion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	293.8	979.2	979.2	979.2	587.5	0	3.81888		
Refrigrator	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	107.1	2.5704	12.37	

Assumed Hourly appliance usage for Medium incame households

Hour of the day	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total KWh/day		
Low wattage appliancec																											
Light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1688	2250	2250	2250	2250	562.5	11.25		
Radio	0	0	0	0	0	0	0	0	14.06	14.0625	14.0625	14.0625	28.13	28.125	28.125	14.0625	14.06	0	0	0	0	0	0	0	0.16875		
cellphone charger	0	0	0	0	0	0	41.25	41.25	41.25	41.25	41.25	103.125	103.1	103.125	103.125	0	0	103.1	206.3	206.3	206.3	206.3	103.1	0	1.65		
High Wattage appliances																									0		
Televesion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	607.5	2025	2025	2025	1215	97.92	7.99542		
Refrigrator	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	7.56	28.62	

Assumed Hourly appliance usage for high incame households

Hour of the day	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total KWh/day		
Low wattage appliancec																											
Light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	855	1140	1140	1140	1140	285	5.7		
Radio	0	0	0	0	0	0	0	0	36.1	36.1	36.1	36.1	72.2	72.2	72.2	36.1	36.1	0	0	0	0	0	0	0	0.4332		
cellphone charger	0	0	0	0	0	0	23.94	23.94	23.94	23.94	23.94	59.85	59.85	59.85	59.85	0	0	59.85	119.7	119.7	119.7	119.7	59.85	0	0.9576		
High Wattage appliances																									0		
Televesion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	560.9	1870	1870	1870	1122	187	7.4784		
Refrigrator	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	678.3	16.2792	30.85	71.84415

Assumed Hourly appliance usage for churches

Hour of the day	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total KWh/day	
Appliancec																										
Light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	160	160	160	160	160	0	0.8	
Fan	0	0	0	0	0	0	0	0	0	0	0	560	560	560	560	0	0	0	0	0	0	0	0	0	2.24	
Micrphone & Keyboard	0	0	0	0	0	0	0	0	40	40	40	40	40	40	0	0	0	0	40	40	40	40	0	0	0.4	3.44

Assumed Hourly appliance usage for health post

Hour of the day	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total KWh/day	
Appliancec																										
Light	0	0	0	0	0	0	0	0	44	44	44	44	44	44	44	44	44	44	44					0	0.484	
Fan	0	0	0	0	0	0	0	0	0	0	0	210	210	210	210	210	210	0	0	0	0	0	0	0	1.26	
TV	0	0	0	0	0	0	0	0	60	60	60	60	60	60	60	60	60	60	60	0	0	0	0	0	0.66	
vaccine freezer	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	0	0	0	0	0	2.66	
computer	0	0	0	0	0	0	0	0	150	150	150	150	150	150	150	150	150	150	150	0	0	0	0	0	1.65	6.714

Assumed Hourly appliance usage for school

Hour of the day	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total KWh/day	
Appliancec																										
Light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	132	132	132	132	0	0	0.528	
Fan	0	0	0	0	0	0	0	0	0	0	0	770	770	770	770	0	0	0	0	0	0	0	0	0	3.08	
computer	0	0	0	0	0	0	0	0	0	540	540	540	540	540	540	0	0	0	0	0	0	0	0	0	3.24	
Radio	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	0	0	0	5	5	5	5	0	0	0.05	6.898

Assumed Hourly usage of water pump

Hour of the day	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total KWh/day		
Appliancec																											
water pump	0	0	0	0	0	0	0	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	0	0	0	0	0	30	30	30

Assumed Hourly usage of street Light

Hour of the day	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total KWh/day		
Appliancec																											
street light lamp	750	750	750	750	750	750	750	0	0	0	0	0	0	0	0	0	0	0	0	750	750	750	750	750	9	9	26.052

total load daily profile for week days and weekend

Hours	Week days	weekend
0	1.99	1.99
1	1.99	1.99
2	1.99	1.99
3	1.99	1.99
4	1.99	1.99
5	1.99	1.99
6	2.08	2.08
7	3.83	3.83
8	4.13	4.17
9	4.68	4.17
10	4.68	4.17
11	5.79	5.07
12	5.84	5.13
13	5.84	5.13
14	5.84	5.09
15	4.26	4.26
16	4.26	4.26
17	4.21	4.21
18	9.33	9.39
19	11.70	11.76
20	11.70	11.76
21	11.70	11.76
22	9.40	9.56
23	3.24	3.24