ADDIS ABABA UNIVERSTY

ADDIS ABABA INSTITUTE OF TECNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

Performance Assessment of PV mini-grids for effective replacement of diesel based mini-grids at selected sites in Ethiopia

A thesis Submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master of Science in Electrical and Computer Engineering (Electrical Power Engineering Stream)

By: Kalkidan Getachew

Advisor: Dr. Ing. Getachew Biru

Performance Assessment of PV mini-grids for effective replacement of diesel based mini-grids at selected sites in Ethiopia

By: Kalkidan Getachew

APPROVAL BY BOARD OF EXAMINERS

_______________________________ _______________________________

CHAIRMAN DEPARTMENT OF GRADUATE COMMITTEE SIGNATURE

_Getachew Biru (Dr.-Ing.)__________ _______________________________

ADVISOR SIGNATURE

_______________________________ _______________________________

INTERNAL EXAMINER SIGNATURE

_______________________________ _______________________________

EXTERNAL EXAMINER SIGNATURE

Declaration

I, the undersigned, declare that this MSc thesis is my original work, has not been presented for fulfillment of a degree in this or any other university, and all sources and materials used for the thesis have been acknowledged.

Name: Kalkidan Getachew

Signature: ______________

Place: Addis Ababa

Date of submission: September, 2023

This thesis work has been submitted for examination with my approval as a university advisor.

Dr - Ing. Getachew Biru ______________

Advisor's Name Signature

Acknowledgements

First of all, I would like to thank God for blessing me with ability to complete this work.

This work couldn't be complete without help and support of several people.

My deep gratitude goes to my advisor, Dr. Ing Getachew Biru who has provided valuable Support, reference, guidance and patience over the past years. Also, for his precious time spent in discussions, valuable commenting, editing and generous assistance.

I am also very grateful to my co-advisor Mr. Kiros Tesfaye for lots of advice and helping in preparing the thesis documentation, but also for good ideas and discussions regarding everything from data organization Homer simulation in general.

My deep appreciations are for all of my family for their support, patience and encouragement. I would like to thank my friends here in AAU and staff for their information and encouragement.

Thanks to everyone who has contributed to this work directly or indirectly.

Kalkidan Getachew

September, 2023

Table of Contents

List of Table

List of Figure

List of Nomenclature

AC	Alternating current
ADELE	Access to Distributed Electricity and Lighting in Ethiopia
BOS	Balance of system
C_{BAT}	Battery capacity
CO_2	Carbon di oxide
CUF	Capacity utilization factor
DC	Direct current
DEA	Data evolvement Analysis
DG	Diesel Generator
DOD	Depth of discharge
EEU	Ethiopian Electric Utility
EEUPPM	Ethiopian Electric Utility Project portfolio Management
ELEAP	Electrification Program
GDP	Gross domestic product
HOMER Pro	Hybrid Optimization Model for Electric Renewables Professional
IDA	International development association
IEC	International electrical
MoWIE	Ministry of Water, Irrigation and Energy
MPPT	Maximum power point tracker
MW	Megawatt
MWh	Megawatt hour
NASA	National Aeronautics and space administration
NEP	National Electrification Program
NES	National Electrification Strategy
PCS	Power conditioning system
PV	Photovoltaic
REBs	Regional Energy Bureaus
R_P	Performance ratio
SCC	Solar charge controller
SoC	State of charge
SoH	State of Health

Abstract

This study highlights the necessity of transforming diesel generator-only mini-grids into solar mini-grids due to their limited run time, high cost, and environmental impact. To achieve this, it is important to evaluate the operational performance of other nearby solar mini-grids in the same geographical area before designing and replacing the diesel generator-only mini-grid with a solar mini-grid at a specific location. The findings of the evaluation can help determine the operational performance of the newly designed solar mini-grid. Out of the 12-pilot solar mini-grids in Ethiopia, two were selected as benchmarks for designing and replacing the diesel-only mini-grid in Dolo Odo town with a solar, battery, and diesel generator hybrid mini-grid. Omorate town solar mini grid, which exhibited good performance, and Qorile town solar mini grid, which exhibited poor performance, are chosen for evaluation. Homer Pro software is used for optimizing the PV system, while PVsyst software is used for evaluating the performance of the PV system. The results indicate that Omorate system experienced 1027.7 kWh/day unutilized solar potential and had an average yearly PV efficiency of 10.28%, while the Qorile system had unutilized solar potential of 1405.8 kWh/day and average six months PV efficiency of 4.32%. Additionally, total system losses in the Qorile system were found to contribute to 6.84 kWh/kWp/day, which is much higher than the corresponding value of 2.9 kWh/kWp/day in Omorate system. Therefore, the performance analysis of both solar mini-grids showed that they are operating with poor performance, indicating that they are not meeting the expected energy output levels. From the benchmarking, it was found that determining and forecasting the energy requirement and sizing the PV system while considering all derating factors for the system equipment's is necessary for efficient and optimal performance. The first optimized system for the Dolo Odo hybrid solar mini-grid system consists of a 2 MW PV module, an 8.06 MW battery pack, 2 MW grid inverter, 1.05 MW power conditioning system, and 0.6 MW diesel generator. This system provides 91% of the electricity demand from solar and Battery and the remaining from the diesel generator. The proposed hybrid mini-grid system not only uses less fuel and emits less CO_2 than the base system but also has a lower levelized cost of energy of 0.211 USD/kWh and a reasonable net present cost of 16.5 million USD.

Key words: Solar mini-grid, diesel-only-mini-grid, HOMER Pro, PV syst, performance analysis, Ethiopia.

CHAPTER 1
1. INTRODUCTION
1.1 Background

Ethiopia is a country located in the horn of Africa with a land area covering about 1.1 million square kilometers and a population of 123.3 million with population growth rate 2.4% [2]. Over 83 % percent of the country's population is still classified as rural. Ethiopian Federal Government is composed of eleven regional states and two administration cities.

Energy plays an essential part in propelling economic growth and social development, both at the individual and national scale. the amount and quality of power generated and the overall energy consumption significantly impact gross domestic product (GDP) of a country. Regardless of geographical location, having access to energy is crucial for elevating income and improving the quality of life. Thus, meeting energy needs has become an essential requirement for achieving sustainable development and promoting well-being [1].

In accordance with its National Electrification Program, Ethiopia has established a target to attain universal access to electricity by the year 2025. The Ethiopian Government introduced the National Electrification Strategy (NES) in June 2016, which delineates key priorities for promoting sustainable growth in the energy sector and expanding electrification [2]. It is designed to support the enactment of the electrification plan, that will be implemented in stages using a cost-effective, spatial-proximity targeting approach. The updated NEP 2.0 serves as the Ethiopian government's implementation guide and investment prospectus, supporting the GTP II objectives of attaining universal access by 2025 and achieving middle-income country status through economic diversification and modernization [3].

The Ethiopian government straggles to supply basic electricity services to the sparsely populated rural areas where the majority of Ethiopians population resides. Compared to other countries the Ethiopian electricity supply system is still underdeveloped and overall access to electricity is quite limited. Like several other Sub-Saharan African nations, Ethiopia faces significant challenges in providing electricity to rural areas, resulting in a significant gap in access to electricity for these regions. Furthermore, Ethiopia experiences the lowest consumption rate, and its electricity consumption is 100 kWh per capita per year [4].

33% of Ethiopia population is connected to the grid and 11% has access to electricity from off grid systems. By the year 2025, it is expected that 100 % of the population will have electricity access, marking a significant advancement towards pre-electrification levels. To achieve universal access, the goal is to connect at least 65% of the population to the grid, while 35% of the population in 2025 are targeted to be connected through off-grid energy solutions [5, 6].

Providing electricity to rural towns or villages through a hybrid power supply that utilizes available clean energy source is the most effective solution, given that extending the grid to these areas is both expensive and impractical [7]. Currently, mini-grid scale-up in the country is being done through collaborations between public and private sectors. The EEU, MoWIE, and REBs are organizations that are involved in the off-grid (mini-grid) sector [8, 9].

The EEP has the responsibility to generate, transmit and to lease power above 66 kilo- volts while EEU is responsible for the generation, transmission, and distribution of electricity below 66 kilovolts, where both are nationalized companies. In areas where grid power is not yet available, EEU runs isolated diesel only or PV, ESS and Diesel generator hybrid generation distribution systems to offer energy access to customers. Generally, these systems are utilized in remote or rural areas where it could fail to be practical or financially viable to extend the grid [10,11,12].

The ADELE project, funded by IDA, supports NEP's goal of achieving universal electricity access by 2025 through transitioning from infrastructure expansion to providing reliable, affordable, and accessible electricity for all. In 2017, the Universal Electricity Access Program was launched through a collaborative effort between Ethiopia and the Korean International Cooperation Agency. The ADELE Project places significant emphasis on the utilization of creative methods, including distributed renewable energy technologies, particularly solar PV mini-grids and individual solar systems. These methods are intended to deliver access to electricity for urban, peri-urban, rural, and deep-rural areas for various groups, including households, smallholder farmers, commercial and industrial users, and social institutions. In 2018, the World Bank authorized the ELEAP to support the first stage of NEP 2.0, which aims to provide sufficient and dependable electricity service for all. A pilot program has been identified, which involves constricting solar mini-grid in 12 towns. At present, 11 of these towns and villages have been electrified and are already furnishing electricity to customers [2].

Furthermore, private companies in Ethiopia are piloting solar, wind, and other renewable mini-grids with support from development partners such as USAID Power Africa.

1.2 Statement of the problem

Despite of the plentiful renewable energy resources in Ethiopia, many villages in the country still live without access to electricity either from the utility grid or independent renewable energy generated electricity. Electricity supply to the population from grid system to each village is challenging due to their geographical locations and economic constraints. The solution to such cases is standalone mini-grid (off -grid) system. Most of the standalone mini-grids in Somali region are diesel generators and this diesel mini-grid powered villages are operated for less than six hours per day with relatively poor efficiency and at high cost. Diesel generator-only mini-grids are designed to offer a limited amount of electricity to the community, usually for few hours in the evening or early morning. Hence, the energy requirement of the community may not be satisfied due to insufficient amount of electricity generated, resulting in frequent power outages and discrepancies. In addition, frequent maintenance and fuel replenishment is mandatory in diesel generator only mini-grids, which can be expensive and time consuming. The mini-grid generator maintenance cost and fuel cost are often passed on to the end users, this resulted in higher energy costs for the community. In addition, diesel generator-only mini-grids that are powered by diesel fuel generate greenhouse gas emissions and contribute to air pollution, which can result in adverse effects on both human health and the environment. Hence, replacing diesel only mini-grids with solar mini-grids can have significant economic and environmental benefits. However, among the 12-pilot solar mini-grids in Ethiopia, there is a mixed performance within the group, with some falling below the expected standard and others performing well. They are not also serving the whole community in the area and hence their working condition and performance over a given geographical area needs to be analyzed before replacing diesel generator-only mini-grids. Hence, the findings can be used to optimize the design and operation of the new upcoming solar mini-grid for achieving higher operational performances.

1.3 Objective of the research

1.3.1 General Objective

The general objective of this research is to evaluate the performance of Omorate and Qorile solar mini-grids in Ethiopia for an improved, effective and efficient design and replacement of diesel generator only mini-grid in Dolo Odo, Somali region.

1.3.2 Specific objective

The specific objective of this research is

- To investigate the working condition of the existing pilot solar mini-grids and diesel generator based mini-grids.
- To analyze the performance of existing pilot solar mini-grids.
- To identify area of improvement in the existing solar mini-grid and apply them to the newly designed solar mini-grid to optimize its performance.
- To conduct a feasibility study of solar mini-grid for replacing the existing diesel generator on the sites.
- Evaluate the technical and economic performance of the PV mini-grid by using tools (Homer Pro and PV syst).

1.4. Research Questions

The research and analysis have focused on answering the following questions:

- How much power is the mini-grid delivering to the load?
- What is the performance of selected solar mini-grid?
- What are the performance issues observed in the solar mini-grid?
- How to mitigate the performance issues observed?
- How to use the findings as a benchmark for improving the performance of PV mini-grids to be designed and operated in the future?

1.5 Scope of the Project

The aim of this research was to evaluate the performance of an existing pilot solar mini-grids at a specific study site and based on the findings and the load assessment of the site design a new solar mini-grid that change diesel generator only based mini-grids and meets customer satisfaction with high reliability and performance.

1.6 Significance of the study

In order to replace diesel generator only based mini-grids with solar mini-grids, evaluating the performance of existing solar mini-grid is crucial for the following reasons.

- Performance comparison: Compering the performance of solar mini-grids by evaluating their performance, designers and energy planners can identify the benefits and drawbacks of each system. A community's energy needs can be determined by this information.
- Challenge identification: When evaluating the performance of solar mini-grids over diesel mini-grids one of the benefits is that it identifies the economic, technical, and social challenges associated with the transition. By addressing these challenges, strategies and policies can be developed.
- Design optimization: Evaluating solar mini-grids performance can inform the design of new systems or the optimization of existing systems to improve their reliability, efficiency, and cost-effectiveness for effective replacement of diesel mini-grids.
- Cost-effectiveness: In comparison to diesel mini-grids evaluating the performance of solar mini-grids can help to identify areas where costs can be reduced, making the system more cost-effective.
- Environmental benefits: Assessing the performance of solar mini-grids can help to identify areas where the it needs to be optimized to reduce its environmental impact compared to diesel mini-grids, examples include reducing greenhouse gas emissions and air pollution.

1.7 Limitation of the study

When conducting research papers, there are often limitations that arise. One such limitation is the lack of cooperation from workers in providing necessary and relevant information and recorded data. The second limitation is the data collected from the diesel generator-based mini-grids is limited to only monthly recorded fuel consumption. Similarly, in the Qorile solar mini-grid, the SCADA system accurately records only the energy consumed by the load but faces synchronization issues in accurately measuring output from the PV and BESS. Consequently, this research uses only six months of data to conduct the analysis.

CHAPTER 2

2. THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Theoretical background

2.1.1 Basic understanding of solar mini-grid

A solar mini-grid refers decentralized, small-scale power system for generating and distributing electricity that harnesses solar power to provide electrical energy to a local community or a group of households. It is commonly used in remote or rural areas where availability or accessibility to the national power grid system is either non-existent or limited [13]. To operate efficiently, solar mini-grid consists several elements, such as PV modules, inverters, batteries, and distribution system infrastructure they can be also tailored to meet the specific energy needs of the local community. They are designed to function either independently or in combination with other sources of energy, such as wind turbines or diesel generators, to guarantee an uninterrupted power supply. The management and operation of such system typically its handled by local communities or private entities. and they can also provide economic opportunities for local businesses and entrepreneurs [14].

2.1.2 Solar mini-grid system components

Solar mini-grids typically consist of several key components:

- PV panels: these panels are the main elements of the system as they convert sunlight in to useable electrical energy.
- Energy storage Batteries: it is a critical element of a solar mini-grid system operations since it can ensure a continuous supply of electricity by storing electrical energy. During the day it stores surplus electrical energy generated and utilize it during periods of low sunlight or at night time.
- Power Conversion System (PCS): it is an essential electronic system that includes bidirectional converter and charge controller, the converter is capable of transforming AC electricity to DC electricity and vice versa. Both the inverter and charge controller operate interdependently to regulate electricity flow between the main components, PV modules, batteries, and the distribution network. Addition of these power conditioning devise in solar mini-grid is vital for the efficient and reliable operation of solar mini-grids, ensuring that the system operates securely and effectively. It is additionally crucial component to guarantee a continuous electricity supply in hybrid mini-grid

systems that include solar PV with other energy sources, such as diesel generators or wind turbines.

- Inverter: it is a conversion device that transform the DC power produced by the PV modules and stored in the batteries in to AC electricity that can be utilized by appliances and devises.
- Charge controller: in regulating the electricity flow between the PV modules, batteries, and inverter the charge controller plays a crucial role to ensure the safe and efficient system operation.
- Distribution network: households and businesses in the community are linked to solar mini-grid through a distribution network, typically through a series of low-voltage cables.
- System monitoring and control: used to monitor the performance of solar mini-grid system, which involves monitoring the energy output, battery storage, and overall system efficiency. This system can assist in identify technical issues and optimizing the system performance.

2.1.3 Solar mini-grid configuration

2.1.3.1 Direct current (DC) coupling system

In a solar mini-grid system DC-coupling configuration, all the system components are interconnected together on the DC bus. The SCC is equipped with a MPPT and they are usually a DC-DC converter. MPPT's role is to enhance the energy amount that can be captured from the PV module while adjusting the voltage to match the level required by the batteries. While, the SCC transforms the DC power produced by PV module in to DC power that is suitable for charging the batteries. It is responsible for optimizing and adjusting the electrical energy amount captured from the PV module [15, 25, 26].

When there is sufficient solar irradiance at the day time, the battery in DC coupled solar mini-grid system is charged to its maximum state of charge. Battery inverter will supply additional energy from the storage battery to power the loads when there is no sun in the evening and if the electricity demand surpasses the amount of power being produced by the PV modules during the day time. The battery inverter will stop operating once the battery SoC reaches its minimum limit. It is advisable to maintain at least 20% of the energy capacity in the lithium batteries to guarantee reliable and consistent power supply.

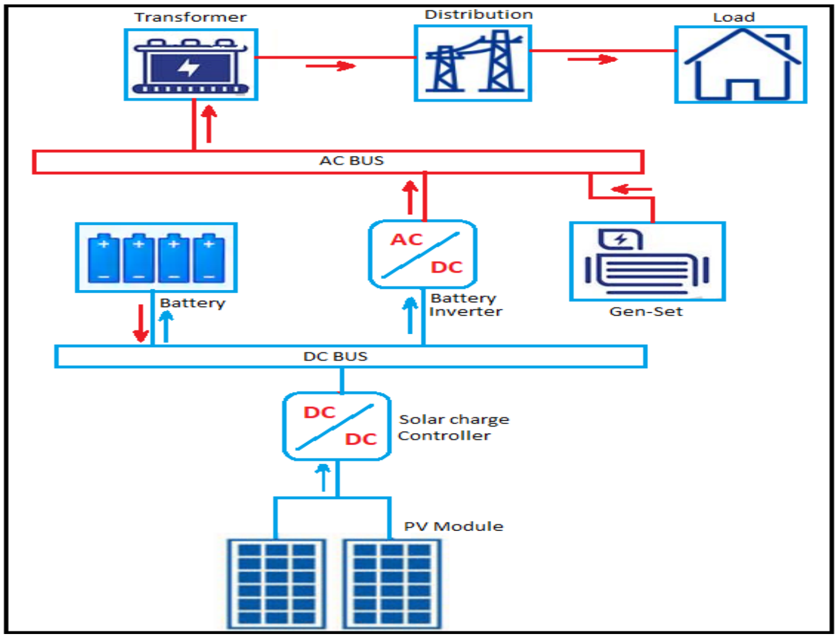


Figure 2.1 DC coupling system

2.1.3.2 Alternating current (AC) coupling system

AC coupling system architecture differs from a DC- coupling system architecture primarily in the grid inverter. In an AC-coupling system, the PV modules and batterie modules are interconnected together on the AC bus through their respective inverters. The PV panels are linked through a grid inverter, which convert the DC power into AC power that can be utilized directly by the loads. When the loads are not consuming the available power supplied by the grid inverter, the battery inverters convert it to DC power and stores it in the batteries. Similar to the charge controller in DC coupling system, the grid inverter in AC coupling system is equipped with MPPT to optimize the energy collected from the PV panels. By using this method, throughout the day, the produced power by the PV panels can be used directly for batterie charging via the battery inverter while simultaneously serving the loads [15, 25, 26].

The other difference from DC coupling system is that, the battery inverter in AC-coupling operates in both directions. When there is sufficient solar irradiance and the battery has low SoC, the battery inverter in an AC-coupling system operates as a charger AC to DC rectifier mode. If the load demand surpasses the amount of power generated by the PV panels, usually during the night or on cloudy days, the inverter switches to a DC-AC inverter mode and utilizes the energy stored in the battery to satisfy the load requirements.

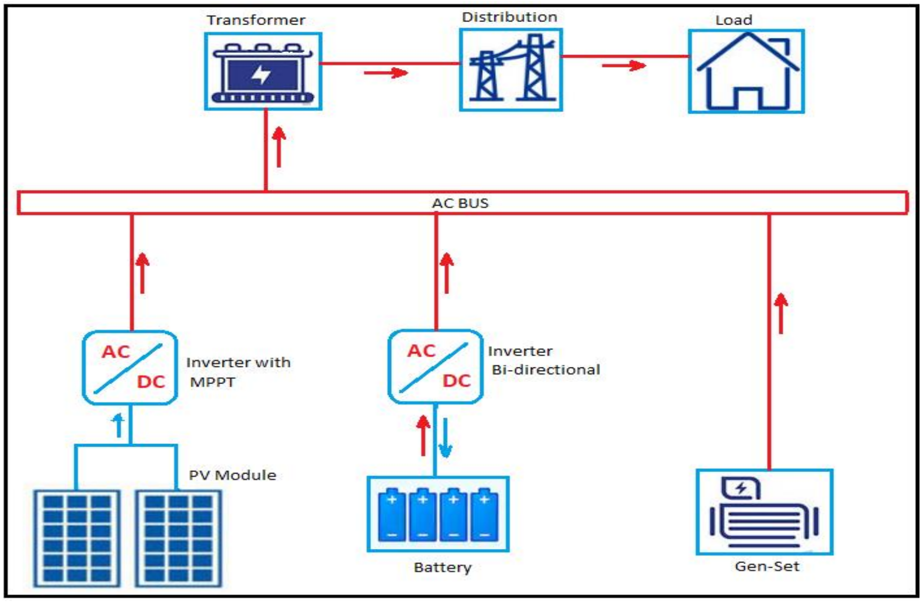


Figure 2.2 AC coupling system

In AC-coupling, due to the bidirectional operation of the battery inverter the losses resulting from current conversion are higher. However, AC-coupling is more advantageous when the peak electricity load occurs during daylight hours since the inversion losses only occur once in the grid inverter. Additionally, AC-coupling is more flexible for system expiation with additional PV arrays or hybridization with another electricity generator. Like the DC-coupling system, the battery inverter in an AC-coupling system should operate in parallel to achieve high power output. The battery inverter serves as the primary controller of grid distribution in a mini-grid, so at least one battery inverter should act as a master providing reference voltage and frequency, while the remaining inverters act as slaves and are connected to the grid [25, 26].

2.1.4 Advantages of solar mini-grids [18, 19]

- **Renewable and clean source of energy**: solar mini-grids produce electricity from sunlight, which is clean and renewable source of energy. As they produce fewer greenhouse gas emission and have smaller carbon footprint compared to traditional power generation methods.
- **Energy independence and reliability**: by producing electricity locally, solar mini-grids can help communities become more energy-independent and less reliant on fuel imports or grid extensions. This can be especially beneficial in areas prone to natural disasters or with unstable grid connections.

- **Promotes local economic development**: the availability of electricity for households, schools, healthcare facilities and businesses through solar powered mini-grids can stimulate local economic growth. To electricity can enhance living standard and generate new income generating prospects.
- **Scalability and modularity**: solar mini-grids can be designed to match the specific energy needs of a community and can be easily expanded or upgraded as demand grows. This modular approach makes them a flexible and cost-effective solution for electrifying rural areas.
- **Reduced transmission and distribution losses**: since it is typically a localized generation of electricity, solar mini grids can reduce the energy losses that typically occur during long distance transmission and distribution.

2.1.5 Challenges of solar mini-grids [18, 19]

- **Initial capital costs**: although the installation costs for a solar mini-grid can be high particularly in remote communities with limited financial resources, the operational expenses in the long run are generally lower than other electrification options, such as diesel generators or grid extension.
- **Intermittent power generation:** solar power generation is dependent on sunlight, which can be intermittent due to the weather condition or the time the day, resulting in intermittent power generation. To address this issue, energy storage systems, such as batteries, can be employed, but this may result in increased initial costs for the mini-grid.
- **Maintenance and skilled technician**: to guarantee optimal performance, regular maintenance skilled technicians are required for solar mini-grids. However, in remote areas, this can be challenging due to limited access to the spare parts and technical expertise.
- **Regulatory and policy support**: supportive policies and regulations such as subsidies, tax incentives, or simplified permitting processes are often necessary for the development of solar mini-grids. However, in some countries, these frameworks may not be established, which can impede the growth of solar mini-grids projects.

Nevertheless, these obstacles, solar mini-grids continue to be a feasible option for contributing clean, dependable, and sustainable energy access to rural and remote communities worldwide.

2.2 Performance

2.2.1 Solar mini-grid performance

Evaluation of a solar mini-grid's performance can be based on various factors, including its reliability efficiency, and cost effectiveness.

- Reliability: the reliability of a solar mini-grid is crucial for its effectiveness, to provide a consistent and reliable supply of electricity to users, the system must be designed with careful planning and consideration of factors such as system capacity, energy demand, and weather patterns. Additionally, appropriate system monitoring and control should be incorporated in to the system to quickly detect and address any issues that may raise.
- Efficiency: a solar mini-grid efficiency refers to its ability in converting the available solar energy in to usable electricity. The system efficiency is influenced by many factors, for instance the quality of the solar modules, battery quality and capacity, and distribution network design. a well-designed solar mini-grid should exabit high efficiency and reduced energy loss during the conversion and distribution process.
- Cost-effectiveness: the sustainability of a solar mini-grid depends on its cost effectiveness. And, this is achieved by designing a system that maximizing the longer-term benefits while minimizing the initial investment costs. This require careful consideration of various factors like the system size, component costs and anticipated energy demand. Furthermore, the system should be appropriately designed to minimize ongoing operational and maintenance costs.

To identify any problem and guarantee that the system is running at its best, regular evaluation and monitoring of solar mini-grids system performance is necessary to detect any issue and ensure that the system is operating at its optimal level. Reliability, efficiency, and cost-effective source of electricity are the measuring metrices to evaluate the effectiveness of solar mini-grid. These are accomplished by designing a system that fulfill communities energy demand while supporting economic development and reducing its environmental impact [18, 27].

2.2.2 Performance measuring parameters

2.2.2.1 Parameters

PV mini-grid performance can be measured by five parameters, These parameters adhere to the guidelines set in IEC Standard 61724 [28, 29]:

(a) PV module performance

(b) System overall performance

(c) Battery performance

(d) Behavior of the load.

(e) Power supply reliability

2.2.2.2 PV module performance

To compare PV systems with varying configurations and locations, their normalized system performance indices can be evaluated, including yields, losses, and efficiencies. Yields are energy amounts that are standardized to the rated array power, while system efficiencies are standardized by the area of the array. Losses are calculated as the difference between yields.

Daily mean yields are determined by dividing the energy quantities by the array's rated installed output power (P_O) in kW. The units of yields are kWh/kWp/day and denote the time in hour that the array module would need to be operated at P_O to produce a certain amount of monitored energy. Yields show the actual performance of the array in relative to its rated capacity.

A) Array yield, denoted by Y_A, is the output amount of energy the PV array produce per day per kilowatt of installed capacity.

$$Y_A = \frac{\tau_r \times \left(\sum_{day} P_A\right)}{P_O} = \frac{E_{DC}}{P_O} \quad [\mathrm{kWh/kWp/day}] \tag{2.1}$$

Where: E_{DC} - Daily DC energy produced by the PV [kWh/day]

P_O - Rated power of the mini grid [kWp]

τ_r - Recording interval [Hr.]

P_A - Power output over a given day [kWh]

The yield, or Y_A, denotes the duration of time in hours that the array would have to operate at its rated output power (P_O) per day to generate an equivalent amount of daily energy, which equal to $\tau_r \times \left(\sum_{day} P_A\right)$.

B) PV system final yield, denoted by Y_F, is the proportion of the total daily net energy output of PV plant that was provided by the PV array per kilowatt of installed capacity.

$$Y_F = Y_A \times \eta_{Load} = \frac{E_{AC}}{P_O} \text{ [kWh/kWp/day]} \qquad 2.2$$

Where: E_{AC} - Daily Total Ac energy [kWh/day]

η_{Load} - Load efficiency %

The yield, or Y_F, indicates the duration in hours per day that the array would need to operate at its rated output power (P_O) to produce the same amount of energy as it contributed to the daily net load.

C) Reference yield, denoted by Y_R., it is determined by dividing the daily total in-plane irradiation by the module's reference in-plane irradiance.

$$Y_R = \frac{\tau_r \times (\sum_{day} G_T)}{G_R} = \frac{A \times \eta_{STC} \times G_T}{P_O} \text{ [kWh/kWp/day]} \qquad 2.3$$

Where: G_T - Total solar irradiance

G_R - Reference irradiance $1kW/m^2$

The reference yield refers to the duration in hours per day when solar radiation must be at the reference irradiance level to generate the same quantity of incident energy as was monitored. If the reference in plane irradiance is $1kW/m^2$ then the in-plane irradiation can be expressed in kWh/m^2 /day, which is equal to the nominal array energy output in units of kWh/ kWp/day. Therefore, Y_R indicates the number of peak sun hours.

D) The solar power conversion efficiency, also referred to as PV system electrical efficiency, (η_{PV}) it is the ratio of the actual energy output (E_{DC}) of the PV array to the total solar radiation that falls on the array surface (kWh/m^2/day). It indicates how much of the solar energy that reaches the PV surface is converted into usable electrical energy while the system operates under real conditions.

$$\eta_{A,Mean} = \frac{E_{A,\tau}}{A_a \times \tau_r \times (\sum_{day} G_T)} = \frac{E_{DC}}{A \times G_T} \text{ [\%]} \qquad 2.4$$

E) Production factor: the photovoltaic (PV) efficiency of an array in generating electricity can be evaluated by production factor, and it is expressed in percentage. PV systems are affected by orientation and tilt of the panels, shading, temperature, and weather conditions and considers all factors. It is computed by dividing the PV array actual energy production over a specific period usually a year by the theoretical maximum energy production that could be achieved if the panels were functioning under perfect condition and at their peak efficiency, with a higher percentage indicating more efficient system.

$$P_F = \frac{E_{PV}}{G_T * P_O} \quad [\%] \qquad 2.5$$

E_{PV}- electricity output from PV array

2.2.2.3 PV system overall performance

The overall PV system performance is evaluated by assessing the losses that occur across the potential energy, PV module, power electronics, batteries, and wiring. This evaluation is represented by performance ratio, capacity factor, and efficiency of each power electronic component. The performance ratio measures the overall impact of losses on the system output, as defined by the IEC 61724 standard.

Normalized losses are determined by subtracting yields from the total energy generated. Losses are expressed usually in units of kWh/kWp/day and designate the duration of time the array would have to be required to operate at its rated power (P_O) to compensate for the losses.

- The term "array capture" losses, or Lc. refers to the energy losses that take place during the energy collection and conversion process of the PV module. These losses are arising because of the operation of the array itself and can arise due to several factors, such as adverse weather condition (e.g. high temperature), the quality and age of PV modules, wiring inefficiencies, shading, soiling and the accumulation of dirt or dust on the modules, among others.

$$L_C = Y_R - Y_A \quad [\text{kWh/kWp/day}] \qquad 2.6$$

- The BOS losses (L_{BOS}): losses on the components and equipment that are not part of the PV module itself but are necessary for the system to function properly. This loss can arise from different parts such as wiring, mounting systems, monitoring equipment, and inverters. Hence, losses in these deviceless such as wiring losses, equipment inefficiencies, and other losses that occur as a result of the system design and installation are represented by L_{BOS}.

$$L_{BOS} = Y_A \times (1 - \eta_{BOS}) \text{ OR } L_S = Y_A - Y_F \quad [\text{kWh/kWp/day}] \qquad 2.7$$

- The Performance ratio (R_P): it is the ratio of the energy delivered to the load (E_{AC}, Load) to the DC energy that would be produced if the system was operating at its nominal efficiency and rated power under standard test conditions (STC). The R_P helps to understand the effect of energy losses that take place during capture, conversion, storage, and distribution on the PV systems rated output. R_P values are usually expressed as percentages and are determined using the following equation.

$$R_P = \frac{Y_F}{Y_R} \quad [\%] \qquad 2.8$$

- The capacity utilization factor (CUF) or capacity factor is a measures PV mini-grids ability to generate electricity in comparison with its hypothetical maximum generation capacity. Although the capacity utilization factor does not account for the intermittency of PV and wind mini-grids, it is still used as a comparable indicator with other types of power plants.

$$CUF = \frac{E_{Load}}{P_O \times 8760h} \ [\%] \qquad 2.9$$

- The overall performance of the PV mini-grid is affected by the sub-systems operation. Hence, the efficiency of each sub system power electronic component can offer valuable information on how match it affects the system. This power electronic components include the SCC for DC-coupling systems, the grid inverter for AC-coupling systems, and the battery inverter.

$$\eta_{SCC} = \frac{E_{SCC}}{E_{PV}} \quad [\%] \text{ - Dc coupling} \qquad 2.10$$

$$\eta_{INV,GRID} = \frac{E_{I,out}}{E_{PV}} \quad [\%] \text{ - AC coupling} \qquad 2.11$$

$$\eta_{INV,BAT} = \frac{E_{LOAD}}{E_{BAT,OUT}+E_{SCC}} \quad [\%] \qquad 2.12$$

2.2.2.4 Battery performance

Backup systems for isolated PV mini-grids can take various forms, including batteries, generators, and other sources of renewable energy power. An isolated PV mini-grid depends on energy storage to provide power backup. In such systems, energy storage is critical because to maintain electricity during rainy or cloudy days and the load reaches its peak at night.

