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

Prague, 2024

MASTER‘S THESIS ASSIGNMENT

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Specialisation: **Management of Power Engineering and Electrotechnics**

II. Master’s thesis details

Master’s thesis title in English:

Feasibility study for power generation off-grid hybrid system in rural area of Ethiopia

Master’s thesis title in Czech:

Feasibility study for power generation off-grid hybrid system in rural area of Ethiopia

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:

1. Patel M. R., Beik O.: Wind and Solar Power Systems; Design, Analysis, and Operation, CRC Press, 2021, ISBN 9780367476939.
2. Federal Democratic Republic of Ethiopia, National Electrification Program 2.0, Integrated Planning for Universal Access, 2019, www.powermag.com/wp-content/uploads/2020/08/ethiopia-national-electrification-program.pdf.
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Date of master’s thesis assignment: **16.02.2023** Deadline for master's thesis submission: **09.01.2024**

Assignment valid until: **22.09.2024**

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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.

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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: ----- ---------

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Acknowledgment

First of all, 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.

Next, I would like to express my special appreciation to my supervisor, Ing. Martin Benes (Ph.D.), for his guidance, constructive comments, feedback, and support that helped me to improve the quality of my work. His supervision of my progress has been instrumental in shaping the outcome of this research.

Finally, my acknowledgment is to my family and friends for the love and support I have received throughout my life journey. Their encouragement has been a relentless source of strength, and I am truly grateful for the enduring bonds that have sustained me.

Abstract

This paper studies the feasibility of implementing an off-grid hybrid power generation system, combining renewable energy sources (RES) with diesel generators (DG), for rural electrification in Ethiopia, a case study on the Wagesho village. The study employs a comprehensive methodology involving energy resource potential assessment, load demand estimation, system design, optimal component sizing, and economic analysis.

The thesis contains the description of load demand for households and community institutions' energy requirements in the village and wind and solar energy resource assessment using data from the NASA database, showing favorable solar energy potential for the village, whereas wind energy potential is found to be inadequate. Afterward, an optimal hybrid system comprising photovoltaic (PV), diesel generator (DG), and battery storage is designed using HOMER simulation software, with 87.6% of power generation from renewable energy and the remaining 12.4% generated power from DG.

Economic analysis is done based on the cash flow model determines the net present value (NPV) using national grid electricity tariffs. The minimum electricity selling price calculated for the designed off-grid hybrid system is 10.98 Birr/kWh ($ 0.19 /kWh) which is found to be higher than the grid tariff. However, GoE is planned to achieve 35% of rural electrification through standalone solar home systems and mini-grids. Implementing this project for the calculated price will give the required rate of return for investors and considering the socio-economic benefits the community in the village will get from this project justify the investment.

Keywords:

Off-grid hybrid system, rural electrification, renewable energy sources, diesel generators, battery storage, feasibility analysis, socio-economic benefits

Contents

List of Abbreviations

CAPM	Capital asset pricing model
CSA	Central statistical agency
DoD	Depth of discharge
DG	Diesel generator
GIS	Geographical information system
GoE	Government of Ethiopia
GPS	Global positioning system
GTP	Growth and Transformation Plan
HAWT	Horizontal axis wind turbine
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 1 Introduction

Energy plays a vital role in socio-economic development, and having access to clean and sustainable energy is necessary to meet sustainable development goals such as reducing poverty, enhancing education, granting access to clean water, and increasing food yield. As per research by the World Bank, a greater proportion of the global population than in previous times had access to electricity. 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 Africa (SSA), the electricity access rates are very low. 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 countries in the region. 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, 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. 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

Ethiopia has abundant potential for renewable energy sources, however, because of the poor electrification rate in the country the majority of the population is dependent on biomass, firewood, and kerosene lamps for their energy needs. Access to energy plays a pivotal role in promoting socio-economic growth and raising the living standards of society by creating employment opportunities, income, and increased productivity. Lack of access to electricity is the main constraint to these benefits and more than 55% of the population, which is more than 60 million people are living without electricity [9].

"Electricity access rate is not proportional in the urban and rural areas. The gap is very high, indicating that about 71.4% of the total households 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 [10]".

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 waste 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 NEP 2.0, which helps 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 [7]. 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 [10]. 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 [10]. 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 using a hybrid power system.

1.2 Overview of the 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 129 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. 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 household 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 household 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 most households connected to electricity use appliances categorized in tier 3, and around 26%, use high-load appliances [7].

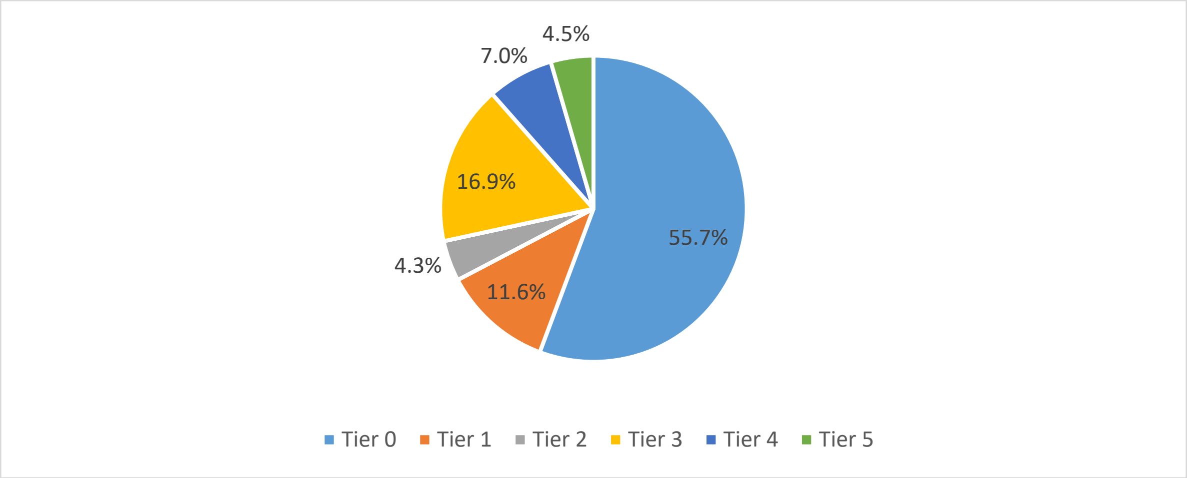


Figure 1.1: Percentage of population with access to electricity categorized in multi-tier [based on data from [6]].

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 [7].

The GoE plan is to 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 by 2025. Another main 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 [7].

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 [7]. The combination of both MTF and GIS creates an opportunity to identify beneficiaries by location and optimal technology solutions by location in the short-term, medium-term, and long-term.

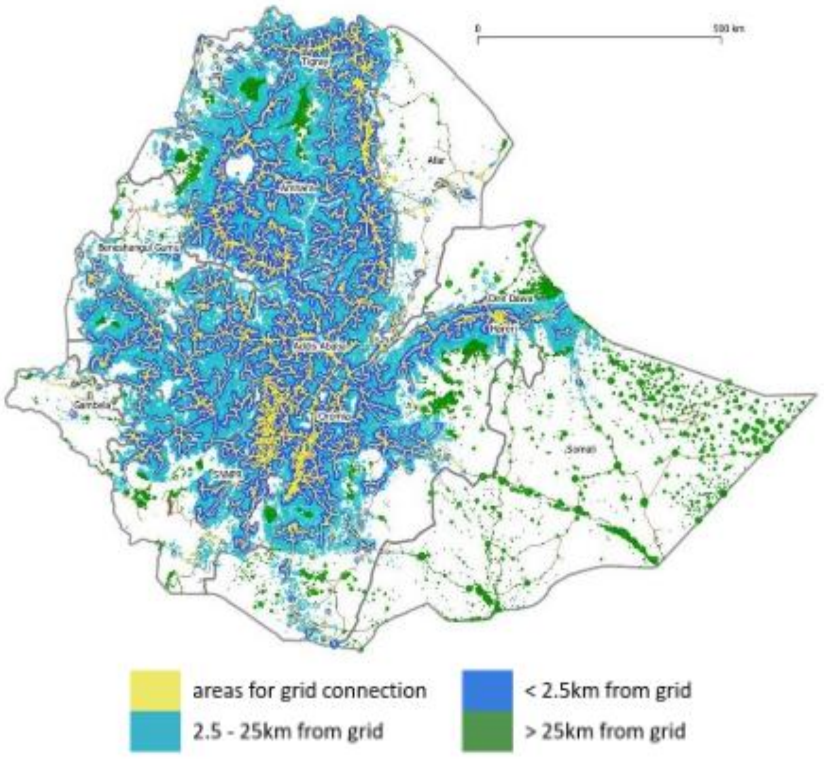


Figure 1.2: - Geo-spatial map of Ethiopia [8]

The comprehensive approach of the Ethiopian national electrification program by 2025 has primary opponents; 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 households to reach a cumulative households connected to the grid of 15 million, which is 65% of the population by 2025. Off-grid access: about one million households are targeted beneficiaries in remote areas, villages less likely to be served by cost- and time-effective ways by grid connectivity [8].

1.3 Objective

Off-grid systems provide an alternative for remote area with no access to the grid electricity. This paper aims to study the feasibility of an off-grid hybrid system from renewable energy sources and diesel generators for rural electrification in Ethiopia from both technical and economic points of view. Wagesho village which is located in the southern part of Ethiopia in Gibe woreda is chosen for the case study. The optimal system component sizing of the hybrid system will be studied using HOMER simulation software.

1.4 Methodology

The method I used to design the off-grid hybrid system to electrify the selected village includes a literature review, energy resource potential assessment, load demand of the village, designing of the hybrid system, optimal system component sizing, and study of financial viability of the project.

Energy resource assessment is the key step to start the designing of the off-grid system in rural areas, both wind and solar energy resource potential can be assessed either on-site measurements or other available databases such as (NASA, SolarGIS, NREL, etc.), I will take data from the NASA database to assess resource potential for this case study. Once the energy potential is assessed, the load demand of the village will be studied for optimal hybrid system design. The load profile estimation will be conducted based on localized information and Microgrid Load Profile Explorer which is developed by the National Renewable Energy Laboratory (NREL) and used for load profile estimation for rural electrification in Africa.

The methodology can be summarized as follows:

- Assessment of the renewable energy source potential, mainly for solar and wind resources, for the selected site for the case study.
- Estimating the load demand of the community in the village.
- Designing the optimal hybrid system to meet the load requirements of the community in the village.
- Evaluation of the feasibility of the project from an economic point of view

Chapter 2 Literature review, solar and wind energy, and resource assessment

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 the combination of 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 [11]. This study was conducted in 2009 and covers most technical optimization; however, sensitivity analysis from an economic point of view is not discussed.

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 0.49$/kWh [12].

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. [13].

Research conducted by Tamrat B. (2007) [14]. 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 off-grid hybrid 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 institutions such as school, 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 and Internal rate of return to see economic feasibility of the project from an investor point of view.

2.2 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 past ten years have seen extremely rapid economic expansion, leading to a steady increase in electricity demand. Ethiopia is facing energy shortages despite 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 hydro-power, 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.

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. 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 [15].

Table 2.1: - Ethiopia's energy potential [based on data from [15]]

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

2.3 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. One of the uses of solar energy is photoelectric conversion which converts solar radiation to electrical energy using solar cells [16]”.

2.3.1 Photovoltaic system

A PV system is a solar energy supply system that directly supplies power to the electrical equipment or feeds energy into the grid. PV systems consist of all the technologies that convert solar photons directly into electricity and supply the load such as solar panels, battery storage, inverters, and charge controllers [17]. In some cases, depending on the system, the purpose of storage may not be necessary.

PV cells

“Among most PV system elements, the PV cell is a crucial component; it consists of three major elements, namely.

- Semiconductor material that absorbs light and converts it into electron-hole pairs.
- The junction formed within the semiconductor separates electrons and holes.
- The contacts in the front and back of the cell allow the current to flow to the external circuit” [18].

Individual PV cells are interconnected and form a PV module called solar panels. PV cells can be manufactured using different types of semiconductor materials.

The two broad categories of PV cell technologies are flat plate technology and concentrated technology. The flat plate technology is further classified into crystalline technology, which is made from ultra-pure silicon raw material, which accounts for the majority of PV cell production, and the second one is thin film, which is made by depositing layers of semiconductor materials onto glass. Using this material reduces the cost of production because the cost of the material used is cheaper than that of the crystalline structure [18].
Monocrystalline and polycrystalline silicon are the most common solar cells among crystalline silicon cells. The polycrystalline cell is formed when molten silicon is cast into ingots, and it is a relatively low-cost and fast process for manufacturing thick crystalline cells [20].

The major advantage of polycrystalline cells is the production process is simple and cost-effective, and they reduce silicon waste compared to mono-crystalline cells. The main drawback is low conversion efficiency compared to monocrystalline cells due to the use of low-purity silicon. Monocrystalline PV cell is widely used for both utility-scale and stand-alone PV systems; this technology has higher efficiency as they are fabricated from high-grade silicon, the manufacturing process of monocrystalline cells is Czochralski process which involves significant silicon wastage [19].

Battery Storage

Energy storage devices are getting attention due to the seasonal, daily, and hourly variation of solar energy resources for power generation. Therefore, it is a critical component for a stand-alone system when there is no sufficient power generation to supply the load such as during cloudy weather and night. In all these cases electric energy storage is necessary to enhance the PV performance by bridging the gap that occurred due to fluctuations of power generation.

Different types of batteries are suitable for use in PV systems for energy storage such as lead acid, lithium, and nickel-cadmium batteries. It is one of the most expensive subsystems in standalone PV systems [20]. An important aspect of battery in PV systems is sizing, which plays a vital role in terms of total plant efficiency, and performance and takes a substantial portion of the total cost of a stand-alone PV system.

Inverter

Energy from the battery bank or any array is in the form of direct current (DC) this can supply DC loads, however, if the loads are operating on alternating current (AC) then current needs to be converted from DC to AC. Inverters are power electronics devices used in different PV system configurations [19].

- grid-connected systems.
- pumping systems
- stand-alone systems with rechargeable batteries.

Because of the specific operating conditions for standalone systems inverters, different conditions should be considered during system design. [19] The most important requirements on inverters for stand-alone PV systems are:

- Little fluctuations in the output voltage and frequency.
- Ability to withstand short-term overloading for appliance starting conditions.
- Output voltage as close as sinusoidal as possible.
- Large input voltage ranges up to + 30% of the rated voltage of the system.

Charge Controller

The charge controller is necessary for the PV system which involves a battery storage system, its basic function is to monitor the charging and discharging of the battery. It prevents the complete charging or discharging of the battery which reduces the life span of the battery. It is also used to prevent a reverse current flow from the battery to the system. The two mainly used charge controllers in the market are pulse width modulation (PWM) and maximum power point tracking (MPPT) [21].

The pulse width modulation charge controller matches the input power of the battery irrespective of the power generated by solar panels. MPPT charge controller helps to have the optimum efficiency and provide more power than PWM for similar conditions. However, MPPT charge controllers are more expensive than PWM charge controllers [21]. To size the charge controller, it is necessary to know the voltage level of the system and the maximum operating current, and the size of the controller should be higher than the operating system for safety reasons.

2.3.2 Factors that affect the PV system performance

Several factors affect PV system performance, the major factors that affect PV systems' performance are tilt angle, orientation, shading, and operating temperature. Optimally designing a PV system by considering the above factors is crucial for the PV module output power, their effect on the system is discussed as follows.

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 [22].

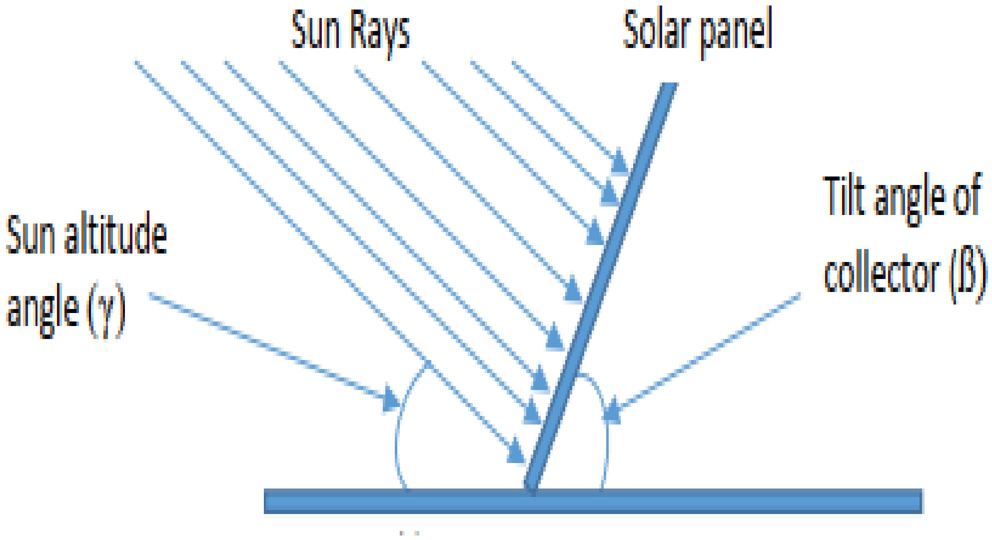


Figure 2.1: - Solar panel installation angle [22]

Temperature effect

The operating temperature affects the output power of the PV system by increasing the short-circuit current and decreasing the open-circuit voltage of the cell. 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 as follows [17].

$$Isc = I_o (1 + \alpha\, \Delta T) \text{ and } Voc = Vo\, (1 - \beta\, \Delta T) \qquad (2.1)$$

$$P=Po\, [1 + (\alpha - \beta)\, \Delta T] \qquad (2.2)$$

Where Isc is the short-circuit current (A), Voc is the open-circuit voltage (V), Io and Vo are the short-circuit current and open-circuit voltage at the reference temperature of the cell, and ΔT is the change in temperature from the reference temperature (ºC), P is power (W). For a single crystal silicon cell, α is about 20×10^{-6} / ºC, and β is about 5×10^{-3}/ ºC. The power is, therefore, given by the following:

$$P=Po\, [1 - 0.005\, \Delta T] \qquad (2.3)$$

In the above 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 [17].