But in this study the attention is on batteries as the energy storage medium, and therefore, the reliability of the system is dependent on the battery's performance. The battery performance can be measured using two parameters:

(a) indicating the operating area of the battery, and

(b) evaluating how well the battery charge acceptance is able to restore the original capacity. These two measurements are used to assess the performance parameters of the battery.

- Battery state of charge (SoC)

$$\text{SoC} = \text{SoC}(0) + \int \frac{P_{BAT}}{C_{BAT}}\, dt \qquad 2.13$$

This equation is commonly used in battery management systems to track the state of charge of batteries over time. The equation represents the State of Charge (SoC) of a battery over time. It states that the SoC at any given time is the same as the initial SoC which is (SoC (0)) plus the integral of the battery power (P_{BAT}) divided by the battery capacity (C_{BAT}) with respect to time (dt).

- Efficiency of Battery (η_{BAT})

$$\eta_{BAT} = \frac{E_{BAT,Discharge}}{E_{BAT\,,Charge}} \qquad 2.14$$

The efficiency of battery refers to how effectively it can convert input energy into output energy and it can be influenced by several factors such as charging/discharging rate, the age and condition of the battery, and temperature. It represents the efficiency of a battery (η_{BAT}), which is determined by the ratio of the energy discharged from the battery ($E_{BAT,\ Discharge}$) to the energy charged into the battery ($E_{BAT,\ Charge}$). Generally, batteries with higher efficiency are desirable as they can result in lower energy costs and longer battery life.

2.2.2.5 The behavior of the load

Generated electricity by an isolated PV mini-grid is used by the surrounding village community, and its performance can also be evaluated based on the amount of electricity consumed by load. The behavior of the load indicates how the pattern of electricity consumption has affected the PV mini-grid's performance and provides insights into the demand pattern of electricity in rural areas. The load behavior is represented by two measurements:

- Load profile; which represents load behavior of the consumers, amount of energy per household, and the trend in electricity consumption.
- Demand factor; which measures the ratio of maximum demand of electricity in comparison with the ability of system to generate electricity.

2.2.2.6 The power supply reliability

The reliability of power supply refers to the ability of an electrical system to provide a continues and stable supply of electricity to its customers. reliability is an important factor for electric utilities because customers relay on steady supply of electricity to power their homes and businesses. The power supply reliability is an important indicator when assessing the performance of a standalone PV system. the reliability of the solar mini-grid is evaluated from the angle of energy reliability. The indices used in this study to measure the energy reliability are presented as follows:

SAIFI: determines average number of power outages experienced by customer over a given period of time.

$$\text{SAIFI} = \frac{\sum_i \lambda_i N_i}{N_T} \quad \text{[Int./Average Customer]} \tag{2.15}$$

SAIDI: determines the average duration of power outages experienced by customers over a given period of time

$$\text{SAIDI} = \frac{\sum_i r_i N_i}{N_T} \quad \text{[Hrs./Average Customer]} \tag{2.16}$$

CAIDI: determines the average duration of power outages experienced by individual customers over a given period of time.

$$\text{CAIDI} = \frac{\sum_i r_i N_i}{\sum_i \lambda_i N_i} = \frac{SAIDI}{SAIFI} \quad \text{[Hrs./Int]} \tag{2.17}$$

ASAI: measures the average percentage of time that a power plant or energy system is available to generate electricity over a given period of time. It considers both planned and unplanned outages, as well as any maintenance or repair down times

$$\text{ASAI} = \frac{\sum_i N_i \times 8760 - \sum_i r_i N_i}{\sum_i N_i \times 8760} \quad [\%] \tag{2.18}$$

N_i - is number of interrupted customers λ_i – is failure rate at load point i

N_T-is total number of customers r_i – is outage time for each interruption

2.3 Solar mini-grid system sizing

The sizing of Solar mini-grid includes determining the energy requirement of the users, the required solar panel capacity, batteries, inverters, charge controllers and other components according to the energy requirements of the mini-grid and also the irradiance available in the mini-grid installation site. The following are steps to consider when sizing a solar mini-grid:

- Determining the energy requirements: to size a solar mini-grid, the first step is to determine the energy need of the community or region that will be covered by the mini-grid. This will require investigating the devices and appliances powered by the mini-grid for their respective power and duration of usage, as well as forecasting the load requirements.
- Determining the location of installation: In sizing the solar mini-grid, the second step involves evaluating the amount of irradiance available in the selected site. This is done by collecting weather patterns and local climate data to determine the location where the mini-grid will be installed.
- Choosing the solar panel technology and type: The third step in sizing a solar mini grid is to select the appropriate PV module. polycrystalline, monocrystalline, and thin-film panels solar panel are some of the available solar panel technologies in the market. It is then essential to select the one that best fits the specific requirements since each has its own set of benefits and drawbacks.
- Determining the required capacity: once the energy requirements and site location are determined the fourth step involves calculating the required capacity of the solar mini-grid. It includes to determining the total amount of energy that needs to be produced by the solar panels in kWh to satisfy the energy need over the desired timeframe.
- Determining the battery capacity: solar mini-grid requires a battery bank, to store excess electrical energy generated during the day time for use during the peak demand hours (night time) or during times when sun light is low. Therefore, the fifth step in solar mini-grid sizing is to determine the required capacity, quality and quantity of battery, by considering the amount of excess electrical energy generated during the day, the duration of electrical energy storage expected (autonomy) and the electrical energy requirement of the mini-grid.

- Determining efficiency and safety considerations: the six step is efficiency and safety, these are crucial factors to consider when sizing a solar mini grid. Solar panels and batteries have limited efficiency, so it's necessary to select system that deliver the necessary output power while also reducing energy losses. Moreover, safety consideration like grounding, overvoltage protection, and circuit protection must be taken in to account to ensure that the mini-grid is operating safely.
- Designing the system: after the above factors have been considered and determined, in the seventh step the solar mini-grid can be designed. This will involve the next four steps

  a) **Battery bank,** capacity of the battery is determined by the ability of the battery to supply peak power demand. The critical design parameters include maximum depth of discharge, (DOD_{MAX}) and number of days of autonomy (D_{aut}), (is the maximum number of days that the batteries can supply the daily electrical requirement assuming that there is no input from the PV array).

  - The total daily energy demand is determined as seen at the DC bus or the battery bank and it is given by the formula:

$$E_T = \frac{E_{AC}}{\eta_{inv}} \quad 2.19$$

Where: E_T - Daily total energy demand from the DC bus in kWh

E_{AC} - Design daily energy AC load in kWh

η_{inv} - Average energy efficiency of the inverter

  - Daily demand (Ah): it is the usual unit used to measure battery capacity

$$Ah_D = \frac{E_T}{V_{DC}} \quad 2.20$$

Where: V_{DC} - Battery system voltage(nominal)

  - Battery storage capacity (B_C)

$$B_C = \frac{Ah_D \times D_{aut}}{DOD_{MAX} \times f_T} \quad 2.21$$

Where: f_T - Temperature correction factor

  - Discharge current (I_{DIS})

$$I_{DIS} = \frac{kW_{AC}}{\eta_{inv} \times V_{DC}} \quad 2.22$$

  - Number of parallel string (N_P)

$$N_P = \frac{B_C}{B_S} \quad 2.23$$

Where: B_S - capacity of selected battery

- Number of series string (N_S), Where: V_S is voltage of selected battery

$$N_S = \frac{V_{DC}}{V_S} \quad 2.24$$

b) **Charge controller** Sizing an appropriate charge controller starts by calculating the maximum current the controller needs to handle. This maximum current comes from the short circuit current of the PV panels that will be used as an input to the charge controller. The charge controller withstanding capability to the total current that is injected from the PV array can be estimated, by determining the short circuit current of each panel and multiplying that by the total number of panels. The number of charge controllers needed can be found by dividing the total required current by the maximum current rating of the individual charge controllers. Other specifications like the voltage rating of the charge controller must match the battery bank voltage to properly charge the batteries. The charge controller must also support the appropriate charge algorithm and charging stages for the battery type.

$$I_{ccc} = I_{sc}\, x\, N_{pm}\, x\, F_{sefe} \quad 2.25$$

$whare$ $\boldsymbol{I_{ccc}}$- Charge controller current

$\boldsymbol{I_{sc}}$ - PV module Short circuit current

$\boldsymbol{N_{pm}}$ - Number of modules in parallel

$\boldsymbol{F_{sefe}}$ - Safety factor to protect the charge controller (1.15) [22]

c) **Inverter** the required solar inverter should have a power rating that is equal to 125% (oversize factor) of the sum of the power of all non-inductive appliances and 3 times the sum of the power of all inductive appliances.

$$P_{nia} = \sum_{n=1}^{\infty} P_{(nia)n} \quad 2.26$$

$$P_{ia} = 3 \times \sum_{n=1}^{\infty} P_{(ia)n} \quad 2.27$$

$$P_i = 1.25(P_{nia} + P_{ia})$$

Where: P_{nia} = Power of all non-inductive appliances

P_{ia} = Power of all inductive appliances
P_i = Total inverter power

d) **Solar panel** the array is sized to meet the average daily demand for electricity during the worst insolation month of the year, and it is critical to compare the nominal voltage of the solar modules with that of the system. The panels must be arranged in series/parallel combinations to achieve the nominal system voltage. The PV array is derated due to certain factors such as manufacturer's tolerance, dirt or dust cover and temperature effects. Equation below used to determine the number of solar panels required to meet a specific energy demand.

$$N_{mod} = \frac{E \times (1 + i)}{P_O \times G \times \eta_{pv}} \qquad 2.28$$

Where: N - the number of solar panels required
E - the energy requirement, in watts (W) or kilowatts (kW)
I - temperature effect coefficient
P_o - the power output per panel, in watts (W)
G - the amount of solar radiation received per unit area, (W/m^2)
η_{pv} the solar panel system efficiency

- System Testing and commissioning: after the system design and installation, the eighth step involves testing and commissioning to confirm that interconnected systems are working properly and safely. This may involve testing the system as a whole under several conditions in addition to the performance of individual components.
- Monitor and maintain the system: Finally, in the ninth step it's important to monitor the solar mini-grid performance overtime and perform maintenance regularly to ensure that mini-grid continues to operate efficiently, effectively and safely. This may involve monitoring panel and battery health, regular cleaning of the panels and other equipment's, replacing warn out components as needed, and performing regular testing and inspections. In addition, it could be important to adjust the system design or capacity over time as the energy requirements, community or location change or expand. It's also important to involve the community or stakeholders in the design, operation, and maintenance of the mini-grid to ensure their buy-in and long-term sustainability of the project.

2.4 Literature review

There are many scholarly articles, reports, and other literature available on the performance of solar mini-grids.

Huld Thomas, Moner-Girona Magda, Kriston Akos developed GIS-based tool to estimate the performance of solar mini-grid systems with battery storage across large geographical regions. This tool covers Africa and most of Southern and Central Asia, and utilizes multi-year hourly time series of solar irradiance and temperature to model PV power production and battery state and losses. Results include maps of energy production, unfulfilled demand, and the reliability of electricity production. The analysis was carried out on a constant PV mini-grid size that was not optimized for each location. Results reveled that the daily energy production of the mini-grid with similar PV capacity drops to less than half by changing the location, highlighting the need to correctly size the PV mini-grid to avoid over- or under sizing the system for the given geographical conditions. Sizing with optimum PV array power and battery capacity that can provide the electrical energy with a desired level of reliability while minimizing the cost was also calculated. The PV mini-grid performance strongly depends on the local climatic conditions, but Areas with strong seasonality require a larger PV and battery size to avoid running out of energy in the months with the lowest solar irradiation. It shows that changing storage technology does not cause a larger difference in performance, and the difference is mostly caused by lower internal losses in Li-ion batteries [23].

Ya, Aung Ze conducted a techno-economic feasibility on five PV mini-grid models in off-grid villages located Myanmar. The study involved simulations using HOMER Pro to determine the best model for a village in Taungtha township. The proposed model includes 208 kW of PV modules, 150 kW of PV-MPPT, 800 kWh of storage battery (lead-acid), and an 80.7 kW converter, with an LCOE of 0.267 $/kWh. The simulation results showed that the model could save 142,978 L/year of diesel fuel and $94,366/year in costs, while also avoiding 374,263 kg/year of CO2 emissions. The research offers insights for optimizing the deployment of PV mini-grids in Myanmar to achieve efficient rural electrification in off-grid areas and mitigate climate change [24].

Atiek Puspa Fadhilah, Bagus Fajar Ramadhani compere the performance of Ac coupled and Dc coupled two solar mini-grids in isolated PV mini-grids in Indonesia and found that both systems are performing lower than their capacity with range of performance ratio is in between 0.2 to 0.3, with similar capacity factor at 5% for both systems. PV mini-grid in Dc coupled operated more efficiently than Ac coupled with 63%, 40% respectively. Most losses are caused by battery inverter in Ac coupled mini-grid, while in Dc coupled losses occurred more in its battery [15].

Aziz Shakila and Chowdhury Shahriar Ahmed examined the results and deductions of a research investigation that assessed the effectiveness of twenty-one mini-grids situated in areas without access to the grid in Bangladesh. The study used a two-stage DEA approach to measure the cost effectiveness of the mini-grids in terms of installed capacity and electricity generation capability, as well as their success in bringing about electricity access and alleviating energy poverty in off-grid areas. In the study it's found that while the mini-grids were close in performance when it came to creating electricity generation capacity within the given amount of funds, there was significant variation in their performance in selling the projected amount of electricity to the expected number of customers, and in reaching full capacity within a given time. The study also found that several of the mini-grids in their respective sites had overestimated the market potential, and that the efficiency of the mini-grids was affected by the local solar irradiance, price and efficiency of the solar panels [25].

Tesfaye Bizuayehu, studied to examine alternative power supply option for rural villages and towns of Kebridehar and Degehabur in Ethiopia, that operate independently from the national power grid. with average daily solar radiation ranges from 5.5 to 7.03 kWh/m2/day, and the monthly average wind speed varies from 4.2 to 8.2 m/s. The simulation results from HOMER showed that a hybrid system consisting of solar, wind, and battery storage with 48 hours of autonomy was the most economically feasible option. The cost of generating energy from the hybrid system was found to be $0.422/kWh and $0.441/kWh for Kebridehar and Degehabur towns, respectively. In comparison, the LCOE for the existing diesel-only system was $0.564/kWh and $0.543/kWh for Kebridehar and Degehabur towns, respectively, assuming diesel prices of $1.0/liter. The study found that the hybrid system would be more cost-effective than the diesel-only system under all scenarios considered, even with different diesel price assumptions. Therefore, the selected hybrid energy system with 100% renewable energy is regarded as the most economically feasible solution for the two towns [26].

This study by Kebede Kassahun, aimed to determine power generation potential of grid-connected solar PV in Ethiopia, with a power PV plant size of 5 MW at each of the 35 locations evaluated. The analysis in the study was conducted using HOMER and RETScreen software. And it is found that PV modules average capacity factor in different locations was 19.8%, with a mean value of 8,674 MWh/year for the electricity exported to the grid. Moreover, cost effectiveness of 5 MW grid connected PV mini-grid in Addis Ababa was examined, and the result suggested solar mini-grid is economically feasible. However, it might not be attractive enough for commercial investors without an incentive mechanism. The study also indicated that the introduction of a feed-in tariff law for solar power generation, which has not yet been implemented, may influence private sector investment decisions [27].

Similar research by Wassie Yibeltal. and Ahlgren, Erik O. acknowledges the potential of solar photovoltaic mini-grid systems for off-grid electrification. It also acknowledges that little is known about their reliability and performance in practical applications. The statement goes on to describe a study that was conducted to analyze the performance of an operating solar mini-grid using 8 months of data. The performance assessment outcome indicated that Omorate solar mini-grid system had an average onsite module efficiency, performance ratio with temperature correction, capacity factor, and overall system efficiency of 9.85%, 42%, 13%, and 8.76%, respectively. The research also shows that the daily energy output from PV was insufficient to satisfy the daily demand, resulting in load shedding for 13 hours a day [28].

Kumar Nallapaneni Manoj, Kumar M. Rohit, Rejoice P. Ruth, Mathew Mobi, conducted a research to study the feasibility of installing PV system to supply an educational institute while assessing 100 kWp grid connected Si poly photovoltaic system performance using PVsyst software. It is found that even if the plane global irradiance is 1,962kWh/m^2 the effective irradiance on the collector is 1,972kWh/ m^2 that leads to energy loss of 0.5% and with 16.16 % efficiency the PV generates 197.5MWh/year with annual performance ratio of 80%. 100 kWp solar PV system can generate DC energy of 165.38 MWh/year and 161. 6MWh AC energy injected to the grid. The PV system has annual average efficiency of 13.17% and the annual average efficiency of the overall system is 12.87% with capture and system loss contribute 1kWh/kWp/day and 0.1 kWh/kWp/day respectively [29].

Kapole Felody, Mudenda Steven, and Jain Prem research highlights the significant sustainability challenges facing the development of solar mini-grid in Zambia using multi-dimensional approach. The study examines the technical, financial, social and ecological sustainability of five major solar mini grids that are operational in Zambia and finds that none of them are technically and financially sustainable. The fundamental challenges faced are unaffordable economic tariff, incorrect system sizing, uses of substandard components, inefficient operation of mini-grids, wastage of subsides, in appropriately structured tariff plans, lack of technical support, poor operation and maintenance. The study also suggests that even though a tariff structure between 0.40USD/kWh to 0.57USD/kWh higher than grid price of 0.07USD/kWh it would make the plants financially stable. Furthermore, public and private partnership could provide a well thought out model for the construction, operation and maintenance of solar mini grid. It also suggests that development of smart subsidies that align the interest and expectations of the government, privets sector, and the clients, instead of the current up front subsidy model [30].

Akinyele Daniel presents a techno-economic analysis of photovoltaic mini-grid systems by using a group of remote houses in three locations in Nigeria as case studies. The study uses a worst-case users' load demand approach to design and analyze the proposed energy system, according to international technical standards. The analysis includes detailed capacity, yield and losses, battery state of charge, reliability, users' load demand increase, and life cycle economic analyses using HOMER simulation tool. The study also considers the effect of a 25% load demand increase on the system. The results indicate that PMs of 68 kW, 76 kW, and 61 kW can meet the users' demand of 63,500 kWh/year with an availability of 99.2% for the respective locations. By including a 30-kVA diesel generator in the PMs' model, an availability of 100% was achieved [31].

Hence, the proposed research work is done by using the performance of existing mini-grids as a benchmark to design a reliable, feasible, and environmentally friendly PV, ESS, and diesel generator hybrid mini-grid that serves with 100 % efficiency.

CHAPTER 3

3. METHODOLOGY

3.1 Introduction

This chapter involves gathering and performing analysis of data to assess the performance of solar mini-grids at selected sites in Ethiopia, with the aim of effectively replacing diesel only mini-grid system. The data used to design the hybrid components are gathered directly from the solar and diesel only mini-grid sites, and from the Ethiopian Metrology agency. To ensure accurate analysis, this metrological data is also compared with NASA metrological data obtained using the latitude and longitude of the site.

3.2 Methods

3.2.1 Flow chart

To conduct the research and to draw relevant and objective conclusions, the following methods and techniques will be employed.

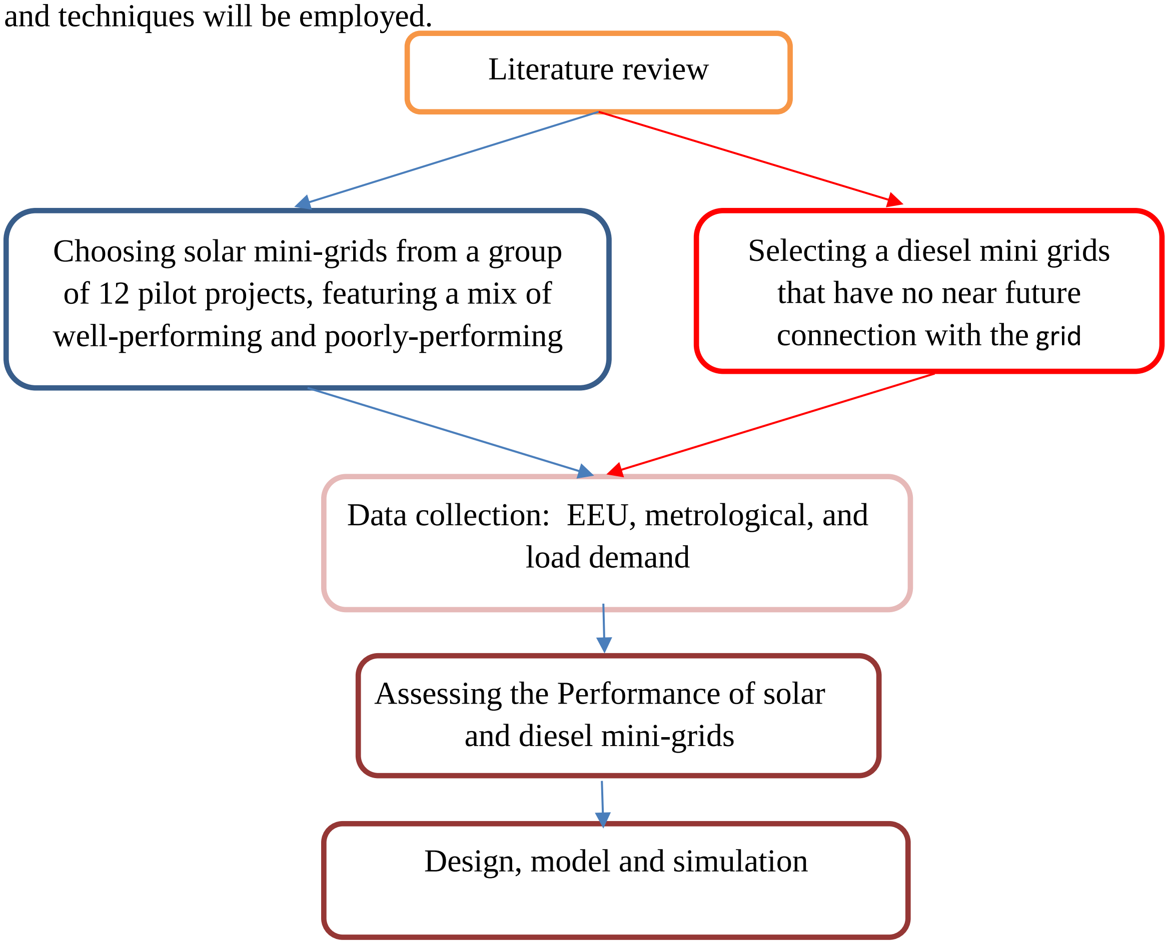


Figure 3.1 Methodology

3.3 Description of the Study Site

3.4.1 Solar mini-grid sites

3.4.1.1 Pilot solar mini-grids

A project has been launched in Ethiopia, to establish 12-pilot solar mini-grids with the goal of providing clean, sustainable and reliable energy to rural areas. These off-grid solar system implementation aims to improve the quality of life for people residing in isolated communities by providing access to electricity for basic needs and economic activities.

3.4.1.2 Project Overview

As part of Ethiopia's wider goal to boost energy access and promote renewable energy, 12-pilot solar mini-grids project is being carried out through a collaboration between the Ethiopian government and development partners such as the world bank, the African development bank, and other international organizations. Its main objectives are:

1. To decrease fossil fuels dependence and encourage the utilization of renewable energy resources.
2. To deliver clean and reliable electricity for those rural communities who are not currently connected to the national grid.
3. To facilitate local economic development by enabling access to electricity for various productive uses.
4. To contribute to Ethiopia's endeavors to attain universal energy access by 2030, consistent with the United Nations' Sustainable Development Goal 7.

3.4.1.3 Key Features of the Solar Mini-Grids

Solar mini-grids are composed of photovoltaic (PV) panels, battery storage systems, diesel generators and distribution networks to provide electricity to households, businesses, and public institutions such as schools and health centers.

3.4.1.4 Impact and Future Prospects

The 12-pilot solar mini-grid project is expected to have a substantial effect on the livelihoods of rural Ethiopian communities by enhancing access to electricity, which can, in turn, boost healthcare, education, and economic opportunities. Moreover, the project will aid Ethiopia's efforts to decrease greenhouse gas emission and advance environmental sustainability.

Furthermore, if the pilot project implantation is successful, it could lead to the establishment of additional solar mini-grids in other distant areas of the nation, thereby increasing access to dependable and clean electricity for the country's rural population.

Table 3.1 The data for 12-pilot solar mini-grids in Ethiopia

Region	**Village/ Town**	**Latitude and Longitude**	**PV Array Capacity (kW)**	**Diesel Genset Capacity (kVA)**	**Battery Storage Capacity (kWh)**	**Condition**
Oromia	Beltu	7.87N, 40.99E	750	125	1500	Operational
Oromia	Behima	7.48N, 41.05E	200	60	400	Operational
Oromia	Mino	9.24N, 41.52E	225	55	450	Operational
Amhara	Benbaho	12.08N, 35.93E	275	90	400	Operational
Amhara	Wasel	12.96N, 38.26E	300	120	450	Operational
SNNP	Tum	6.25N, 35.52E	550	130	750	Operational
SNNP	**Omorate**	**4.80N, 36.05E**	**375**	**100**	**600**	**Operational**
Somali	**Qorile**	**7.50N, 45.01E**	**325**	**85**	**550**	**Operational**
Tigray	Arae	14.46N, 39.66E	275	70	400	Not constructed
Afar	Kusrewad	13.44N, 40.51E	75	40	200	Operational
Gambela	Ungoge	7.77N, 33.93E	175	50	250	Operational
Benshangul	Albasa	10.43N, 36.13E	275	65	600	Operational

3.4.1.5 Omorate

"Omorate" is a small village located in the Dasenech district of the south omo zone in the southern nations, nationalities, and people's region of Ethiopia near the border of Kenya and South Sudan. It is situated 290 kilo meters away from Arbaminch, with a latitude and longitude of 4.80^{o} and 36.05^{o} respectively. The village is positioned on the eastern bank of the omo river, which serves as a critical water source for the people and animals in the area.

Figure 3.2 Map of Omorate village

Omorate is renowned for its diverse range of ethnic groups, such as the Dasenech, Hamer, Mursi, Karo, Nyangatom, and Turkana peoples, who reside in the surrounding areas. These communities retain their unique cultures, languages, and customs, making Omorate a culturally rich and vibrant center. Recently the area become a destination for tourists interested in discovering more about the local communities' traditional ways of life, as well as the omo national park, which is famous for its abundant wildlife and distinct land scape. Nevertheless, the region has encountered development related obstacles, such as limited access to electricity, clan water, health care, and education.

In order to encourage sustainable pastoralism and enhance access to vital services in the Omorate region, a solar mini-grid is in service with a capacity of 375-kW and a battery of 600-kWh has been combined with a 100-kVA diesel generator to create a hybrid system.

Figure 3.3 Omorate 375 kW solar mini grid

3.4.1.6 Qorile

Qorile is a town located in Somali region of Ethiopia, with a latitude and longitude of 7.504^o and 45.01^o, respectively. It is situated in warder zone, which is in southeastern section of the Ethiopia Somali region near the Somalia border. Qorile is a small town with a population of approximately 2,000 individuals, and it serves as a commercial hub for the rural area surrounding it. The region surrounding Qorile is recognized for its pastoralist communities who depend on livestock herding as their primary source of income. The town is situated in semi-arid area where water is a scarce, and droughts are frequent. Nevertheless, efforts are underway to encourage sustainable pastoralism and aid pastoralist communities, which includes advancing access to electricity, water education, and healthcare to promote sustainable livelihood in the region.

Figure 3.4 Map of Qorile village

There is a hybrid 325-kW solar mini-grid with a 550-kWh battery and a 100-kVA diesel generator that has been installed in the area around Qorile to support the promotion of sustainable pastoralism and improved access to essential services.

Figure 3.5 Qorile village 325kW solar mini-grid

3.4.2 Diesel generator only mini-grid sites

3.4.2.1 Diesel only mini-grids in Somali region

Southeastern part of Ethiopia is where the Somali regional state is located, and it is identified by its arid and semi-arid topography. The region is home for numerous pastoralist communities who depend on livestock herding as their principal source of income. Nonetheless, these communities face significant challenges due to their disconnection from the primary grid and the inadequate supply of electricity. To address this challenge, the EEU office in the region has resorted to diesel mini-grids option to produce electricity. These mini-grids generally comprise a diesel generator, a distribution network, and a billing system, providing electricity to households, businesses, and public services like schools and health centers however the dependability and accessibility of electricity from these mini-grids can be restricted, as they often run for only few hours each day and may be impacted by fuel scarcities, mechanical complications and other problems.

Within the Somali regional state of Ethiopia, there are 24 mini-grids that solely relay on diesel generator for power generation. However, out of these 24 sites, there are currently no immediate plans to connect 15 of mini-grids in the region to the main-grid in the near future. This lack of connection is a challenge for the region, as its constraints access to affordable and reliable electricity for households, public services, and businesses. The region is making efforts to increase access to electricity, which includes promoting renewable energy sources and constricting new mini-grids and grid connections.

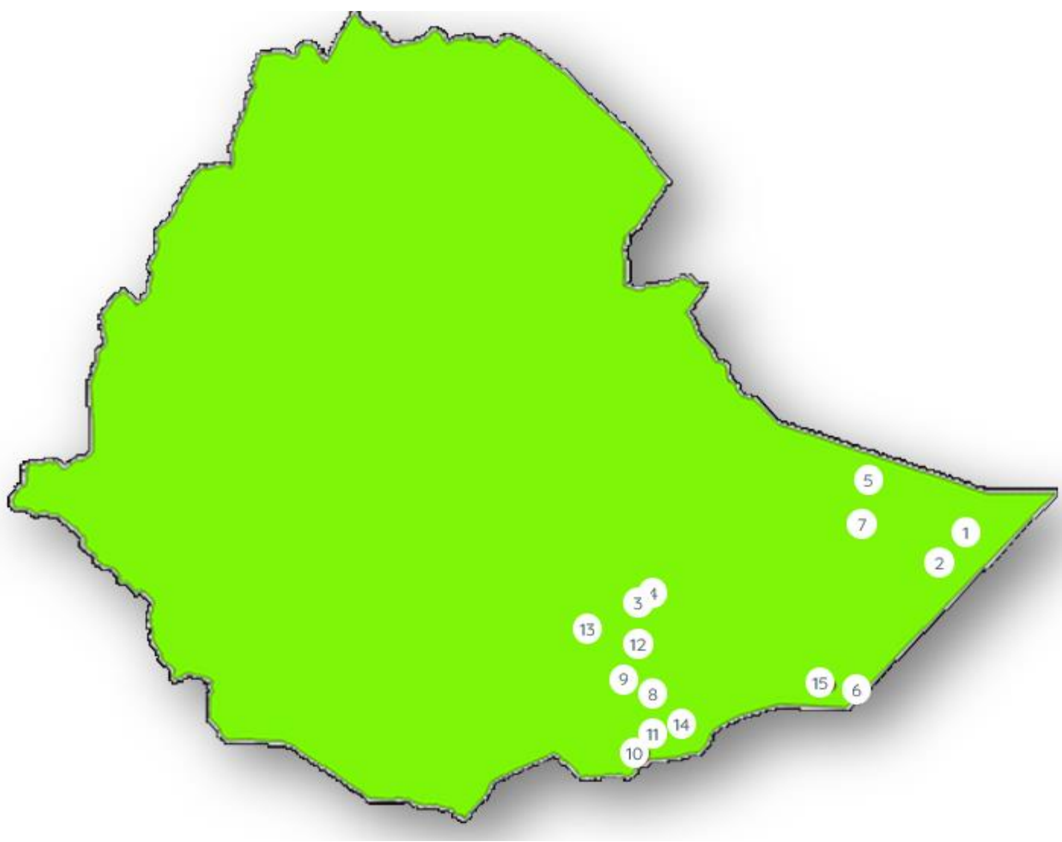


Figure 3.6 Geographic location of 15 diesel only mini-grids

Table 3.2 Summary of 15 villages connected to diesel-only mini-grid

No	**Region**	Zone	**Name of Town/kebele/Village**	**Number of Population**	**Number of Household (HH)**	**Center of town, GPS point of town respectively (N, E)**	
						Latitude	**Longitude**
1	**Somali**	Dolo	Bohe	38,500	7,000	7°26'N	46°38'37"E
2		Dolo	Geladin	26,136	4,752	6°58'N	46°24'50"E
3		Shebelle	West emie	20,614	3,748	6°27'N	42°8'13"E
4		Shebelle	East emie (Imi-bari)	29,721	5,404	6°28'N	42°10'49"E
5		Jerer	Gashamo	33,000	6,000	8° 7'2N	45°20'52"E
6		Shebele	Ferfer	16,500	3,000	5° 4'5N	45° 7'38"E
7		Dolo	Danot	11,000	2,000	7°33'N	45°17'31"E
8		Afdear	Hargele	33,000	6,000	5°13'N	42°10'31"E
9		Afdear	Chereti	30,800	5,600	5°20'N	41°52'46"E
10		**Afdear**	**Dolo Odo**	**59,290**	**8,470**	**4°16N**	**42°0'1.5"E**
11		Afdear	Dolo Baye	13,602	2,473	4°16'N	42° 3'40"E
12		Afdear	Elkere	20,900	3,800	5°50'N	42° 6'7"E
13		Liben	Gurobekekisa	18,000	3,273	6° 2'N	41°20'56"E
14		Afdear	Bare	15,950	2,900	4°38'N	42°37'12"E
15		Shebele	Mustahil	12,000	2,182	5°14'N	44°43'51"E

3.4.2.2 Dolo Odo

Dolo Odo or Dolo Ado is a town found in the Somali regional of Ethiopia, also identified as the Ogden, which is one of the eleven ethnical based regional state in the nation. The region is located in the southeastern part of Ethiopia neighboring Somalia to the east, Kenya to south, and the Oromia region to the west and north.

Dolo Odo is located near the confluence of the Dawa an Genale rivers precisely at 4.167°N 42.067°E, near the border between Ethiopia and Somalia, resulting in the areas rich and fertile land. The town is also proximity to the Kenyan border. The region has semi-arid climate with seasonal rainfall, hot temperatures, and arid conditions prevailing for the majority of the year. Dolo Odo town has a population of close to 59,290 with 8,470 households.

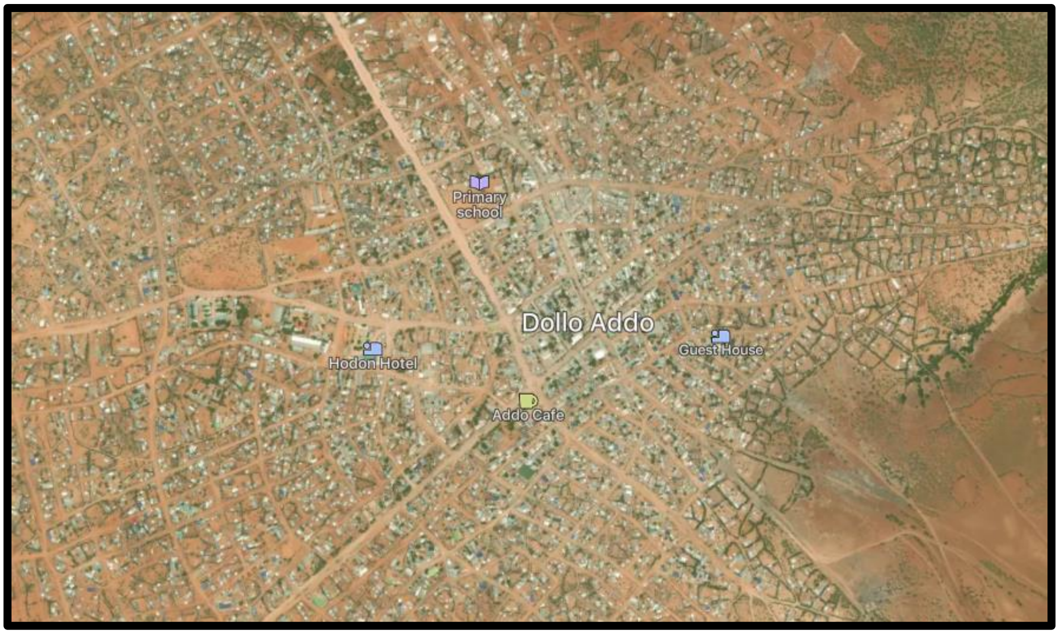


Figure 3.7 Map of Dolo Odo village

3.4 Data Gathering

The performance assessment of solar mini-grids and the transition from diesel mini-grids involve the collection of data directly from the site and the Ethiopian Metrology agency. To ensure the accuracy of the analysis, the metrological data is compared with NASA data obtained using the latitude and longitude of the site.

3.5 Energy Demand

3.5.1 Determining energy demand

Energy demand analysis is essential in developing effective and sustainable energy solution for these communities. The outcome of the analysis can help to identify the specific energy needs of the community, households, public services, and businesses. It can also be used to select the most cost-effective and efficient ways to meet those needs. It can be used to design and implement energy systems that are tailored to the specific circumstances and requirements of those communities. Additionally, it can help identifying opportunities for energy conservation and efficiency measures, which can reduce energy costs and improve the sustainability of energy consumption.

The amount of electricity required to operate a device or a system within a specific time frame can be determined, the power rating of the device or system is multiplied by the anticipated hours of usage and the quantity of devise to ascertain the total electrify demand. The following is the general formula for estimating electricity demand:

$$E_D = \frac{P_C \times t \times n}{10^3} \text{ in kWh} \qquad 3.1$$

The variables considered are E_D the amount of electricity demand, measured kWh, the power consumption of the equipment P_C, measured in watts (W), "n" the number of devices and the maximum duration of the device's usage time" t ", measured in hours (t).

Table 3.3 Estimated countryside Energy consumption template from EEUPPM [32]

No	Description for energy consuming service	Estimate energy consumption daily (kWh/day)	No	Description for energy consuming service	Estimate energy consumption daily (kWh/day)
1	House hold	0.8	22	Barber	2
2	kindergarten	2	23	Tailor shops	2
3	Temporary School	1	24	Flour mills	35
4	Elementary School (1-4)	1	25	Farmer Training Center	1
5	Elementary School (1-8)	2.4	26	Governmental office	2
6	High school (9-10)	3	27	Store House	1
7	Preparatory School (11-12)	4	28	Video hall	3
8	Technical Collage (TVET)	7	29	Photo studio	2
9	Hospital	20	30	Garage	7
10	Health Centers	15	31	Tire repair	3
11	Health post	2	32	Metal work	5
12	Clinic	4	33	Wood work	5
13	Pharmacy	5	34	NGO Office	2
14	Animal Clinic	2	35	Telecommunication BTS	10
15	Church	3	36	Bakery	5
16	Mosque	3	37	Fuel Station	3
17	Hotels	5	38	Water pump for drinking	15
18	Restaurant & Bars	3	39	Water pump for Irrigation	5
19	Tea/coffee House	2	40	Tannery	1
20	Animal Slaughter	2	41	Hollow brick Production	1
21	Shops	1	42	Dairy Farms	2

3.5.2 Omorate energy consumption

The design of the mini-grid feasibility study was to supply electricity to a total of 3,930 peoples, which equates to serving 786 customers. Specifically, Omorate was planned to connect a total of 786 customers to the solar mini-grid, out of which 570 are residential customers and the remaining 216 are non-residential customers (a mix of public and commercial).

Table 3.4 Daily power demand of Omorate

Time	Commercial Load (kW)	Public Load (kW)	Residential Load (kW)	Total (kW)
0:00	0:00	0.55	11.40	11.95
1:00	0:00	0.55	11.40	11.95
2:00	20:09	0.47	11.40	15.71
3:00	0:00	0.91	11.40	12.31
4:00	2:09	1.56	11.40	13.05
5:00	3:27	9.51	11.40	29.05
6:00	23:21	9.83	17.10	39.90
7:00	20:05	8.06	19.95	47.85
8:00	22:00	12.29	19.95	61.16
9:00	19:56	14.57	19.95	63.35
10:00	6:36	11.83	19.95	56.05
11:00	3:56	5.04	19.95	59.15
12:00	22:02	11.45	19.95	63.32
13:00	22:22	12.03	19.95	73.92
14:00	8:02	9.62	19.95	55.90
15:00	0:48	8.16	19.95	103.14
16:00	10:17	6.98	22.80	103.21
17:00	15:21	9.52	28.50	117.66
18:00	1:02	12.96	48.45	141.45
19:00	8:55	10.63	48.45	88.45
20:00	16:59	8.90	48.45	75.06
21:00	19:31	4.01	48.45	60.28
22:00	14:35	0.55	37.05	42.21
23:00	9:12	0.55	19.95	20.88
			Deferable Load	30
			Total(kWh)/day	1,396.96

The combined electricity consumption of residential households, commercial loads, public loads and deferable load in the village of Omorate was 567.15 kWh/day, 629.29 kWh/day, 170.52 kWh/day, and 30 kWh/day respectively, resulting in a total energy consumption of 1,396.96kWh/day. As shown in Figure 3.8 bellow, the load profile of the village indicates that the peak load occurs between 18:00 and 21:00 due to the expected high-power demand for lighting in households, while the minimum load occurs from 24:00 to 06:00 when energy consumption is very low at night.

Omorate solar mini-grid site has a total approximate daily energy consumption 1,396.96kWh per day, which result annual energy consumption of 509,890.4kWh(509.890MWh) within one year. Additionally, the hourly average load demand is 58.2kW, and the peak load with 40% average load factor is 145kW.

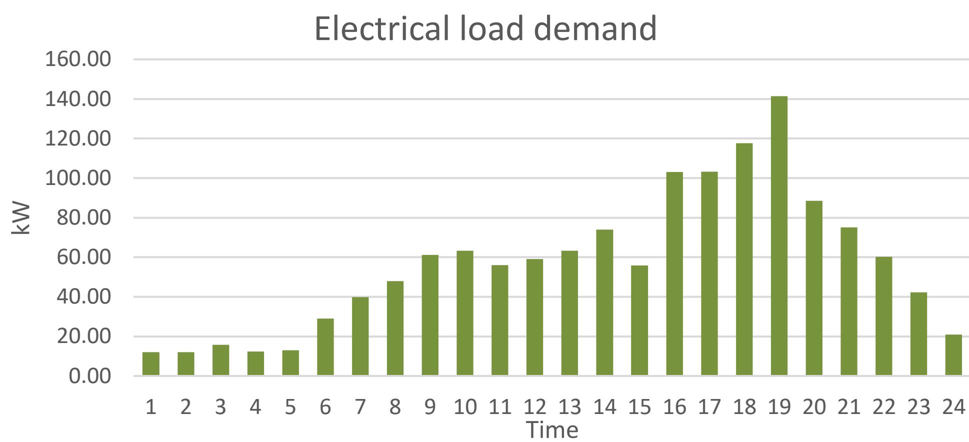


Figure 3.8 load profile of Omorate

3.5.3 Qorile energy consumption

Table 3.5 Daily power demand of Qorile

Time	Commercial (kW)	Public (kW)	Residential (kW)	Total (kW)
0:00	0:00	1.10	7.79	8.89
1:00	0:00	1.10	7.79	8.89
2:00	13:55	0.94	7.79	9.31
3:00	0:00	1.82	7.79	9.61
4:00	2:09	3.13	7.79	11.01
5:00	6:59	6.97	7.79	16.05
6:00	23:25	7.61	15.58	25.16
7:00	1:15	6.08	19.48	28.61
8:00	4:27	7.93	23.37	42.49
9:00	4:46	9.03	23.37	49.60
10:00	13:49	7.43	23.37	45.37
11:00	12:00	5.00	23.37	39.87
12:00	6:00	6.67	23.37	42.29
13:00	6:15	7.03	23.37	39.66
14:00	13:43	5.83	23.37	35.77
15:00	2:12	4.91	23.37	40.37
16:00	23:59	5.49	31.16	44.65
17:00	3:15	7.15	38.95	54.24
18:00	6:06	9.43	54.53	70.22
19:00	4:34	9.23	54.53	70.95
20:00	6:51	6.30	54.53	67.11
21:00	3:04	4.16	54.53	61.82
22:00	16:42	1.10	38.95	40.74
23:00	1:23	1.10	15.58	16.73
			Deferable	15
			Total (kWh)/day	894.41

The purpose of the mini-grid feasibility study was to provide electricity for population of 5,000 people. To meet this objective, a solar mini-grid was designed for Qorile, capable of servicing the electrical load of 900 customers, assuming an average of 5.5 individuals per household. From these customers, 779 are residential, while the remaining 121 are non-residential, including both commercial and public customers. The total daily energy is estimated using the energy consumption template provided in Table 2.3, and the results are presented in Table 3.5.

Figure 3.9 below illustrates that in Qorile village, the total energy consumption is 894.41kWh/day, with residential households consuming 611.52kWh/day, commercial loads consuming 141.37kWh/day, and public loads consuming 126.52kWh/day. The load profile of the village reveals that the highest power demand for electricity occurs between 18:00 to 22:00, as households require lighting during this time. Conversely, the minimum load occurs from 23:00 to 06:00, when energy consumption is significantly lower due to reduced activity at night.

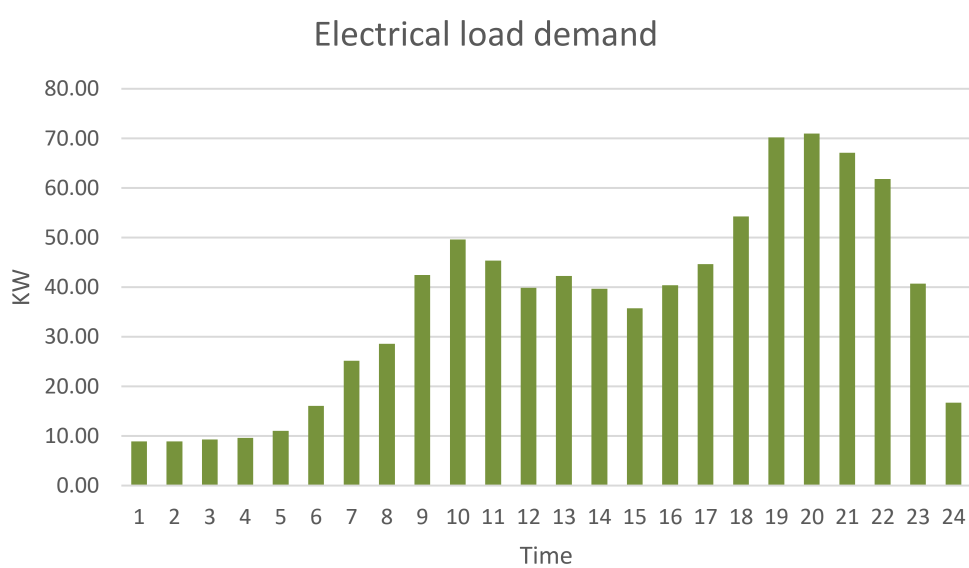


Figure 3.9 load profile of Qorile

The total daily energy consumption of the Qorile village is approximately 894.41kWh/day, which results in an annual energy consumption 326,459.65 kWh/year (326.459 MWh/year) calculated by multiplying the daily consumption by 365. Additionally, the average load demand per hour is 37.26 kW, and the peak load is 93.2kW determined by dividing the average load demand by the load factor of 40%.

3.5.4 Dolo ado energy consumption

Dolo Odo has total population of 59,290 and total number of potential customers 8,470, from this 8,381 are residential customers and the remaining 89 are non-residential customers, which include a combination of commercial and public customers. Which is 71 potential customers being commercial customers, and 18 potential public customers. From the field survey it is found that the residents in Dolo Odo mostly use electricity for lighting, and cooking and in some parts of the household there are refrigerators and washing machines, and since the place is near to the Ethiopia and Somalia border there are shelters for refugees that are operated by NGO offices.

Table 3.6 Daily power demand of Dolo Odo

Time	Commercial (kW)	Public (kW)	Residential (kW)	Total (kW)
0:00	0:00	4.05	83.81	87.86
1:00	0:00	0.55	83.81	84.36
2:00	19:12	0.47	83.81	85.08
3:00	0:00	0.91	83.81	84.72
4:00	0:00	1.56	83.81	85.37
5:00	7:46	2.68	83.81	87.81
6:00	8:16	3.00	167.62	172.97
7:00	21:40	2.37	209.53	215.80
8:00	12:24	4.88	251.43	266.83
9:00	17:21	5.40	251.43	268.56
10:00	10:36	4.81	251.43	266.68
11:00	4:43	2.21	251.43	261.84
12:00	8:46	4.43	251.43	267.23
13:00	19:04	4.56	251.43	267.78
14:00	18:35	3.50	251.43	262.71
15:00	11:10	3.87	251.43	272.77
16:00	2:53	3.00	335.24	352.36
17:00	7:26	3.72	419.05	438.09
18:00	6:19	4.31	586.67	605.24
19:00	12:06	8.12	586.67	602.29
20:00	4:55	7.16	586.67	600.04
21:00	4:33	6.06	586.67	595.92
22:00	23:02	4.05	419.05	424.06
23:00	1:55	4.05	167.62	171.75
			Deferable load	60.00
			Total (kWh)/day	6,888.1

Figure 3.10 below illustrates that in the village of Dolo Odo, the total energy consumption is 6,881.1kWh/day, with residential households consuming 6,579.09kWh/day, commercial loads

consuming 159.29kWh/day, and public loads consuming 89.72kWh/day. The load profile of the village reveals that the highest demand for electricity occurs between 18:00 to 23:00, as households require lighting during this time. Conversely, the minimum load occurs from 24:00 to 06:00, when energy consumption is significantly lower due to reduced activity at night.

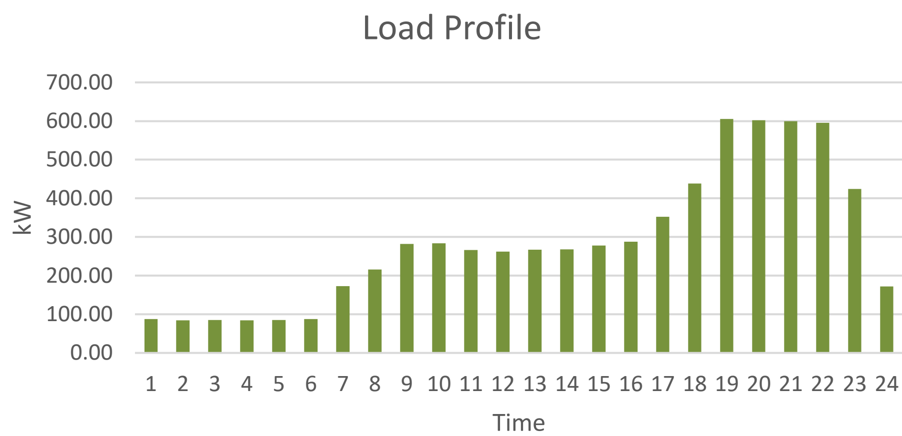


Figure 3.10 load profile of Dolo Odo

The total daily energy consumption of the Dolo Odo town with 100% market penetration is approximately 6,881.1kWh/day, which results in an annual energy consumption 2,511,601.5 kWh/year (2,511.6MWh/year) calculated by multiplying the daily consumption by 365. Additionally, the average load demand per hour is 286.7 kW, and the peak load is 716.78kW determined by dividing the average load demand by the load factor of 40%.

3.6 Load demand forecasting

Load demand forecasting pertains to predicting the quantity of electricity that will be necessary to satisfy the demands of consumers at a particular time in the future. This is a crucial understanding as it enables effective and cost-efficient planning and management of power generation systems. One method of forecasting involves utilizing the existing power system load to estimate the future load growth with exponential increasing function.

$$P_n = P_O(1 + r)^n \qquad 3.2$$

Where: P_n = population at time n in the feature

P_O = present population

r = annual growth rate of population

n = Year of projection

To forecast the load, the annual population growth rate of the village was considered. According to CSA data, the village had a total population of 47,300 in 2015 (preceding year) and 48,795 in 2016 (later year).

$$R = \frac{\text{Population of later year} - \text{Population of preaciding year}}{\text{Population preaciding year}} \times 100 \qquad 3.3$$

$$= \frac{48{,}795 - 47300}{47300} \times 100 = 3.16\ \%$$

The energy approach forecasting considers a 5% demand growth rate, a 10% design margin (loss rate), a 10% operating reserve, a coincident factor of 0.8 the load factor is currently 40% and is expected to increase by 1% every 5 years, and 50% market penetration over service life. These factors account for losses, potential fluctuations in demand, and ensure sufficient generating capacity to meet unexpected changes in demand or supply [26, 7].

Table 3.7 Dolo Odo energy consumption forecast for 25-year

Year	population growth (H.H)	Load factor (%)	Domestic load (kWh/day)	Commercial load (kWh/day)	Public load (kWh/day)	Total energy consumption (kWh/day)	Peak demand (kW)
2024	8684	40	3491.25	164.30	82.00	2990.04	311.46
2025	8898	40	3665.81	172.52	86.10	3139.54	327.04
2026	9112	40	3849.10	181.14	90.40	3296.52	343.39
2027	9327	40	4041.56	190.20	94.92	3461.34	360.56
2028	9541	41	4243.64	199.71	99.67	3634.41	369.35
2029	9755	41	4455.82	209.69	104.65	3816.13	387.82
2030	9969	41	4678.61	220.18	109.88	4006.94	407.21
2031	10183	41	4912.54	231.19	115.38	4207.28	427.57
2032	10398	41	5158.17	242.75	121.15	4417.65	448.95
2033	10612	42	5416.07	254.88	127.21	4638.53	460.17
2034	10826	42	5686.88	267.63	133.57	4870.46	483.18
2035	11040	42	5971.22	281.01	140.24	5113.98	507.34
2036	11254	42	6269.78	295.06	147.26	5369.68	532.71
2037	11469	42	6583.27	309.81	154.62	5638.16	559.34
2038	11683	43	6912.44	325.30	162.35	5920.07	573.65
2039	11897	43	7258.06	341.57	170.47	6216.08	602.33
2040	12111	43	7620.96	358.65	178.99	6526.88	632.45
2041	12325	43	8002.01	376.58	187.94	6853.22	664.07
2042	12540	43	8402.11	395.41	197.34	7195.88	697.28
2043	12754	44	8822.21	415.18	207.20	7555.68	715.50
2044	12968	44	9263.33	435.94	217.56	7933.46	751.27
2045	13182	44	9726.49	457.74	228.44	8330.14	788.84
2046	13396	44	10212.82	480.62	239.86	8746.64	828.28
2047	13611	44	10723.46	504.65	251.86	9183.98	869.69
2048	13825	45	11259.63	529.89	264.45	9643.17	892.89

3.7 Solar radiation assessment

3.7.1 Solar insolation determination

To perform this analytical estimation of the solar radiation, the following input data are used:

- The monthly average daily global solar radiation
- The latitude of the study site
- The declination angle of the sun for each day
- The average day of the month
- The recorded sunshine hour data

Using the above input data's, along with the Angstrom-Prescott correlation model and regression analysis, we can estimate the solar radiation for the study site. The regression constants in the model were calculated to optimize the estimation.

Solar potential is a vital for the design and implantation of solar mini-grid and it gives reliable information on the quantity of sunlight that reaches the proposed solar collector surface. It refers to the solar energy quantity that can be collected from a particular location to precisely determine the solar potential of a site. Generally, the amount of solar radiation that falls on a specific area during a particular period and tilt angle is measured in irradiance. Though, in many cases, it may be necessary to estimate this data from other sources since gathering several years' worth of irradiance data for a specific location can be challenging and expensive. There are several methods for estimating irradiance data, including:

- Site measurements: This is the most accurate method directly estimating irradiance data, but it requires that the meteorological sensors to be installed and maintained for an extended period of time.
- Nearby site data: in this method it is assumed that the solar conditions at the proposed site are similar to the nearby site are to be a good approximation. It is employed when there are no sensors at the proposed site, data from nearby locations with similar solar conditions can be used to estimate the irradiance.
- Solar atlas or database: This approach is less accurate than site measurements. But, can be useful for estimating solar potential in areas where there is no other data available. Such information can be gathered from official solar atlas or database, and they can provide estimated solar irradiance data for a given location based on historical weather patterns and other factors.

Overall, accurate irradiance data is essential for predicting solar potential, and there are various methods available for estimating this data when it is not possible to measure directly. One of the methods is a linear regression equation that relates the monthly average daily radiation to the clear day radiation at a specific location, as well as the average fraction of possible sunshine hour data. Which is a commonly used method for estimating solar radiation data based on sunshine duration and other meteorological parameters, the equation is derived from the Angstrom-Prescott method. This equation, can allow for approximation the solar potential of a particular site and improving the design and efficiency of solar energy systems. The linear regret ion equation is presented in mathematical form and can be employed to anticipate the quantity of solar radiation that will be obtained at a specific location.

$$H= H_O(a + b\frac{n}{N}) \qquad 3.4$$

The variables "H", "H_O", "n", and "N" are used in Angstrom's correlation method to estimate monthly average daily global solar radiation. "H" represents the actual solar radiation received at a given location, while "H_O "represents the extraterrestrial solar radiation that would be received in the absence of atmospheric interference and "n" represents the monthly average daily hours of sunshine recorded by a sunshine recorder, while N represents the maximum possible hours of sunshine for a given month. This parameters "n" and "N" are used in the correlation method to account for the effects of cloud cover and other factors on solar radiation. Lastly, "Ho" is the extraterrestrial solar radiation that would be received at a given location and it can be determined by using the Solar Constant., the average day of the month and the declination angle.

$$H_o= \frac{24*3600*G_{sc}}{\pi}[1 + 0.033 * \text{Cos}\left(\frac{360*n_d}{365}\right)](Cos\Phi * Cos\delta * Sin\omega_0 + \left(\frac{\pi*\omega_0}{180}\right)\text{Sin}\Phi * \text{Sin}\delta) \qquad 3.5$$

Where "G_{sc}" is the solar constant, which is the average amount of solar radiation that reaches the Earth's upper atmosphere on a per unit area basis and has a value of 1367W/m². "n_d" represents the number of days in the year starting from January 1st, and is used in conjunction with the sunrise hour angle to calculate the solar radiation that can be expected at a specific location during a specific time period. Lastly, "ω_o", represents the mean sunrise hour angle for a given month, which is the angle between the sun and the horizon at sunrise averaged over the entire month.

$$N = \left(\frac{2}{15}\right)\omega_o \quad 3.6$$

$$\omega_S = cos^{-1}(-\tan\Phi \times \tan\delta) \quad 3.7$$

Where ϕ and δ represents selected site latitude and the solar declination angle for the average day in the month respectively. A sine function can be expressed in a specific equation that can be used to approximate the solar declination angle throughout the year.

$$\delta = 23.45\, Sin\left(\frac{240+n_d}{365}\right) \quad 3.8$$

Using Goliathan equation the values of "a" and "b" can be correlated to the latitude, elevation, and percentage of possible sunshine for any location around the world. By including the effects of elevation, sunshine duration, and latitude, it is possible to improve the accuracy of the estimated regression coefficients "a" and "b".

$$a = -0.11 + 0.235\,\text{Cos}\,\Phi + 0.323\left(\frac{n}{N}\right) \quad 3.9$$

$$b = 1.449 - 0.553\,\text{Cos}\,\Phi - 0.694\left(\frac{n}{N}\right) \quad 3.10$$

The Ethiopian Meteorological Service gathers data on the average sunshine hours for certain cities within the country. From this data, the solar radiation is estimated using the equations provided earlier. The Tables from 3.8 up to 3.13 below show the estimated solar radiation values for the villages, based on the average sunshine hours collected by the service. These values are important for designing the solar mini-grid, as they help to determine the amount of energy that can be generated from the solar panels.

3.7.2 Case study sites solar resources estimation

Ethiopian meteorology agency runs stations in the country for measuring solar radiation. They measure various solar radiation parameters, including direct normal irradiance, diffuse horizontal irradiance, and global horizontal irradiance. The collected data from this station can be used for performance optimization of solar power systems and to estimate the amount of solar energy that can be generated in the region.

Table 3.8 NMA average solar hour data from Kebridehar

Month	2015	2016	2017	2018	2020	Average
Jan	9.13	9.21	9.31	9.18	8.53	9.07
Feb	9.28	9.38	8.52	8.24	8.19	8.72
Mar	8.19	8.11	8.42	8.49	7.22	8.09
Apr	7.20	7.93	7.72	7.16	8.19	7.64
May	7.78	7.93	7.78	7.72	7.16	7.68
Jun	8.28	7.17	7.21	5.28	8.08	7.20
Jul	6.82	5.55	5.28	5.28	5.50	5.69
Aug	8.15	8.12	6.57	6.25	6.37	7.09
Sep	8.68	8.47	5.26	6.53	8.53	7.49
Oct	7.01	7.67	6.28	9.30	6.53	7.36
Nov	8.53	9.01	9.36	8.04	8.13	8.62
Dec	10.28	9.38	8.82	9.68	9.55	9.54

From the data collected by NMA over a period of five years shows that, Kebridehar receives an average of 7.85 hours of sunlight per day throughout the year. According to Figure 3.11 the month with the lowest average sunshine hour is July, while the months of November, December, January, February, and March have the highest average sunshine hours.

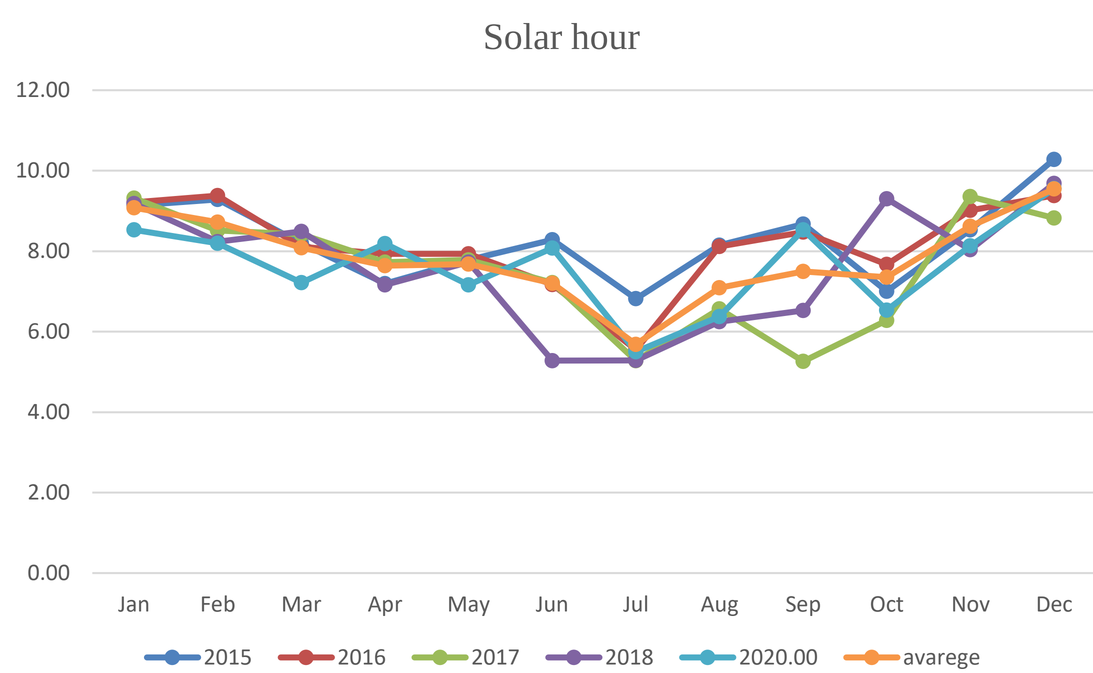


Figure 3.11 Kebridehar solar hour

In this study, modified Angstrom equation is used to estimate the monthly average solar radiation of the Qorile by using the available Kebridehar station's sunshine duration data.

Table 3.9 Sunrise hour angle and declination angle for Qorile

No	Mid of the month	n_d	δ	ω_s	N	n	n/N
1	15-Jan	15	-21.27	89.95	11.99	9.07	0.76
2	14-Feb	45	-13.62	89.97	12.00	8.72	0.73
3	15-Mar	74	-2.82	89.99	12.00	8.09	0.67
4	15-Apr	105	9.41	90.02	12.00	7.64	0.64
5	15-May	135	18.79	90.04	12.01	7.68	0.64
6	15-Jun	166	23.31	90.06	12.01	7.20	0.60
7	15-Jul	196	21.52	90.05	12.01	5.69	0.47
8	15-Aug	227	13.78	90.03	12.00	7.09	0.59
9	15-Sep	258	2.22	90.01	12.00	7.49	0.62
10	15-Oct	288	-9.60	89.98	12.00	7.36	0.61
11	15-Nov	319	-19.15	89.95	11.99	8.62	0.72
12	15-Dec	349	-23.34	89.94	11.99	9.54	0.80

Using Kebridehar average of 7.85 hours of sunlight per day throughout the year, it is estimated that Qorile village has an average of 6.9 ($kWh/m^2/day$).