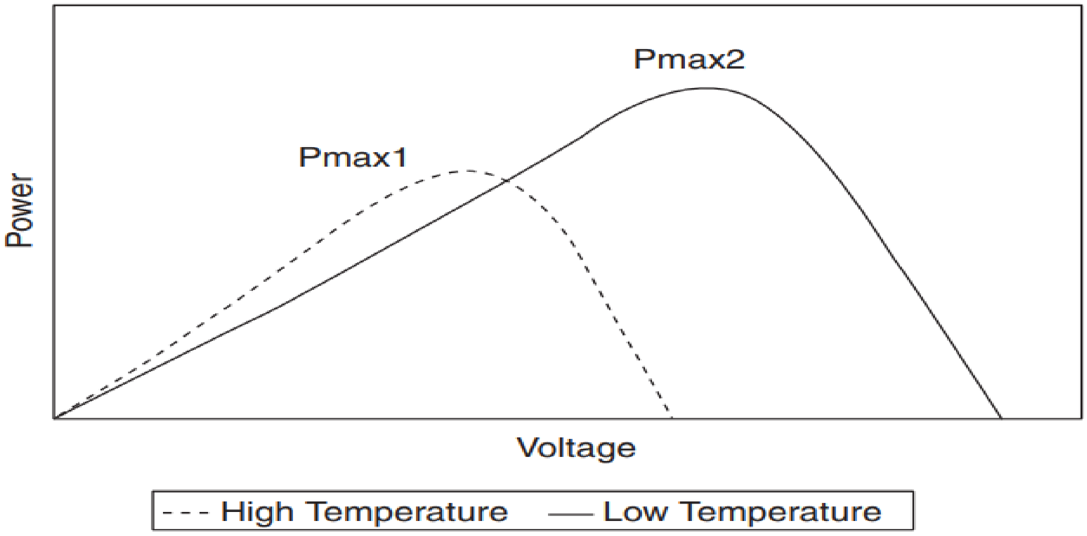


Figure 2.2: - Temperature effect on P-V characteristics [17]

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. The minimum spacing of the rows of PV modules is also crucial to preventing the possibility of shading PV modules against each other [23].

Dirt and other effects

Dirt and other contaminants like bird droppings on the face of the solar arrays can affect the output power of the PV system. Site condition should be assessed to measure such a problem associated with the dirt, frequently cleaning the PV array is the mitigating solution to improve the performance.

2.3.3 Solar resource potential assessment for the Wagesho village

Accurate determination of the hourly solar radiation received during the average day of each month is a requirement for the different applications. Since weather patterns are difficult to predict because of their randomness with time and place, historical data records are useful analytical tools. Long-term measured solar radiation data are usually available as monthly averaged total solar radiation per day on the horizontal surface.

Pvsyst is the most widely used tool for simulating solar energy yield estimation and the optimal design of solar power plants. By entering the geographical coordinates, it runs based on directly imported solar resources from the NASA Surfaces Methodology and Solar Energy database [24]. So, the latitude and longitude of the selected site is 7^{o} 40’ 35” N and 37^{o} 44’ 35” E. The average solar radiation for the Wagesho village is presented in the table below.

Table 2.2: Average daily solar radiation for each month for the Wagesho village.

Months	Average daily radiation [kWh/ (m^2. day)]	Clearness index	Temperature (°C)
January	5.86	0.586	20.8
February	6.27	0.604	21.9
March	6.26	0.596	22.3
April	6.01	0.589	20.7
May	5.81	0.602	18.7
June	5.24	0.563	17.7
July	4.61	0.489	16.8
August	4.86	0.490	16.9
September	5.55	0.537	17.4
October	5.93	0.572	17.6
November	6.09	0.603	18.5
December	5.97	0.602	20.0

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.

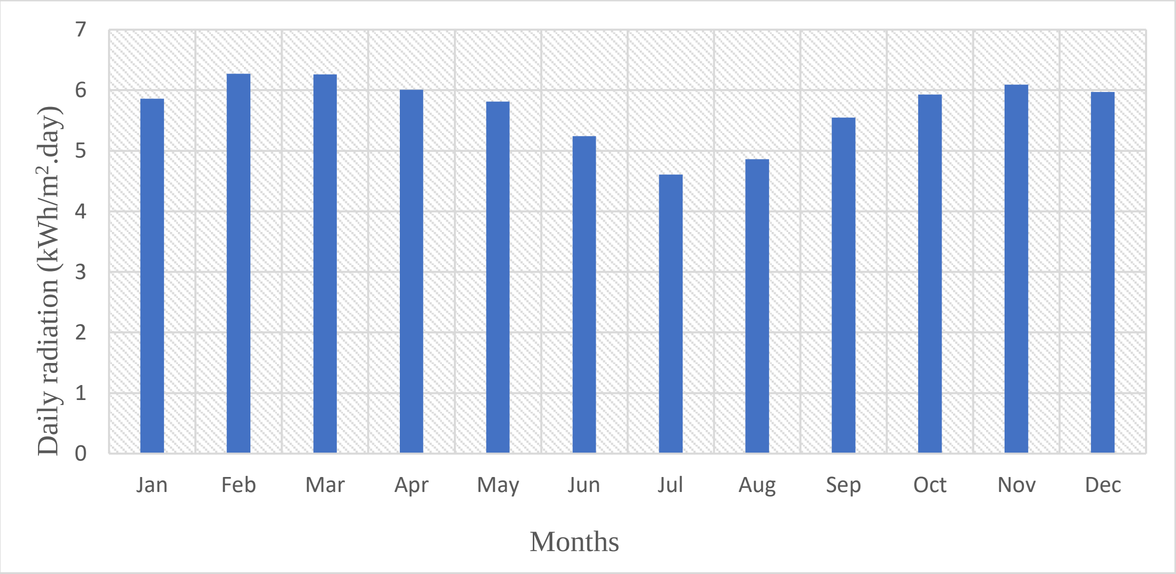


Figure 2.3: - Daily radiation pattern of the Wagesho village

2.4 Wind energy

Wind is the movement of the air due to the pressure difference within the atmosphere. The pressure difference exerts a force that causes the air masses to move from the high-pressure region to the low-pressure area. Such pressure differences are caused primarily by the Sun's differential heating effect on the Earth's surface. The generation and movement of the wind are complicated due to different factors such as uneven solar heating, the Coriolis force, the Earth's self-rotation, which affects the wind speed and direction, and local geographical conditions [25].

2.4.1 Wind energy characteristics

Wind energy is a form of kinetic energy that can be obtained by air as it flows; it can be used for many applications, such as converting it into electrical energy by power-converting machines or directly used for pumping water, sailing ships, or grinding gain [26].

Principle of wind power

Wind power depends on the amount of air, speed of the air, and mass of the air. When the wind passes over the wind turbine, it slows down the wind speed from v to v_d. The power extracted by the wind turbine is the kinetic energy per unit of time. The mechanical power generated by the differences between the upstream and the downstream velocity is shown in the equation below [12].

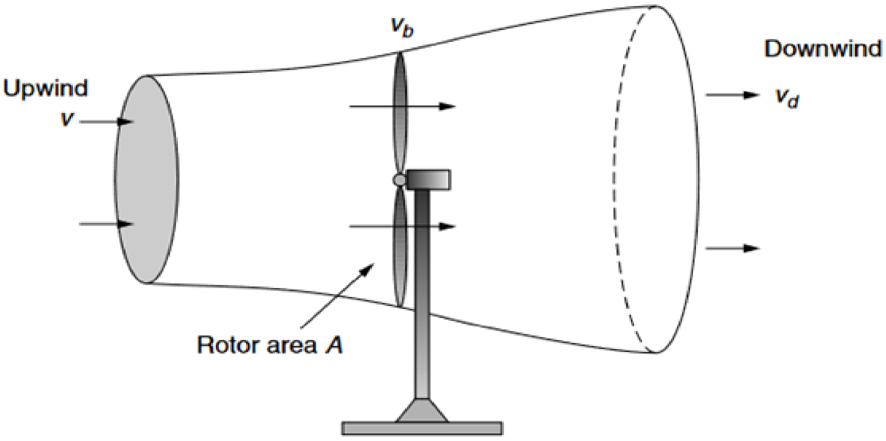


Figure 2.4: Power extraction by wind turbine blades [28].

$$P_{mech} = \frac{1}{2}\dot{m}(v-v_d)^2 \tag{2.4}$$

Where $P_{mech:}$ is mechanical power extracted by the wind turbine (W), $\dot{m}$ is the mass flow rate (kg/s), v is the upwind speed at the entrance of the rotor blade (m/s), v_d is the downwind speed at the exit of the rotor blade (m/s).

The mass flow rate $\dot{m}$ at the plane of the rotor can be explained using the following expression [26].

$$\dot{m}=\rho A \left(\frac{V+Vd}{2}\right) \tag{2.5}$$

Where $\dot{m}$ is the mass flow rate (kg/s), ρ is air density (kg/m^3) and A is the swept area by the rotor blade (m^2). The output power of the turbine can be expressed as follows

$$P = \frac{1}{2}\rho A v^3 C_p \quad (2.6)$$

C_p 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 [27,17]. 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 [28, 17].

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. If the rotor turns too slow its efficiency is reduced because the blades let too much wind pass unaffected and, when the rotor turns too fast reduces the efficiency of the rotor as the turbulence caused by one blade affects the following blade [28].

$$\text{TSR} = \frac{\omega R}{\text{V}} \quad (2.7)$$

Where ω is the angular velocity of the rotor in rad/s, v is the wind speed in m/s, and R is the radius of the rotor blade.

2.4.2 Wind power density

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 [17]. The available power P in the wind speed v for the area of the rotor A is.

$$\frac{P}{A} = \frac{1}{2}\rho v^3 \quad (2.8)$$

The air density ρ (kg/m^3) is an important parameter for the estimation of wind power density. It has a significant effect on the performance of the wind energy system. The following correlation can be used to estimate air density at different elevations z (m) of the wind speed measurement [17,11].

$$\rho = 1.225 - (1.194 \times 10^{-4})\, z \quad (2.9)$$

2.4.3 Wind turbine technology

The wind turbine first converts kinetic energy in the wind to the rotational kinetic energy in the turbine and then to electrical energy. The energy available for the conversion depends on the available wind speed and the swept area of the turbine. Wind turbines are available in different types and various sizes.

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 to generate electricity [17].

Vertical-axis wind turbine: The main rotor shaft is positioned vertically. The yaw mechanism is not necessary for vertical axis turbines 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 the vertical axis wind turbine, especially in areas where wind direction is highly variable [17].

Horizontal-axis wind turbine: **-** The main rotor shaft and electrical generator of horizontal-axis wind turbines 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 horizontal axis turbines. The reason for this is stability, and using an uneven number of blades helps to avoid stability problems during the rotation of the blade [11].

The main parts of a modern horizontal-axis wind turbine 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 [17].

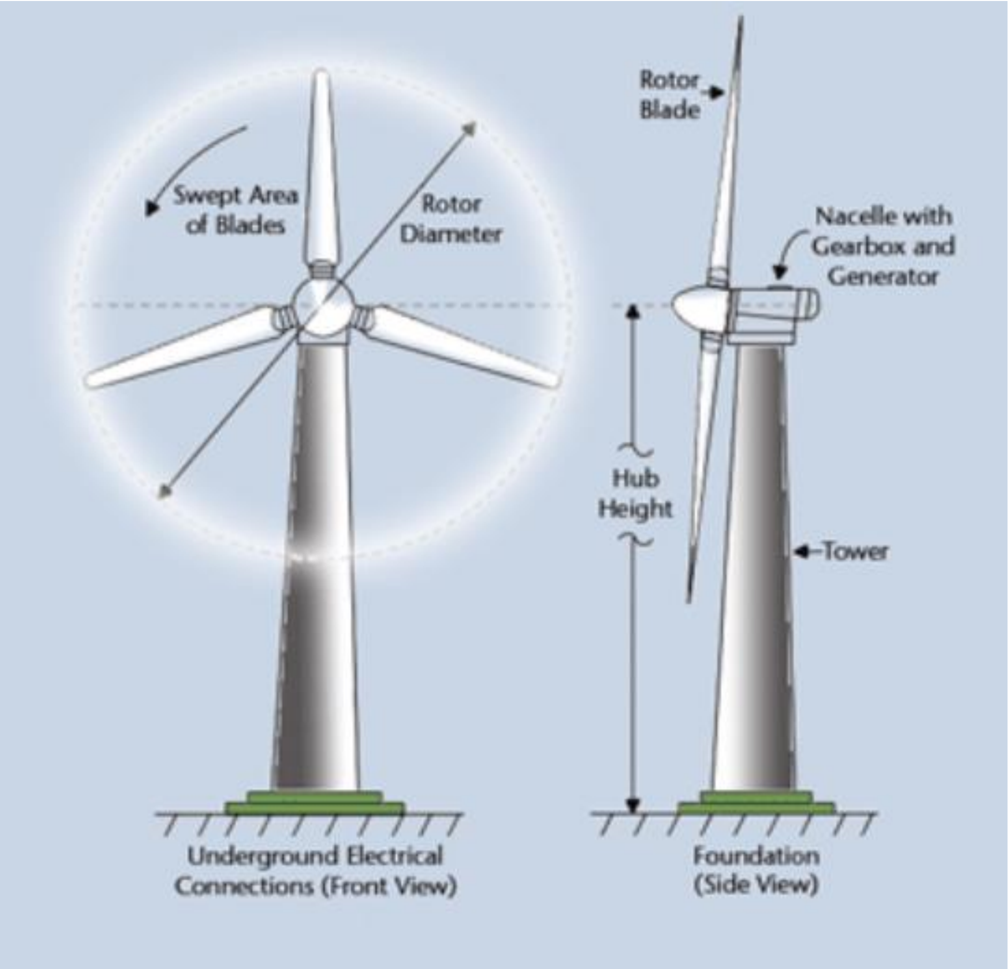


Figure 2.5: Horizontal-axis wind turbine [29]

2.4.4 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 [12, 17].

$$f(v) = \frac{\pi v}{2\nu^{2}} \exp\left[- \frac{\pi}{4} \left(\frac{v}{\nu^{\cdot}}\right)^{2}\right] \qquad (2.10)$$

Where f (v) is the Weibull probability density function of wind speed, v is instantaneous wind speed (m/s), and $\nu^{\cdot}$ is mean speed (m/s)

2.4.5 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 based on the wind power classification by the US Department of Energy (DOE) [30]. The wind class ranges from poor to excellent wind regimes, identifying the country's land area that falls under this category is explained in the table below.

Table 2.3: - Categorizing wind resources and their power density into classes [30].

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

The above table explains different classes of wind resources and power density based on the mean wind speed at different elevations, 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. Usually, class 3 and above are considered more economical for power generation.

Wind energy resource in Ethiopia

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 [30].

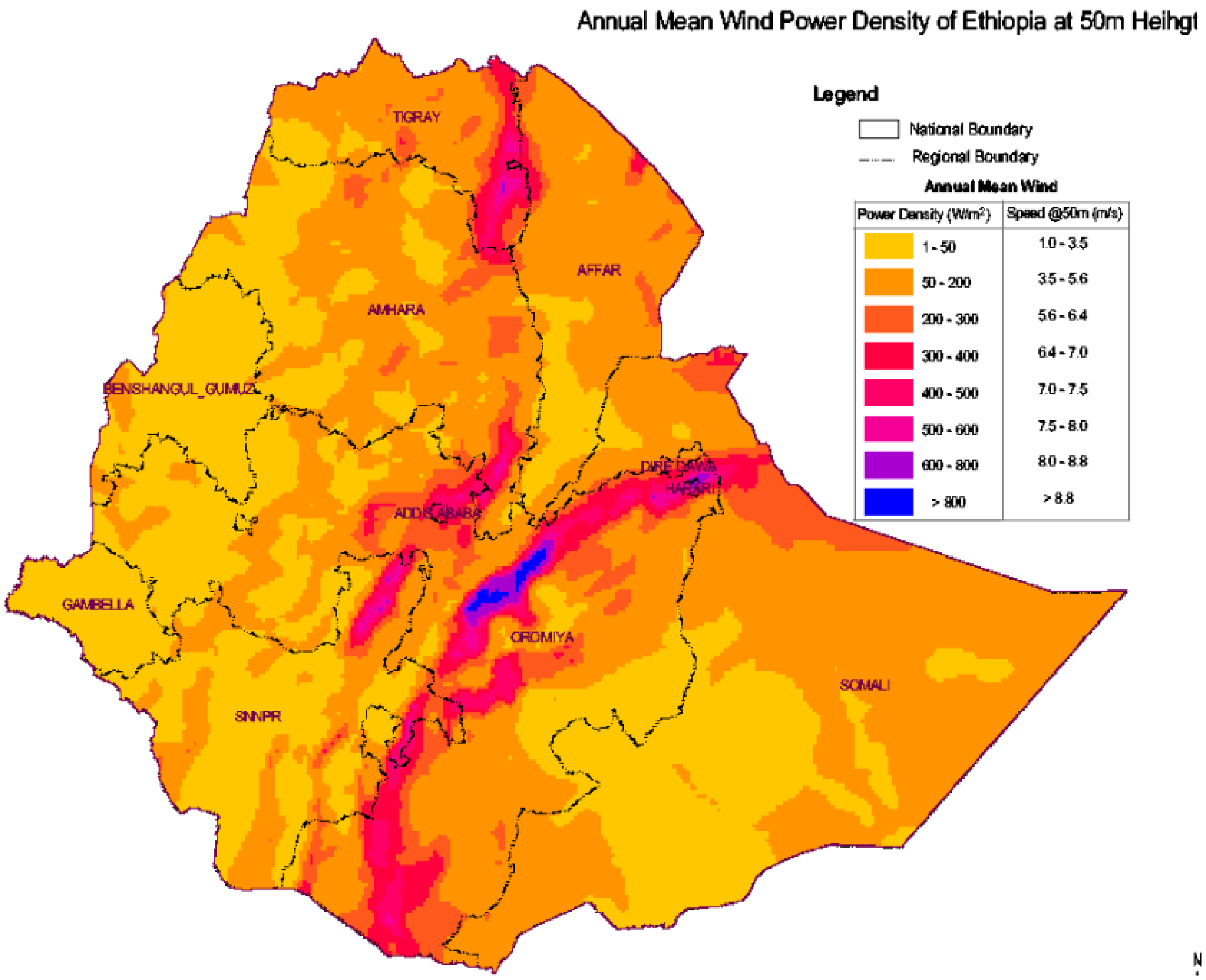


Figure 2.6: -Wind speed and power density of Ethiopia at 50m height [30]

Wind energy resource in Wagesho village

This study assess the potential of wind energy resources in a Wagesho village by analyzing wind speed data obtained from NASA. The organization provides meteorological data that includes wind speed measurements at different heights for specific locations. Wind speed data was taken at a height of 10 m for five years, from 2017 to 2021, as presented in the table below.

The data obtained from NASA is a useful resource for renewable energy research, and it allows us to accurately assess the feasibility of wind energy projects in the selected village. Utilizing this data can be useful for better understanding the wind energy potential of the area which helps decision-making regarding the design and implementation of the wind energy project.

Table 2.4: - Wind speed (m/s) [31]

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

The maximum mean wind speed at the height of 10 m 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 m for the village falls under class one based on the evaluation of the wind power classification by the US Department of Energy (DOE) [30].

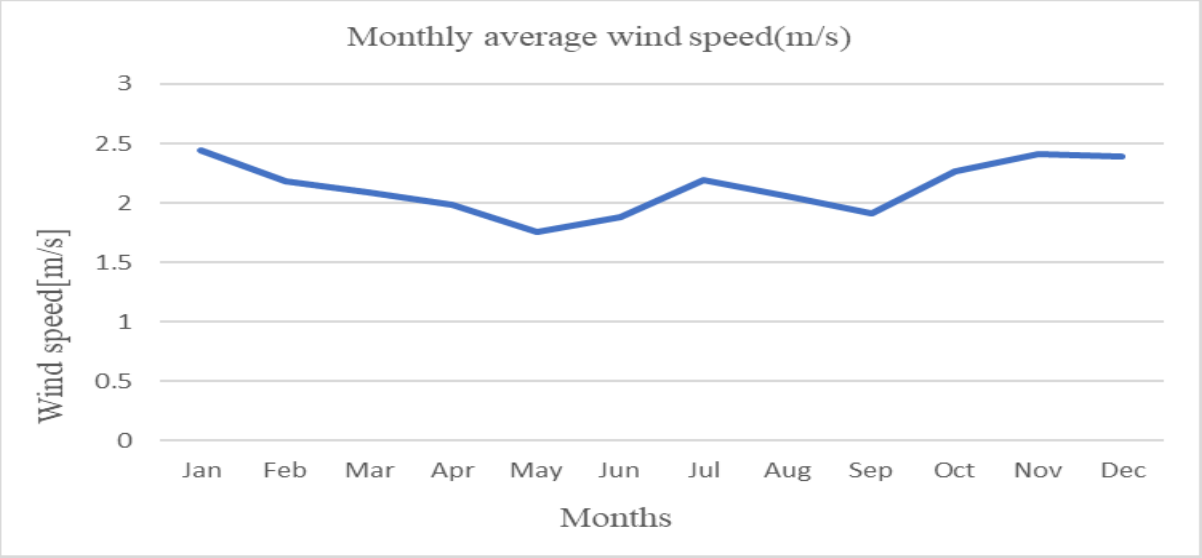


Figure 2.7: -Monthly average wind speed (m/s) at a height of 10 m for Wagesho village [31].

Since wind power is proportional to the cube of the wind speed, the economic impact of wind speed on wind power is significant. One approach to generating wind power at high wind speed is mounting wind speed on the taller tower.

In the few hundred meters above the ground, wind speed is greatly affected by the air friction that can be experienced as it moves across the earth's surfaces. The surface wind speed can be slowed with considerable high irregularities such as buildings and forests. The variation of the speed with elevation is modest, and the following expression is used to characterize the impact of the roughness of the earth's surface on the wind speed [26].

$$\frac{V2}{V1} = \left(\frac{h2}{h1}\right)^{\alpha} \tag{2.11}$$

Where v_2 (m/s) is the wind speed at height h_2 (m), v_1 (m/s) is the wind speed at height h_1 (m), and α is friction coefficients, which is a function of the terrain over the wind blows.

Table 2.5: Friction coefficient α for various terrain characteristics [32]

Terrain characteristics	Friction coefficient (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

The wind speed data for the village at the height of 10 meters is extrapolated for different turbine hub heights using equation 2.11, and the value of friction coefficient factor α is taken as 0.2 and. The following table summarizes wind speed and power density at 10 m, 30, and 50 m above the ground.

Table 2.6: - Wind speed and power density at the different heights for the Wagesho village

Months	At 10 m		At 30 m		At 50 m	
	Wind speed (m/s)	Power density (W/m^2)	Wind speed (m/s)	Power density (W/m^2)	Wind speed (m/s)	Power density (W/m^2)
Jan	2.44	7.30	3.04	14.05	3.36	18.97
Feb	2.18	5.18	2.72	10.06	3.00	13.5
Mar	2.09	4.56	2.60	8.78	2.88	11.95
Apr	1.98	3.88	2.46	7.44	2.73	10.17
May	1.76	2.73	2.20	5.32	2.43	7.17
Jun	1.88	3.32	2.34	6.40	2.60	8.78
Jul	2.19	5.25	2.73	10.17	3.02	13.77
Aug	2.06	4.37	2.56	8.38	2.84	11.45
Sep	1.91	3.48	2.38	6.74	2.64	9.20
Oct	2.27	5.85	2.83	11.33	3.13	15.33
Nov	2.41	7.00	3.00	13.50	3.33	18.46
Dec	2.39	6.83	2.97	13.10	3.30	17.97
Average	2.13	4.90	2.43	7.17	2.94	12.7

The above table shows extrapolated wind speed and power density for the study site. According to wind power density classification by the US Department of Energy (DOE) [30], areas designated in class 4 and higher are generally considered suitable for most wind turbine applications, class 3 is suitable for the application of wind turbines with tall hub height is used and class 2 is marginal, and areas categorized into class 1 are not suitable for wind energy development.

The average speed obtained at a height of 10 m, 30 m, and 50 m above the ground for the Wagesho village falls under class 1. Therefore, wind energy development does not apply to the village based on wind energy assessment results and evaluation based on wind power density classification.

Chapter 3 Load profile estimation

3.1 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 7^{o} 40' 35'' N and 37^{o} 44' 35'' E. This village has 215 households; the community is made up of smallholder farmers, and the main sources of income in the village are mixed farming for crop production and livestock. 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 3.1; Image of the Wagesho village, taken from Google Earth.

3.2 Load profile estimation for household

The consumption profile describes the hourly energy use schedule anticipated for the village's rural community. In cases where there are already electricity consumers, this information can be obtained directly by measuring the amount of electricity consumed over a specific period. However, for the communities with no access to electricity, the demand and load pattern can be estimated based on the type of appliances and their respective duration of usage by households.

The assumption made to estimate the load profile of the village is that the household consumption in the village is not uniform. The main reasons for this assumption are differences in the income level of households in the village and the ability to own appliances.

The load profile estimation is made based on the above assumption for the community in the village; the total households of the village are categorized based on their income levels into three groups such as households having a relatively low standard of living, households with relatively medium standards of living, and household having a relatively high standard of living. According to the Ethiopian Rural Socioeconomic Survey (ERSS) of 2013 [38], the average household size in the rural part of the SNNPR is 5.3 individuals. Based on the information obtained from the local administration in the selected village; Table 3.1 shows the demographic and income level data of the village.

Table 3.1 Data for the case study village

Household category	Quantity
Low-income household	102
Medium-income household	75
High-income household	38
Average population size per household	5.3

For the load estimation, I considered the following electrical equipment, lighting, mobile phone chargers, television, refrigerators, and radio. The wattage of the proposed appliances and the number of appliances per household categorized by income level are explained in the table below. The wattage for the proposed appliances listed in Table 3.2 and Table 3.5 is based on the standard wattage values for home appliances [33,34].

Table 3.2: Proposed household appliances and their wattage.

Appliances	Wattage [W]	Low-income household number of appliances	Middle-income household number of appliances	High-income household 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 appliance ownership is considered for the households based on their income level category. I adapted Table 3.3 from the USAID Power Africa Project in Ethiopia, which did off-grid solar market assessment projects in different rural areas of Ethiopia [35], and Power Africa Load profile estimation [36].

Table 3.3: Household appliance ownership [based on data from [35,36]]

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

To estimate the load pattern of an unelectrified rural community using a data-driven load profile helps to minimize the differences between the estimated and later consumption patterns for off-grid electrification. I adapted Table 3.4 from the Power Africa load profile estimation [36] for household appliance consumption, which is used to calculate consumption throughout each hour of the day. It provides data to estimate the energy consumption pattern for various appliances proposed for households.

Table 3.4: - Assumed hourly appliance usage by households (%) [based on data from [36]]

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	0.25	0.25	0	1
15:00	0	0.25	0	0	1
16:00	0	0.25	0	0	1
17:00	0	0.25	0.25	0	1
18:00	0.75	0.25	0.5	0.3	1
19:00	1	0.25	0.5	1	1
20:00	1	0.25	0.5	1	1
21:00	1	0.25	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	4	4	4	24

Consumption for the refrigerator will be calculated by considering the duty cycle for the compressor.

3.3 Load profile estimation for community institutions

Community services consist of activities necessary to satisfy the needs of the population such as education, clean water, and good health. Some of the community loads considered in this study include one school, two churches, one health post, street lighting, and a public water system.

School load: - estimating school load is determining which appliances the school will use by considering the state of the local community. There is one primary school in the Wagesho village, and it has eight classrooms, three offices, and one toilet; the proposed appliances are desktop computers, lighting, fans, and radio. The wattage of the proposed appliances and the number of appliances will be explained in the table below.

Church load: - there are two churches in the village. The churches have four small rooms and one main hall each; the main energy-consuming appliances proposed for churches are lighting for each room, air conditioning for the main hall used for worship, and a microphone. Types of appliances and their wattage are explained in the table below.

Health post load: health posts are the smallest with the most basic facilities, and energy demand is relatively lower than that of health clinics. The proposed appliance for the health post in the village includes a vaccine refrigerator, lighting, television, fan, and desktop computer.

Table 3.5: 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	5	2	10
Proposed appliances and their load for school			
Appliances	Power[W]	Quantity	Total load[W]
Light bulbs	10	12	120
Radio/tape	5	1	5
Desktop computer	150	3	450
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
Desktop computer	150	1	150
Proposed street light load			
Streetlight	25	30	750

Table 3.6: Consumption hours for community institutions

Appliances	School load consumption time(h)	Health-post load consumption time(h)	Churches load consumption time(h)	Streetlight 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	-
Desktop Computer	9:00-14:00	8:00-18:00	-	-
Refrigerator	-	0:00-23:00	-	-
Microphone	-	-	10:00-13:00,18:00-20:00	-
Radio	9:00-14:00	-	-	-
TV	-	8:00-18:00	-	-

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. 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 [37]. Based on this information, the village's daily water consumption is 28,488 liters.

According to a study conducted in the Hadiya zone, households with higher incomes own an average of 7 cattle and 4 sheep. In comparison, households with medium and low incomes own 5 cattle and 3 sheep, and 2 cattle and 2 sheep, respectively [39]. 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 [40] has been adapted for this project. The assumed water consumption of the livestock is explained in the table below.

Table 3.7: Average daily water consumption by livestock.

Livestock	The average number of livestock for lower-income household	The average number of livestock for medium-income household	The average number of livestock for higher income household	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 m^3 (1 m^3 = 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 m^3 per hour.
It is necessary to consider the total dynamic head (h), 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 total pumping head has been determined to be 122 meters.

The energy required per day (kWh) for water pumping can be calculated using the following formula [41]

$$\text{Energy required} = \rho V g h \tag{3.1}$$

Where ρ is supplied water density (1000 kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), h is the total pumping head (m), and V is the volume of water required per day (53.1 m^3).

$$\text{Energy required} = (1000\ \text{kg/m}^3)\ (53.1\ \text{m}^3)\ (122\ \text{m})\ (9.81\ \text{m/s}^2)$$

$$=63551142\ \text{J}$$

$$=63.6\ \text{MJ}$$

1 kWh = 3.6 MJ; therefore, the energy required per day 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% [42]. 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.

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. The village's estimated daily load demand amounts to around 124 kWh on weekdays, while it decreases to approximately 121 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.

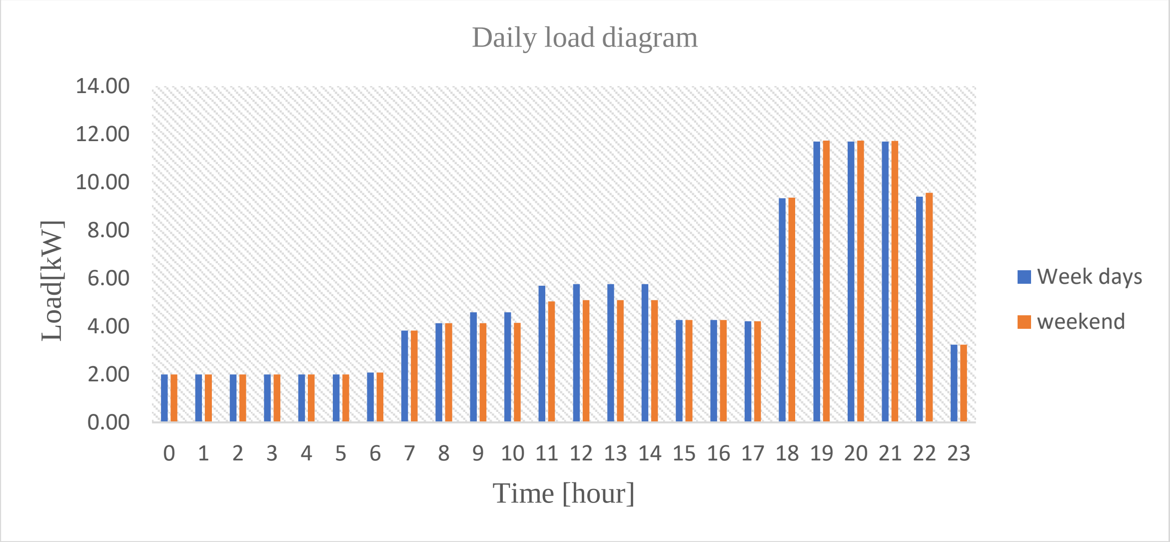


Figure 3.2: Estimated daily load profile of the village for weekdays and weekends.