Table 3.10 Average solar irradiance in $kWh/m^2/day$ of Qorile

Month	H_o ($kWh/m^2/d$)	a	B	Estimate) H ($kWh/m^2/d$)
Jan	9.160	0.215	0.734	7.06
Feb	9.789	0.205	0.755	7.38
Mar	10.340	0.188	0.792	7.46
Apr	10.488	0.176	0.818	7.31
May	10.260	0.177	0.816	7.17
Jun	10.033	0.164	0.843	6.72
Jul	10.088	0.124	0.931	5.69
Aug	10.320	0.161	0.849	6.84
Sep	10.342	0.172	0.826	7.12
Oct	9.936	0.169	0.834	6.76
Nov	9.294	0.203	0.761	6.96
Dec	8.939	0.228	0.707	7.06
			Average	**6.96136303**

Based on the NMA data collected over a period of four years, Arbaminch area receive an average of 6.37 hours of sunlight throughout the year.

Table 3.11 NMA solar hour data from Arbaminch

Month	2015	2016	2017	2018	Average
Jan	8.75	7.86	8.19	6.45	7.81
Feb	7.18	7.69	6.54	5.68	6.77
Mar	6.60	6.37	6.03	6.32	6.33
Apr	5.34	6.11	5.94	5.20	5.65
May	6.16	5.43	5.79	5.76	5.79
Jun	5.94	6.80	5.93	6.53	6.30
Jul	5.82	4.70	5.00	5.74	5.32
Aug	6.19	6.21	6.81	5.30	6.13
Sep	5.58	5.99	6.29	6.27	6.03
Oct	6.44	5.59	6.01	5.90	5.98
Nov	7.34	7.50	7.51	6.13	7.12
Dec	6.82	8.07	6.80	7.14	7.21

Figure 3:12 below shows that, the highest average sunshine hour is occurred on November, December, January, February, and March, while July has the lowest average sunshine hours.

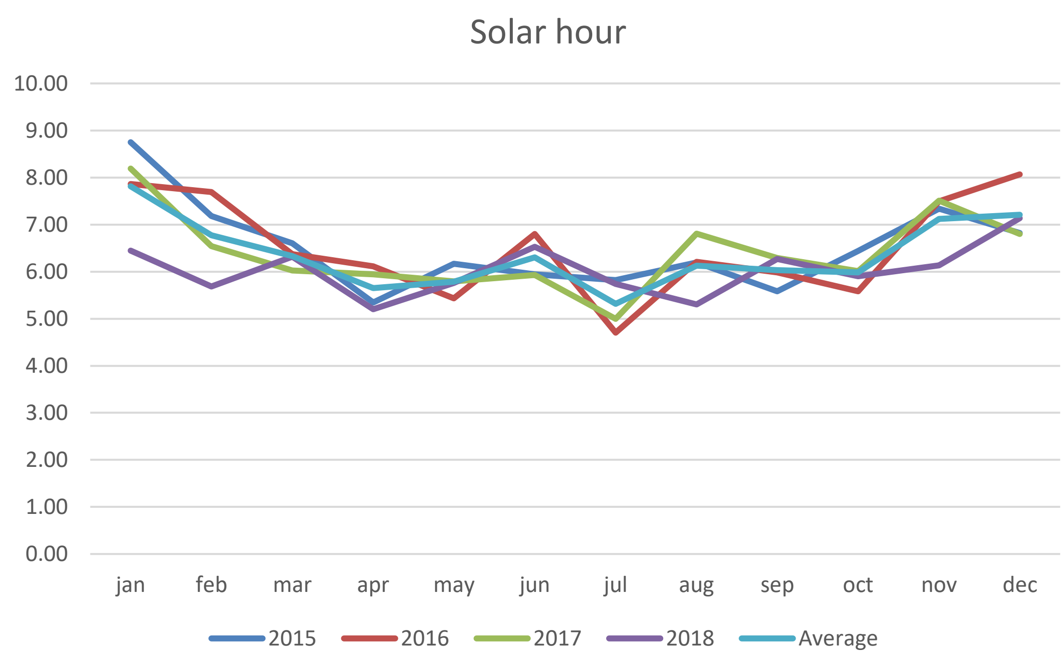


Figure 3.12 Arbaminch Sun hour

In this study, modified Angstrom equation is used to estimate the monthly average solar radiation of the Omorate by using the available Arbaminch station's sunshine duration data.

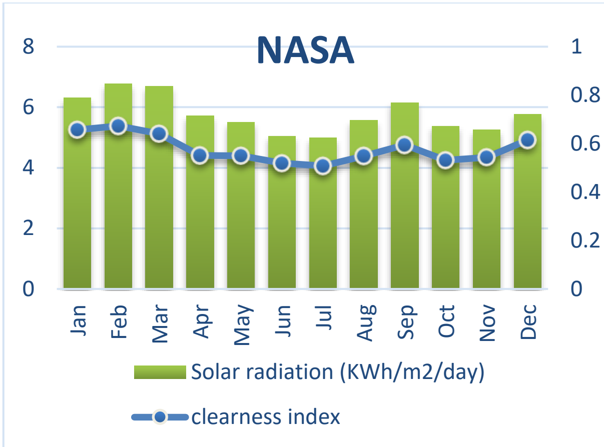
Table 3.12 Sunrise hour angle and declination angle for Omorate

No	Mid of the month	n_d	Δ	ω_s	N	n	n/N
1	15-Jan	15	-21.27	89.97	12.00	7.81	0.65
2	14-Feb	45	-13.62	89.98	12.00	6.78	0.57
3	15-Mar	74	-2.82	90.00	12.00	6.33	0.53
4	15-Apr	105	9.41	90.01	12.00	5.64	0.47
5	15-May	135	18.79	90.03	12.00	5.79	0.48
6	15-Jun	166	23.31	90.04	12.00	6.30	0.52
7	15-Jul	196	21.52	90.03	12.00	5.32	0.44
8	15-Aug	227	13.78	90.02	12.00	6.13	0.51
9	15-Sep	258	2.22	90.00	12.00	6.03	0.50
10	15-Oct	288	-9.60	89.99	12.00	5.98	0.50
11	15-Nov	319	-19.15	89.97	12.00	7.12	0.59
12	15-Dec	349	-23.34	89.96	12.00	7.21	0.60

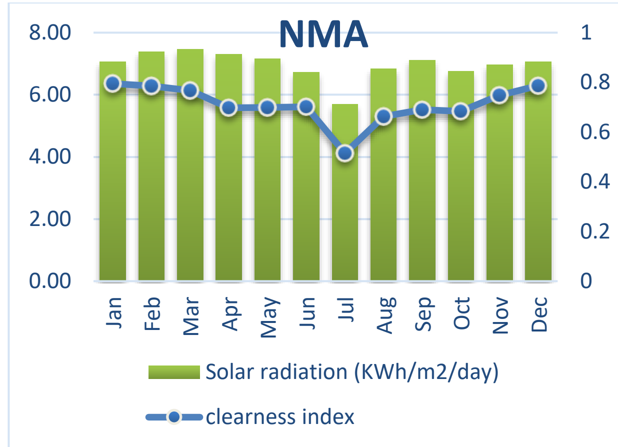
Using Arbaminch average of 6.37 hours of sunlight per day throughout the year, it is calculated that Omorate village has an estimated average of 6.24 $kWh/m^2/day$. When comparing the calculated solar irradiance value with the 8 month site measured data obtained by Yibeltal and Ahlgren [28], which shows an average daily solar radiation of 6.1 kWh/m2/day, the difference is approximately 0.14 kWh/m2/day. This difference is less than 2% for all months.

Table 3.13 Average solar radiation in $kWh/m^2/day$ of Omorate

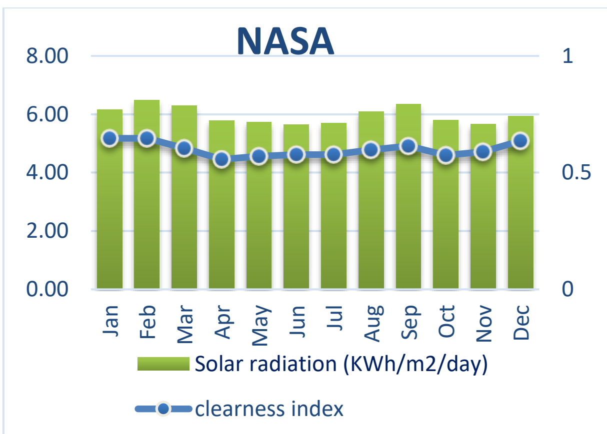
Month	H_o ($kWh/m^2/d$)	a	b	Estimate) H ($kWh/m^2/d$)
Jan	9.498	0.121	0.949	7.02
Feb	10.027	0.093	1.008	6.65
Mar	10.431	0.081	1.035	6.54
Apr	10.415	0.062	1.075	5.91
May	10.067	0.066	1.066	5.84
Jun	9.785	0.080	1.036	6.11
Jul	9.863	0.054	1.093	5.30
Aug	10.191	0.075	1.046	6.21
Sep	10.365	0.073	1.052	6.24
Oct	10.118	0.072	1.055	6.04
Nov	9.603	0.102	0.989	6.62
Dec	9.303	0.105	0.984	6.47
			Average	**6.245**



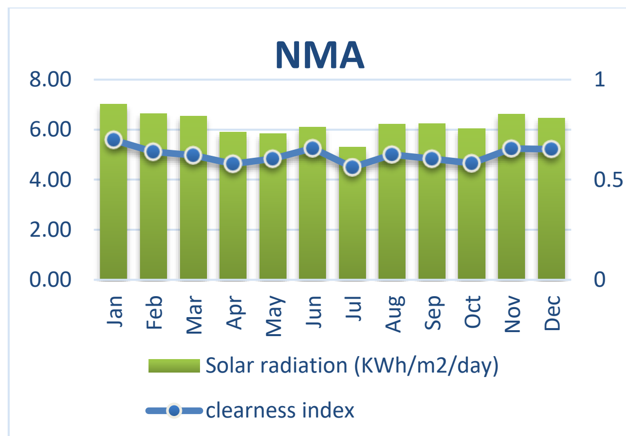
(a)Qorile



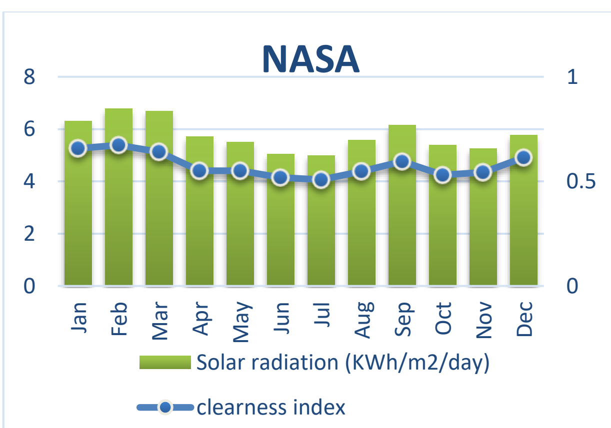
(b) Qorile



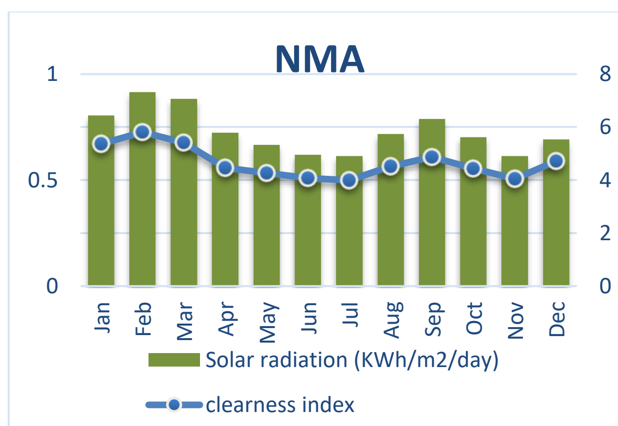
(a) Omorate



(b) Omorate



(a) Dolo



(b) Dolo

Figure 3.13 Global solar irradiation of case study sites (a)NASA, (b) NMA

3.8 Performance of selected solar min-grid sites

3.8.1 Omorate solar mini-grid performance

3.8.1.1 Energy production

The collected data from the mini-grid energy management system HMI indicates that the mini-grid can generate a total of 442,260kWh/year of DC energy, resulting in an average daily DC power output of 1,211.6 kWh/day. Moreover, the mini-grid produces a total of 424,570 kWh/year of AC energy, which corresponds to a daily energy output of 1,163.2kWh/day (1182 kWh/day obtained by Yibeltal and Ahlgren in the span of 245 days [28]).

3.8.1.2 PV modules performance

- Potential power: There are 1210 PV modules each with 310-Watt capability, maximum efficiency 18.94 % and with dimension of 1650 × 992(mm)

  Potential power = area × irradiance × efficiency at STC

  $$1980.5m^2 \times 5.97\ kWh/m^2/day \times 18.94\% \quad = \underline{2239.3\ kWh/day}$$

- Reference, Array and final yield

Table 3.14 Calculated monthly yields for Omorate

Month	Indices		
	Y_R (kWh/kWp/day)	Y_A (kWh/kWp/day)	Y_F (kWh/kWp/day)
Jan	6.161753	3.19874552	3.070796
Feb	6.491847	3.28343254	3.152095
Mar	6.29179	3.00250896	2.882409
Apr	5.791647	3.1425	3.0168
May	5.741633	3.11953405	2.994753
Jun	5.651608	3.5637963	3.421244
Jul	5.701622	2.94041219	2.822796
Aug	6.091733	3.37177419	3.236903
Sep	6.351807	3.0862037	2.962756
Oct	5.80165	3.13297491	3.007656
Nov	5.66161	3.40277778	3.266667
Dec	5.931687	3.54265233	3.400946
Average	**5.976245**	**3.20406001**	**3.075898**

The eight-month data by Yibeltal and Ahlgren [28], shows that the calculated yields to be 5.9kWh/kWp/day reference yield, 3.15kWh/kWp/day array yield, and 2.75kWh/kWp/day final yield with negligible difference from the yearly calculated yields.

- Unutilized solar potential: this may happen in solar mini-grid due to multiple factors, such as weather-related events, equipment failure, or dust in the PV panels. Unexpected changes in weather conditions, such as cloud cover or storms, can cause a reduction in the amount of solar energy available, leading to unintentional loss of energy.

Unutilized solar potential = 2239.3kWh/day -1211.6kWh/day = 1027.7 kWh/day

- PV efficiency and production factor

The efficiency of PV module is affected by several factors like shading, temperature, and weather conditions. Where PV module efficiency is highest on clear, and sunny days, and has lower efficiency on cloudy or overcast days. The PV system production factor is a metric that measures the system effectiveness in generating electricity over a given specific period, usually a year. A variety of factors can affect the output of a PV module, for example shading, temperature, the orientation and tilt of the panels.

Table 3.15 Omorate monthly calculated PV efficiency and production factor

Months	PV efficiency (%)	Production factor (%)
Jan	9.83	52.0
Feb	9.58	46.0
Mar	9.04	48.0
Apr	10.28	53.0
May	10.29	54.0
Jun	11.94	61.0
Jul	9.77	52.0
Aug	10.48	55.0
Sep	9.20	47.0
Oct	10.23	54.0
Nov	11.38	58.0
Dec	11.31	60.0
Average	**10.28**	**53.0**

Yibeltal and Ahlgren [28], shows the power generation efficiency over the 8-month period to be 9.85% with a difference of 0.43% from the calculated yearly average PV efficiency.

3.8.1.3 PV system overall performance

- Array capture loss and system loss

The mini-grid management system has provided valuable data on the capture loss and system loss of the Omorate mini-grid. This data has been recorded in an excel spreadsheet and is used to calculate the array capture loss and system loss as presented in the Table 3.16 below.

$$L_T = L_A + L_S = 2.77 + 0.13 = 2.9 \text{kWh/kWp/day}$$

The total loss (L_T) of the system can be calculated by adding the array capture loss (L_A) and system loss (L_S) together which is 2.9kWh/kWp/day. This information is essential for understanding the efficiency of the mini-grid and identifying areas for improvement.

Table 3.16 Calculated monthly array capture loss and system loss for Omorate

Months	Indices	
	L_A (kWh/kWp/day)	L_S (kWh/kWp/day)
Jan	2.96	0.13
Feb	3.21	0.13
Mar	3.29	0.12
Apr	2.65	0.13
May	2.62	0.12
Jun	2.09	0.14
Jul	2.76	0.12
Aug	2.72	0.13
Sep	3.27	0.12
Oct	2.67	0.13
Nov	2.26	0.14
Dec	2.39	0.14
Average	**2.77**	**0.13**

Yibeltal and Ahlgren [28], shows the monthly average array capture loss to be 2.77kWh/kWp/day and system loss accounts for 0.4 kWh/kWp/day over the 8-month period.

- Performance ratio (R_P) and capacity utilization factor (CUF)

The performance ratio and capacity utilization factor are crucial metrics for evaluating the performance of a solar energy system. Yibeltal and Ahlgren [28], 8-month data shows the monthly average performance ratio 47.92% and capacity utilization factor 13%. Yearly calculated values for the Omorate site, is presented in Table 3.17 below.

Table 3.17 Calculated monthly performance ratio and capacity utilization factor for Omorate

Months	Indices	
	R_P (%)	CUF (%)
Jan	49.84	11.20
Feb	48.55	11.69
Mar	45.81	10.82
Apr	52.09	11.39
May	52.16	11.47
Jun	60.54	12.66
Jul	49.51	10.24
Aug	53.14	11.78
Sep	46.64	10.46
Oct	51.84	10.96
Nov	57.70	11.66
Dec	57.34	11.47
Average	**51.62**	**11.30**

- Grid inverter efficiency

From Omorate solar mini-grid site data yearly average monthly DC energy output of the PV is 36,855 kWh/Month, while the yearly average monthly AC energy output from the grid inverter is 35,380.8 kWh/Month. Therefore, the yearly grid inverter efficiency can be calculated as:

$$\eta_{INV,GRID} = \frac{E_{I,out}}{E_{PV}} = \frac{35{,}380.8}{36{,}855} = 96\ \%$$

3.8.1.4 Battery efficiency

Omorate solar mini-grid HMI provides valuable information on the status of battery's charging and discharging. The battery plus and battery minus indicate the charging and discharging of the battery, respectively. Table 3.18 below shows the data collected for July and Table 3.19 shows yearly data collected from the HMI and recorded in excel spreadsheet is presented.

$$\eta_{BAT,Average} = \frac{E_{BAT,Discharge}}{E_{BAT,Charge}} = \frac{441.7831}{520.564} \times 100 = \mathbf{85}\%$$

Table 3.18 Omorate July BESS reading from SCADA

Time	15/07/2021			PVG	BESS	DG	Load
	Ia(A)	Ib(A)	Ic(A)	P(kW)	P(kW)	P(kW)	P(kW)
00:00	0	0	0	0	1	0	0
01:00	0	0	0	0	1	0	0
02:00	0	0	0	0	1	0	0
03:00	0	0	0	0	1	0	0
04:00	0	0	0	0	2	0	0
05:00	0	0	0	0	2	0	0
06:00	0	0	0	0	1	0	0
07:00	8	7	7	4	-2	0	0
08:00	41	42	42	29	-25	0	0
09:00	135	135	134	87	-12	0	74
10:00	131	131	130	81	-2	0	77
11:00	165	164	164	112	-32	0	78
12:00	298	299	298	204	-118	0	81
13:00	136	136	136	85	4	0	85
14:00	113	113	113	79	-76	0	0
15:00	262	262	261	182	-162	0	13
16:00	103	103	103	69	-50	0	14
17:00	16	16	15	0	23	0	18
18:00	32	32	31	22	-20	0	0
19:00	3	2	2	-1	3	0	0
20:00	0	0	0	0	109	0	106
21:00	0	0	0	0	105	0	103
22:00	0	0	0	0	94	0	92
23:00	0	0	0	0	77	0	76
24:00	0	0	0	0	1	0	0

Table 3.19 Calculated monthly Omorate battery efficiency

Months	Bat + (kWh)	Bat- (kWh)	Battery efficiency (%)
Jan	444.1935	-498.129	89.63
Feb	430.1429	-502.25	86.43
Mar	455.129	-490.806	92.82
Apr	432.2333	-494.9	87.56
May	554.4194	-603.871	96.41
Jun	465.8333	-583.3	81.43
Jul	425.9677	-519.613	84.52
Aug	445.1613	-507.29	92.10
Sep	365.4333	-494.433	75.48
Oct	449.129	-528.226	88.00
Nov	423.3667	-511.467	84.50
Dec	410.3871	-512.484	80.27

- Battery state of charge (SoC)

Battery SoC and SoH can be determined by the SCADA output reading values. Where the battery plus (+) indicates it is discharging while minus (-) indicate it is charging. The SoC is a measure of the amount of charge that is currently available in the battery, while the SoH is a measure of the battery's overall health and capacity.

The State of Charge (SoC) is a critical parameter for the battery in a PV mini-grid system, and it is essential to monitor it regularly to ensure that the battery is operating efficiently and within safe limits. Using data obtained from the Omorate solar mini-grid system, yearly average SoC is 33.117%.

Table 3.20 Monthly calculated Omorate SoC

Months	SOC_{MAX}	SOC_{MIN}	$SOC_{Average}$
Jan	0.56	0.151	0.295269
Feb	0.59	0.110	0.320179
Mar	0.43	0.123	0.259462
Apr	0.45	0.156	0.304444
May	1.01	-0.533	0.282419
Jun	0.73	-0.300	0.395778
Jul	0.68	-0.073	0.356075
Aug	0.67	-0.511	0.303548
Sep	0.76	-0.218	0.408065
Oct	0.75	-0.171	0.331828
Nov	0.65	0.076	0.346833
Dec	0.63	0.038	0.370161

3.8.1.5 The behavior of the load

A feasibility study was conducted for Omorate before the mini-grid was erected and it reveals that a solar mini-grid system was a feasible and sustainable solution for providing electricity to the local community and design was done for a solar mini-grid system that could provide electricity to 786 households. However, currently it is serving 488 customers, indicating that there is a capacity shortage to connect all the customers. It is found that out of the total 488 connected customers, 370 were households, and the remaining 118 were commercial and public customers. The energy demand of the connected customers was estimated to be approximately 1,031.6 kWh/per day, with the highest demand occurring in the evening. In the residential load from 0:00 - 5:00 the estimated power 7.40 kW for the 370 potential customers each consuming 20 W/hr./household which corresponds low power need in the specific time.

Table 3.21 Estimated daily power demand for Omorate

Time	Commercial Load (kW)	Public Load (kW)	Residential Load (kW)	Total (kW)
0:00	0:00	0.55	7.40	7.95
1:00	0:00	0.55	7.40	7.95
2:00	19:12	0.47	7.40	11.67
3:00	0:00	0.91	7.40	8.31
4:00	0:00	1.56	7.40	8.96
5:00	10:42	5.69	7.40	17.54
6:00	16:30	6.01	11.10	25.80
7:00	6:30	4.88	12.95	34.10
8:00	22:21	8.04	12.95	43.92
9:00	16:54	9.32	12.95	43.98
10:00	13:58	7.78	12.95	39.32
11:00	0:47	3.45	12.95	47.44
12:00	2:14	7.41	12.95	47.45
13:00	9:36	7.73	12.95	58.08
14:00	1:54	6.12	12.95	79.15
15:00	21:49	5.64	12.95	88.50
16:00	4:00	4.42	14.80	89.38
17:00	20:30	6.59	18.50	98.94
18:00	16:17	8.08	31.45	75.21
19:00	11:53	7.88	31.45	61.83
20:00	10:04	5.90	31.45	51.77
21:00	17:01	3.16	31.45	41.32
22:00	13:26	0.55	24.05	29.16
23:00	9:07	0.55	12.95	13.88
			Total (kWh/ day)	1,031.60

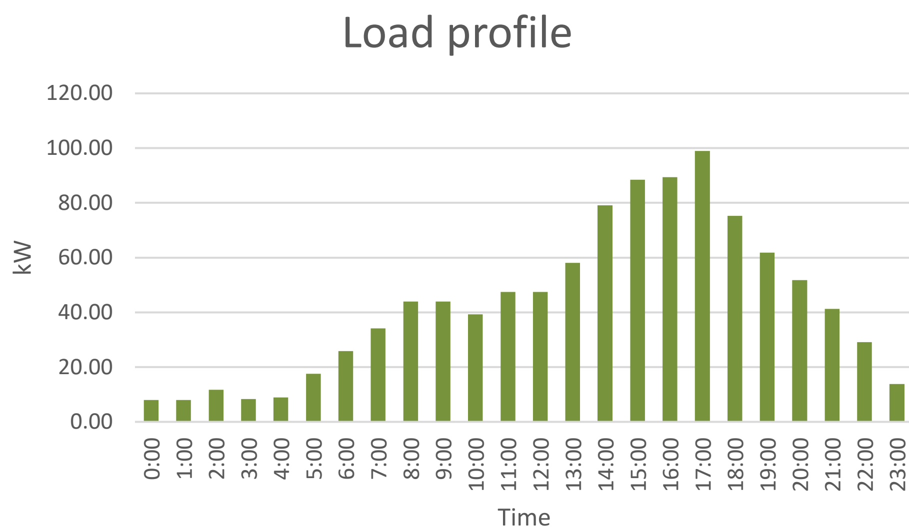


Figure 3.14 Omorate load profile

3.8.1.6 Omorate solar mini-grid Reliability

Omorate solar mini-grid reliability analysis is determined by using the day to day solar mini-grid human machine interface load output data. The data is organized in excel spread sheet for each month starting from May 2021 up to April 2022. From the excel spread sheet the following interruption duration and interruption frequency is presented in Table 3.22.

Table 3.22 Omorate frequency and duration of interruption

Month	Interruption duration (Hrs.)	Interruption frequency (Interruption)
Jan	407	66
Feb	356	56
Mar	409	63
Apr	401	64
May	231	35
Jun	349	60
Jul	406	69
Aug	390	62
Sep	404	59
Oct	418	62
Nov	405	60
Dec	407	62
Average	**381.9**	**59.8**

- Customer based indices for reliability

Customer based reliability indices in Table 3.23 using Equation 2.15 – 2.18 is presented. During an energy - demand imbalance in Omorate solar mini-grid operator's blackout all customers, resulting the total customers interrupted to be the same as the total number of customers. The monthly SAIDI 382 Hrs./Customer is comparable to Yibeltal and Ahlgren [28].

Table 3.23 Omorate customer-based indices for reliability

Indies		Value
SAIDI	$\frac{\sum_i r_i N_i}{N_T} = \frac{4583 * 488}{488}$	4583 Hrs./Avg.Customer
SAIFI	$\frac{\sum_i \lambda_i N_i}{N_T} = \frac{718 * 488}{488}$	718 Int./Avg.Customer
CAIDI	$\frac{SAIDI}{SAIFI} = \frac{4583}{718}$	6.4 Hrs./Int
ASAI	$\frac{\sum_i N_i \times 8760 - \sum_i r_i N_i}{\sum_i N_i \times 8760} = \frac{488 \times 8760 - 4583 * 488}{488 \times 8760}$	47.68 %

3.8.2 Qorile solar mini grid performance

3.8.2.1 Energy production

According to the gathered data from Qorile solar mini-grid energy management system HMI, the mini-grid generated 165.79 MWh AC energy only in year 2021, which comes to an average 454.3kWh/day. In the same year the PV generated 175,656kWh/year DC energy, which comes to an average 481.25kWh/day. The load is provided with total AC energy of 36,793 kWh in the period of six months (182 days), from April 2021 until September 2021. This corresponds to an average daily energy consumption of 202 kWh.

3.8.2.2 PV modules performance

- Potential power: there are 976 PV modules each with 335-Watt capability, maximum efficiency 19.85 % and with dimension of 1684 ×1002(mm)

  Potential power = Area × irradiance × efficiency at STC

  = 1646.87m^2 × 5.69 kWh/m^2/day × 19.85 % = 1860.1 kWh/day

- Reference, Array and final yield

Table 3.24 Calculated monthly energy yield for Qorile

Month	Indices		
	Yr. (kWh/kWp/day)	Ya. (kWh/kWp/day)	Yf (kWh/kWp/day)
Apr	8.8379	1.480769	1.397846
May	8.6699	1.480769	1.397846
Jun	8.1335	1.480769	1.397846
Jul	6.8865	1.480769	1.397846
Aug	8.2787	1.480769	1.397846
Sep	8.6069	1.480769	1.397846

In Qorile solar mini-grid there is unutilized solar potential due to several factors, including equipment malfunction, dust in PV modules, or weather-related events. Changes in weather conditions, like sudden storms or cloud cover, can reduce the amount of available solar energy, which can unintentionally lead to energy loss.

Unutilized solar potential = 1860.1kWh/day - 454.3kWh/day = 1405.8 kWh/day

- PV efficiency and production factor

Similar to that of Omorate, Qorile solar mini-grid PV module is affected by several factors like shading, temperature, and weather conditions where PV module efficiency is highest on clear, and sunny days, and has lower efficiency on cloudy or overcast days. The PV system production factor is a metric that measures the system effectiveness in generating electricity over a given specific period, usually a year. Table 3.25 presented after the data gathered from the mini grid is evaluated for 182 days.

Table 3.25 Qorile monthly calculated PV efficiency and production factor

Month	Production factor (%)	PV Efficiency (%)
Apr	20.267	3.998
May	20.660	4.076
Jun	22.022	4.344
Jul	26.010	5.131
Aug	21.636	4.268
Sep	20.811	4.105
Average	**21.901**	**4.320**

3.8.2.3 PV system overall performance

- Array capture lose and system loss

The Qorile mini-grid's management system records data over the six months is evaluated on excel spread sheet and Table 3.26 shows the capture and system loss. It is found that the losses are high and they contribute to the total loss to be high. The total loss (L_T) of the system 6.84 kWh/kWp/day. This information helps assess the mini-grid's efficiency and identify areas for improvement.

$$L_T = L_A + L_S = 6.75479 + 0.082923 = \underline{6.84\ kWh/kWp/day}$$

Table 3.26 Calculated monthly array capture loss and system loss for Qorile

Month	Indices	
	L_A (kWh/kWp/day)	L_S (kWh/kWp/day)
Apr	7.357101	0.082923
May	7.189147	0.082923
Jun	6.652711	0.082923
Jul	5.405765	0.082923
Aug	6.797915	0.082923
Sep	7.126142	0.082923
Average	**6.75479**	**0.082923**

- Performance ratio (R_P) and capacity factor (CUF)

Qorile solar mini-grid similar to Omorate the performance ratio and capacity utilization factor are crucial metrics for evaluating the performance of a solar energy system. Table 3.27 shows the calculated metrics for the Qorile site using an excel spreadsheet.

Table 3.27 Calculated monthly performance ratio and capacity utilization factor for Qorile

Month	Indices	
	R_P (%)	CUF (%)
Apr	15.817	2.615
May	16.123	2.477
Jun	17.186	2.488
Jul	20.298	2.292
Aug	16.885	2.829
Sep	16.241	2.936
Average	**17.092**	**2.606**

- Grid inverter efficiency

The six month (182 days) average monthly DC energy output from the PV is 454.3 kWh, while the yearly average monthly AC energy output from the grid inverter is 481.25 kWh. The grid inverter efficiency for the year can be calculated by dividing the AC energy output by the DC energy input and that grid inverter efficiency is found to be 94.4%.

3.8.2.4 Battery efficiency

The battery management system is a crucial component of any solar energy system, and the human-machine interface (HMI) provides valuable information on the battery's charging and discharging status. Hence, the battery state of charge for the three battery management systems is maximum 97.1 % and minimum 59 %.

3.8.2.5 The behavior of the load

A feasibility study was conducted for Qorile before the mini-grid was erected and it reveals that a solar mini-grid system was a feasible and sustainable solution for providing electricity to the local community and design was done for a solar mini-grid system that could provide electricity to 900 customers. However, currently it is serving 238 customers, and there are no new requests for connection at this time.

It is found that out of the total 238 connected customers, 204 were households, and the remaining 34 were commercial and public customers. The energy demand of the connected customers was estimated to be approximately 217 kWh per day, with the highest demand occurring in the evening.

Table 3.28 Estimated daily power demand for Qorile

Time	Commercial (kW)	Public (kW)	Residential (kW)	Total (kW)
0:00	0:00	0.00	2.04	2.04
1:00	0:00	0.00	2.04	2.04
2:00	4:48	0.00	2.04	2.24
3:00	0:00	0.00	2.04	2.04
4:00	0:00	0.00	2.04	2.04
5:00	4:48	0.70	2.04	2.94
6:00	9:36	0.70	4.08	5.18
7:00	19:12	0.59	5.10	6.49
8:00	9:39	1.43	6.12	10.95
9:00	9:18	1.67	6.12	12.18
10:00	21:27	1.43	6.12	11.45
11:00	14:33	0.31	6.12	9.03
12:00	19:03	1.43	6.12	11.35
13:00	0:30	1.48	6.12	10.62
14:00	22:24	1.11	6.12	9.17
15:00	11:34	1.15	6.12	10.75
16:00	1:18	0.57	8.16	10.79
17:00	8:26	1.03	10.20	13.58
18:00	18:29	1.12	14.28	17.17
19:00	2:22	1.12	14.28	17.49
20:00	0:41	0.96	14.28	17.27
21:00	2:00	0.39	14.28	15.75
22:00	5:45	0.00	10.20	10.44
23:00	0:28	0.00	4.08	4.10
			Total kWh/day	217.10

Table 3-28 illustrates that in the village, the total energy consumption is 217.1kWh/day, with residential households consuming 160.14 kWh/day, commercial loads consuming 39.77

kWh/day, and public loads consuming 17.19 kWh/day. Figure 3.15 below shows the load profile of Qorile, with the maximum load occurring between 18:00 and 23:00.