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 streetlights, 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 from the peak months by 5.5%. The pattern of consumption is described in the figure below.

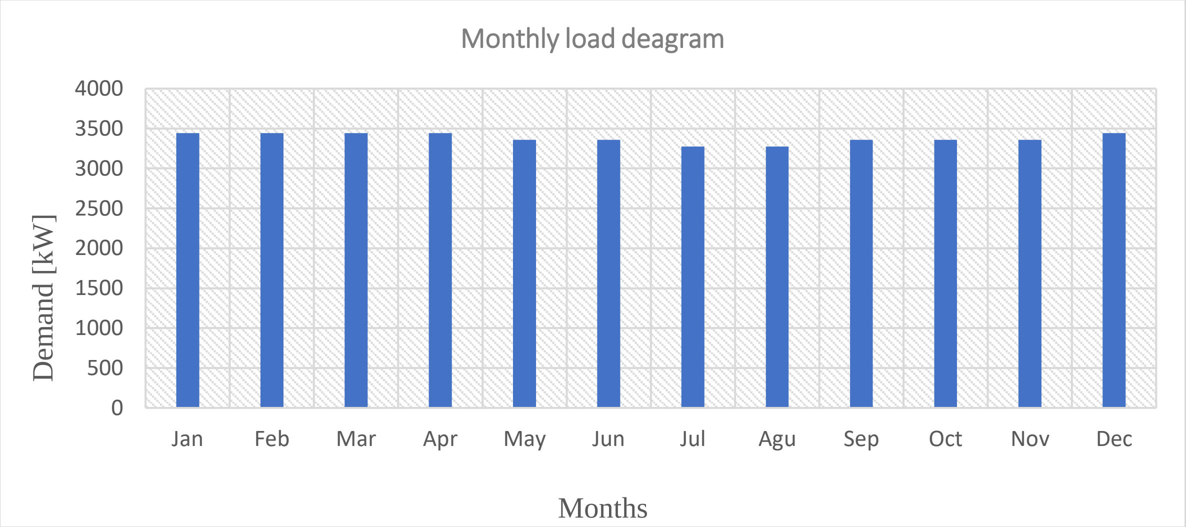


Figure 3.3: - Monthly energy consumption for the Wagesho village

Chapter 4 Hybrid system, system components, and sizing

In this chapter, I will focus on the study of the benefits of an off-grid hybrid energy system and the optimal system components sizing using HOMER simulation software.

Due to geographical location, long distance from the main grid, and high cost of the electric power transmission lines, access to electricity has become a main concern in remote rural areas. Because of the distributed power generation advantage, renewable energy sources, mainly solar and wind, can be a good solution to a power supply in remote rural areas. The standalone solar home system and mini-grid system are more appropriate when the main interests are related to the following [44]:

- Constructing power transmission lines expensive or technically constrained
- When the location of the site is a remote rural area, connecting to the main grid is not possible.
- When preference is given to renewable energy sources for environmental concerns.
- Low operating cost

4.1 Hybrid system

The intermittent nature is one of the main problems of renewable energy sources, which results in energy supply fluctuation due to load demand. This problem can be avoided by a hybrid system, which provides stable power output from the resources. In addition, it maximizes the utilization of various accessible renewable energy sources. In most applications, a hybrid energy system is a parallel combination of different but complementary power generation systems [43].

Hybrid energy systems combine different forms of energy to generate electricity [11], and they may contain a combination of:

- Renewable energy sources (solar, wind, micro-hydro, biomass)
- Internal combustion generator (diesel/gasoline generator)
- Energy storage (battery)
- Power conditioning equipment (inverter, battery charge controller)

The combination of hybrid systems can vary widely depending on the specific requirements. Hybrid renewable energy resources are the combination of PV and wind or one of the renewable energies with conventional energy sources. Diesel generators and energy storage systems are considered energy sources in mini-grids to maintain the system reliability under the renewable energy sources (RES) intermittent behavior over the period. Consideration and preference are given to RES to charge the storage system to keep the operation flexible [44].

The proposed hybrid energy system comprises a Photovoltaic (PV) array, battery, diesel generator, and power converter. Wind energy is not included in the hybrid system based on the wind resource potential assessment for the Wagesho village. The estimated mean wind speed for the village is categorized into the poor class with very low wind power density according to the US Department of Energy wind resource classification, which is explained in the previous chapter. The hybrid system is designed to supply power to the village load requirement on 24/7 basses. HOMER software is used in this paper to optimize system components sizing and operational strategy for the hybrid energy system.

4.2 HOMER simulation 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 [45].

It is mainly used for optimization and decision analysis of hybrid renewable projects for grid-connected and off-grid systems. HOMER 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 can provide 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 [46].

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 [46].

HOMER software allows us to perform three principal tasks simulation, optimization, and sensitivity analysis based on the input data. The input data are the daily load profiles for weekdays and weekends for each month, energy resources: - input data for solar radiation, wind speed, and temperature, and system design: - it includes all technical and economic parameter settings for components such as PV, wind turbine, battery, generator, and DC-AC converter. The simulation compares the energy supply from the system with the load demand on an hourly basis throughout the year and decides on the strategy to operate the battery and diesel generator. The purpose of the optimization is to have multiple simulations and decide the optimal configuration based on the decision variables. The decision variables are PV array size, number of wind turbines, size of the generator, size of DC-AC converter, battery size, and dispatching strategy. The optimized system minimizes the size of battery and fuel consumption. Sensitivity analysis helps to examine the effect of the change on the input parameter on the system design [46].

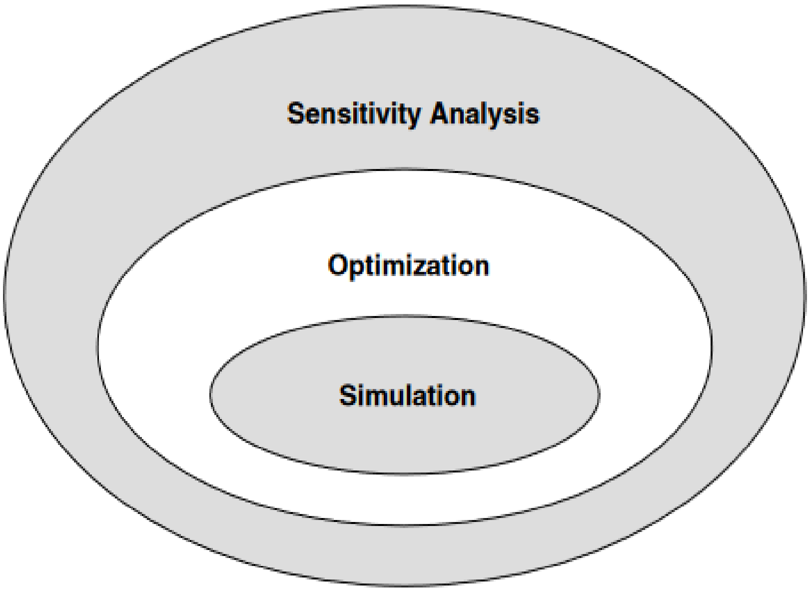


Figure 4.1**:** Simulation, optimization, and sensitivity analysis by HOMER software on system modeling [46].

4.3 System configuration

The designed system comprises of PV, battery bank, Inverter, and DG. Optimized modeling of the system 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 loads. The system schematic structure is described in the figure below.

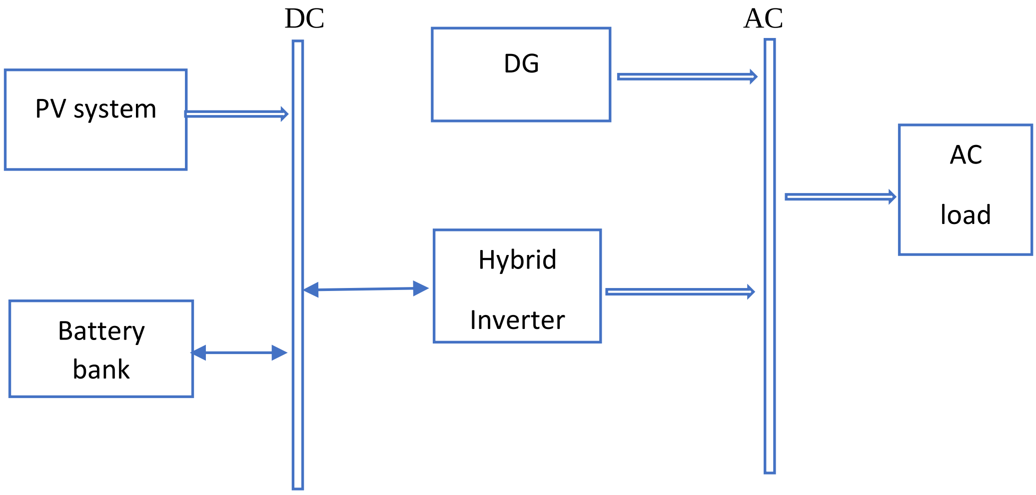


Figure 4.2: Schematic diagram of power generation model on HOMER software from PV/DG.

In the above schematic, both the renewable energy source and diesel generator supply the load requirements of the village directly, which increases overall system reliability. The inverter and diesel generator can provide load in parallel mode. When there is enough power generation from the PV system is obtained then it supplies the load and charges the battery. When the power generated from PV is not enough to satisfy the village load demand, then stored energy from the battery is used to meet the requirements. However, power generation is not possible during nighttime, at times of high demand, or when battery storage is not enough, then diesel generator supply load.

4.4 System components

Photovoltaic (PV) module

From the designed system PV array is the primary source that provides energy to the customer and charges the battery. When selection is made for the photovoltaic (PV) modules it is essential to make careful consideration, as it impacts the project's financial and technical viability. The two most common used types of PV modules are polycrystalline and monocrystalline, and each has a unique set of advantages and characteristics.

For the proposed system, polycrystalline silicon cell PV modules with 300 Wp manufactured by Jinko Solar are selected based on cost and technical performance, and their price is $0.1/watt [47].

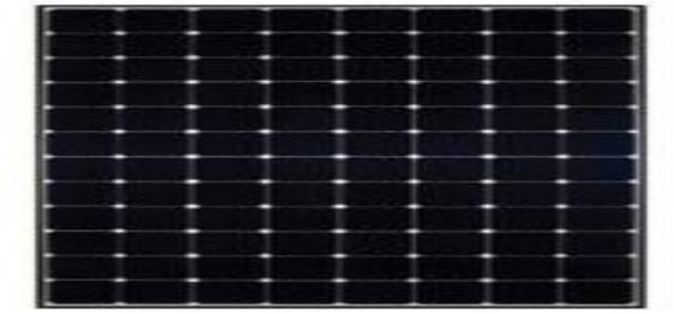


Figure 4.3: - Eagle PERC 60 300 model solar panel [47]

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 [46].

$$P_{pv} = f_{pv}\, Y_{pv}\, \frac{It}{Is}\,(1 - \alpha_p\, \Delta T) \tag{4.1}$$

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 from PV power output, Y_{pv} is the rated capacity of the PV array in (kW) at the standard test condition, It is the solar radiation in PV array in current time step (kW/m^2), Is is incident radiation at standard test condition (1 kW/m^2), α_p is the temperature coefficient of the power (0.5%/^{o}C), and ΔT is the temperature difference between the PV cell under standard test conditions and the PV cell in the current time step (^{o}C).

Battery 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 when power generation from RES is not available or sufficient.

The important aspect of batteries in the standalone system is sizing, it plays a vital role in terms of system efficiency, performance, and operating cost of the off-grid system. It also takes up a substantial portion of the total cost of the system. Its sizing should be carried out to optimize the cost and performance of the system. Lower sizing results in reduced battery lifetime due to the higher charge and discharge rate of the batteries [20].

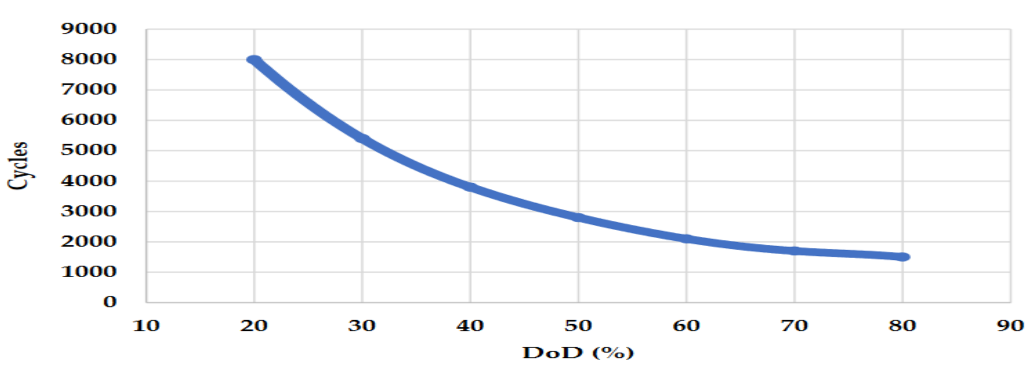


Figure 4.4: - Battery service life dependence on depth of discharge (DoD) [48]

For the proposed system, a 6-GFM-250 lead acid battery with a nominal capacity of 250 Ah and a nominal voltage of 12 V, and a designed life is 12 years, manufactured by Yangtze Solar, is chosen with a cost price of $170 per piece. The key feature of the selected battery is its low self-discharge, maintenance-free, and wide suitability of the ambient temperature range. The technical specification is attached in appendix [49].

Figure 4.5: 6-GFM-250 lead acid battery [49]

Two independent factors may limit the lifetime of the storage bank. The storage floats life and lifetime throughput, which means batteries can die either from old age or from use. HOMER software uses the following equation to estimate the life of the battery bank in years when the life of the battery is limited by time and throughput [46].

$$R_b = \mathrm{MIN}\left\{ \frac{\mathrm{Nbatt\ Qlifetime}}{\mathrm{Qthrput}}, R_{batf} \right\} \tag{4.2}$$

Where R_b is the service lifetime of the battery, N_{batt} is the number of batteries in the storage bank, $Q_{lifetime}$ is the lifetime throughput of the single storage (kWh), and Q_{thrput} is the annual storage throughput in (kWh/yr), and R_{batf} is storage battery float life [yr].

Inverter

To decide the proper size of the inverter, which needs to have the ability to deal with all the power that the appliances consume at the same time, this paper proposes an inverter made and provided by Schneider. Its rated power is 6.8 kW, with an efficiency of 96% and a life range of 10 years. The selected inverter costs $2999 per unit, and a complete Conext power system can feature solar charge controllers, monitoring, and automated generator control modules which enable further adaptability [50]. For this paper, two inverters will be associated with 13.6 kW, which assists with providing peak load.

Figure 4.6: - Schneider Conext XW inverter [50]

Diesel generator

In the hybrid system, the energy generated by the PV panels and stored in the battery bank has priority to supply the load. When the stored energy in the battery is discharged to its minimum allowable level then the diesel generator as a backup source starts to supply the load.

HOMER simulation software compares the load requirement with the available generated energy by PV for each hour step and decides to charge or discharge the battery and operate the diesel generator [46].

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 [51].

The Caterpillar automatic standby diesel generator- DE14E3S; its fuel is diesel, and a rated power of 13 kW is used for the optimal configuration. The price of the select generator is $7267 [52].

Figure 4.7: - Caterpillar automatic standby diesel generator- DE14E3S [52]

Table 4.1: Description of DE14E3S diesel generator [52]

Generator technical data	
Nominal power	13 kW
Nominal voltage	230 V
Rotational speed	1500 RPM
Frequency	50 Hz
Fuel consumption	
At 100%	4.3 l/h
At 75%	3.3 l/h
At 50 %	2.6 l/h

Unlike the lifetime for the other components, the generator lifetime is specified in hours of operations instead of years. This is because the generator's life largely depends on its hours of operation rather than its age. Obtaining the lifetime of the generator is not easy, as it can depend on operating conditions, maintenance frequency, fuel quality, generator sizing, and other factors. Considering that a diesel generator is cooled by water and runs at low speed it can go to an estimated lifetime of 20000 hours [46].

4.5 HOMER simulation result

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.

I considered in the sizing of the system the overall derating factor of 85% which is obtained by multiplying the individual factors such as 95% for soiling, 98% for DC wiring, 103% for module power tolerance, and 99.5% for diode and connections, and 90% for solar module aging factor [53,47], this derating factor is without including inverter efficiency and temperature loss which are given to HOMER as input separately.

HOMER software performed the optimization process of the system components sizing by calculating the hourly energy production throughout the year, and based on the calculation, the proposed system is composed of a 26 kW PV panel, 60 batteries each of 250 Ah, 13 kW diesel generator, and two inverters of 6.8 kW each.

The projected project lifespan is 25 years, and the expected lifespan of the diesel generator is 20 years. The following table depicts the share of the electricity production from each major system component.

Table 4.2: - Size of the component used and energy produced by PV/DG/battery system.

Component	Size	The energy produced by PV and DG	Renewable fraction %
PV panel	26 kW	43.95MWh/yr	87.6
Diesel Generator	13 kW	6.20 MWh/yr	12.4
Batteries	180 kWh		
Hybrid inverter	13.6 kW		

The village electricity demand is mainly covered by renewable energy sources; the PV system covers around 87.6% of production, and DG produces the remaining 12.4%. The total energy produced is approximately 50 MWh/year; from this, about 45 MWh/year will be consumed. The energy produced exceeds consumption by 5 MWh.

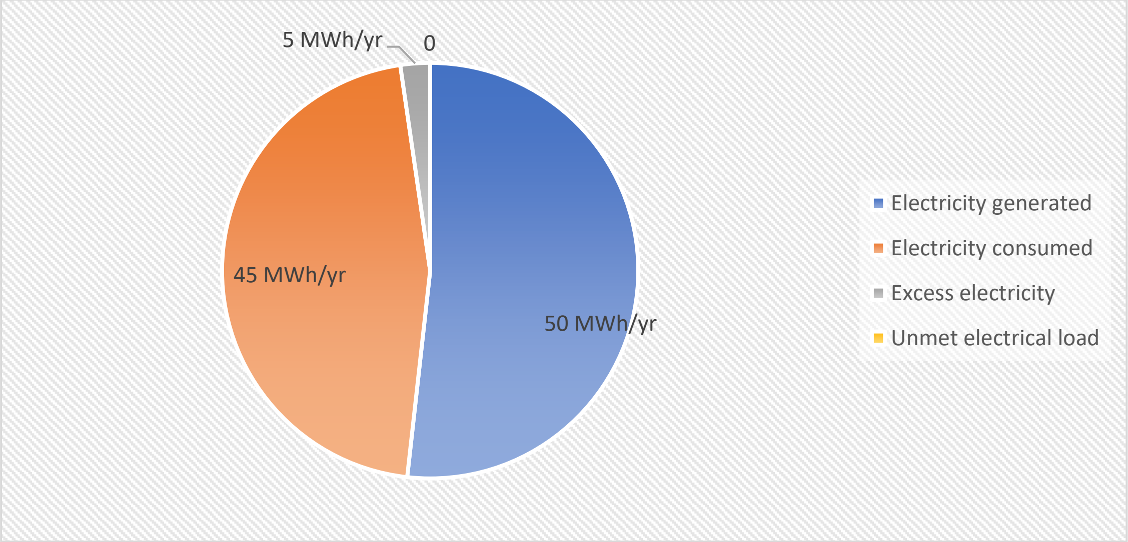


Figure 4.8: Electricity generated, consumed, and excess energy by the designed system

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.

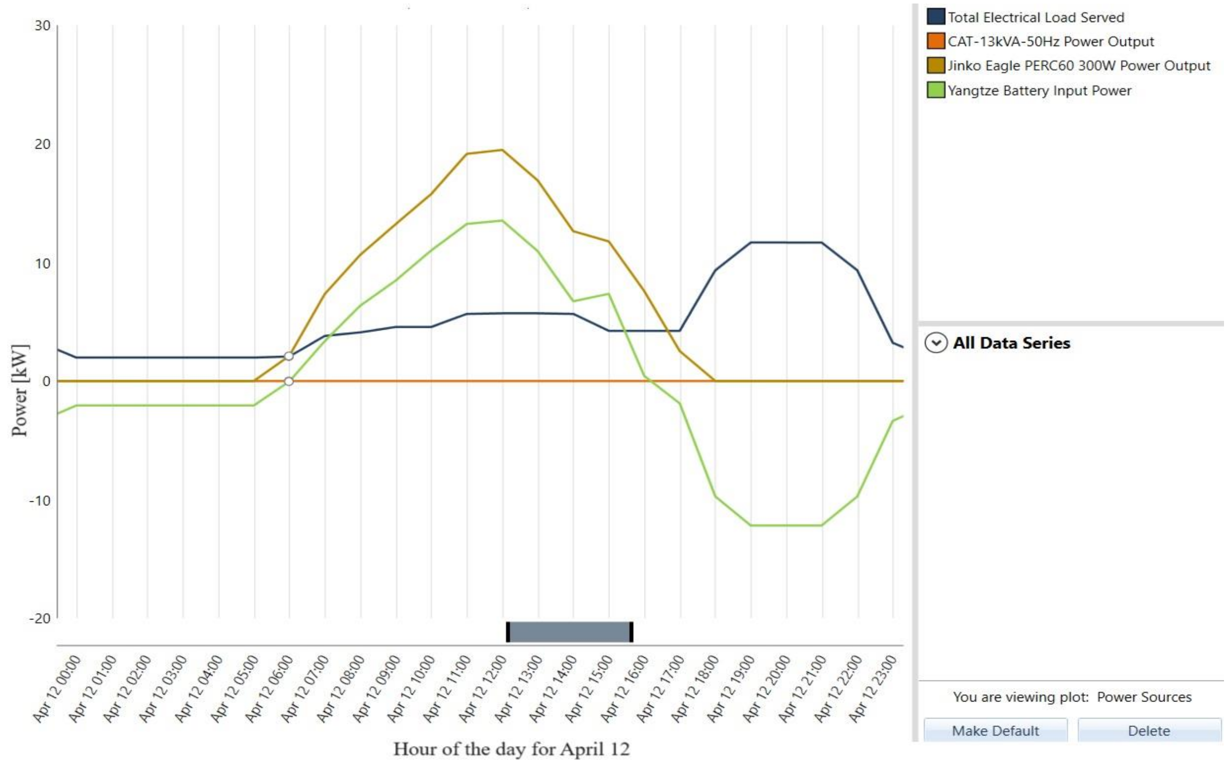
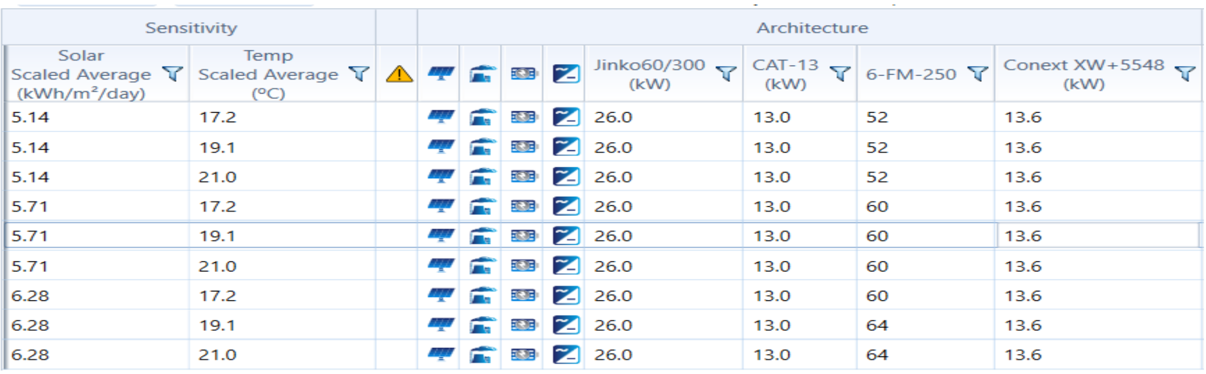


Figure 4.9: Hourly power production and consumption from PV/DG/battery system from HOMER simulation result for April 12

4.6 Sensitivity analysis on technical parameters

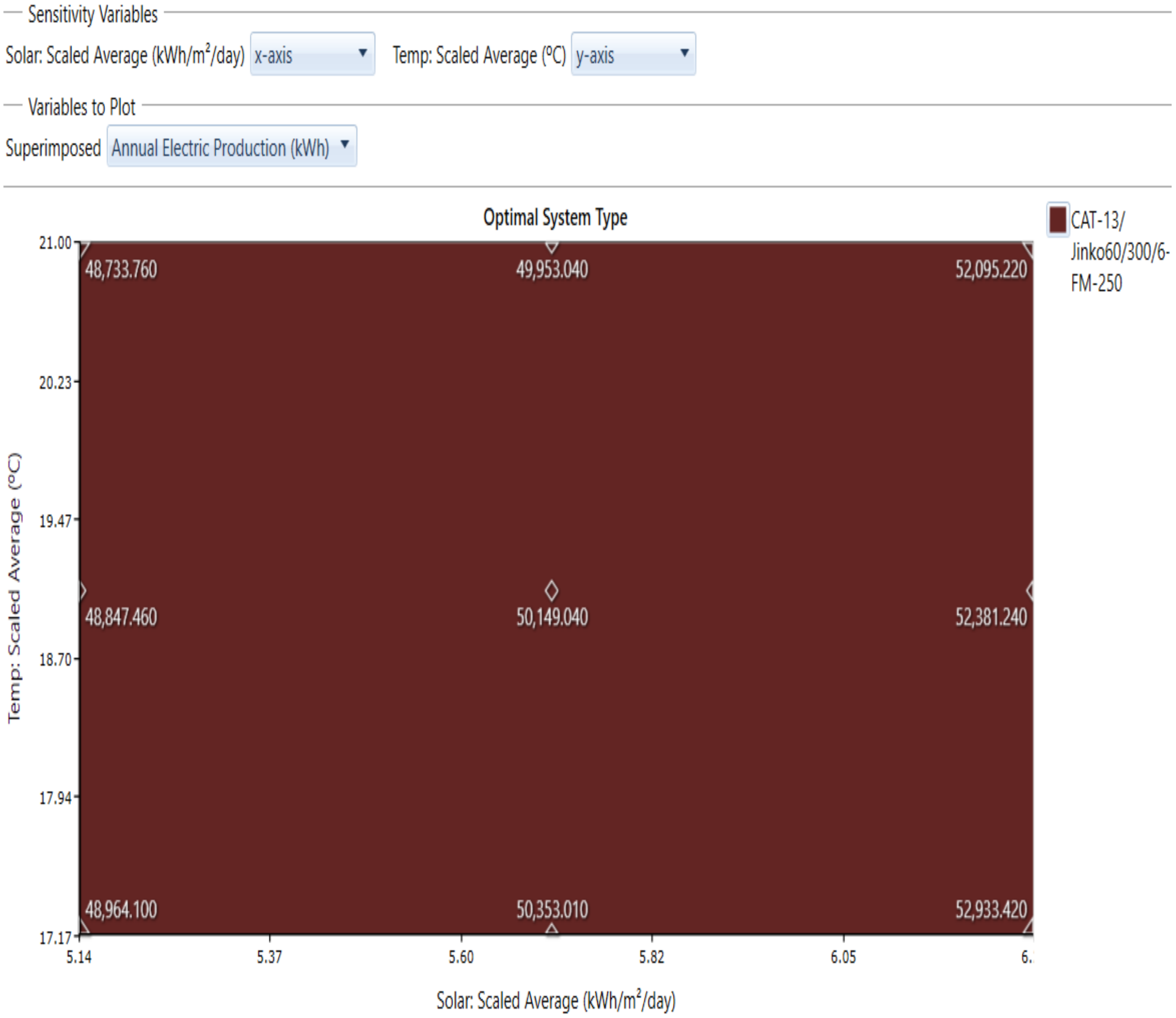
Sensitivity analysis is used to study the impact of the input parameter change when we are uncertain about the value of the decision variables. The two sensitivity variables considered in this paper are amount of the solar radiation for the study site and temperature. The average annual solar radiation for the study site was 5.71 kWh/ (m^2. day) then three values were given to HOMER software (5.14 and 6.28 kWh/(m^2. day) which are 10% variations from the annual average annual radiation. The annual average temperature of the study site is 19.1 ^{o}C. Plus, and minus 10% from the annual average temperature value is given to HOMER to study the effect on the system performance. The output of the sensitivity analysis from the simulation software is shown in the figure below.



Sensitivity			Architecture							
Solar Scaled Average (kWh/m²/day)	Temp Scaled Average (ºC)	⚠					Jinko60/300 (kW)	CAT-13 (kW)	6-FM-250	Conext XW+5548 (kW)
5.14	17.2						26.0	13.0	52	13.6
5.14	19.1						26.0	13.0	52	13.6
5.14	21.0						26.0	13.0	52	13.6
5.71	17.2						26.0	13.0	60	13.6
5.71	19.1						26.0	13.0	60	13.6
5.71	21.0						26.0	13.0	60	13.6
6.28	17.2						26.0	13.0	60	13.6
6.28	19.1						26.0	13.0	64	13.6
6.28	21.0						26.0	13.0	64	13.6

Figure 4.10: scaled annual solar radiation and temperature and system configuration.

The following figure shows that the annual electricity produced by the designed system under the varying conditions of solar radiation and temperature. From the figure, it can be seen how the fluctuation in the environmental conditions (temperature and solar radiation) impacts the energy yield. This two-variable sensitivity analysis shows their combined effect on the system performance.



Sensitivity Variables

Solar: Scaled Average (kWh/m^2/day) x-axis

Temp: Scaled Average (°C) y-axis

Variables to Plot

Superimposed Annual Electric Production (kWh)

Figure 4.11: Effect of solar radiation and temperature on energy production

In the above figure, the HOMER simulation software uses the unit kWh/m^2/day instead of kWh/(m^2.day) for the average solar radiation a certain area receives in a day.

4.7 Distribution system components

Since there is no national grid transmission line in the village, the generated power from the off-grid hybrid system will be distributed through the distribution line. Important factors to consider when designing the distribution network for mini-grid systems are the location of the powerhouse, placing the line, locating poles, and line configuration [54].

Distribution Method

For this project, the powerhouse location is assumed to be at the centre of the village, a single-phase two-wire feeder line will be taken from the powerhouse to serve the entire community. The main feeder route will be constructed along the road.

Table 4.3: Condition for planned distribution route

Project area	Length of distribution line (km)	Conditions
Wagesho village	1.5	• Poles will be erected along the route possibly by vehicles. • Vehicles will be used to transport equipment to the construction site.

Support

Poles of concrete, wood, and steel are the most commonly used to support the conductor. 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 [54]. The wooden pole is considered to support the distribution line because of its cost-benefit and local availability. and 30 meters between the two poles is considered. Considering the local availability of the trees, I considered $25 per piece for a wooden pole.

Types of cable

For electricity distribution copper and aluminium are generally used materials. 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 line. Bare conductors are one of the most common types of conductors used with the conventional low voltage distribution system around the world because they provide an increased safety hazard for people working with the line or the villagers [54]. For this case study bare copper conductor with a cross-sectional area of 29 mm^2 is considered for distributing power to consumers, the price of the conductor is $0.95 per meter [55].

Insulator

The insulators are used to isolate the conductors from the poles and are mounted on every pole of the electrical line. Spool insulators are used in low-voltage distribution lines. They can be mounted in either vertical or horizontal positions. The price of the selected spool insulator is $3 per piece [56].

Other equipment

Other equipment used in overhead low-voltage distribution lines are cross-arms, line accessories, guard wires, and earth coils [54].

4.8 Fuel consumption calculation for DG

To analyse 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 [57].

$$Q_s = K_{nl} Q_n + (1-K_{nl}) Q_n \frac{Pout}{\text{Prated}} \text{ [g/kWh]} \qquad (4.3)$$

Where P_{out} is the actual power produced by the diesel generator (6.44 kW), P_{rated} is the rated capacity of the DG (13 kW). K_{nl} is the no-load fuel consumption coefficient of a diesel engine which can be approximated to 0.3 [57], Q_s is the specific fuel consumption, and Q_n is the nominal fuel consumption of the chosen generator (Q_n= 271 g/kWh).

With the knowledge of specific fuel consumption for the corresponding load mode, then the fuel consumption for the volume of energy generated by the DG over the given period can be calculated by the following formula [57]:

$$Q_a = Q_s\ E_{gen} \tag{4.4}$$

Where Q_a is annual fuel consumption, and Q_s is specific fuel consumption, which can be calculated by the above formula. E_{gen} is the annual energy generated by diesel generators to supply the village's load demand when RE generation and battery storage are insufficient. E_{gen} by DG for the PV/DG/battery hybrid system is 6.2 MWh.

Based on the above two formulas and information on the energy generated, the annual fuel consumption is calculated as (Q_a = 1087 kg).

4.9 Emission calculation

Carbon dioxide (CO_2) emission is crucial when evaluating how energy use affects the environment, especially when burning fossil fuels. CO_2 is one of the main greenhouse gases that causes climate change. The following method can be used to calculate CO_2 emissions from fuel usage for energy generation [58].

$$CO_2 = Q_a\ K_1\ NCV\ K_2\ \frac{44}{12} \tag{4.5}$$

Where CO_2 is annual emissions in tons (t), Q_a is annual fuel consumption (t), K_1 is the coefficient of carbon oxidation in fuel which shows the carbon combustion efficiency factor (0.99), NCV is the net calorific value that measures heat content on diesel oil (43.33 TJ/ 1000 t), K_2 is carbon emission factor (20.2 tC/TJ), and $\frac{44}{12}$ is the conversion factor of carbon into carbon dioxide which represents the molecular weight of carbon dioxide relative to that of carbon [58].