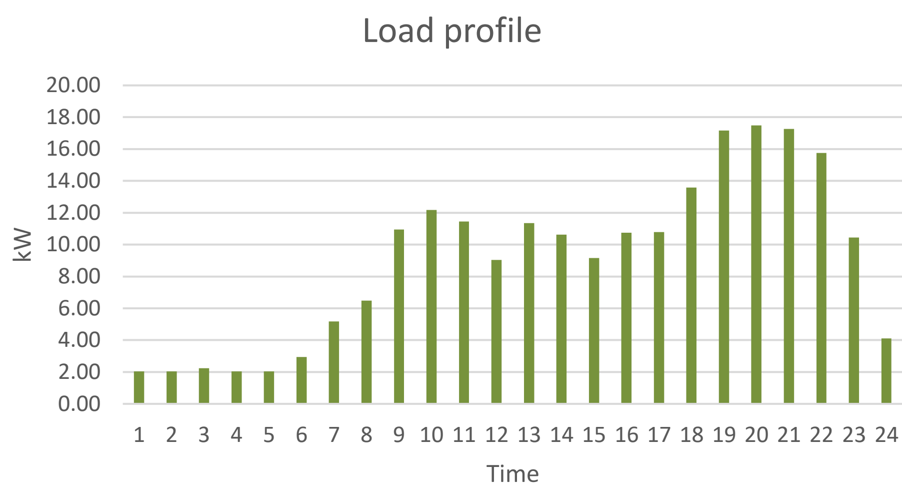


Figure 3.15 Qorile load profile

3.9 Diesel mini-grid performance

Diesel mini-grids can provide reliable power to off-grid communities, but there are some key performance factors to consider:

- Reliability and availability: Diesel generators are a mature technology and can provide consistent power as long as there is fuel available and proper maintenance is performed. The main causes of outages tend to be lack of fuel or mechanical failures, so good operation and logistics procedures are important.
- Cost: Diesel fuel can be expensive, especially in remote areas. The overall cost of power from a diesel mini-grid depends on the efficiency of the generators, cost of diesel fuel, and other operational expenses like maintenance and staffing costs. Costs are often higher than large grid power.
- Scalability: Diesel mini-grids requires significant capital investment. typically built with excess capacity to allow for load growth over time. However, they require the addition of more generators and fuel storage to scale up in size. Hence, they are best suited to relatively small-scale mini-grids.
- Effect on environment: If diesel generators are not properly maintained, they can have negative environmental and health impacts. carbon dioxide, nitrogen oxides,

and sulfur oxides are pollutants that are produced in diesel mini-grids. To minimize the emission, it is recommended to use ultra-low sulfur diesel fuel and particle filters.

- Energy efficiency: Diesel generators tend to have lower fuel conversion efficiencies compared to some other technologies like solar PV and micro hydro. The overall system efficiency of a diesel mini grid depends on the sizing, loading and operating parameters of the generators. Hence, proper sizing and load management can help maximize efficiency.

Table 3.29 Somali region diesel generator-only mini-grids daily fuel consumption

	Woreda	Gen	Operation hours (Hr.)	Capacity of Diesel Generator (kVA)	Daily generated kWh	Fuel consumption per day (liters)
1	Bohe	*	6	375	750	100
2	Geladin	*	6	250	640	100
3	West Emie	**	6	140	350	140
4	(Imi-bari)	**	6	140	250	120
5	Gashamo	*	6	400	55	120
6	Ferfer	*	6	140	300	100
7	Danot	**	6	140	400	100
8	Hargele	*	6	250	900	200
9	Chereti	*	6	250	840	150
10	Dolo Odo	***	6	400/187	2000	250
11	Dolo Baye	**	6	140	200	120
12	Elkere	*	6	250	375	100
13	Gurobekekisa	**	6	140	650	120
14	Bare	*	6	250	625	150
15	Mustahil	**	6	400	300	100
Generators for each woreda **(*) volte Penta 740, (**) volt Penta 720, (***) volt Penta 1241**					**Total**	**1970**

Dolo Ado is a densely populated area that relies on a diesel-powered mini-grid to provide electricity to its residents. Which can be expensive to operate and maintain due to that it is only powered by a diesel generator. They are known to produce harmful emissions that contribute to air pollution and climate change. Due to capacity shortages, the mini-grid is currently operational for only 6 hours a day, serving 396 connected customers only out of 8,470 potential customers, which are mostly household customers.

Table 3.30 Dolo Odo yearly fuel consumption

Year	Dolo Odo		
	Fuel consumption per day	Fuel and transportation cost Br/Lt	Yearly Cost Br
2018	5500	21.6607	119,133.85
2019	21000	26.7264	561,254.4
2020	5030	33.5704	168,859.112
		Total Br.	849,247.362

3.10 Sizing of solar mini-grid

3.10.1 Solar mini-grid sizing for Dolo Odo

3.10.1.1 Factors for solar sizing

The sizing of a solar mini-grid for Dolo Odo would depend on several factors such as the current demand for electricity, the expected growth in demand, and the availability of solar resources in the region. As shown in Figure 3.16 below, the proposed high-level modular AC coupled mini-grid topology for Dolo Odo includes solar mini-grids, each having a 100kW PV system with dedicated modular inverters, PCS for bi-directional conversion and frequency regulation, as well as a metering and protection system at the buses. The mini-grid system (PV, ESS and diesel) provide power without service interruptions. The addition of a diesel generator provides redundancy and reliability, backup power, and the capability to meet additional power requirements during peak loads. At least 90% of the energy supplied to the loads are from renewable sources (PV + ESS) and 10% from diesel and the storage sizing is considered to be available for one cloudy day.

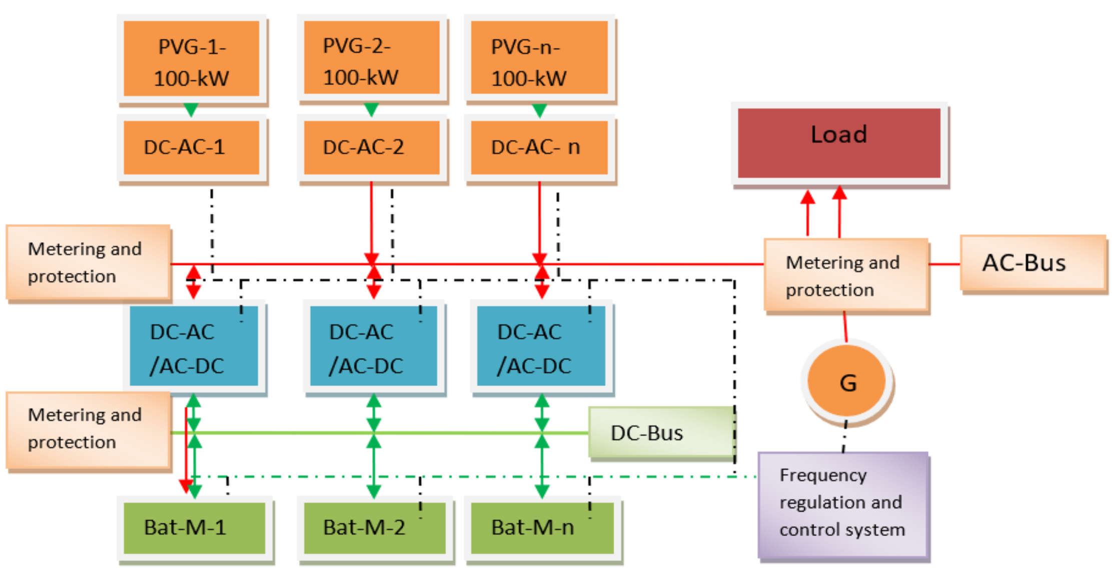


Figure 3.16 AC coupled mini-grid topology for Dolo Odo

3.10.1.2 Grid inverter sizing

The DC-AC inverter is responsible for converting the DC voltage from the PV array or storage batteries to AC at the appropriate voltage level for consumption by the loads. To size the inverter, the possibility that all the loads may be turned on at the same time and run continuously is considered. This however, means that most of the time that the inverter is running, it is operating at a smaller load than its rated load [11]. Running the system at a lower load reduces the efficiency and consequently, some energy is wasted. From the daily demand estimation, it is found that out of the total demand 715.5kW about 22.24 % of the load is inductive. From Appendix-B inverter specification inverters with 100 kW power rating and max PV voltage range of 200-1000V is selected for the design.

$P_{nia} = \sum_{n=1}^{\infty} P_{(nia)n}$ = **556.4 kW** *and* $P_{ia} = 3 \times \sum_{n=1}^{\infty} P_{(ia)n}$ =3(159.13) = **477.4kW**

$$P_i = 1.25(P_{nia} + P_{ia}) = 1.25\ (\mathbf{556.4} + \mathbf{477.4}) = \underline{\mathbf{1,293kW}}$$

3.10.1.3 Storage Battery system sizing

The process of battery sizing involves determining the appropriate battery capacity for a given system or application. In this case, the battery cell configuration selected is 8P/16S. The representation "8P/16S" indicates the specific arrangement of the battery cells. where "P" indicates number of battery cells connected in parallel and "S" refers to number of battery cells connected in series.

Table 3.31 Battery cell specification

CELL TYPE	EFP27148130-40Ah
Normal Capacity	40Ah
Normal Voltage	3.2V
Energy Density	125Wh/kg
AC Internal Resistance	≤0.8mΩ
Dimension (mm)	27.5*148.0*132.6
Stack specification	
Rack Type	15×Module+1 String Box
Normal Capacity	245.76kWh
Normal Voltage	768V

Figure 3.17 Battery cell

Assuming 8 parallel and 16 series configurations for the battery cell arrangement in one module with 51.2 V and 320Ah and having a stack of 15 modules to get nominal voltage of 768V with 245.76kWh capacity.

Adjusted energy demand for energy efficiency of inverter

$$E_T = \frac{E_{AC}}{\eta_{inv}} = \frac{7555.68\text{kWh}}{0.96} = 7870.5 \text{ kW}$$

Energy Demand in Ampere-hour with nominal system voltage 768 volt

$$Ah_D = \frac{E_T}{V_{DC}} = \frac{7870.5 \text{ kWh}}{768} = 10.25\text{kAh}$$

Adjusted battery capacity using days of autonomy, depth of discharge and temperature factor

$$B_C = \frac{Ah_D \times D_{aut}}{DOD_{MAX} \times f_T} = \frac{10.25\text{kAh} \times 1}{0.8 \times 0.97} = 13.2kAh$$

Number of Series and parallel battery stacks

$$N_P = \frac{B_C}{B_S} = \frac{13.2kAh}{320Ah} = 42 \; battery \; stack$$

$$N_S = \frac{V_{DC}}{V_S} = \frac{768V}{768V} = 1 \; battery \; stack$$

3.10.1.4 PV array sizing

The sizing of the PV array to satisfy the energy demand of 7,555.68 kWh per day for Dolo Odo considers 0.85 battery round-trip efficiency, 5% temperature correction factor, 83% efficiency for the PV array sub-system, and 4.81 kWh/m^2/day insolation. From Appendix-B specification, a 450-watt PV panel with a maximum voltage of 33.9 V and assuming a 92% derating factor is used for the analysis.

Adjusted total energy demand per day for battery round trip efficiency:

$$E = \frac{E_{AC}}{\eta_{Bat}} = \frac{7{,}555.68\text{kWh}}{0.85} = 8888.9kWh$$

Total number of modules series and parallel:

$$N_{mod} = \frac{\text{E} \times (1 + \text{i})}{P_O \times G \times \eta_{pv}} = \frac{8{,}888.9\text{kWh} \times (1 + 0.05)}{414 \times 4.81 \times 0.83} = 5647 panel$$

$$N_s = \frac{V_{nominal}}{V_{modue}} = \frac{768\text{V}}{33.9} = 22 panel$$

$$N_p = \frac{N_{mod}}{N_S} = \frac{5{,}647}{22} = 256 \; panel$$

3.10.1.5 Charge controller sizing

A charge controller starts by determining the maximum current it needs to handle from the PV array. From that required total current, we can calculate the number of individual charge controllers needed based on their maximum current ratings. Using the specification data from Appendix-B 450-watt PV panel the short circuit current capacity is 13.85A.

$$I_{cc} = I_{sc}\, x\, N_{pm}\, x\, F_{sefe} \;=\; 13.85 \;\times\; 256 \;\times 1.15 = 4{,}077 \text{ Amp}$$

For individual charge controllers $I_{icc} = I_{cc} \;\div$ Number $of\ inverters = 4{,}077 \div 25 = 163.1A$

3.10.2 Optimization and economic analysis

3.10.2.1 Homer optimization

Mini-grids are highly dynamic systems that involve multiple variables that can change continuously and simultaneously. The solar energy availability varies significantly based on local weather patterns, while the energy demand can fluctuate rapidly, leading to peaks and transients. Additionally, batteries and electronic devices have their own logic and respond differently to changes in electrical parameters. These variables interact with one another in complex ways, making microgrid analysis and optimization challenging [33].

To addresses these challenges, modelling and simulation is used to optimize technical performance and economic viability of mini-grids. The two main objectives of the simulation are, first, to determine whether the system is feasible enough to meet the required electricity demand and second, is to estimate the system lifecycle cost. The lifecycle cost is calculated as the net present cost, which includes all costs and revenues that occur during the project's lifetime, with future cash flows discounted to the present.

The high-level components capacity design of Dolo Odo village is optimized using HOMER Pro simulation software. Considering future rural load growth of 5% per annum, 3.16 % per annum population growth rate in Dolo Odo and the storage sizing is considered to be available for one cloudy day.

- Economic Analysis

The economic analysis serves to assess the economic viability of rural town mini-grid power plant and low voltage power distribution project. For this purpose, the economic costs of the project are compared to its economic benefits. Both costs and benefits are set up as cash flows over the economic lifetime of the mini grid power system, including the construction period and the operation period. Assuming that the mini-grid is commissioned in end of 2024 and that it has an economic lifetime of 25 years, the evaluation covers the period up to 2048. All costs and benefits are expressed in USD to make them comparable to the costs considered in the recent studies for mini-grid projects. The key assumptions made for the economic analysis are summarized in Table 3.32 below. The exchange rate and discount rate data are taken on May, 2023 also the average Ethiopia inflation rate is used [34].

Table 3.32 Economic analysis indicators

No.	Item	Value
1	Nominal Discount rate	8%
2	Expected inflation rate	9%
3	Exchange rate	54 Birr/USD
4	Construction time	1 year
5	Economic lifetime	25 year

Table 3.33 Estimate Solar PV generation Plant cost from EEUPPM [32]

No.	**Description**	**Unit Price**
1	Cost of solar PV(USD/kW) with inverter and all transport, civil work and PV structures and Design of system (USD/kW)	**1,855.00**
2	Cost of Battery (USD/kWh)	**250.00**
3	Cost of DG set (USD/kVA)	**610.00**
4	Cost of Converter(kW)	**285.00**

- PV panel

The size of the array is determined based on the amount of electricity needed to meet the demand. The PV system is manually determined with rating of 2,534kW since it considers oversizing factors, but the capacity selected by the simulation is 2,000kW is being considered. To account for the cost of components other than the solar panels, such as wiring and support structures, the initial cost, replacement cost, operation, and maintenance costs are adjusted accordingly. Table 3.34 below provides information about the parameters of the solar panels.

Table 3.34 Parameters for Solar PV and Battery module

Module parameter	Value
Type	Generic
Rated capacity (kW)	2,000
Panel type	Flat plate
Lifetime(year)	25
PV derating factor (%)	80
Capital cost ($)/kW	1850
Replacement cost ($)/kW	1850
Operation and maintenance cost $/kW/year	5
Module parameter	Value
Type	Idealized Battery model
Nominal voltage of single cell (V)	51.2
Nominal system voltage(V)	768
Nominal Ampere hour (Ah)	328
Nominal capacity (kWh)	16.8
Round trip efficiency (%)	97
Minimum charge current (A)	263
Minimum discharge current (A)	328
Annual throughput (kWh)	168,000
Initial state of charge (%)	100
Minimum state of charge (%)	30
String size	15
Capital cost ($)/kW	4200
Replacement cost ($)/kW	4200
Operation and maintenance cost ($/kW/year)	5
Lifetime (year)	10

Table 3.35 Parameters for Bi-directional converter

Module parameter	Value
Type	Generic large, free converter
Inverter efficiency (%)	96
Rectifier efficiency (%)	96
Rectifier relative capacity (%)	100
Capital cost ($/kW)	300
Replacement cost ($/kW)	300
Operation and maintenance cost ($/year)	10
Lifetime(year)	15

Table 3.36 Parameter for grid inverter

Module parameter	Value
Type	Generic large, free converter
Inverter capacity (kW)	2000
Inverter efficiency (%)	96
Capital cost ($/kW)	285
Replacement cost ($/kW)	285
Operation and maintenance cost ($/year)	5
Lifetime(year)	15

3.10.2.2 Dolo Ado System component and configuration

The high-level AC coupled mini-grid system (PV, ESS and diesel) provide power without service interruptions. At least 90% of the energy supplied to the loads are from renewable sources (PV + ESS) and 10% from diesel generator. System architecture bellow shows the system components generator, PV, converter, energy storage system (Battery) and loads (primary and deferable) with their respective busses for connection and Simulation and optimization with HOMER-Pro software. Table 3.37 below presents the winning system architecture system capacity.

Table 3.37 Dolo Odo proposed solar mini-grid System architecture

Component	Name	Size	Unit
Generator	Auto size Genset	1,200	kW
PV	Generic flat plate PV	2,000	kW
PV dedicated converter	PV inverter	2,000	kW
Storage	Lithium Ion	8,060.9	MWh
System converter	Generic large, free converter	1,050	kW

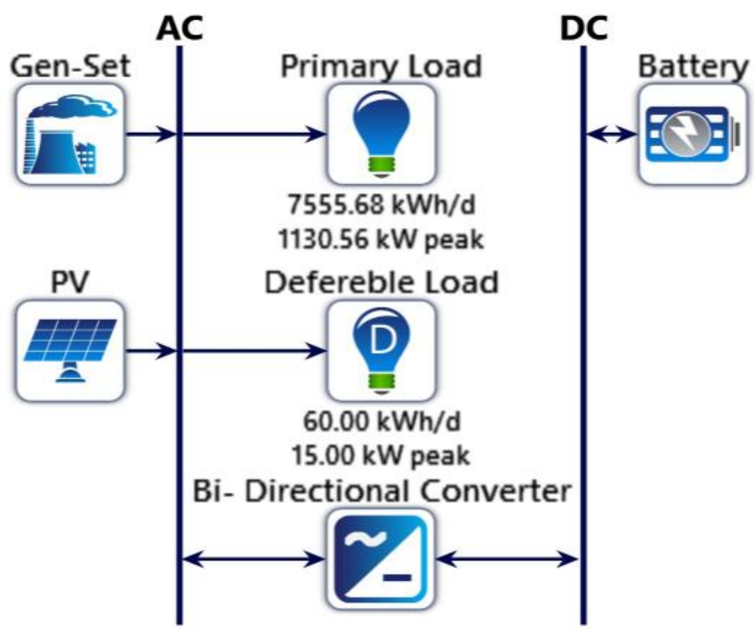


Figure 3.18 System component and configuration

CHAPTER 4
4. RESULT AND DISCUSSION

4.1 Introduction

This section covers performance analysis of three different systems: a solar mini-grid system in Omorate and Qorile, a diesel-only mini-grid system in Dolo, and a proposed solar mini-grid system design for Dolo Odo. Firstly, the performance of the solar mini-grid system in Omorate and Qorile is discussed. Next, the discussion moves on to the diesel mini-grid system in Dolo. Finally, the section concludes with a discussion of the simulation and optimization of the proposed solar mini-grid system design.

4.2 Performance of solar mini-grids

Out of the twelve-pilot solar mini-grid sites, the case study focuses on two specific sites: the Omorate solar mini-grid, located in the SNNP region of Ethiopia, and the Qorile solar mini-grid, located in the Somali region of Ethiopia. These two sites have capacities of 375 kW and 325 kW, respectively. The performance analysis of these sites is conducted in accordance with the guidelines outlined in IEC Standard 61724.

- Solar resource assessment result

When comparing the data estimated by using modified Angstroms equation, it was observed that the Qorile registered an average global radiation of 6.96 kWh/m^2/d whereas NASA reported an average of 6.0kWh/m^2/d. This comparison reveals that there is difference of 0.96kWh/m^2/d. Similarly, Omorate average global solar radiation using angstroms equation is 6.24 kWh/m^2/d but NASA recorded an average of 5.97 kWh/m^2/d, there is still a difference of 0.27 kWh/m^2/d between the two sources.

Table 4.1 Data comparison between NASA and NMA Qorile

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NMA	7.06	7.38	7.46	7.31	7.17	6.72	5.69	6.84	7.12	6.76	6.96	7.06
NASA	6.18	6.76	6.81	6.14	5.96	5.42	5.22	5.88	6.36	5.54	5.81	5.93
Error	0.88	0.62	0.65	1.17	1.21	1.30	0.47	0.96	0.76	1.22	1.15	1.13

Table 4.2 Data comparison between NASA and NMA Omorate

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NMA	7.02	6.65	6.54	5.91	5.84	6.11	5.30	6.21	6.24	6.04	6.62	6.47
NASA	6.16	6.49	6.29	5.79	5.74	5.65	5.70	6.09	6.35	5.80	5.66	5.93
Error	0.86	0.16	0.25	0.12	0.10	0.46	-0.40	0.12	-0.11	0.24	0.96	0.54

4.2.1 Qorile Solar mini-grid performance result

The original scheme for the mini-grid was to give electricity with a capacity of 325kW Solar, ESS and a diesel generator hybrid system, providing 894.1 kWh/day to 900 customers, but currently it only serves 238 customers (26.4 %) with 217.1 kWh/day. This finding shows that only 24.28 % of planned energy requirement is met. Furthermore, the amount of electricity produced every day is 74.1 % less than the planned energy requirement. Hence, the solar PV system and the other BOS equipment's must be checked for their quality and efficiency.

Based on the energy demand of 217 kWh per day, commercial customers account for 18% of the total demand, while the majority of customers are households (85%) which account for 74% of the total demand and Public customers account for 8% of the total demand.

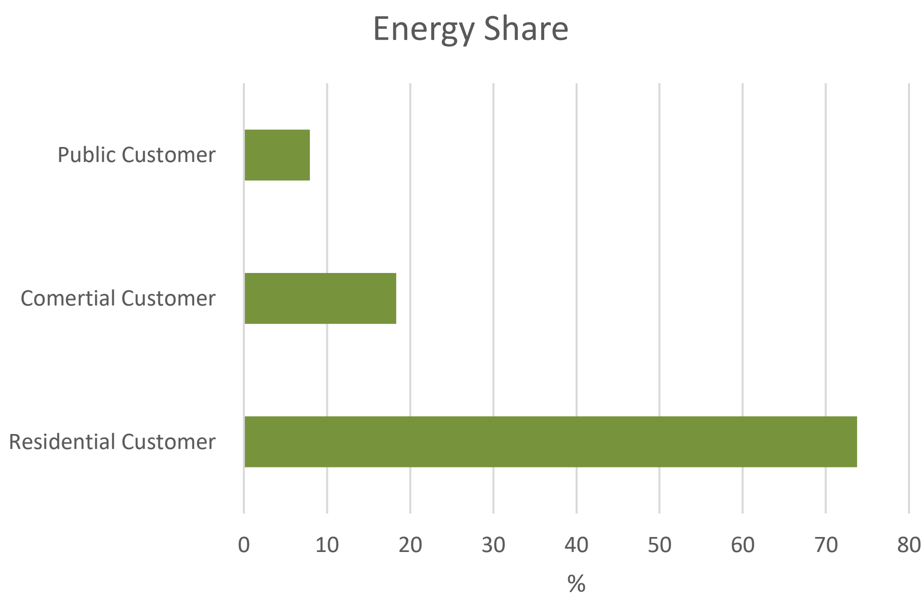


Figure 4.1 Qorile customers energy share

From the analysis conducted to evaluate the potential power of the mini-grid and the efficiency of the PV panel, the results indicated that the mini-grid has a significant potential power output of 1,860.1 kWh per day. This represents the theoretical maximum amount of energy that can be produced by the mini-grid, based on the capacity of the PV panel with conversion efficiency of 19.85%.

However, the yearly DC electricity output from the PV module is 175,656kWh (175.656 MWh) and AC electric output 165,790 kWh (165.79 MWh). The actual energy collected by the mini-grid PV module was found to be much lower, at only 481.25 kWh per day (25.87% of 1860.1 kWh per day). This represents a significant amount of unutilized solar potential of 1,378.8 kWh per day (75.57%), indicating that a significant portion of the potential energy output is being lost without collection. Moreover, the average daily AC energy delivered to the load is 203.27kWh/day, when we compare it to AC energy available 454.2 kWh/day it means only 44.74 % of the available energy is consumed by the load and the remaining 251 kWh/day (55.25 %) is used to charge 550kWh battery.

- Power conversion efficiency

The research determined that the daily power conversion efficiency of the PV module in the span of 6 months was 4.32%, which is way lower than the 19.85% declared by the manufacturer. This indicates that the PV module is only utilizing 21.76 % of its conversion capability, which highlights the significant loss of energy and inefficiencies in the system. This suggests there are factors that contribute to the reduced PV module efficiency, such as weather condition, suboptimal operating conditions or other technical factors.

The research result also revealed that various factors, like temperature, weather, and other technical details, can influence how well a PV module works. Qorile site ambient temperature over the 6 months ranges between 37 ^{0}C to 21 ^{0}C and with an average of 27.9 which led to 3^{0}C increase than the STC, with the manufacturer specification for the PV module states that the output of module is sensitive to temperature and the module's efficiency drops by 0.35% for every degree of temperature change, which could be why some energy is being cut off.

Moreover, the amount of sunlight that reaches the PV module can be reduced with weather conditions such as cloudy or overcast skies, as a result it can decrease module efficiency. The debris and dust accumulated on the external surface of the PV module can block sunlight and further reduce its efficiency. These factors highlight the need to implement actions to control or regulate and maintain the cleanliness of the PV module's surface to enhance its efficiency and maximize the energy output of the solar mini-grid system.

The production factor is expressed as a percentage for the 182 days and ranges from 20.26 % in April to 26 % July, with an average of 21.9 %. Basically, these values are a measure of the actual energy output of the solar mini-grid system compared to its maximum potential output, which is represented by the PV capacity of 375 kW.

Moreover, the research results reveled that the production factor is low, indicating the system is not operating at its full potential. In addition, the analysis shows that the off-grid PV system is performing poorly with average performance ratio of 17.1 % and rages between 15.8% in April up to 20.3 % in July, while the simulation of the PVsyst shows the performance ratio to be 10.9% , and the average capacity utilization factor 2.6 % which is smaller than 15-16% [27].

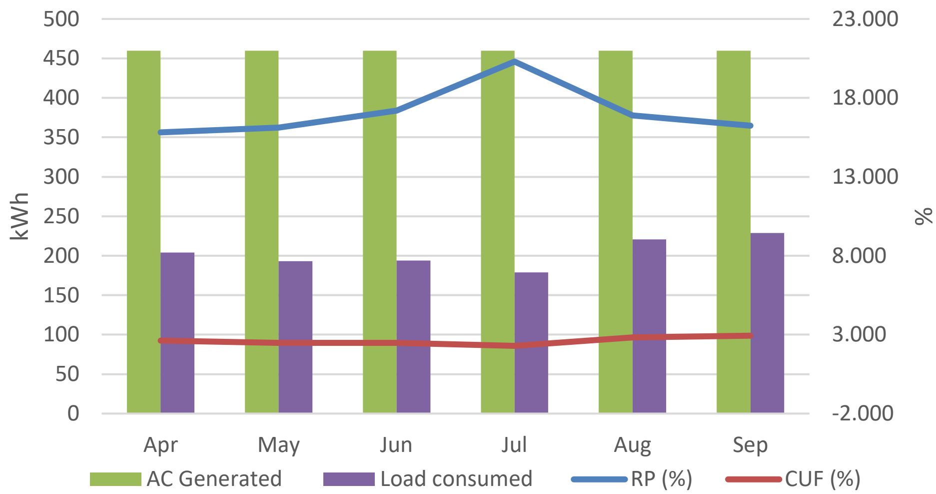


Figure 4.2 Qorile energy consumption

- Qorile PV syst software result

The PV syst simulation result presented in the appendix D and the loss diagram in Figure 4.3 demonstrates that there is 84.9 % reduction in power output due to the battery being fully charged, 11.3 % reduction due to the temperature loss, 2.2 % reduction due to mismatch loss, 1.4% reduction due to wiring loss 5.1% reduction due to AC side converter loss, 6.7 % due to battery efficiency loss and 2.7% charge/ discharge loss in the battery. The average performance ratio is 10.9 % and the system produces 79,260kWh of useful energy per year. The manually calculated figure are almost identical to the simulation result.

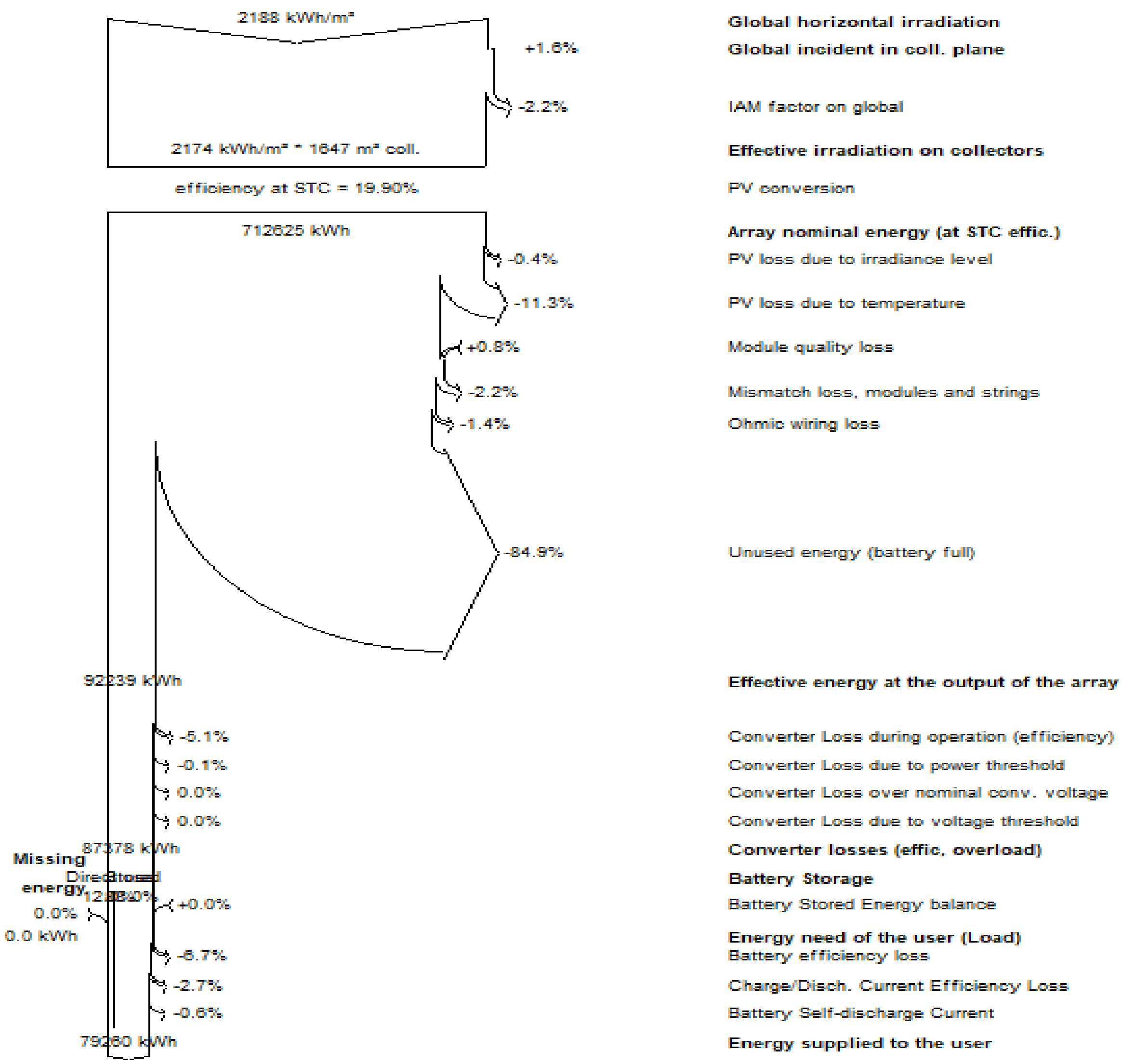


Figure 4.3 Qorile loss diagram from PV syst

Table 4.3 Yearly averaged Yields and loss

Indices	Calculated (kWh/kWp/day)	PV syst (kWh/kWp/day)
Yr.	8.235566	6.09
Ya.	1.480769	0.77
Y_f.	1.397846	0.66
L_A	6.754797	5.32
L_S	0.082923	0.11

Table 4.3 above indicates that there is slight difference between the simulated and calculated result and this may be due to the simulation result takes many parameters like the ohmic loss, module mismatch loss which are not included in the manual calculation. However, the results indicate that the Qorile solar PV array is harvesting only 18 % of the potential solar energy available at its surface. The difference between the reference yield and array yield can be attributed to energy losses and inefficiencies in capturing and converting solar energy. A daily capture loss of 6.754 kWh/kWp/day and a system loss of 0.0829 kWh/kWp/day results in a 98.78% energy capture loss. The remaining 1.21% is attributed to other distribution and system losses. From these findings we can conclude that there is significant room for improvement in the capture and conversion of solar energy, which could help to increase the overall energy output and efficiency of the solar mini-grid system.