Using the above formula and fuel consumption by the PV/DG/battery hybrid system, I calculated the annual CO_2 emission as:

$$CO_2 = (1.087)\ (0.99)\ (0.04333)\ (20.2)\ (\frac{44}{12})\ = 3.45\ t$$

Chapter 5 Evaluation of the designed hybrid system from an economic point of view

In this chapter, I describe and discuss the important economic evaluation criteria that will be used to evaluate the attractiveness and decide whether the designed off-grid hybrid system is worth the investment from an investor's point of view. The most important input parameter for the project evaluation is future cash inflows and outflows. Alongside the cash flow model, sensitivity analysis will be conducted to see the impact of change on the input parameter on the decision-making process.

5.1 Evaluation criteria

Evaluation of the projects is a vital process that helps to determine the effectiveness of the project and provides necessary data and information for decision-making by assessing the economic viability of the project by analyzing cash flows and potential return on investment. Important economic evaluation criteria such as NPV, IRR, and payback period are valuable tools for project evaluation [59].

Net Present Value (NPV)

Net present value (NPV) is the return on the investment respecting the time value of money. Cash flow from each year is discounted back to the present and summed [59].

$$\mathrm{NPV}= \sum_{t=1}^{T} \mathrm{C_t} \,.\, (1+\mathrm{r})^{-\mathrm{t}} - \mathrm{C_0} \tag{5.1}$$

Where

C_0 - initial investment

T- lifetime of the project,

r - discount rate,

C_t - cash flow at t year.

The investor prefer to invest on the project 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. 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 [59].

Internal Rate of Return (IRR)

Internal rate of return (IRR) is the discount rate required to achieve zero net present value for an investment [59].

$$\mathrm{NPV} = \sum_{t=1}^{T} \mathrm{C_t} \,.\, (1+\mathrm{IRR})^{-\mathrm{t}} - \mathrm{C_0} = 0 \tag{5.2}$$

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 [59].

Payback Period

The payback period (PP) is the time takes to fully recover the initial investment in the project. It does not consider the time value of money and the cash after the payback period will not be considered in decision-making [59].

$$\sum_{t=0}^{PP} C_t = 0 \qquad (5.3)$$

Where

C_t - cash flow in period t

t – time period

For decision-making, the shorter is PP, the more attractive the project is for investors.

5.2 Input parameter for evaluation criteria

It is essential to consider 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 fuel costs, maintenance costs, loan interest if the project is financed by a loan), as well as personal costs.

Discount rate

The discount rate is the rate of return an investor wants from investing in a specific project. The capital asset pricing model (CAPM) is used to estimate the required rate of return on investment by reflecting investment risk. The expected return from an investment based on CAPM can be calculated using the following formula [59].

$$r = r_f + \beta\,(r_m - r_f) \qquad (5.4)$$

Where

r_f - the risk-free return in the Ethiopian government's long-term bond is 6% [60]

$r_m - r_f$ - the risk premium investors require for investing in risky businesses is 17.77% [61].

β - the systematic risk of the investment

Estimating the 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 [59].

$$\beta_l = \beta_{u.}\,(1 + (1\text{-Tax})\,\frac{D}{E})) \qquad (5.5)$$

Where

β_l - levered beta,

β_u - unlevered beta for the power sector for the emerging market (β_u =0.53) [62],

(1-Tax) - a tax shield; the tax rate in Ethiopia is 30% [63]

$\frac{D}{E}$ - debt to equity ratio, I assumed the debt financing 40%.

Based on the above information I calculated β_l = 0.77. The discount rate for the project is therefore calculated as r = 19.6%.

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. The historical inflation rate recorded in Ethiopia by the Ethiopian Statistical Agency is shown in the figure below [64].

Table 5.1: -Historical inflation rate in Ethiopia

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
Average inflation %	16.3%										

From this historical inflation rate, there is a high inflation rate rise between 2019-2022 averaging around 26.6%. The main reason for the sharp rise between this time interval is a civil war in the country caused political tension between different ethnic armed groups, global geopolitical situation and covid-2019 have also impacts for the sharp rise of inflation. I decided to use the long-term average value of the inflation rate which is 16.3% for the economic model of the long-term project.

Using data from Table 4.1, plot of the historical inflation rate is drawn in the following figure below.

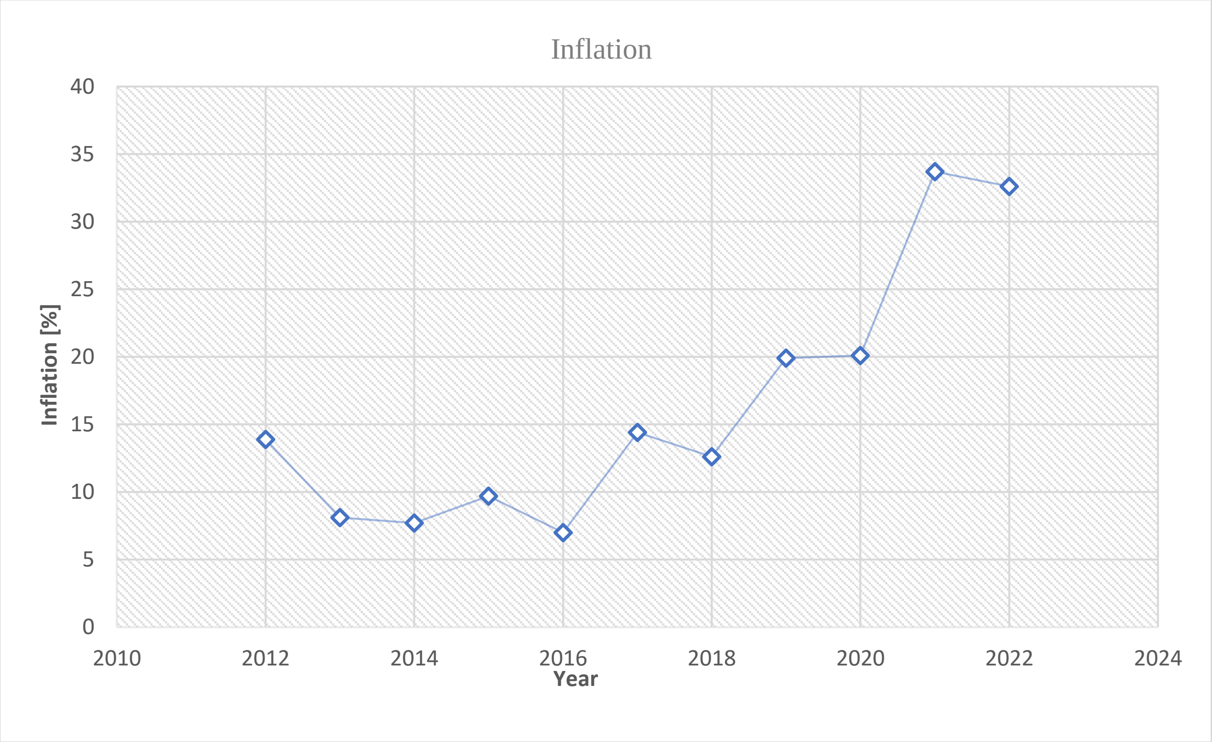


Figure 5.1: Historical inflation rate in Ethiopia [64].

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 [63].

Depreciation

Deprecation is used to distribute the cost of an asset over its useful life. It shows 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 [65].

Based on the Ethiopian income tax regulation, Taxpayers choose from the following depreciation methods and use the same method of deprecation in the financial account for all depreciable assets [66].

- Straight line deprecation method
- Accelerated depreciation method

The annual amount of deprecation in relation to an asset is the product of the capital expenditure on the asset and rate of the deprecation determined for the asset. The depreciation rate for the depreciable asset is determined using the following formula [65].

$$D_{ep} = \frac{1}{T} \text{Capex} \tag{5.6}$$

Where

D_{ep} - deprecation

Capex- capital expenditure on the asset

T- useful life of the depreciable asset.

Land rent expense

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 [67]. 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 assuming all these factors, I assumed 10% of the initial investment for installation and transportation costs.

Initial project investment

The initial investment for proposed hybrid system components includes 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 56.9 based on Commercial Bank of Ethiopia exchange rate information [68].

Table 5.2: - Components cost for the proposed hybrid system.

System components	Size	Cost in USD ($)	Cost in Ethiopian Birr (Birr)
PV panels	26 kW	2,860	162,734
Inverter	13.6 kW	6,600	375,540
Diesel generator	15 kW	7,994	454,858
Battery bank	168 kWh	13,200	751,080
Total cost		30,654	1,744,212

Table 5.3: - Distribution components cost.

System Component	Quantity	Unit price ($)	Total cost ($)	Total cost in Ethiopian Birr (Birr)
Bare copper conductor (29 mm^2)	3,000	0.95 per meter	3,135	178,382
Wooden pole (6-meter).	50	25	1,375	78,238
Spool insulator	100	3	330	18,777
Total cost			4,840	287,856
Other costs	25%		1,210	68, 849
Grand total cost			6,050	344,246

The cost of the component is calculated in the above tables including installation and transportation cost which is 10% of the cost of the individual components. Based on the above tables, the total cost of PV/DG/battery hybrid power generation system components is \$ 30,654 (1,744,213 Birr), and the cost of the distribution network is \$ 6,050 (344,246 Birr). Therefore, the initial investment in the project components is (C_0 = 2,088,458 Birr).

Since the project life is 25 years, the selected component's service life should be the same as the designed project life. The useful life of the selected battery is 12 years, the useful life span of the diesel generator is approximately 20 years, and the life span of the inverter is 10 years. Therefore, it is necessary to replace this componenets at the end of their useful life span.

The initial price of the battery is 751,080 Birr, this value should be adjusted with an inflation rate of 16.3% to get the replacement cost of the battery:

$$C_{battery,\ 12} = 751{,}080\ (1+0.163)^{12} = 4{,}598{,}781 \text{ Birr} \quad (5.7)$$

$$C_{battery,\ 24} = 751{,}080\ (1+0.163)^{24} = 28{,}157{,}841 \text{ Birr} \quad (5.8)$$

The battery will be sold for the residual at the end of the project life and the residual value of the battery is calculated as follows:

$$\text{Residual value,}_{\text{battery}} = 28{,}157{,}841\ (\tfrac{11}{12}) = 25{,}811{,}354 \text{ Birr} \quad (5.9)$$

The initial price of the diesel generator is 454,858 Birr, this value should be inflated to get the replacement cost:

$$C_{DG,20} = 454{,}858\ (1 + 0.163)^{20} = 9{,}321{,}164 \text{ Birr} \quad (5.10)$$

Therefore, there is an investment for a diesel generator in the first and twenty years which is equal to 454,858 Birr and 9,321,164 Birr respectively. After 25 years, the diesel generator will have a residual value for the remaining years, which means after the end of the project life the generator can be sold for the residual value and it can be calculated as follows:

$$\text{Residual value}_{\text{, DG}} = 9{,}321{,}164\ \left(\frac{15}{20}\right) = 6{,}990{,}872\ \text{Birr} \qquad (5.11)$$

The initial price of the inverter is 375,540 Birr, this value should be inflated to get the replacement cost of the inverter in the 10^{th} and 20^{th} years are calculated as follows.

Replacement cost of inverter:

$$\mathrm{C}_{\text{Inverter,10}} = 375{,}540\ (1 + 0.163)^{10} = 1{,}700{,}017\ \text{Birr} \qquad (5.12)$$

$$\mathrm{C}_{\text{Inverter,20}} = 375{,}540\ (1 + 0.163)^{20} = 7{,}695{,}741\ \text{Birr} \qquad (5.13)$$

Inverter after the end of the project life can be sold for the residual value and it can be calculated as follows:

$$\text{Residual value}_{\text{, Inverter}} = 7{,}695{,}741\ \left(\frac{5}{10}\right) = 3{,}847{,}870\ \text{Birr} \qquad (5.14)$$

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 [69]. I considered 2% of the initial investment for the operation and maintenance cost of PV panels yearly; the battery and inverter are maintenance-free based on the manufacturer data.

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 [70]. I also considered 5% of the initial investment for the operation and maintenance cost of the distribution system.

Financing of the project

This project can be financed using investor equity, and part of the investment can be financed by a loan from the government bank. For financing by loan, the Commercial Bank of Ethiopia provides loans in different terms, 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% [71].

Fuel expense

For the proposed PV/DG/ battery hybrid systems, DG generates 6.2 MWh yearly, and the annual fuel consumption for the generated power is calculated at 1087 kg. According to [72], the density of the diesel fuel is 0.873 kg/l. Based on this information, annual fuel consumption is 1,245 liters. The diesel fuel price in Ethiopia is 79.75 Birr per litter [73]. Using all the inputs, fuel expense for power generation from DG is calculated as follows:

$$\mathrm{C}_{\text{fuel}} = (79.75)\ (1{,}245) = 99{,}288\ \text{Birr} \qquad (5.13)$$

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

Salary expense

For the proposed system, I assumed two electricians would monitor the operating conditions of the system. To estimate the expense, the Ethiopian civil servant salary scale is taken as the base, and the monthly salary expenditure for employees is 4,130 Birr [74]. Employers are required to contribute 11% of their salary to social security [75]. So, the annual salary expense is calculated as follows:

$$C_{\text{salary}} = (2)\,(4{,}130)\,(1+0.11)\,(12) = 110{,}023 \text{ Birr} \tag{5.14}$$

The salary expenses will be recalculated for the following years using 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 [76]. Since the proposed power consumption for the village is very low, this tariff is used to calculate the revenue.

$$R = E_c\, C_{et} = (45{,}000 \text{ kWh})\,(2 \text{ Birr/kWh}) \tag{5.15}$$

Where

R– revenue from selling electricity.

E_c – annual energy consumption [45,000 kWh].

C_{et} - an electricity tariff [2 Birr/kWh].

Revenue generated from sales of electricity will be 90,000 Birr; this value in year "t" will change with the escalation rate, as follows:

$$R = 90{,}000\,(1+\text{escalation})^{t} \text{ Birr} \tag{5.16}$$

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 the consumers from a mini-grid and compare it with the current existing tariff.

5.3 The economic model calculation result

In this section, I created an economic model on an Excel sheet. Cash inflows represent revenue generated by selling electricity to the village consumers. I used the existing electricity price to sell electricity to the village consumers, while cash outflows included all the expenses related to this project which are mentioned in the above section. The straight-line deprecation method is used for asset depreciation over time.

Net present value with grid tariff

Based on the cash flow calculation, the designed off-grid hybrid system has a negative net present value (NPV of the designed project is -6,349,161 Birr. The negative NPV of the project can be explained as selling the electricity to consumers from the mini-grid system to the village consumer with the existing electricity price will not be profitable. However, the designed system is for remote areas without access to the national grid, so investors can calculate the minimum selling price to invest in this project.

Minimum price

Since investors do not prefer to invest in a project with a negative NPV, I calculated the minimum price for this project by setting the net present value to zero, which means the investor would sell at a minimum price to get the return, which is equal to the discount rate. The minimum price calculated for this project is 10.98 Birr/kWh ($ 0.19/ kWh).

The current electricity tariff structure in Ethiopia is set below electricity generation cost, which means the current tariff falls significantly short of covering the actual expenses. In Ethiopia, the average power generation cost is about 5.12 Birr/kWh, but the tariff is about 2 Birr/kWh [77].

The minimum selling price calculated for this project is significantly higher than the current electricity selling price. Many scholars designed off-grid hybrid systems for rural electrification in different parts of the country. From their results, the cost of electricity for the mini-grid is higher than the cost of electricity for the grid system. Based on the literature review from previous works, particularly from the work of Dr. Getachew Bekele, who is currently an assistant professor at Addis Ababa University in Ethiopia, conducted a feasibility study for power generation from a hybrid off-grid system in Ethiopia for his doctoral degree dissertation in KTH Royal Institute of Technology in Sweden, from the result of his work, the cost of electricity was 17 Birr/kWh ($ 0.3 /kWh)[11], which is almost eight times higher than national grid electricity tariff.

According to [79], a typical household in the rural area of the southern part of Ethiopia spends on average 343 Birr on firewood and 263 Birr on electricity monthly. The average monthly electricity price for this project is 192 Birr which is lower than the average electricity price of households in rural areas of the southern part of Ethiopia.

5.4 Sensitivity analysis

Sensitivity analysis is used to investigate the effect that a change in the value of various variables would have on the NPV. Finding the factors that affect the project and identifying the critical variable that affects the project the most are helpful [78].