The solar mini-grid inverter and PCS efficiency is 94.4 % and 98.8% respectively. The reduction in the grid inverter from the manufacturer data sheet efficiency (98.8%) can be due to the decreased load requirement that led inverter to change the operating point to serve the decreased load requirement and this might result a decrease in efficiency.

By using data obtained from the PV mini-grid system, Qorile 550kWh battery is designed to serve for 1:30 hrs. at full load (325kWh) but due to the load requirement of the village its now serving at 1/10 (32kWh) peak load per day which means batteries can serve maximum 17 hrs. The BMS indicates that the battery averaged monthly SOC_{MAX} is 91% and minimum is 59% holding approximately half of its total capacity throughout the year. The SoH for the three clusters battery banks is above 91 %. Hence, it can conclude that the battery is in a good functionality. Mismatch as in the case of Qorile, led to a situation where the PV system generate more power than the load requirements causing the excess power to be clipped off and wasted.

4.2.2 Omorate Solar mini-grid performance result

The initial plan for the mini-grid aimed to supply power to 786 customers with 1,396.96 kWh/day, but as of now, it only serves 488 customers (62%) with 1,031.6 kWh/day. This indicates that at 62% currently connected customer, the load requirement is almost 73.8% of the original energy requirement. Therefore, it is evident that the energy demand of the community was not appropriately considered during the design phase. Therefore, it needs to be reevaluated to find the accurate energy demand and load profile of the community.

From EEU customers data the total number of connected customers is 488, Households 370, Commercial customers 81, and Public customers 37. From the customer type wise energy share out of total energy demand 1031.60 kWh per day, commercial customers take 53.32% of total demand, residential (households) customers take 35.68% of total demand, and public customers take 11 %. Hence, the majority of the customers were households (76%) but the majority of the energy demand was from the commercial customers (53.57%). The total energy demand from all customers was 1,031.6 kWh per day with the highest demand in the evenings. Analysis was conducted to evaluate the potential power of the mini-grid and the efficiency of the PV panel. The results indicated that the mini-grid has a significant potential output energy of 2,239.3 kWh per day. This represents the theoretical maximum amount of energy that can be produced by the mini-grid, based on the capacity of the PV panel with conversion efficiency of 18.94%.

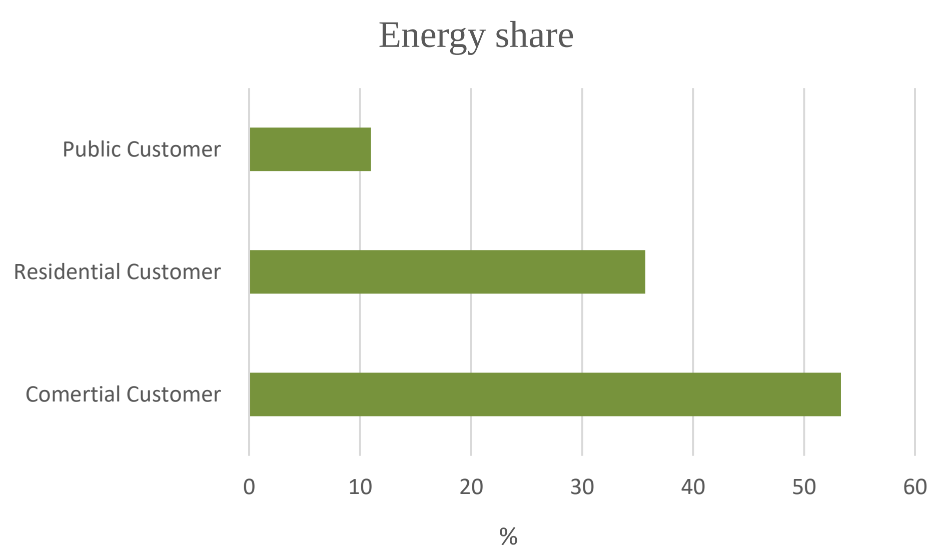


Figure 4.4 Omorate customers energy share

However, the total yearly DC electricity output from the PV module is 442,260 kWh (442.260 MWh) and AC electric output 424,570 kWh (424.57 MWh). The monthly DC electricity generation shows that the lowest monthly electricity generation was found in July with 32,815 kWh when the solar irradiance is also low (5.3 $kWh/m^2/day$) and the highest in December 41,183 kWh when the solar insolation is also high (6.47 $kWh/m^2/day$). The actual energy collected by the mini-grid PV module was found to be much lower, at only 1,212 kWh per day (54.1%), this represents a significant amount of unutilized solar potential of 1,027.3 kWh per day (45.89%), indicating that a significant portion of the potential energy output is being lost without use. Moreover, the average daily AC energy delivered to the load is 1,018.6 kWh/day when we compare it to AC energy available 1,163.2 kWh/day it accounts for 87.57 % of the available energy that is consumed by the load and the remaining 12.43% is lost in distribution and system losses.

- Power conversion efficiency

The analysis found that the average daily power conversion efficiency of the PV module over a year is 10.28%, as determined from the equation used in the study. This is lower than the efficiency level of 18.94% stated in the manufacturer data sheet of the PV module. From the research result there is significant loss of energy and inefficiencies in the Omorate solar mini-grid system and suggests that there may be derating factors contributing to the reduced efficiency of the PV module, such as dust, suboptimal operating conditions or other technical factors.

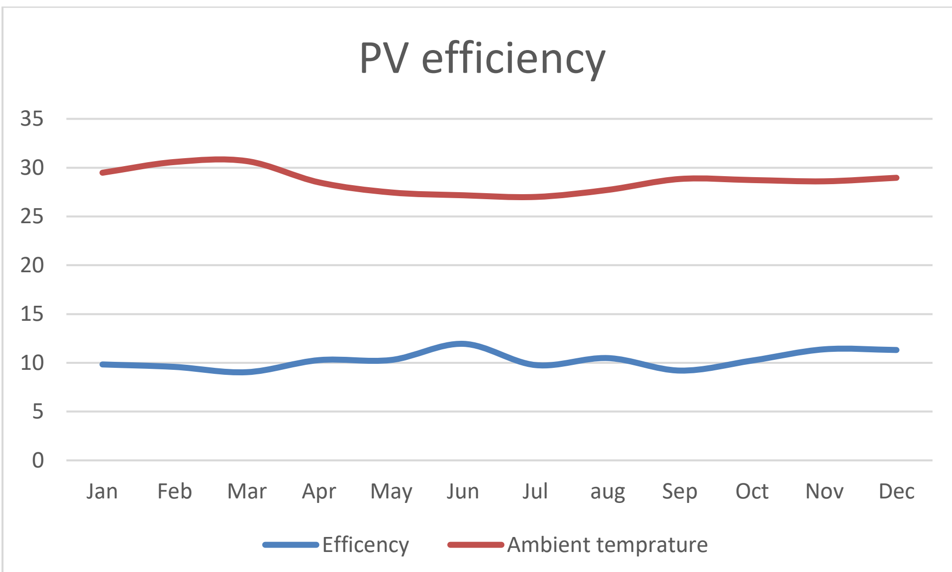


Figure 4.5 PV efficiency VS Temperature

- Omorate PV syst software result

The PV syst simulation result presented in the appendix C and the loss diagram in Figure 4.6 demonstrates that there is a 37.4 % reduction in power output due to the battery being fully charged, 13.9 % reduction due to the temperature loss, 2.1% reduction due to mismatch loss, 1.4% reduction due to wiring loss 4.1% reduction due to AC side converter loss, 10.8 % due to battery efficiency loss and 1.5% loss that was planned to be produced by the diesel generator.

The average performance ratio is 43.46% and the system produces 376,071kWh of useful energy per year.

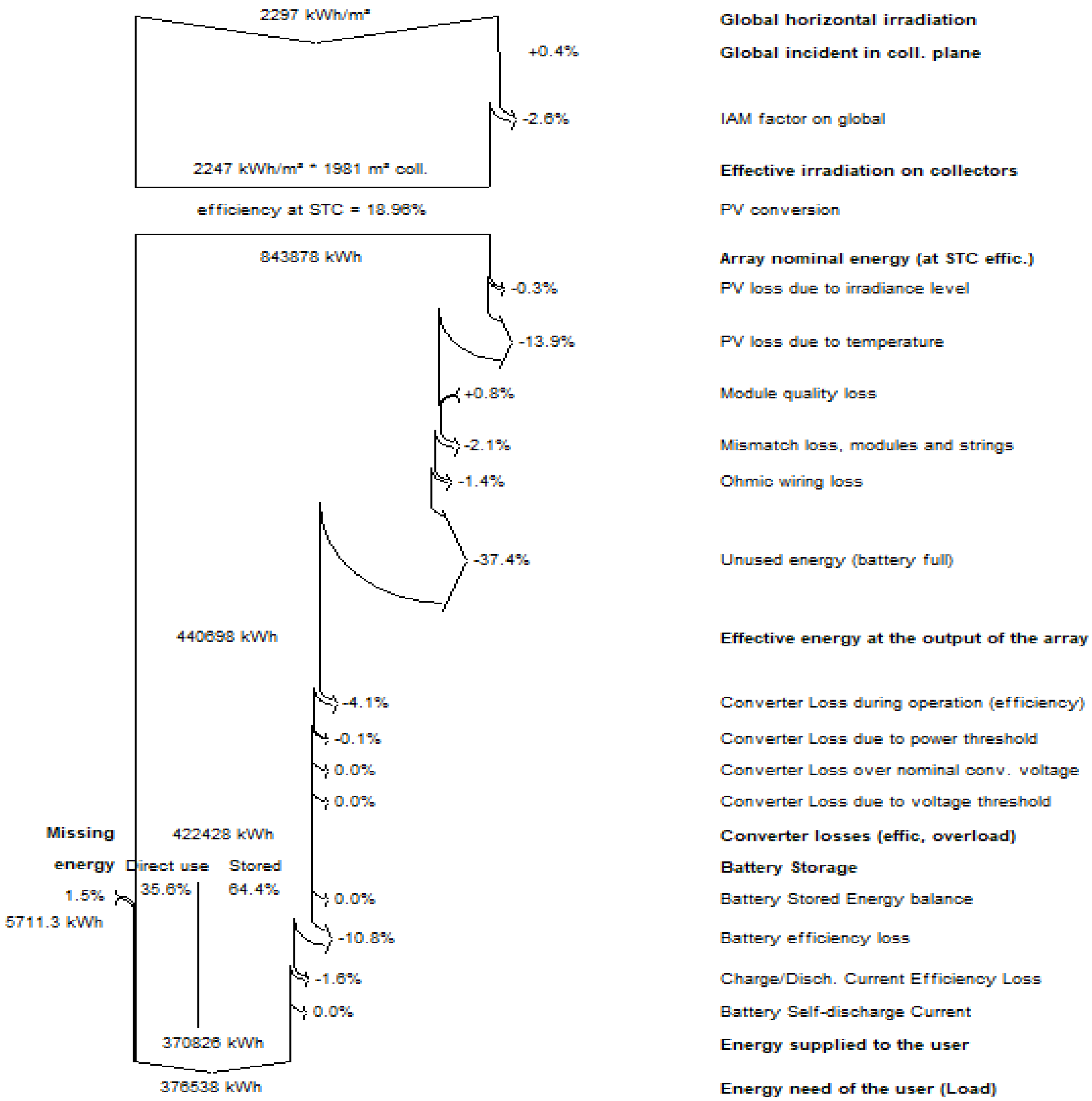


Figure 4.6 Omorate loss diagram from PV syst

There is a day to day significant variation in the PV module efficiency, reaching a maximum efficiency of 14.2 % in December and a minimum efficiency of 2.29 % in September. The average monthly module efficiency ranged from 9.03 % in March to 11.94 % in June. There are various factors that can affect PV module efficiency, such as temperature, weather conditions, and other technical factors. The module efficiency is influenced by temperature, and that regular actions must be taken to control or regulate temperature in order to enhance the performance of the system. The negative impact of ambient temperature on PV module efficiency for Omorate solar mini-grid is shown in Figure 4.5 above and can be disclosed that in June, efficiency of the PV module is high when the temperature is cooler and in March the efficiency is lower when the temperature is hotter. Specifically, the 335-watt PV module manufacturer specification states that the module's output is sensitive to temperature, with a decrease of 0.39 %/°C, which may be contributing to the unutilized solar potential observed.

Furthermore, other metrological factors like cloudy or overcast skies can reduce the amount of sunlight that reaches the PV module, leading to decreased PV module efficiency. In addition, debris and dust that accumulate on the external surface of the PV module can block sunlight and further reduce its efficiency and it is observed from filed survey the PV modules are covered by Dust. These factors highlight the need to implement actions to control or regulate temperature and maintain the cleanliness of the PV module's surface to enhance its efficiency and maximize the energy output of the solar mini-grid system.

The study reveals that Omorate solar mini-grid production factor ranges from 46.0 % to 61.0 %, with an average of 53.0 %. In addition, there is a significant change in day to day production factor, with a maximum production factor occurred in December is 78 % and a minimum production factor occurred in September is 12.6 %. These values show a comparison between the actual energy output of the solar mini-grid system with its maximum potential output, which is represented by the PV capacity of 375 kW and as can be seen the mini-grid have low production factor.

The findings suggest that the production factor is relatively low, indicating that the system is not operating at its full potential. The analysis also shows that the off-grid PV system is performing poorly with average performance ratio of 51.62 % in the manual calculation and 42.85% in the PV syst simulation result, and the average capacity utilization factor 11.3 % and rages between 10.24 % in July up to 12.66 % in Jun.

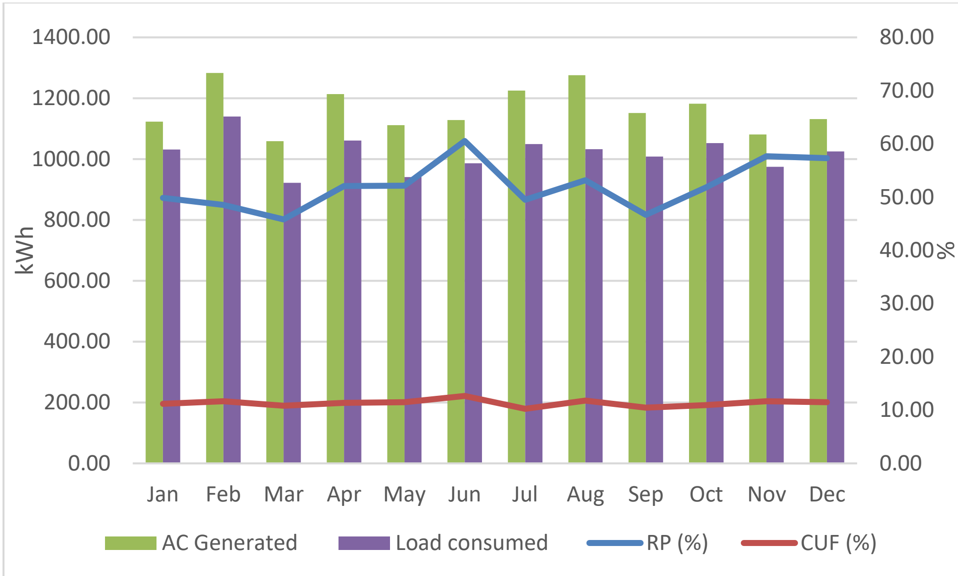


Figure 4.7 Omorate performance ratio and CUF

Table 4.4 Yearly averaged Yields and loss

Indices	Calculated (kWh/kWp/day)	PV syst (kWh/kWp/day)
Yr.	5.97624	6.32
Ya.	3.20406	3.22
Y_f.	3.07589	2.71
L_A	2.77218	3.10
L_S	0.12816	0.51

Table 4.4 similar to Qorile there is slight difference between the simulated and calculated result and this may be the simulation result takes many parameters like the ohmic loss, module mismatch loss which are not included in the manual calculation. However, we can observe that the solar PV array is harvesting only 53.69% of the potential solar energy available at its surface. The substantial difference between the reference yield and array yield can be attributed to energy losses and inefficiencies in capturing and converting solar energy. A daily capture loss of 2.772 kWh/kWp/day and a system loss of 0.128 kWh/kWp/day results in a 95.5% energy capture loss. The remaining 4.41% is attributed to other distribution and system losses. These findings suggest that there is significant room for improvement in the capture and conversion of solar energy, which could help to increase the overall energy output and efficiency of the solar mini-grid system.

The grid inverter and PCS are operating as expected with 96 % and 95 % respectively. Using the data obtained from the PV mini-grid system, battery state of charge is high in May 100 %

and the low is in march 43% indicates that amount of yearly average charge that is available in the battery, is 0.33117 or 33.117 %. This indicates, on average, the battery is holding approximately one-third of its total capacity throughout the year. Moreover, from the performance analysis it is found that the battery efficiency is high on May 96 % and low in September 75% and shows that the battery efficiency is within the specification limit.

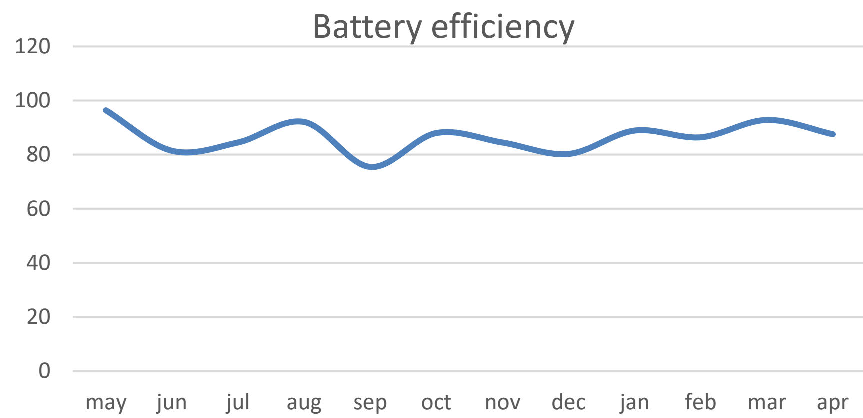


Figure 4.8 Omorate Battery efficiency

The 600kWh battery for Omorate is designed to serve quarterly (0.25C) charging and discharging rate, which means it can serve four hours with 150 kWh demand.

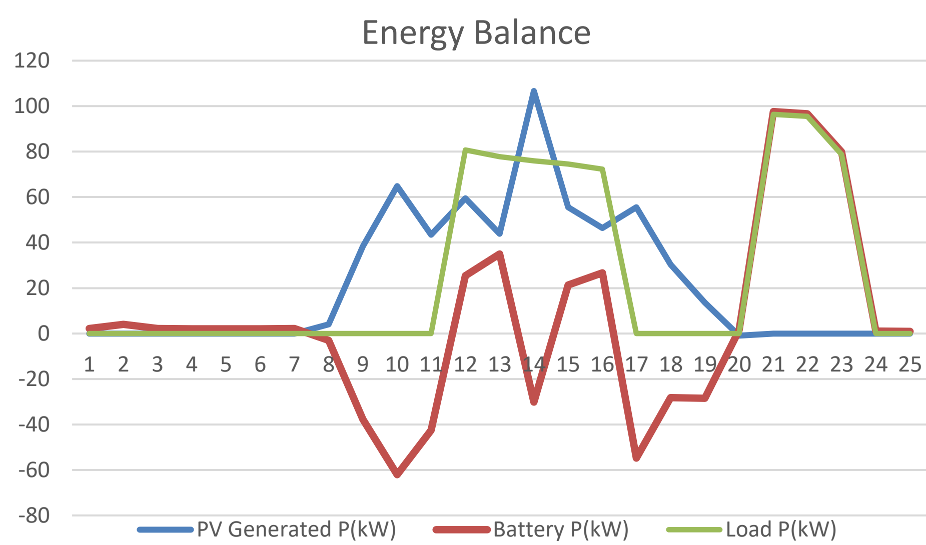


Figure 4.9 Omorate Battery characteristics from SCADA

The Figure 4.9 above illustrates the lowest electricity production, which is July 24th when the PV generate 584 kWh/day. On the previous day July 23rd, the battery state of charge was 30 %. the battery was subjected to charge two times and discharged three times in one day. First it is charged from 8:00-11:00 with a maximum of 60 kWh and then from 16:00-18:00 with a maximum of 55 kWh, charged with a lesser amount than the designed charging rate of 150 kWh. The battery was then discharged, first from 12:00-13:00 with maximum demand of 35kWh, then from 15:00-16:00 with maximum demand of 27kWh, and finally from 20:00-24:00, with a maximum power demand of 100 kWh a total of 6 hours, and leading to a minimum limit shutdown. This indicates 70 % of the battery capacity is utilized and causing it to fall short to deliver the expected demand and this might be because of the battery is not charged to the maximum level 100 % during the day by the solar or diesel generator. Additionally, the battery may have low capacity and also it is forced to charge and discharge multiple times in a day which can shorten the battery lifespan from the expected 8 years to 4 years and since the system is modular this can be enhanced by adding extra battery to the system. Mismatch in the case of Omorate due to the load requirement is higher than the PV capacity and the system is not able to meet the energy demand of the community. Clipping occurs in Omorate due to that the inverter is unable to handle the maximum power output of the PV system and this might be because of that the battery capacity is small and can be improved by adding batteries to the system.

- Omorate solar mini-grid power supply reliability

The solar mini-grid in Omorate experiences significant reliability issues, where the grid is forced to shut down when there is a mismatch between the energy generated and the load requirement.

To address this issue, the operators have implemented a load management strategy throughout the year. This includes daily disconnecting of the main power from the second feeder that goes out to the loads between 17:00-19:00 and 21:00-08:00. The aim of this strategy is to conserve energy during periods of low demand and redirect it to meet the peak demand in the evening hours 19:00 up to 22:00. Moreover, this frequent load-side management strategy of connecting and disconnecting the power in Omorate damages the fuse holders and circuit breakers that leads to extra cost.

The data presented in Figure 4.10 shows that Omorate solar mini-grid experiences a high duration and frequency of interruption throughout the year. The average duration for the entire year is 382 hours, with the longest interruption duration of 418 hours occurring in October, and shortest is 231 hours occurring in May, which is the first month that the mini-grid start operation and also in this month the number of customers is low. Furthermore, the average interruption frequency is 60 with the highest 69 and lowest 35 occurring in July and May respectively.

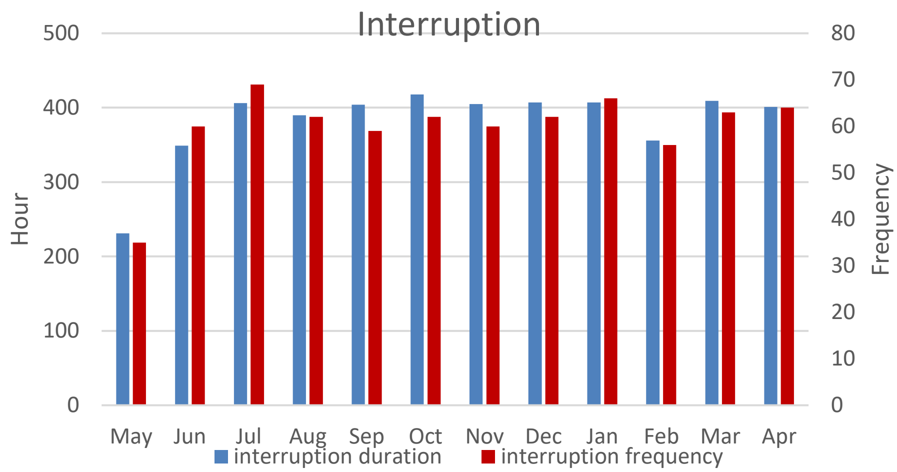


Figure 4.10 Omorate interruption

- Customer based indices for reliability

Both SAIDI and SAIFI values are very high compared to the quality assurance frame work given by national renewable energy laboratory [35].

Table 4.5 NREL and OMERATE

Indices	NREL	OMERATE
	Unplanned	Unplanned
SAIFI	< 2 per year	718 per year
SAIDI	< 1.5 hours	4583 hours

The other indices for reliability are CAIDI and ASAI where CAIDI is 6.4 hrs./interruption, which shows the average time it takes to restore power after an interruption. This indicates that on average each customer experiences 717.71 minutes or approximately 11.96 hours of interruption duration. The ASAI value which shows the availability of power from the mini-grid is low with only 47.68 %. Which makes the Omorate solar mini-grid reliability very low and the major causes is design error and may be the quality of PV panels and equipment's used.

- Diesel-only mini-grid system in Dolo

In Somali regional state there are 15 diesel-only mini-grids that serve the community for 6 hours with frequent interruptions. The interruption is due to lack of regular supply and high cost of diesel fuel. The impact of CO_2 emission to the environment is also another side effect of such generators. In addition, maintenance and service to the engine is another big challenge in case of diesel generators. and there is no near future plan to connect these mini-grids to the national grid.

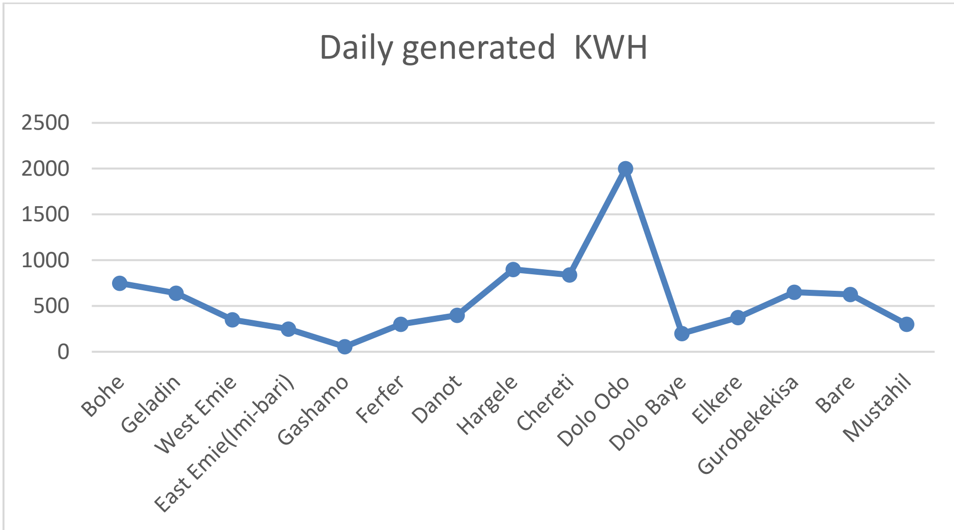


Figure 4.11 Somali region Diesel only mini-grid energy

The highest energy generation site is Dolo Odo, it has two diesel generators with 400 kVA and 187 kVA capacity and serves 396 residential customers. However, the customers are not satisfied by the service due to its intermittent availability and they are unwilling to pay for the electrical energy they consumed and this has a significant impact on the operation of mini-grid. It’s also difficult to connect this site to the national grid because the nearest substation, Godey, is located 360 kilometers away. The diesel fuel consumption per day of the diesel only mini-grids is 1,970 litters with Dolo Odo having the highest, 250 litters/day.

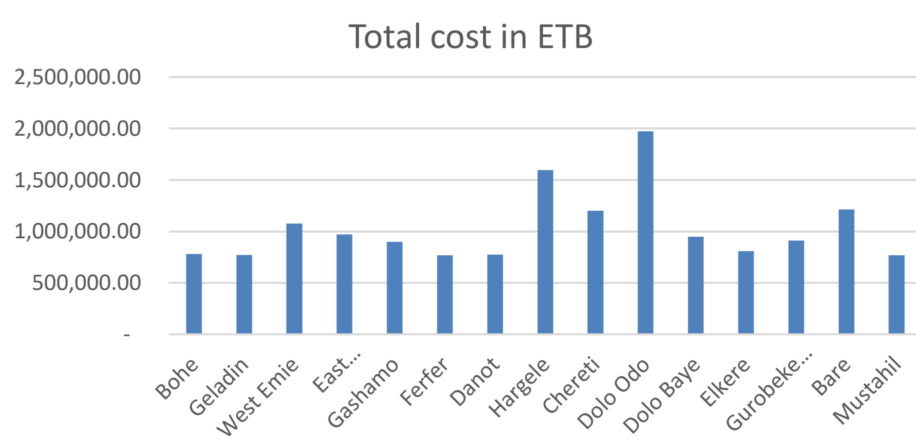


Figure 4.12 Somali region Diesel only mini-grid yearly cost 2019 E.C

Table 4.6 Dolo Odo total expense and customers bill collected

Year		2022
Dolo Odo	yearly customer paid	76,359.37 Br.
	yearly fuel used	13,205.69 Lt.
	Fuel and transportation cost	32.4032 Br/Lt.
	Yearly Cost	427,906.6 Br

Table 4.6 clearly shows that the customer's bill does not even cover the fuel cost. The lack of interest to pay may be due to dissatisfaction with the service provided, which only operates for a maximum of 6 hours and sometimes experiences diesel fuel shortages, resulting in electricity unavailability for more than 5 days. This lack of interest in paying the monthly bill could negatively impact the operation of the diesel mini-grid. As mentioned in the Table 4.6, only 17.84% of the total diesel expense is covered by customers.

- Proposed solar mini-grid system design for Dolo Odo

Dolo Odo currently uses a diesel-only mini-grid, which only runs for maximum six hours per day and it is unable to meet 100% of the community’s energy demand.as a result of this Numerous social, economic, and environmental issues has arisen. Hence, in order to avoid this road blocks to the community in specific and to the society of the country in large a dependable source of energy is mandatory for the community and in this regard a combination of solar, ESS and diesel generator energy source is chosen to offer constant electricity for the village in Dolo Odo. The optimization is carried out using Homer Pro optimization tool and the result of the optimization is presented below.

- Benchmarking

The benchmarking in this study comperes the performance of two solar mini-grids located in different location in Ethiopia, Omorate SNNP region and Qorile Somali region. By analyzing the strength and weaknesses of the existing solar mini-grids and identifying the best practices and tailor the design of Dolo Odo mini-grid to ensure optimal performance. This approach can help to ensure that the Dolo Odo solar mini-grid design to meet the energy needs of the community and is sustainable in the long term.

From the performance analysis of the pilot solar mini grids it is observed that:

- It is essential to accurately determine the population number and electricity consumption for effective sizing of the solar mini-grid system. In Omorate, the electricity demand and population number were underestimated, while in Qorile, they were overestimated, leading to a significant energy imbalance.
- Both solar mini-grid sites had poor energy demand forecasting, which did not adequately account for future community growth and energy needs.
- Sizing of the PV, ESS, and generator for the solar mini-grid system was based on the community's energy demand requirements, which were affected by the population and energy demand estimation errors, leading to system inefficiencies as a whole.
- It has been observed that PV module output power is significantly affected by factors such as temperature, dust, debris and manufacturer tolerances. hence choosing a higher efficiency module is recommended and regular cleaning is necessary to maintain optimal performance.
- To prevent mismatch and clipping of power between the load requirements and PV capacity, it is important to appropriately size the inverters and power conditioning systems (PCS).
- To ensure optimal performance, the energy storage system (ESS) must be appropriately sized. While the ESS is functioning well in Qorile with an average of 50%, it is depleting rapidly in Omorate and is sometimes unable to meet the energy demand when the solar PV is not generating. Therefore, it is crucial to properly size the ESS and choose a high-quality system that can meet the energy requirements of the community.
- All system sizing derating factors must be used to analyze the system performance. The purpose of applying a derating factor is to ensure that the solar component or system operates reliably and efficiently under real-world conditions. Some common factors of derating include:
    - Temperature: Solar panels tend to produce less electricity as their temperature increases. A derating factor is used to adjust the rated capacity of the panels to account for this temperature effect.
    - Round-trip efficiency: In the context of battery systems, the round-trip efficiency is often used to account for the energy losses during the charging and discharging processes.

- The tolerance of a solar panel indicates the acceptable range within which the panel's actual performance can deviate from its rated specifications.
- Dust and Soiling: Accumulation of dust, dirt, or other debris on solar panels can reduce their efficiency. A derating factor is applied to account for the expected loss in performance due to dust and soiling.