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 price

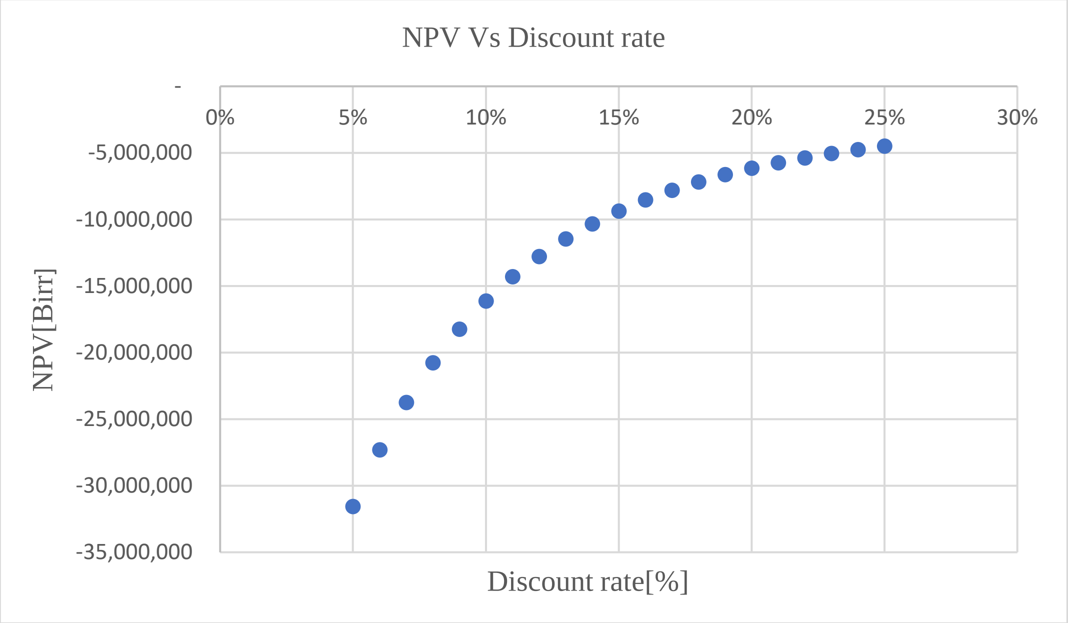


Figure 5.2: Dependence of NPV on discount rate

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.

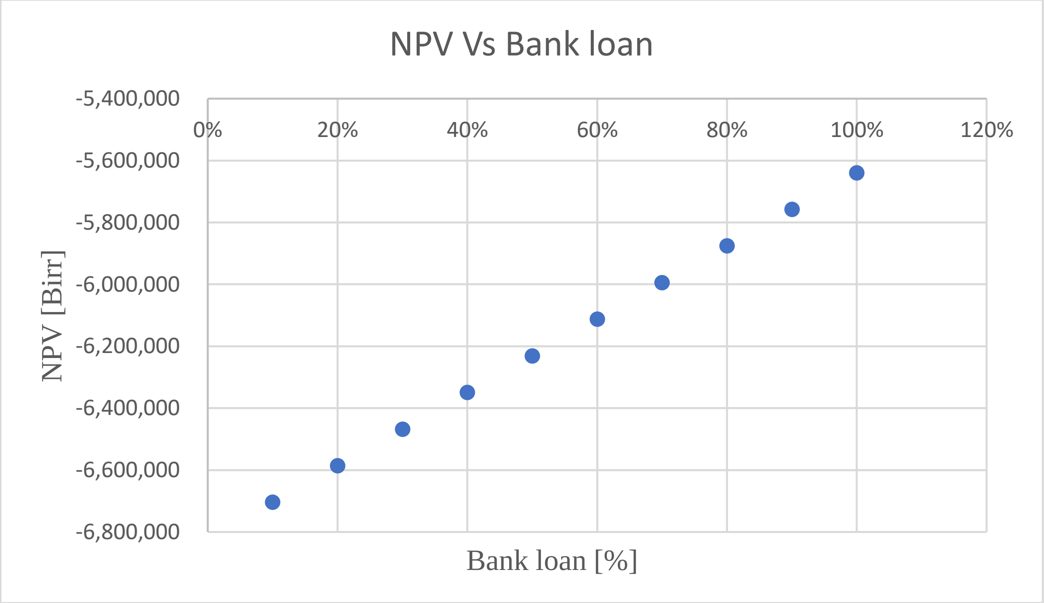


Figure 5.3: Dependence of NPV on financing method

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.

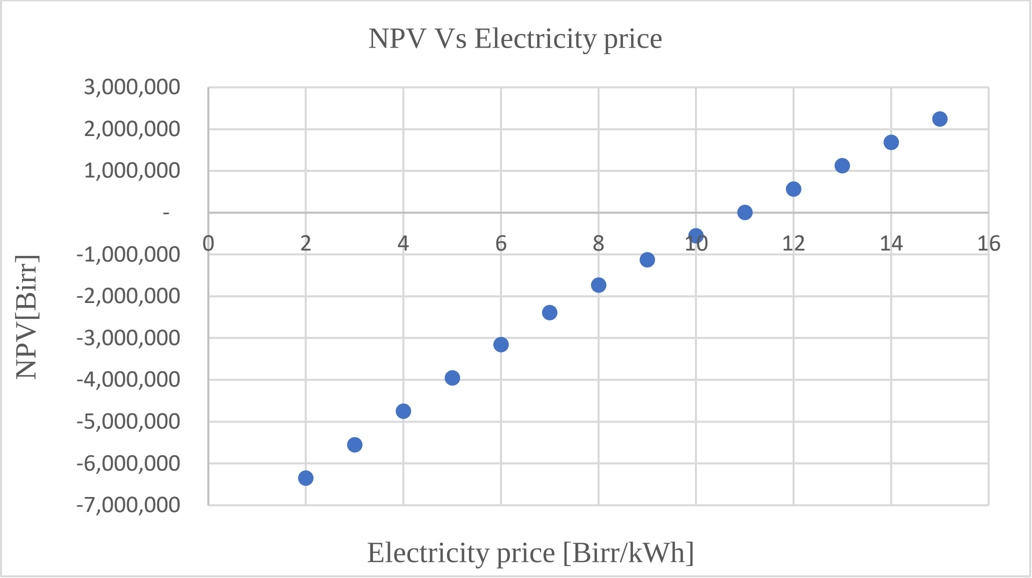


Figure 5.4: Dependence of NPV on electricity price

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 \$0.19/kWh (10.98 Birr/kWh).

Selling electricity below breakeven point makes the NPV value negative, which make the project nonprofitable, and any price above the minimum price will also make the NPV positive.

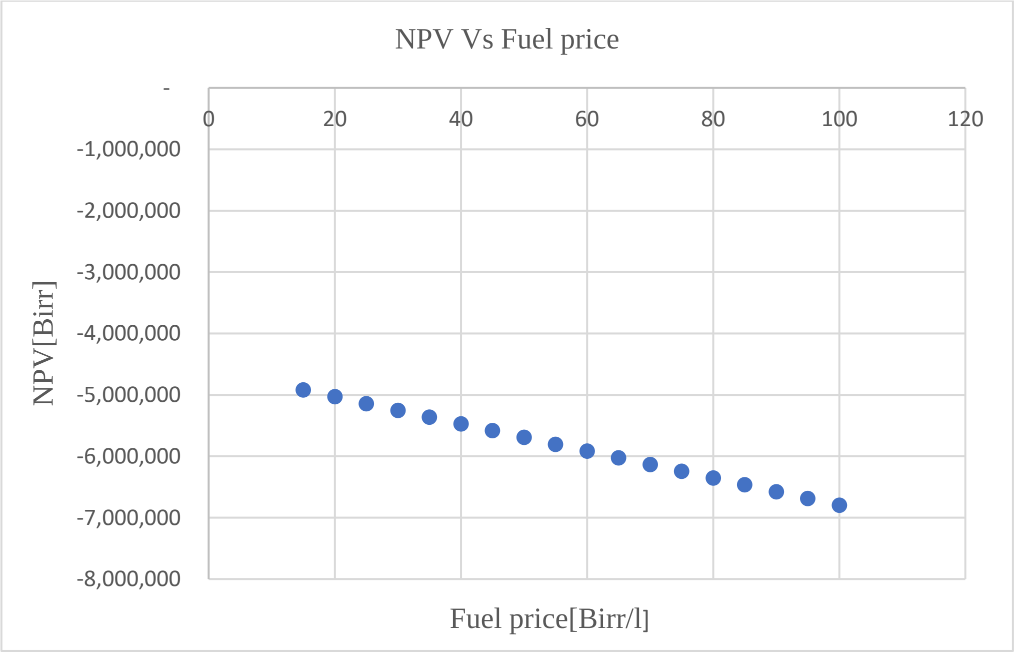


Figure 5.5: Dependence of NPV on fuel price

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 6 Conclusion

This study presents the feasibility analysis for power generation from off-grid hybrid systems from RES and DG in the rural area of Ethiopia. The case study is done for a community of 215 households living in the Wagesho village.

To achieve the objective of this paper by designing the off-grid hybrid system, firstly feasibility of the energy resources in the selected site is conducted by assessment of energy resource potential for both solar energy and wind energy resources. For wind energy potential, the wind speed for the village based on five-year average data from the NASA database obtained at the height of 10 m is 2.13m/s based on the wind power density classification this speed is classified into the poor class which is not suitable for application of wind power generation, whereas the solar energy potential of the selected village is 5.71 kWh/m^2, which is higher than the average exploitable potential in the country level, which is 5.5 kWh/m^2 [15].

Load demand estimation is made for households based on their income level for ownership of the appliance using Microgrid Load Profile Explorer which is developed for Power Africa load profile estimation using inputs from Power Africa projects which is a data-driven approach for estimation of load demand in the rural area connecting to electricity for the first time. Moreover, energy demand for community institutions such as school, churches, streetlights, and heal-post is also calculated.

After load profile estimation and energy resource potential assessment off-grid hybrid system consisting of PV, DG, and battery is optimally designed using HOMER simulation software. From the proposed hybrid system 87.6% of power generation is achieved by a renewable fraction and the remaining 12.4% is generated using DG. The annual CO_2 emission calculated from DG is 3.45 t.

Economic analysis is conducted for the designed PV/DG/battery hybrid systems using the cash flow model, the NPV is calculated using the electricity tariff from the national grid, which gives the NPV of (-6,349,161 Birr). From the investor's point of view, the minimum electricity selling price is calculated to invest in this project to get the return, which is the same as the discount rate and the result is 10.98 Birr/kWh ($ 0.19/kWh).

The minimum electricity selling price calculated for the proposed system is higher than the electricity tariff. However, the village is not near the national grid and GoE short-term plan is to extend grid connectivity to the area near the existing national grid. By implementing this project in the village investors will get the required rate of return from the investment and the benefits for the community are reducing deforestation which helps to protect against soil degradation and improve the productivity of the farmers in the village, providing clean water also helps to avoid water diseases and costs for medication, helps to avoid the traditional lighting system (kerosene lamp) which has hazardous gas, and improve the quality of the life of the people living in the village.

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.

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Appendices

Appendix A: Components technical specification

Technical data for Eagle PERC 60 300 model solar panel

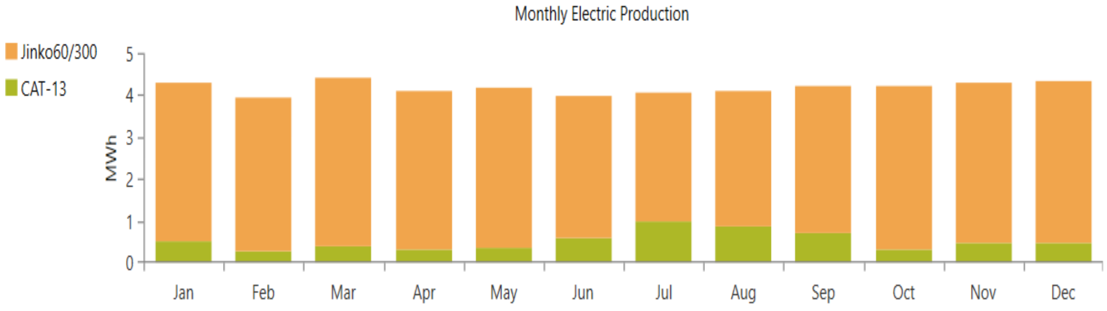
Electrical data at STC	• Maximum power(Pmax)	300 Wp
	• Voltage at maximum power	32.6 V
	• Current at maximum power	9.21 A
	• Voc	40.1 V
	• Isc	9.71 A
	• Panel efficiency	18.3%
Thermal ratings	• Operating temperature	-40 to 85 ^{0}C
	• Temperature coefficient of Pmax	-0.39 %/°C
	• Temperature Coefficient 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

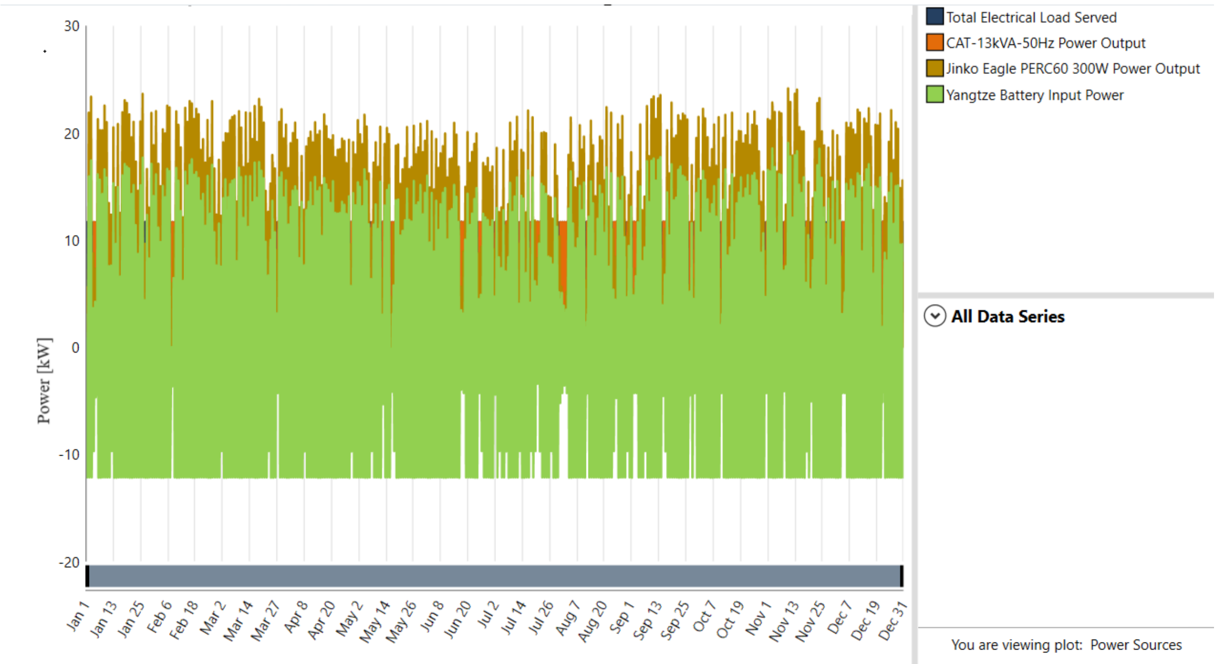
Functional parameters	• Nominal Voltage	12 V
	• Nominal Capacity	250 A.h
	• Number of Cells	6 cells
	• Internal resistance	2 mOhom
	• Maximum Discharge Current	3750A (5s)
	• Maximum charging current	62.5 A
Environment temperature	• charge temperature	0-50 ^{0}C
	• discharge temperature	-20-60 ^{0}C
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

Appendix B: HOMER simulation result

Monthly electricity production from PV and DG

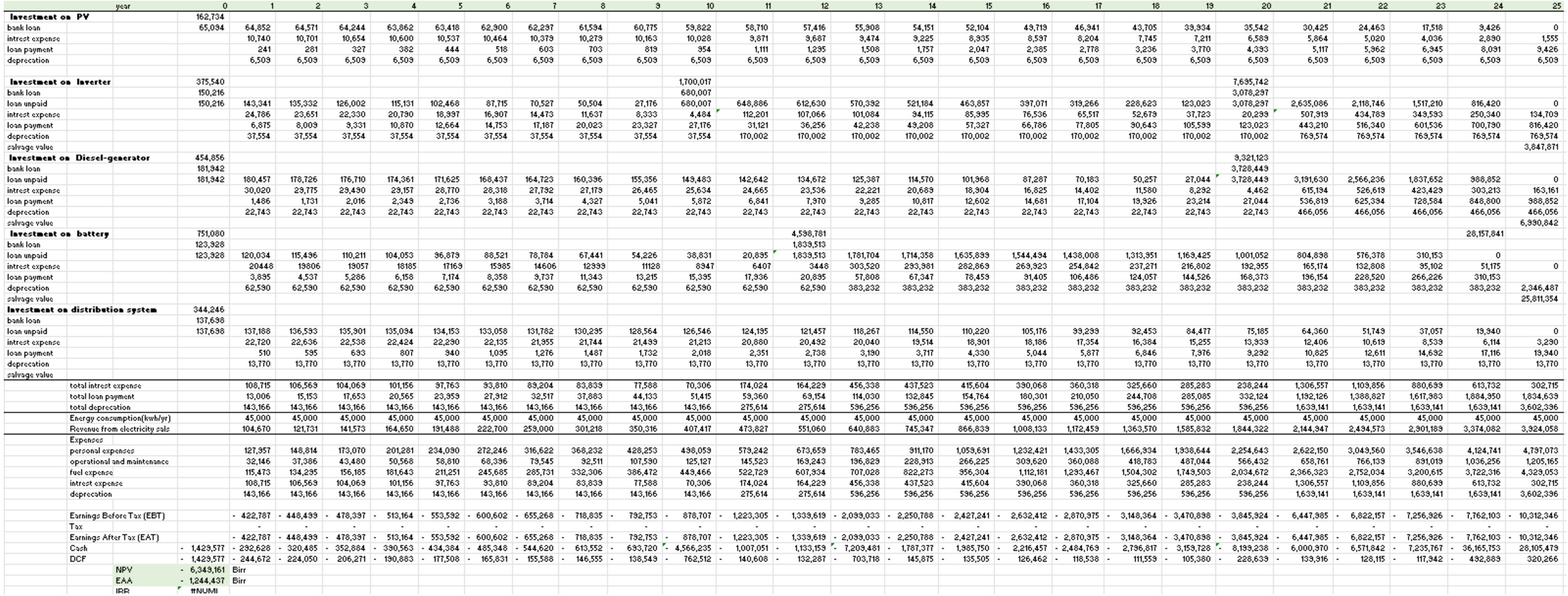


Production, consumption and storage pattern from the hybrid system



Appendix C: -Cash flow model calculation result

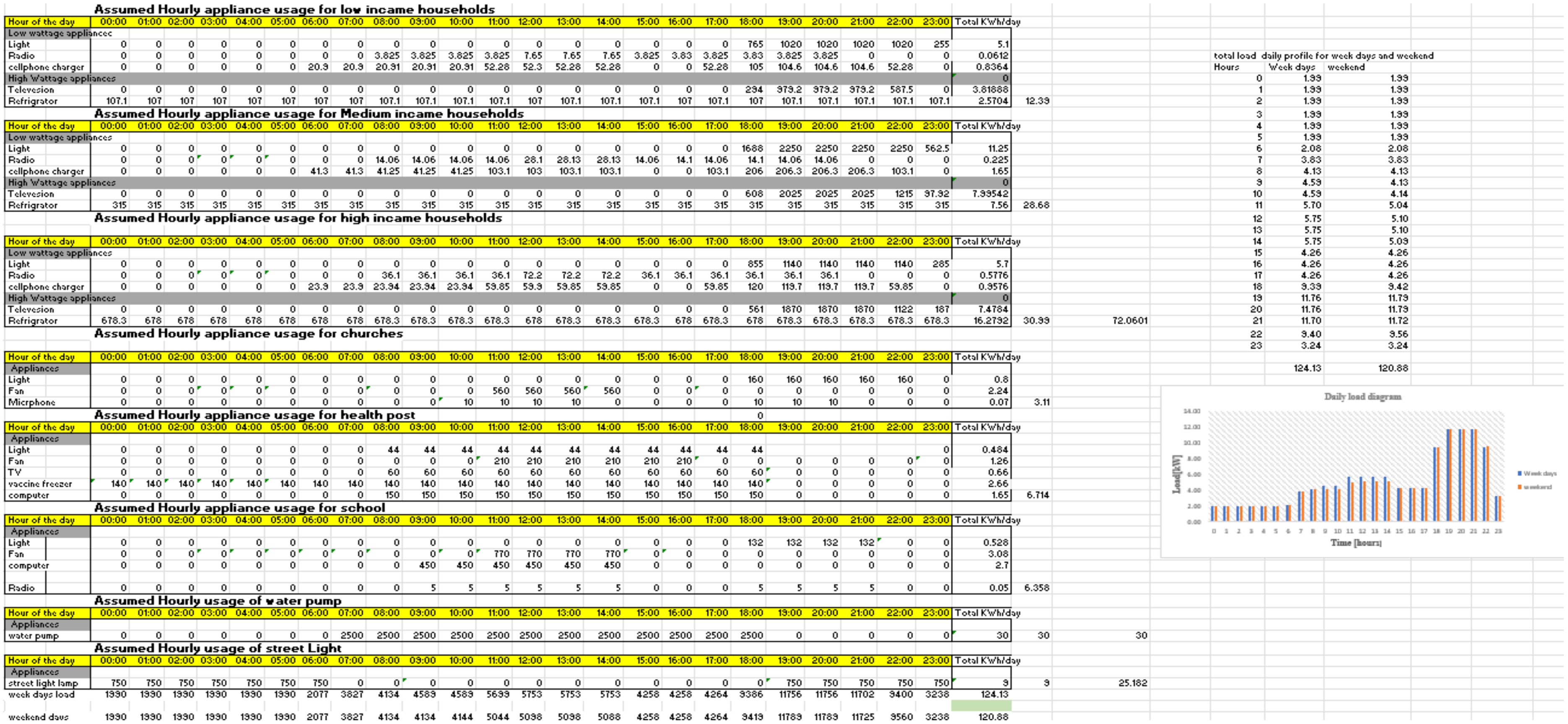
Calculation for the proposed system



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	162,734																									
bank loan	65,094	64,852	64,571	64,244	63,862	63,418	62,900	62,297	61,594	60,775	59,822	58,710	57,416	55,908	54,151	52,104	49,719	46,941	43,705	39,934	35,542	30,425	24,463	17,518	9,426	0
intrest expense		10,740	10,701	10,654	10,600	10,537	10,464	10,379	10,279	10,163	10,028	9,871	9,687	9,474	9,225	8,935	8,597	8,204	7,745	7,211	6,589	5,864	5,020	4,036	2,890	1,555
loan payment		241	281	327	382	444	518	603	703	819	954	1,111	1,295	1,508	1,757	2,047	2,385	2,778	3,236	3,770	4,393	5,117	5,962	6,945	8,091	9,426
deprecation		6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509	6,509
Investment on Inverter	375,540										1,700,017										7,695,742					
bank loan	150,216										680,007										3,078,297					
loan unpaid	150,216	143,341	135,332	126,002	115,131	102,468	87,715	70,527	50,504	27,176	680,007	648,886	612,630	570,392	521,184	463,857	397,071	319,266	228,623	123,023	3,078,297	2,635,086	2,118,746	1,517,210	816,420	0
intrest expense		24,786	23,651	22,330	20,790	18,997	16,907	14,473	11,637	8,333	4,484	112,201	107,066	101,084	94,115	85,995	76,536	65,517	52,679	37,723	20,299	507,919	434,789	349,593	250,340	134,709
loan payment		6,875	8,009	9,331	10,870	12,664	14,753	17,187	20,023	23,327	27,176	31,121	36,256	42,238	49,208	57,327	66,786	77,805	90,643	105,599	123,023	443,210	516,340	601,536	700,790	816,420
deprecation		37,554	37,554	37,554	37,554	37,554	37,554	37,554	37,554	37,554	37,554	170,002	170,002	170,002	170,002	170,002	170,002	170,002	170,002	170,002	170,002	769,574	769,574	769,574	769,574	769,574
salvage value																										3,847,871
Investment on Diesel-generator	454,856																				9,321,123					
bank loan	181,942																				3,728,449					
loan unpaid	181,942	180,457	178,726	176,710	174,361	171,625	168,437	164,723	160,396	155,356	149,483	142,642	134,672	125,387	114,570	101,968	87,287	70,183	50,257	27,044	3,728,449	3,191,630	2,566,236	1,837,652	988,852	0
intrest expense		30,020	29,775	29,490	29,157	28,770	28,318	27,792	27,179	26,465	25,634	24,665	23,536	22,221	20,689	18,904	16,825	14,402	11,580	8,292	4,462	615,194	526,619	423,429	303,213	163,161
loan payment		1,486	1,731	2,016	2,349	2,736	3,188	3,714	4,327	5,041	5,872	6,841	7,970	9,285	10,817	12,602	14,681	17,104	19,926	23,214	27,044	536,819	625,394	728,584	848,800	988,852
deprecation		22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	22,743	466,056	466,056	466,056	466,056	466,056
salvage value																										6,990,842
Investment on battery	751,080												4,598,781												28,157,841	
bank loan	123,928												1,839,513													
loan unpaid	123,928	120,034	115,496	110,211	104,053	96,879	88,521	78,784	67,441	54,226	38,831	20,895	1,839,513	1,781,704	1,714,358	1,635,899	1,544,494	1,438,008	1,313,951	1,169,425	1,001,052	804,898	576,378	310,153	0	
intrest expense		20448	19806	19057	18185	17169	15985	14606	12999	11128	8947	6407	3448	303,520	293,981	282,869	269,923	254,842	237,271	216,802	192,955	165,174	132,808	95,102	51,175	0
loan payment		3,895	4,537	5,286	6,158	7,174	8,358	9,737	11,343	13,215	15,395	17,936	20,895	57,808	67,347	78,459	91,405	106,486	124,057	144,526	168,373	196,154	228,520	266,226	310,153	
deprecation		62,590	62,590	62,590	62,590	62,590	62,590	62,590	62,590	62,590	62,590	62,590	62,590	383,232	383,232	383,232	383,232	383,232	383,232	383,232	383,232	383,232	383,232	383,232	383,232	2,346,487
salvage value																										25,811,354
Investment on distribution system	344,246																									
bank loan	137,698																									
loan unpaid	137,698	137,188	136,593	135,901	135,094	134,153	133,058	131,782	130,295	128,564	126,546	124,195	121,457	118,267	114,550	110,220	105,176	99,299	92,453	84,477	75,185	64,360	51,749	37,057	19,940	0
intrest expense		22,720	22,636	22,538	22,424	22,290	22,135	21,955	21,744	21,499	21,213	20,880	20,492	20,040	19,514	18,901	18,186	17,354	16,384	15,255	13,939	12,406	10,619	8,539	6,114	3,290
loan payment		510	595	693	807	940	1,095	1,276	1,487	1,732	2,018	2,351	2,738	3,190	3,717	4,330	5,044	5,877	6,846	7,976	9,292	10,825	12,611	14,692	17,116	19,940
deprecation		13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770	13,770
salvage value																										
total intrest expense		108,715	106,569	104,069	101,156	97,763	93,810	89,204	83,839	77,588	70,306	174,024	164,229	456,338	437,523	415,604	390,068	360,318	325,660	285,283	238,244	1,306,557	1,109,856	880,699	613,732	302,715
total loan payment		13,006	15,153	17,653	20,565	23,959	27,912	32,517	37,883	44,133	51,415	59,360	69,154	114,030	132,845	154,764	180,301	210,050	244,708	285,085	332,124	1,192,126	1,388,827	1,617,983	1,884,950	1,834,639
total deprecation		143,166	143,166	143,166	143,166	143,166	143,166	143,166	143,166	143,166	143,166	275,614	275,614	596,256	596,256	596,256	596,256	596,256	596,256	596,256	596,256	1,639,141	1,639,141	1,639,141	1,639,141	3,602,396
Energy consumption(kwh/yr)		45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000	45,000
Revenue from electricity sals		104,670	121,731	141,573	164,650	191,488	222,700	259,000	301,218	350,316	407,417	473,827	551,060	640,883	745,347	866,839	1,008,133	1,172,459	1,363,570	1,585,832	1,844,322	2,144,947	2,494,573	2,901,189	3,374,082	3,924,058
Expenses																										
personal expenses		127,957	148,814	173,070	201,281	234,090	272,246	316,622	368,232	428,253	498,059	579,242	673,659	783,465	911,170	1,059,691	1,232,421	1,433,305	1,666,934	1,938,644	2,254,643	2,622,150	3,049,560	3,546,638	4,124,741	4,797,073
operational and maintenance		32,146	37,386	43,480	50,568	58,810	68,396	79,545	92,511	107,590	125,127	145,523	169,243	196,829	228,913	266,225	309,620	360,088	418,783	487,044	566,432	658,761	766,139	891,019	1,036,256	1,205,165
fuel expense		115,473	134,295	156,185	181,643	211,251	245,685	285,731	332,306	386,472	449,466	522,729	607,934	707,028	822,273	956,304	1,112,181	1,293,467	1,504,302	1,749,503	2,034,672	2,366,323	2,752,034	3,200,615	3,722,316	4,329,053
intrest expense		108,715	106,569	104,069	101,156	97,763	93,810	89,204	83,839	77,588	70,306	174,024	164,229	456,338	437,523	415,604	390,068	360,318	325,660	285,283	238,244	1,306,557	1,109,856	880,699	613,732	302,715
deprecation		143,166	143,166	143,166	143,166	143,166	143,166	143,166	143,166	143,166	143,166	275,614	275,614	596,256	596,256	596,256	596,256	596,256	596,256	596,256	596,256	1,639,141	1,639,141	1,639,141	1,639,141	3,602,396
Earnings Before Tax (EBT)		- 422,787	- 448,499	- 478,397	- 513,164	- 553,592	- 600,602	- 655,268	- 718,835	- 792,753	- 878,707	- 1,223,305	- 1,339,619	- 2,099,033	- 2,250,788	- 2,427,241	- 2,632,412	- 2,870,975	- 3,148,364	- 3,470,898	- 3,845,924	- 6,447,985	- 6,822,157	- 7,256,926	- 7,762,103	- 10,312,346
Tax		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Earnings After Tax (EAT)		- 422,787	- 448,499	- 478,397	- 513,164	- 553,592	- 600,602	- 655,268	- 718,835	- 792,753	- 878,707	- 1,223,305	- 1,339,619	- 2,099,033	- 2,250,788	- 2,427,241	- 2,632,412	- 2,870,975	- 3,148,364	- 3,470,898	- 3,845,924	- 6,447,985	- 6,822,157	- 7,256,926	- 7,762,103	- 10,312,346
Cash	- 1,429,577	- 292,628	- 320,485	- 352,884	- 390,563	- 434,384	- 485,348	- 544,620	- 613,552	- 693,720	- 4,566,235	- 1,007,051	- 1,133,159	- 7,209,481	- 1,787,377	- 1,985,750	- 2,216,457	- 2,484,769	- 2,796,817	- 3,159,728	- 8,199,238	- 6,000,970	- 6,571,842	- 7,235,767	- 36,165,753	28,105,479
DCF	- 1,429,577	- 244,672	- 224,050	- 206,271	- 190,883	- 177,508	- 165,831	- 155,588	- 146,555	- 138,549	- 762,512	- 140,608	- 132,287	- 703,718	- 145,875	- 135,505	- 126,462	- 118,538	- 111,559	- 105,380	- 228,639	- 139,916	- 128,115	- 117,942	- 492,889	320,266
NPV	- 6,349,161	Birr																								
EAA	- 1,244,437	Birr																								
IRR	#NUM!																									

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	3.83	3.825	3.83	3.825	3.825	0	0	0	0.0612	
cellphone charger	0	0	0	0	0	0	20.9	20.9	20.91	20.91	20.91	52.28	52.3	52.28	52.28	0	0	52.28	105	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	294	979.2	979.2	979.2	587.5	0	3.81888	
Refrigrator	107.1	107	107	107	107	107	107	107	107.1	107.1	107.1	107.1	107	107.1	107.1	107.1	107	107.1	107	107.1	107.1	107.1	107.1	107.1	2.5704	12.39

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 appliances																										
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	14.06	14.06	14.06	28.1	28.13	28.13	14.06	14.1	14.06	14.1	14.06	14.06	0	0	0	0.225	
cellphone charger	0	0	0	0	0	0	41.3	41.3	41.25	41.25	41.25	103.1	103	103.1	103.1	0	0	103.1	206	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	608	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	28.68

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 appliances																											
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	36.1	36.1	36.1	36.1	0	0	0	0.5776		
cellphone charger	0	0	0	0	0	0	23.9	23.9	23.94	23.94	23.94	59.85	59.9	59.85	59.85	0	0	59.85	120	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	561	1870	1870	1870	1122	187	7.4784		
Refrigrator	678.3	678	678	678	678	678	678	678	678.3	678.3	678.3	678.3	678	678.3	678.3	678.3	678	678.3	678	678.3	678.3	678.3	678.3	678.3	16.2792	30.99	72.0601

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	
Appliances																										
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	0	0	0	0	0	0	0	0	0	0	10	10	10	10	0	0	0	0	10	10	10	0	0	0	0.07	3.11
																			0							

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	
Appliances																										
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	
Appliances																										
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	450	450	450	450	450	450	0	0	0	0	0	0	0	0	0	2.7	
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	6.358

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		
Appliances																											
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		
Appliances																											
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	25.182
week days load	1990	1990	1990	1990	1990	1990	2077	3827	4134	4589	4589	5699	5753	5753	5753	4258	4258	4264	9386	11756	11756	11702	9400	3238	124.13		
weekend days	1990	1990	1990	1990	1990	1990	2077	3827	4134	4134	4144	5044	5098	5098	5088	4258	4258	4264	9419	11789	11789	11725	9560	3238	120.88		

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	4.13
9	4.59	4.13
10	4.59	4.14
11	5.70	5.04
12	5.75	5.10
13	5.75	5.10
14	5.75	5.09
15	4.26	4.26
16	4.26	4.26
17	4.26	4.26
18	9.39	9.42
19	11.76	11.79
20	11.76	11.79
21	11.70	11.72
22	9.40	9.56
23	3.24	3.24
	124.13	120.88