Therefore, the design of the Dolo Odo solar mini-grid system will consider the above-mentioned points to ensure that the system is appropriately sized and can operate without problems throughout its intended lifetime.

The design process of the proposed PV, ESS and Diesel generator hybrid system begin first by enumerating input data that demonstrate technical specification, resources and costs that are relevant for the designing the entire system on Homer Pro software and the following result is obtained after the modeling and optimization of the solar mini-grid.

Table 4.7 PV electrical summery from Homer Pro

Quantity	Value	Units
Rated capacity	2,000	kW
Mean Output	341	kW
Mean Output	8,195	kWh/d
Capacity Factor	17.1	%
Hours of operation	4,363	Hrs./ year
Total Production	2,991,234	kWh/yr.
Dedicated converter	2,000	kW

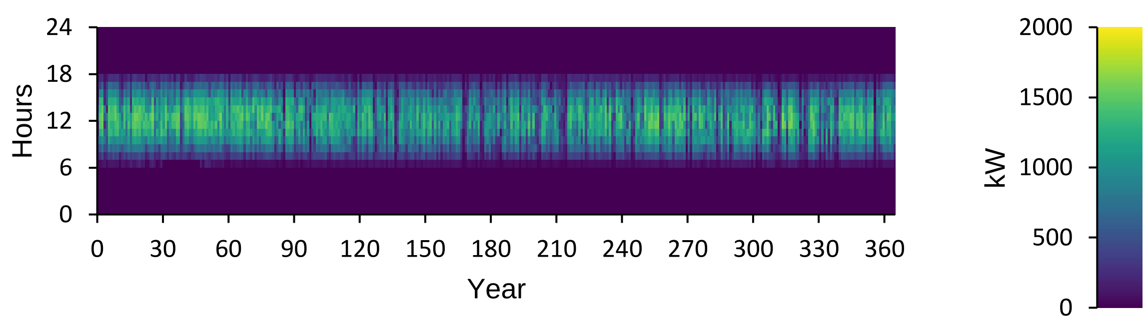


Figure 4.13 PV electric production in kW

The system includes a battery with a capacity of 16.8 kilowatt-hours (kWh), a voltage of 52.1 volts, and 328 ampere-hours (Ah). Also, minimum depth of discharge is set to 30%. After conducting a simulation, the results are presented in Table 4.8 below.

Table 4.8 Battery Electrical Summery from Homer Pro

Quantity	Value	Units
Batteries	480	sets
String size	15	batteries
String in parallel	32	sets
Average Energy Cost	0.0476	$/kWh
Energy In	1,505,221	kWh/yr.
Energy Out	1,465,476	kWh/yr.
Storage Depletion	5,495	kWh/yr.
Losses	45,240	kWh/yr.
Annual Throughput	1,487,966	kWh/yr.
Autonomy	17.8	hr.
Nominal Capacity	8,064	kWh
Usable Nominal Capacity	5,645	kWh
Expected life time	10	years

Throughout the year, the state of charge of the battery system remains almost above 47 %, and the number of charging and discharging cycles per day is close to one. These factors contribute to a longer lifespan for the battery system and ensure that the energy backup remains at a high level.

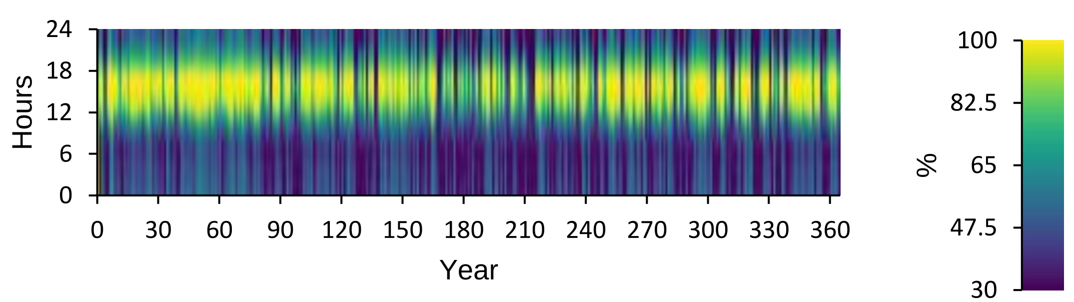


Figure 4.14 Battery state of charge

The diesel generator with a capacity of 1,200kW is selected in the optimization and the simulation result is presented in Table 4.9 below.

Table 4.9 Diesel generator summery from Homer Pro

Quantity	Value	Units
Capacity	1200	kW
Electrical Production	301,332	kWh/yr.
Mean Electrical Output	370	kW per month
Minimum Electrical Output	300	kW per month
Maximum electrical output	969	kW per month
Fuel Consumption	86,669	L/ yr.
Specific Fuel Consumption	0.288	L/kWh
Fuel Energy Input	852,820	kWh/yr.
Mean Electrical Efficiency	35.3	%
Capacity Factor	2.87	%
Hours of Operation	814	hrs./yr.
Number of Starts	412	starts/yr.
Operational Life	18.4	yr.
Fixed Generation Cost	110	$/hr.
Marginal Generation Cost	0.307	$/kWh

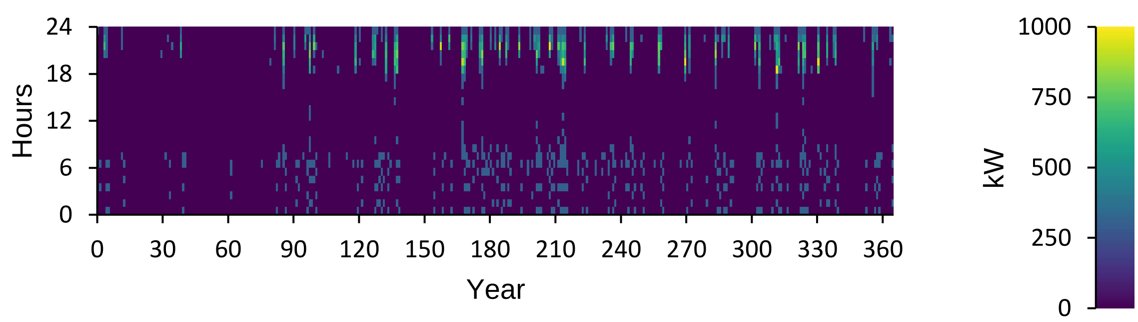


Figure 4.15 Genset Output (kW)

The Auto size generator is serving for maximum 9.15 % of the daily demand of the community with 412 starts per year. From Figure 4.16 bellow it can be observed that the diesel generator is operating at very small loading with daily average maximum is below 400kWh. Hence, half the capacity of the diesel generator (600 kW) can be assumed.

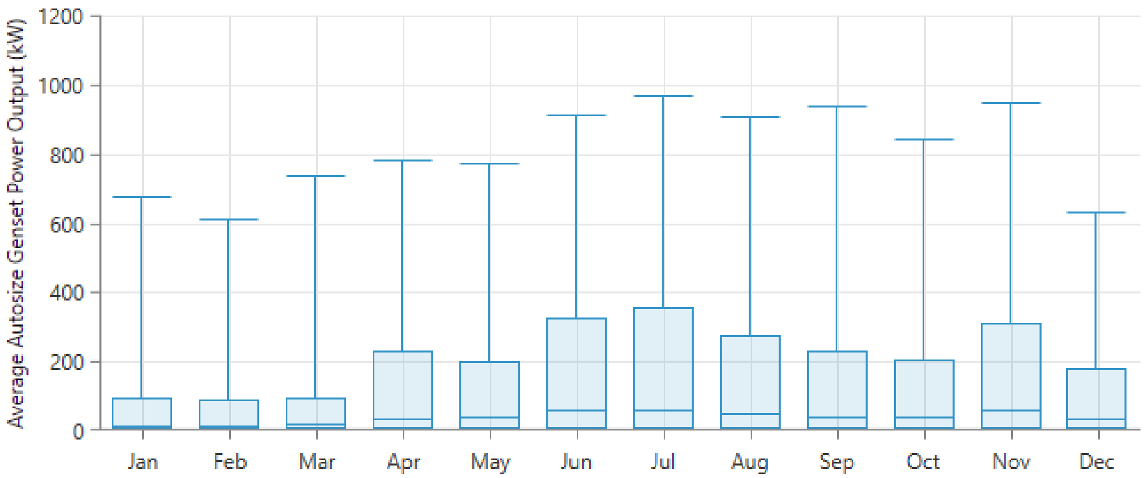


Figure 4.16 Monthly generator output

The bi-directional converter is responsible for controlling the movement of energy between the solar panels and the battery storage. It utilizes a rectifier to convert AC power to DC power, allowing the energy generated by the solar panels to be stored in the battery during periods of high solar power generation. Conversely, during low solar power generation, the bi-directional converter uses an inverter to convert the DC power stored in the battery into AC power that can be used by the load.

Table 4.10 Bi-directional converter electrical summery

Quantity	Value	Units
Hours of Operation	4,893	hrs./yr.
Mean Output	161	kW
Maximum Output	952	kW
Energy Out	1,461,416	kWh/yr.
Energy In	1,522,309	kWh/yr.
Capacity Factor	15.3	%
Losses	58,619	kWh/yr.

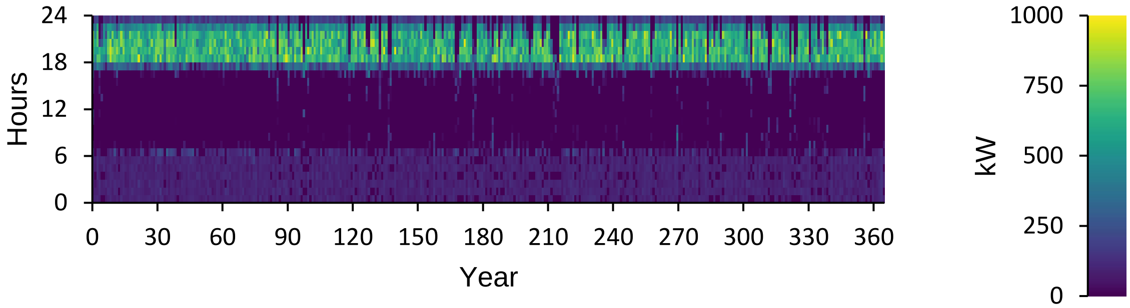


Figure 4.17 Converter Inverter Output (kW)

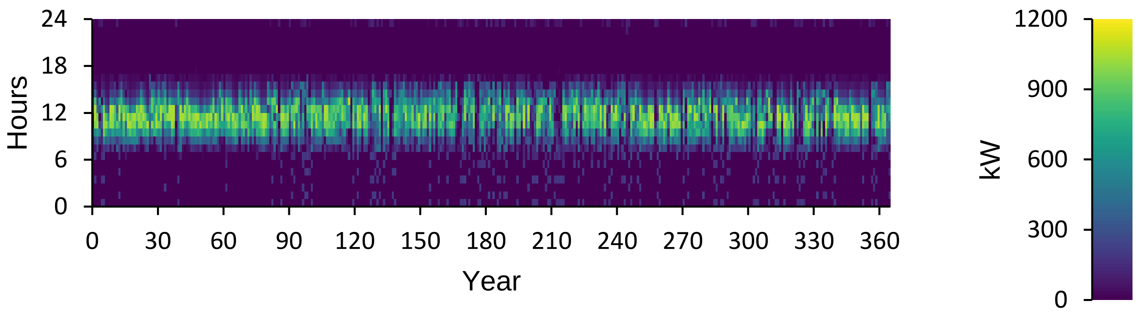


Figure 4.18 Converter Rectifier Output (kW)

The winning system architecture provides a total of 3,292,566 kWh/year (equivalent to 3,292.57MWh/year) of electricity, with the primary load demand accounting for 99.2% of the total, or 2,757,823 kWh per year. The remaining 0.78% of the demand, which is deferable, accounts for 21,870 kWh per year. Overall, the system achieves an 89.2% renewable penetration rate.

Table 4.11 Production summery from Homer Pro

Component	Production (kWh/yr.)
Generic flat plate PV	2,991,234
Auto size Genset	301,332
Total	3,292,566

The hybrid system design shows that the system can serve 100 % with PV, ESS and diesel generator for 24 hours without interruption with energy share 91percent from solar and ESS and 9 percent from diesel generator.

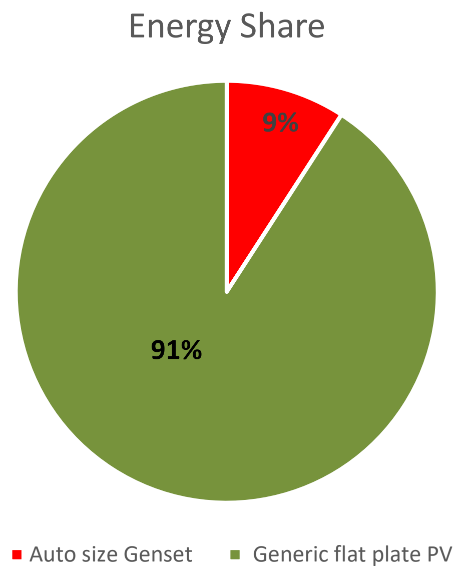


Figure 4.19 Dolo Odo proposed solar mini-grid Energy share

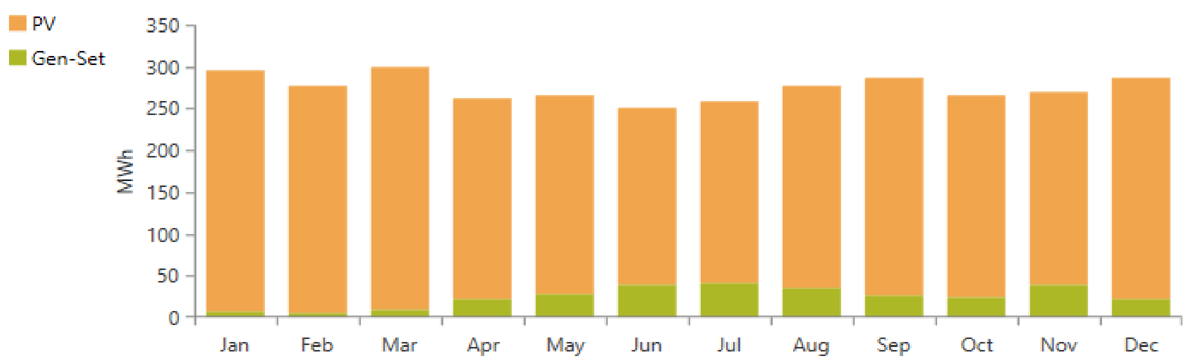


Figure 4.20 Monthly averaged electric production

Table 4.12 Electrical consumption Summery from Homer Pro

Component	Consumption (kWh/yr.)	Percent
AC Primary Load	2,757,823	99.2
DC Primary Load	0	0
Deferrable Load	21,870	0.787
Total	2,779,693	100

The optimization of the hybrid system indicates that it is capable of meeting all energy demands without any unsatisfied load and also generates excess electricity amounting to 10.7%, which can be utilized to meet any additional energy requirements.

Table 4.13 Excess and unmet electricity Summery from Homer Pro

Quantity	Value	Units
Excess Electricity	351,784	kWh/yr.
Unmet Electric Load	0	kWh/yr.
Capacity Shortage	0	kWh/yr.

The optimization results showed that the winning system architecture, which incorporates PV, ESS, and DG, consumes significantly less fuel than the base case DG-only system required to meet the community's electrical demand. Specifically, the fuel consumption of the winning system architecture is only 9 % of that required by the diesel-only system. Furthermore, the emissions generated by the base case system is significantly higher than the optimized winning system architecture. Specifically, it produces emissions that is only 9% of those produced by the base case system.

Table 4.14 Fuel consumption summery from Homer Pro

Quantity	Value		Units
	Proposed System (PV/ESS/DG)	Base System (DG)	
Total fuel consumed	86,669	964,435	L
Avg fuel per day	237	2,642	L/day
Avg fuel per hour	9.89	110	L/hour

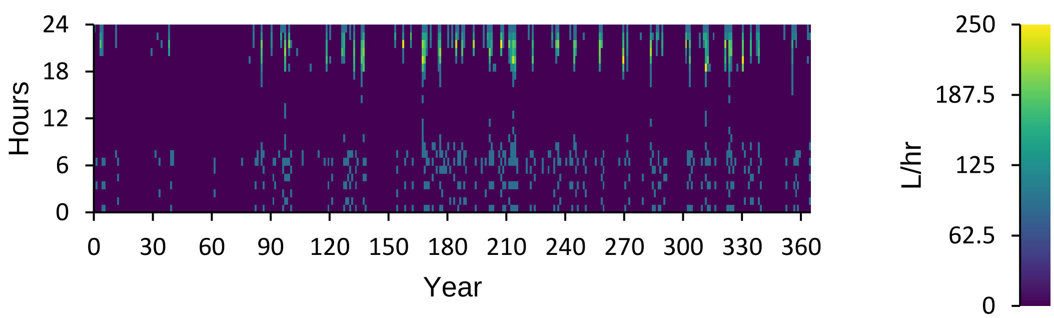


Figure 4.21 Diesel Consumption (L/hr.)

Table 4.15 Emission Summery from Homer Pro

Pollutant	Quantity		Unit
	Proposed System (PV/ESS/DG)	Base System (DG)	
Carbon Dioxide	226,865	2,524,527	kg/yr.
Carbon Monoxide	1,430	15,913	kg/yr.
Unburned Hydrocarbons	62.4	694	kg/yr.
Particulate Matter	8.67	96.4	kg/yr.
Sulfur Dioxide	556	6,182	kg/yr.
Nitrogen Oxides	1,343	14,949	kg/yr.

3.10.2.2 Economic summary

The economic analysis summary shows that the project's IRR is 25.4 %, with a ROI of 21 %. The simple payback period is 3.79 years, and the discounted payback period is 3.72 years. This investment opportunity is considered attractive because the IRR exceeds the 8% discount rate.

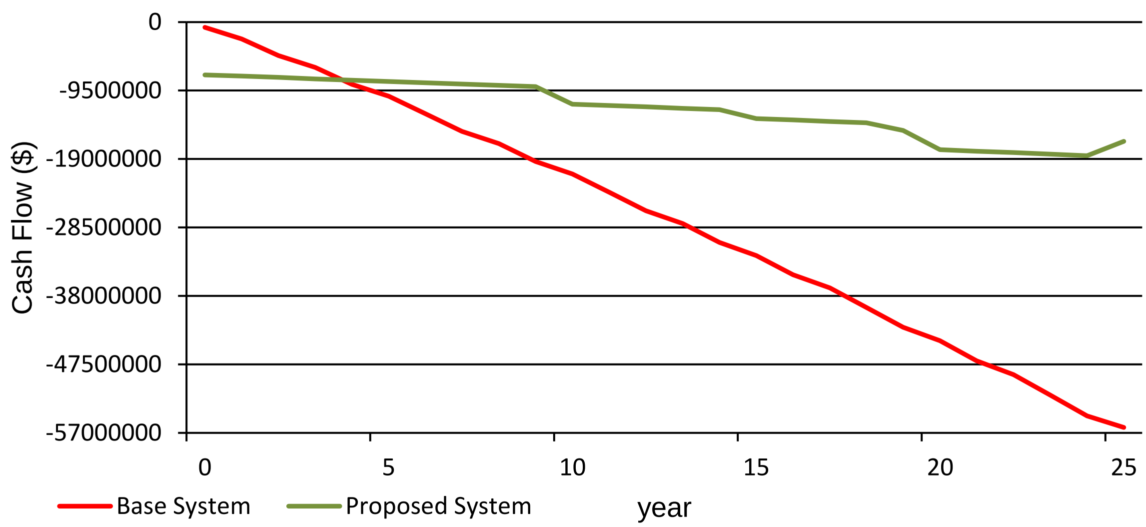


Figure 4.22 Cumulative discounted cash flow

Table 4.16 Proposed solar mini grid system Economic summery from Homer Pro

Components	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Selvage ($)	Total ($)
Gen set	732,000	867,504.41	827,677.85	3,182,291	-592,946.7	5,016,527.14
Battery	2,016,000	4,634,710.86	40,672.13	0.00	-1,269,197	5,422,185.83
PV	3,700,000	0.00	282,445.35	0.00	0.00	3,982,445.35
Bi-directional converter	315,034	361,742.42	296,600.22	0.00	-132,222.5	841,154.70
Grid - converter	570,000	654,509.56	282,445.35	0.00	-239,233.5	1,267,721.31
System	7,333,034	6,518,467.25	1,729,840	3,182,291	-2,233,600	16,530,034.3

Table 4.17 Proposed system NPC and LCOE from Homer Pro

Indices	Base System ($)	Proposed System ($)
Net Present Cost	56.2M	16.5M
Initial Capital	732,000	7.33M
LCOE (per kWh)	0.716	0.211

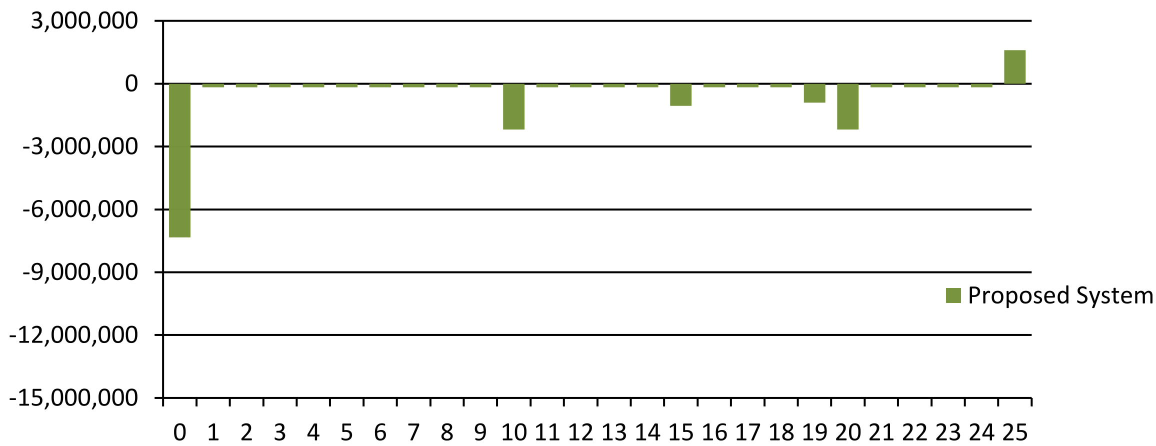


Figure 4.23 Proposed Annual Nominal Cash Flows

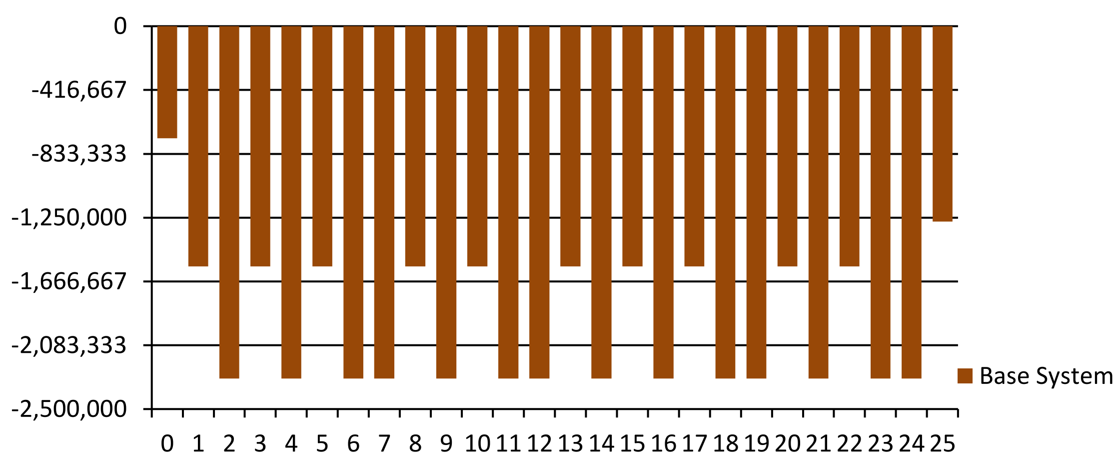


Figure 4.24 Base System Annual Nominal Cash Flows

- Dolo Odo PV syst software performance result

The PV syst simulation result presented in the appendix E and the loss diagram in Figure 4.25 demonstrates that there is 21.5 % reduction in power output due to the battery being fully charged, 9.8 % reduction due to the temperature loss, 2.2% reduction due to mismatch loss, 1.2 % reduction due to wiring loss a 4.2% reduction due to AC side converter loss, 2 % due to battery efficiency loss and 4.8% loss that was planned to be produced by the diesel generator. The average performance ratio is 62% and the system produces 2,626,072kWh of useful energy per year. The remaining 131,698kWh/year will be produced by the backup diesel generator.

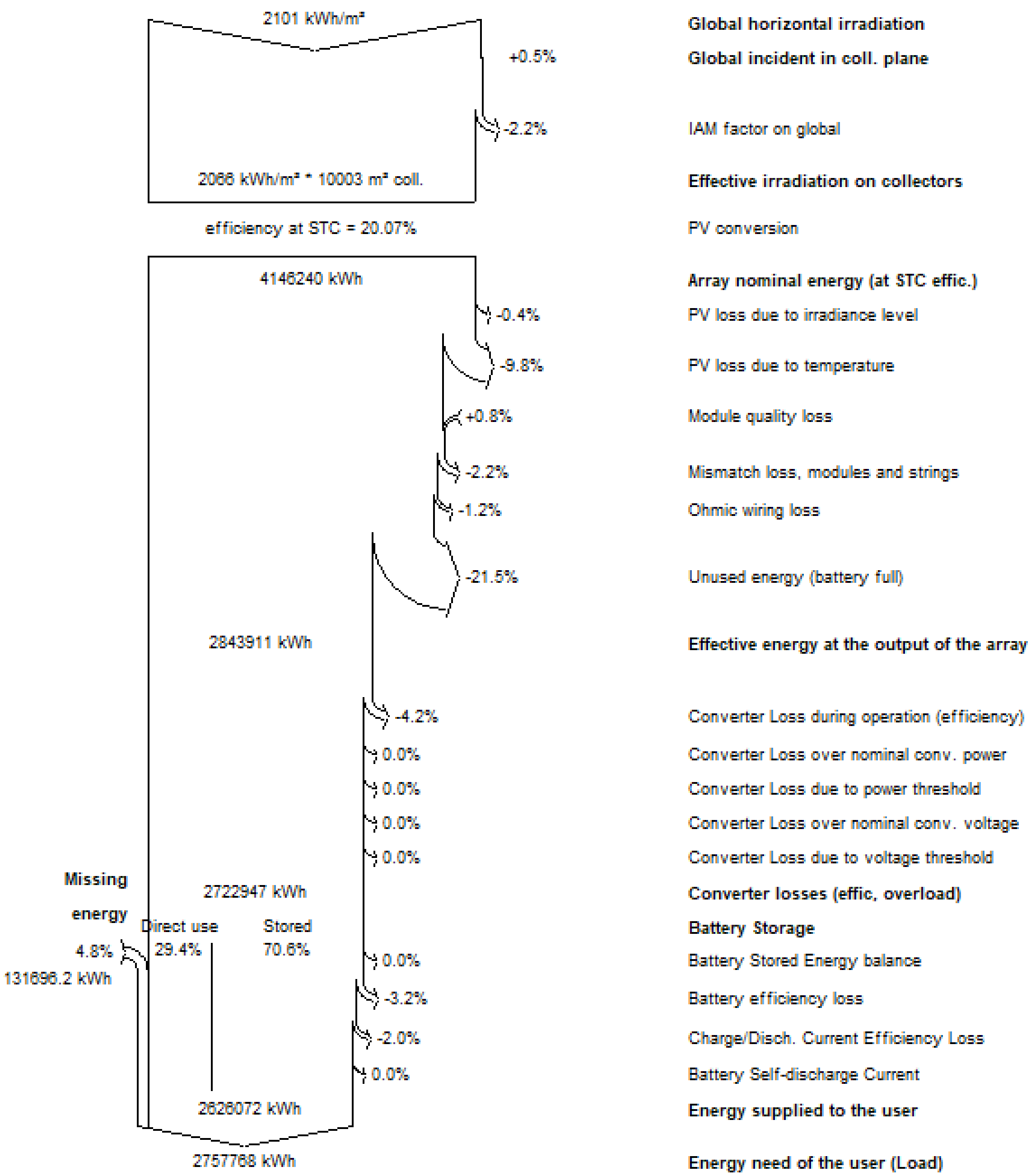


Figure 4.25 Dolo Odo loss diagram from PV syst

- Selected system architecture

The comparison between the manually calculated and the simulated result is presented in Table 4.18. It is evident that most of the normalized performance indices of the PV syst selected architecture is preferable due to that there is 20.9 % increase in performance ratio, the capture loss is 26% less than the manually calculated value, unused energy that have a high contribution on the performance of solar mini-grid system is 61% lower than the manually calculated. Hence, the winning system architecture for Dolo Odo is 2MW solar mini-grid system.

Table 4.18 Comparison between the manually calculated and PV syst selected

Parameters		Manually calculated	Selected by PV syst
PV capacity (kWp)		2,534	2,000
Battery capacity		10,322	8,061
Required energy demand by the community		7556kWh/day or 2,757,768 kWh yearly	
Energy produced by PV and ESS (kWh/Year)		5,226,775	4,146,240
PV loss due to temperature (%)		9.8	9.8
Unused energy (%)		35	21.5
Converter loss (%)		4.2	4.2
Energy supplied to the load (kWh/Year)		2,735,772	2,626,072
Missing capacity (%)		0.8	4.8
Performance indices	Yr. (kWh/kWp/day)	5.78	
	Yf. (kWh/kWp/day)	2.97	3.59
	Ls. (kWh/kWp/day)	0.25	0.3
	La. (kWh/kWp/day)	2.57	1.9
	R_p (%)	51.3	62

CHAPTER 5

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this research, from 12-pilot solar mini-grids that are operational in Ethiopia, Omorate solar mini-grid which is poorly operating and Qorile solar mini-grid which is efficiently operating are selected and used as a benchmark to design and replace diesel only mini-grid in Somali region of Ethiopia selectively for Dolo Odo since it has a higher consumption. In the benchmarking the performance of the solar mini-grids is analyzed and the findings are out lined and used for efficient system design and replacement of diesel only mini-grid.

Qorile solar mini-grid has 325kW installed capacity PV system that can generate 1,860.1kWh/day with 363kW inverter and 550kWh battery storage system. The mini-grid is designed to serve 900 customers with 894.1kWh/day total AC energy requirement. However, currently the mini-grid is generating on average 481.25 kWh/day DC side and 454.2kWh/day AC side, which is 74.13% less than the installed capacity. It is serving 238 customers with average load requirement of 203 kWh/day (55.26 %) less than available AC energy generated. The performance analysis reveals that there is significant amount of unutilized solar potential of 1,378.8kWh/day, with 4.32%, daily power conversion efficiency of the PV module, which is much lower than the manufacturer declared efficiency of 19.85%. The mini-grid is operating with an average of 21.9 % Production factor, 17.1% performance ratio, 2.6% capacity utilization factor and from the total loss 6.84 kWh/kWp/day 98.78% is energy capture losses. The PCS efficiency is 98.5% but since grid inverter is operating at lower load, where peak load is 32kW ($1/10^{th}$ of 325kW) the efficiency is decreased to 94.4 % less than the manufacturer efficiency of 98.8%. Since the mini-grid is operating with $1/10^{th}$ load requirement the 550kWh battery storage system is serving for 17 hours with 91% state of health and retaining minimum half of its total capacity throughout the 6 months. In conclusion, even if Qorile 325kW solar mini-grid is serving the currently connected customers with 100% reliability, with the above-mentioned performance values we can conclude that the mini-grid is performing poorly.

Similarly, Omorate solar mini-grid has installed capacity 375kW PV system that can generate 2,239.3 kWh/day with 400kW inverter and 600kWh battery storage system. It is designed to serve 786 customers with 1,396.96kWh/day total AC energy requirement. However, currently the mini-grid is generating on average 1,212 kWh/day DC side and 1,163kWh/day AC side energy which is 45.9% less than the installed capacity. It is serving 488 customers with average load requirement of 1,031.6 kWh/day (88.7 %) of available AC energy generated. The performance analysis reveals that there is significant amount of unutilized solar potential of 1,027.3 kWh/day (45.89%), with 10.28% daily power conversion PV efficiency which is much lower than the manufacturer declared efficiency of 18.94%. It is serving with an average of 53.0 % Production factor, 51.62 performance ratio, 11.30% capacity utilization factor, and from total loss 2.9kWh/kWp/day 95.5% is energy capture losses with Inverter and PCS efficiency of 95% and 96% respectively. Furthermore, 600kWh battery storage system is not operating in determined way, only serving for 2-3 hours with maximum 120kW peak load (1/3th of the capacity 375kW). The battery is not charged with the designed rate 0.25C, retaining minimum 1/3 of its total capacity throughout the year with 91% state of health. Furthermore, Omorate experiences daily disconnecting of the main power in order to retain energy during periods of low demand and redirect it to meet the peak demand from the feeder that goes out to the loads between 17:00-19:00 and 21:00-08:00. As a result, we can conclude that Omorate 375kW solar mini-grid is not serving the currently connected customers with 100% reliability, and with the above-mentioned performance values it is evident that the mini-grid is operating with poor performance.

The diesel mini-grids operated in Somali regional state are operating maximum 6 hours, with many outages and interruption due to fuel shortage and maintenance problem. Hence it has become imperative to transform diesel only mini-grids into environmentally friendly sustainable energy resource. For this study, the highest generating station among the 15 operational diesel mini-grids in Somali region, Dolo Odo, is selected. This mini-grid serves 396 customers, mostly households, out a potential customers base of 8,470, using 400kVA and 187kVA generators that consumes 250 liters of diesel fuel per day to generate maximum 2MWh daily demand. The yearly fuel cost of this mini-grid is 427,906 Birr and it is observed that in this diesel only mini-grid, only 17.84% of the total diesel expense is covered by customers, due to lack of interest in paying the monthly bill. This lack of interest might be due to lack of satisfaction with the service. Hence, this study proposes a solar mini-grid system to transform the diesel only mini-grid to PV, ESS and DG hybrid mini-grid that run 90% from PV and ESS and 10 percent from backup diesel generator.

The findings from both solar mini-grid and diesel-only-mini-grid serves as a benchmark to designing a solar mini-grid for Dolo Odo town. The essential factors to consider include solar availability, load factor of 40%, which increase by 1% every 5 years, 3.1% population growth rate, 5% demand growth rate, 10 % design margin, 50 % market penetration, 10 % operating reserve, and 0.8 coincident factor. This factor ensure that the generating capacity of the system is sufficient to meet the community's energy needs while accounting for losses and unexpected changes in demand or supply. After manually calculating the required PV, inverter, and battery capacity, the system is simulated using HOMER Pro software to determine the most economical and feasible system architecture with the highest renewable fraction. In addition, PV syst software was used for performance analysis. The selected winning system architecture comprises of 2MW PV module, 8.06MW battery pack, 2MW grid inverter, 1.05MW PCS and 0.6 MW diesel generator with 89.2% renewable fraction. The system comperes the winning system with base case system (DG) and shows that the winning system uses 9% less fuel and emission than the base system. The base system has a LCOE 0.716 while the cost of energy is 0.211 USD/kWh (10.85 Birr) With an NPC 16.5 Million USD in the winning architecture. Even if it is higher than the current price per kWh, subsidizing it could improve the living standards of the community significantly.

5.2 Recommendation

Although Ethiopia has abundant solar resource, the country has yet effectively harnessed this surplus energy. with regard to the country's plan of green economy and that still 56% of the population in the country are out of electricity and since there is a need to electrify 35 % with off grid energy source, and currently the country is looking to construct more solar mini-grids in different parts of the country where the national grid not accessible. Hence, many studies must be done for different places so that the findings can be used as a reference for the government or concerned body. This 12-pilot solar mini-grids that are constructed with high foreign currency to give at least 90 % service reliability to the communities, there operation and performance must be analyzed in order to have a good insight of the mini grid's operation and working condition.

References

[1] M. J. B. Kabeyi and O. A. Olanrewaju, "Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply," *Front. Energy Res.*, vol. 9, p. 1032, Mar. 2022, doi: 10.3389/FENRG.2021.743114/BIBTEX.

[2] "New World Bank Financing Supports Ethiopia's Goal of Universal Electricity Access by 2025." https://www.worldbank.org/en/news/press-release/2021/03/29/new-world-bank-financing-supports-ethiopia-s-goal-of-universal-electricity-access-by-2025 (accessed May 25, 2023).

[3] "Ethiopia to Provide Universal Access to Electricity by 2025." https://www.ezega.com/News/NewsDetails/7026/Ethiopia-to-Provide-Universal-Access-to-Electricity-by-2025 (accessed Jun. 01, 2023).

[4] G. Beyene, "The Challenges and Prospects of Electricity Access in Ethiopia," p. 67, 2018, [Online]. Available: http://etd.aau.edu.et/bitstream/handle/123456789/7919/Getachew Beyene.pdf?sequence=1&isAllowed=y

[5] "Ethiopia.pdf." [Online]. Available: https://www.worldenergy.org/assets/downloads/Ethiopia.pdf

[6] "Document control. Ethiopian Regulatory Environment and Capacity Constraints in Off-Grid Energy Sector Report - PDF Free Download." https://docplayer.net/185777760-Document-control-ethiopian-regulatory-environment-and-capacity-constraints-in-off-grid-energy-sector-report.html (accessed Jun. 06, 2023).

[7] T. Emebet, "Design of Standalone (PV/Micro-Hydro/DG) Hybrid Power Supply for off Grid Rural Community – A Case Study of Maji District (Tum) in South Nation Nationality People Region (SNNPR).," 2016, Accessed: Jun. 01, 2023. [Online]. Available: http://etd.aau.edu.et/handle/123456789/15214

[8] "EnergyNet Ltd. / Press release | Government of Ethiopia to launch the 2nd National Electrification Program during East Africa conferences this March."

https://energynet.africa-newsroom.com/press/government-of-ethiopia-to-present-updates-on-national-electrification-program-20-nep-during-east-africa-conferences-this-month?lang=en (accessed Jun. 01, 2023).

[9] "Environment and social systems assessment (essa) addendum additional financing of the ethiopia electrification program prepared by the world bank September 2022," no. September, 2022.

[10] M. T. & A. L. O. Mesfin Tafesse, Mekdes Mezgebu and Efliel Wabi, "Electricity regulation in Ethiopia: overview | Practical Law." https://uk.practicallaw.thomsonreuters.com/w-028-1702?transitionType=Default&contextData=(sc.Default)&firstPage=true (accessed Jul. 04, 2023).

[11] "Welcome | EEU Portal." http://www.ethiopianelectricutility.gov.et/history/detail/137?lang=en (accessed Jul. 04, 2023).

[12] "EEP History – eep." https://www.eep.com.et/en/eep-history/ (accessed Jul. 04, 2023).

[13] D. Nagpal and B. Parajuli, "Off-grid renewable energy solutions to expand electricity access: An opportunity not to be missed," *Int. Renew. Energy Agency (IRENA), Abu Dhabi*, 2019.

[14] C. T. Tsai, Y. B. Muna, H. Y. Lin, C. C. Kuo, and R. Hsiung, "Optimal design and performance analysis of solar power microsystem for mini-grid application," *Microsyst. Technol.*, vol. 27, no. 4, pp. 1267–1281, Apr. 2021, doi: 10.1007/S00542-018-4213-7/METRICS.

[15] B. F. R. Atiek Puspa Fadhilah, "Measuring System Performance of Isolated Photovoltaic Mini-grid in Rural Indonesia," 2017.

[16] "Performance Analyzing of Stand-Alone PV Hybrid Mini-Grid System with PV at DC and AC Coupling. Applied Mechanics and Materials, 839, 23–28 | 10.4028/www.scientific.net/amm.839.23." https://sci-hub.se/https://www.scientific.net/AMM.839.23 (accessed Jul. 04, 2023).

[17] G. Soyumer and Z. Iqbal, "TECHNO-ECONOMIC FEASIBILITY STUDY OF SOLAR HYBRID MINI GRID IN SOLAB, RAS AL KHAIMAH".

[18] "Advantages & Disadvantages of Solar Energy | GreenMatch." https://www.greenmatch.co.uk/blog/2014/08/5-advantages-and-5-disadvantages-of-solar-energy (accessed Nov. 15, 2023).

[19] "Advantages & Disadvantages Of Solar Panels in 2022." https://lightning-energy.com.au/comparative-guide-advantages-disadvantages-of-solar-panels/ (accessed Nov. 15, 2023).

[20] *IEC. (2016).IEC TS 61724-2 Photovoltaic system performance – Part 2: Capacity evaluation method: Geneva, Switzerland.*

[21] *IEC. (2016). IEC TS 61724-3:2016. Photovoltaic system performance – Part 3: Energy evaluation method*.

[22] E. N. Mbinkar, D. A. Asoh, R. Tchuidjan, and A. Baldeh, "Design of a Photovoltaic Mini-Grid System for Rural Electrification in Sub-Saharan Africa," pp. 91–110, 2021, doi: 10.4236/epe.2021.133007.

[23] T. Huld, M. Moner-Girona, and A. Kriston, "Geospatial analysis of photovoltaic mini-grid system performance," *Energies*, vol. 10, no. 2, pp. 1–21, 2017, doi: 10.3390/en10020218.

[24] A. Z. Ya, "A novel analysis of standalone PV mini-grid model for climate change mitigation in Myanmar's rural village," *J. Renew. Energy Smart Grid Technol.*, vol. 14, no. 1, 2019.

[25] S. Aziz and S. A. Chowdhury, "Performance evaluation of solar mini-grids in Bangladesh: A two-stage Data Envelopment Analysis," *Clean. Environ. Syst.*, vol. 2, p. 100003, 2021, doi: https://doi.org/10.1016/j.cesys.2020.100003.

[26] B. Tesfaye, "Improved Sustainable Power Supply for Dagahabur and Kebridahar Town of Somalia Region in Ethiopia," p. 164, 2011, [Online]. Available: http://en.ru.is/media/reyst/Bizuayehu-Tesfaye-Tilahun.pdf

[27] K. Y. Kebede, “Viability study of grid-connected solar PV system in Ethiopia,” *Sustain. Energy Technol. Assessments*, vol. 10, pp. 63–70, 2015.

[28] Y. T. Wassie and E. O. Ahlgren, “Performance and reliability analysis of an off-grid PV mini-grid system in rural tropical Africa: A case study in southern Ethiopia,” *Dev. Eng.*, vol. 8, pp. 1–28, 2023, doi: 10.1016/j.deveng.2022.100106.

[29] N. M. Kumar, M. R. Kumar, P. R. Rejoice, and M. Mathew, “Performance analysis of 100 kWp grid connected Si-poly photovoltaic system using PVsyst simulation tool,” *Energy Procedia*, vol. 117, pp. 180–189, 2017, doi: 10.1016/J.EGYPRO.2017.05.121.

[30] F. Kapole, S. Mudenda, and P. Jain, “Study of major solar energy mini-grid initiatives in Zambia,” *Results Eng.*, vol. 18, Jun. 2023, doi: 10.1016/J.RINENG.2023.101095.

[31] D. Akinyele, “Analysis of photovoltaic mini-grid systems for remote locations: A techno-economic approach,” *Int. J. Energy Res.*, vol. 42, no. 3, pp. 1363–1380, Mar. 2018, doi: 10.1002/ER.3886.

[32] E. Template, EEU, “Country side energy consumption and Estimate for Solar PV generation Plant cost.”

[33] T. F. Fofang and E. Tanyi, “Design and Simulation of Off-Grid Solar/Mini-Hydro Renewable Energy System using Homer Pro Software: Case of Muyuka Rural Community,” *Int. J. Eng. Res. Technol.*, vol. 9, no. 9, pp. 597–604, 2020, [Online]. Available: https://www.researchgate.net/publication/344401458

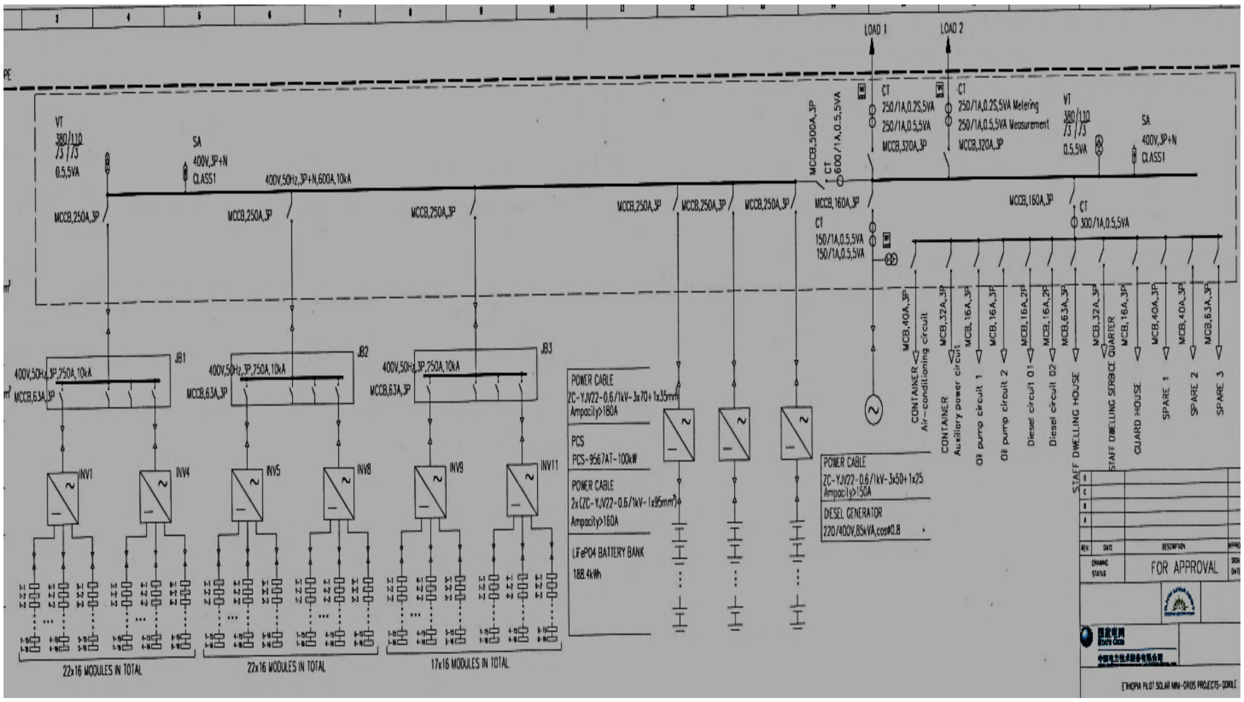
[34] “Inflation rates in Ethiopia.” https://www.worlddata.info/africa/ethiopia/inflation-rates.php (accessed Oct. 25, 2023).

[35] I. Baring-Gould, K. Burman, M. Singh, and S. Esterly, “Quality Assurance Framework for Mini-Grids,” *Natl. Renew. Energy Lab. Glob. LEAP Rep.*, vol. 11, no. November, pp. 1–58, 2016.

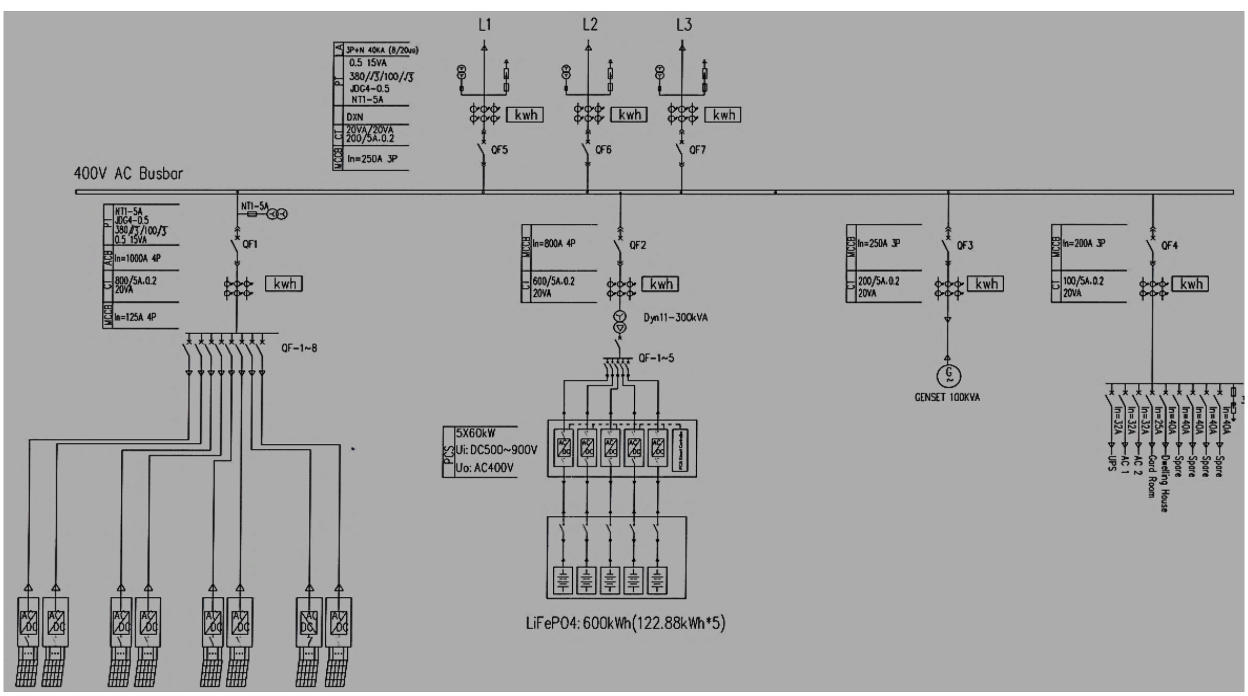
Appendix

Appendix A: Single line diagram

1. Qorile single line diagram



2. Omorate diagram



Appendix B: Solar PV module and inverter specification

SPECIFICATIONS

Module Type	JKM450M-60HL4 JKM450M-60HL4-V		JKM455M-60HL4 JKM455M-60HL4-V		JKM460M-60HL4 JKM460M-60HL4-V		JKM465M-60HL4 JKM465M-60HL4-V		JKM470M-60HL4 JKM470M-60HL4-V	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	450Wp	335Wp	455Wp	339Wp	460Wp	342Wp	465Wp	346Wp	470Wp	350Wp
Maximum Power Voltage (Vmp)	33.91V	31.73V	34.06V	31.91V	34.20V	32.07V	34.37V	32.12V	34.56V	32.32V
Maximum Power Current (Imp)	13.27A	10.55A	13.36A	10.61A	13.45A	10.67A	13.53A	10.77A	13.60A	10.82A
Open-circuit Voltage (Voc)	41.18V	38.87V	41.33V	39.01V	41.48V	39.15V	41.63V	39.29V	41.78V	39.43V
Short-circuit Current (Isc)	13.85A	11.19A	13.93A	11.25A	14.01A	11.32A	14.09A	11.38A	14.17A	11.344
Module Efficiency STC (%)	20.85%		21.08%		21.32%		21.55%		21.78%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1000/1500VDC (IEC)									
Maximum series fuse rating	25A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.35%/℃									
Temperature coefficients of Voc	-0.28%/℃									
Temperature coefficients of Isc	0.048%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

SPECIFICATIONS

Module Type	JKM325M-60H JKM325M-60H-V		JKM330M-60H JKM330M-60H-V		JKM335M-60H JKM335M-60H-V		JKM340M-60H JKM340M-60H-V		JKM345M-60H JKM345M-60H-V	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	325Wp	242Wp	330Wp	246Wp	335Wp	250Wp	340Wp	253Wp	345Wp	257Wp
Maximum Power Voltage (Vmp)	33.6V	31.6V	33.8V	31.8V	34.0V	32.0V	34.2V	32.2V	34.4V	32.4V
Maximum Power Current (Imp)	9.68A	7.66A	9.77A	7.74A	9.87A	7.82A	9.96A	7.86A	10.04A	7.94A
Open-circuit Voltage (Voc)	41.1V	38.0V	41.3V	38.2V	41.5V	38.4V	41.7V	38.6V	41.9V	38.8V
Short-circuit Current (Isc)	10.20A	8.54A	10.31A	8.65A	10.36A	8.74A	10.55A	8.86A	10.64A	8.97A
Module Efficiency STC (%)	19.26%		19.56%		19.85%		20.15%		20.45%	
Operating Temperature (℃)	-40℃~+85℃									
Maximum System Voltage	1000/1500VDC (IEC)									
Maximum Series Fuse Rating	20A									
Power Tolerance	0~+3%									
Temperature Coefficients of Pmax	-0.35%/℃									
Temperature Coefficients of Voc	-0.29%/℃									
Temperature Coefficients of Isc	0.048%/℃									
Nominal Operating Cell Temperature (NOCT)	45±2℃									

SPECIFICATIONS for Inverter

Input Data

MODEL	MAX 100KTL3 MV
Max.DC power	130 000W
Max.DC voltage	1100V
Start Voltage	250V
PV voltage range	200V-1000V
Full load DC voltage	730V-850V
Nominal voltage	730V
Max. input current per MPPT	25A
Number of MPP trackers/ strings per MPP tracker	7/2

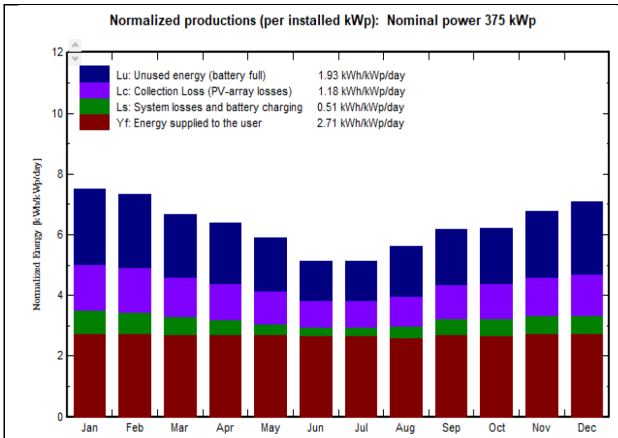
Output (AC)

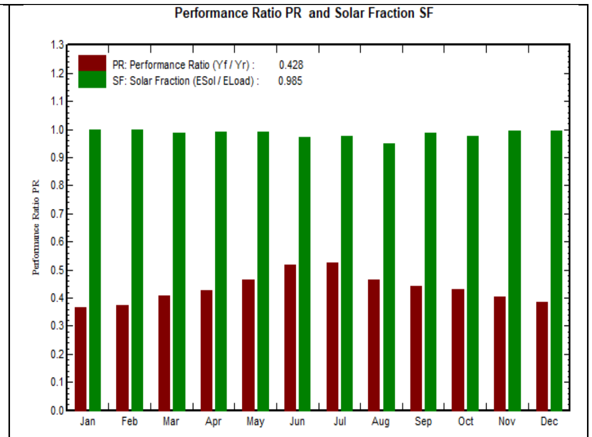
MODEL	MAX 100KTL3 MV
Rated AC output power	100.000W
Max. AC apparent power	111.000VA
Max. output current	128.6A
AC nominal voltage/range	288V/500V 425-540VAC
AC grid frequency	50Hz/60Hz
Power factor	0.8leading ...0.8lagging
THDI	<3%
AC grid connection type	3W+PE

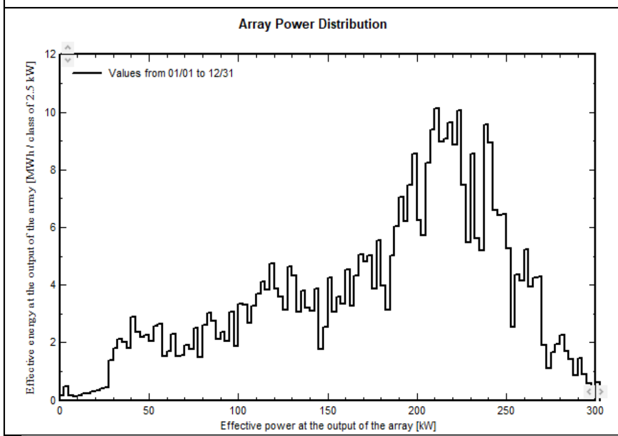
Efficiency

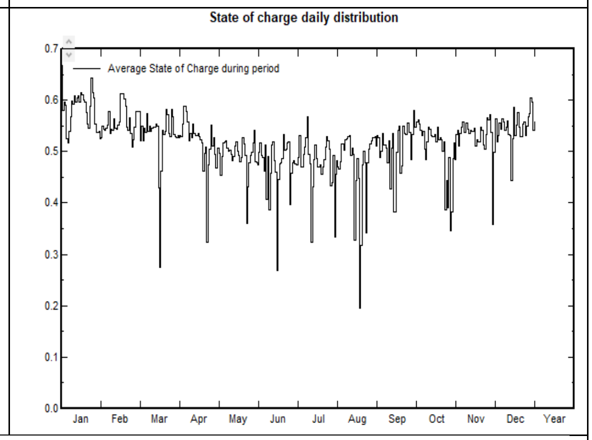
MODEL	MAX 100KTL3 MV
Max. Efficiency	99.0%
Euro – eta	98.5%
MPPT efficiency	99.9%

Appendix C: Omorate solar mini-grid PV syst simulation result









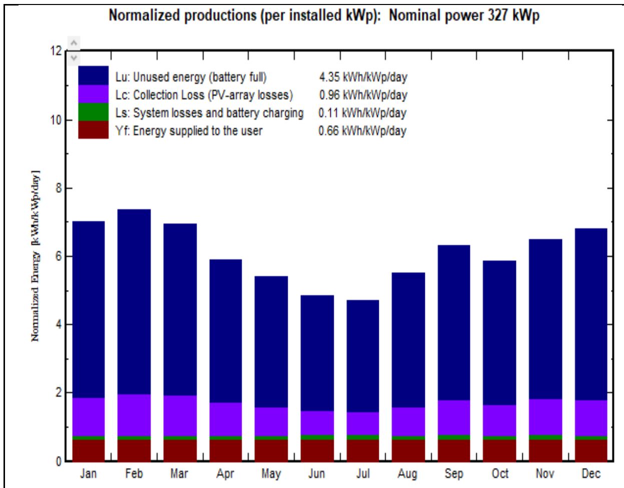
New simulation variant
Balances and main results

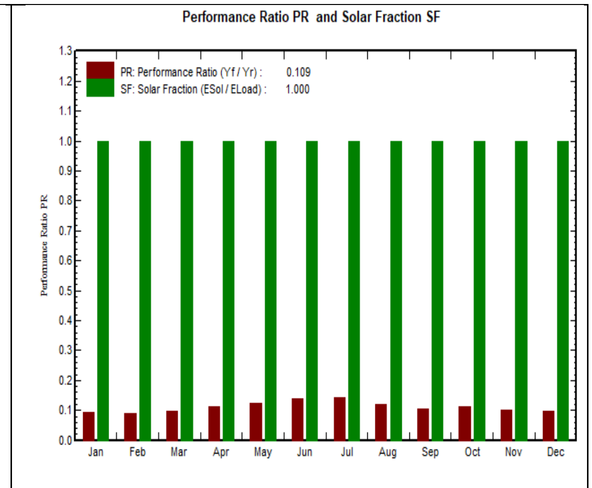
	GlobHor	GlobEff	E_Avail	EUnused	E_Miss	E_User	E_Load	SolFrac
	kWh/m²	kWh/m²	kWh	kWh	kWh	kWh	kWh	ratio
January	206.7	227.7	68259	29001	0	31980	31980	1.000
February	191.5	201.1	59889	25280	0	28885	28885	1.000
March	205.2	202.2	60818	24067	468	31512	31980	0.985
April	201.5	186.1	56930	22230	320	30628	30948	0.990
May	202.9	176.2	54525	20330	321	31659	31980	0.990
June	174.0	148.7	46552	14561	912	30037	30948	0.971
July	176.1	153.1	48011	14938	752	31227	31980	0.976
August	186.5	169.0	52415	19142	1572	30408	31980	0.951
September	188.4	180.6	55348	20486	361	30588	30948	0.988
October	185.8	188.5	57337	21171	737	31243	31980	0.977
November	184.9	198.9	60731	24623	154	30794	30948	0.995
December	193.3	215.3	65386	27945	114	31866	31980	0.996
Year	2296.9	2247.5	686201	263773	5711	370826	376538	0.985

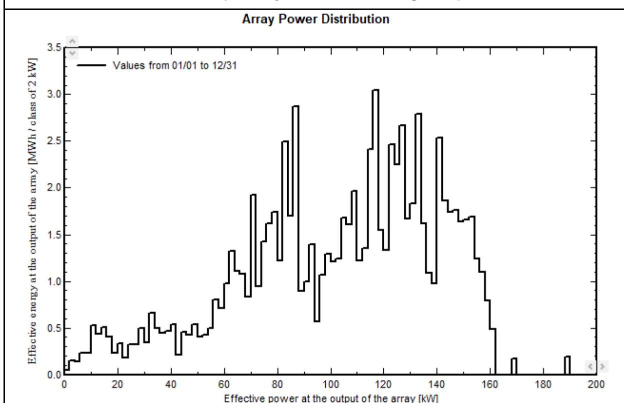
New simulation variant
Normalized Performance Coefficients

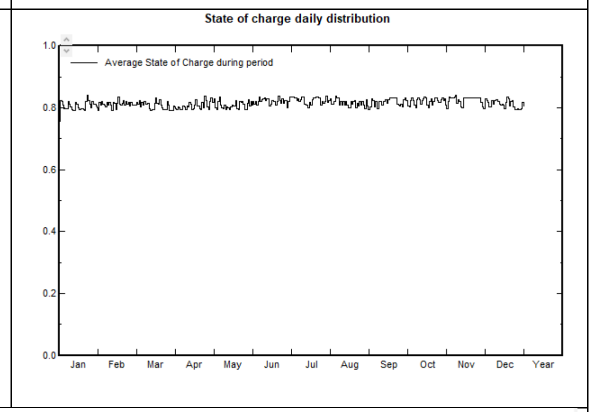
	Yr	Lu	Yu	Lc	Ya	Ls	Yf	PR
	kWh/m²/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	ratio
January	7.50	2.49	7.50	3.99	3.52	0.77	2.75	0.367
February	7.33	2.41	7.33	3.89	3.44	0.69	2.75	0.375
March	6.67	2.07	6.67	3.38	3.30	0.59	2.71	0.406
April	6.38	1.98	6.38	3.16	3.22	0.49	2.72	0.427
May	5.88	1.75	5.88	2.81	3.07	0.35	2.72	0.463
June	5.14	1.29	5.14	2.17	2.97	0.30	2.67	0.519
July	5.12	1.28	5.12	2.14	2.97	0.29	2.69	0.525
August	5.61	1.65	5.61	2.62	2.99	0.38	2.62	0.466
September	6.18	1.82	6.18	2.95	3.23	0.51	2.72	0.440
October	6.23	1.82	6.23	2.98	3.24	0.56	2.69	0.431
November	6.78	2.19	6.78	3.44	3.34	0.60	2.74	0.403
December	7.10	2.40	7.10	3.75	3.35	0.61	2.74	0.386
Year	6.32	1.93	6.32	3.10	3.22	0.51	2.71	0.428

Appendix D: Qorile solar mini-grid PV syst simulation result









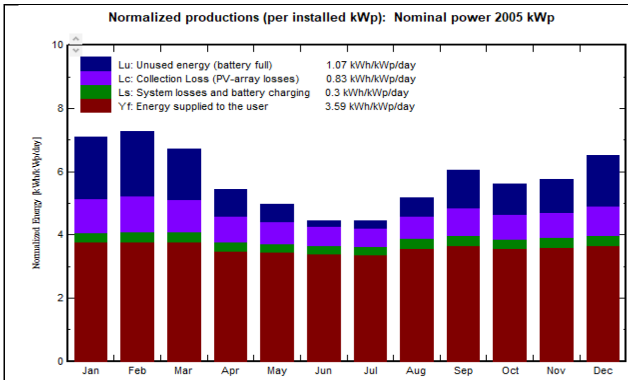
New simulation variant
Balances and main results

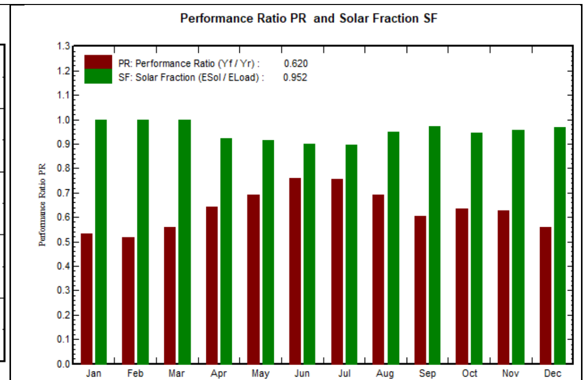
	GlobHor	GlobEff	E_Avail	EUnused	E_Miss	E_User	E_Load	SolFrac
	kWh/m²	kWh/m²	kWh	kWh	kWh	kWh	kWh	ratio
January	191.6	213.9	59469	52004	0.000	6732	6732	1.000
February	189.3	202.6	56144	49389	0.000	6080	6080	1.000
March	211.1	211.2	58086	50652	0.000	6732	6732	1.000
April	184.2	172.3	48048	40917	0.000	6515	6515	1.000
May	184.8	162.4	45654	38437	0.000	6732	6732	1.000
June	162.6	140.6	39898	32748	0.000	6515	6515	1.000
July	161.8	141.6	40280	32924	0.000	6732	6732	1.000
August	182.3	166.8	46935	39635	0.000	6732	6732	1.000
September	190.8	185.7	51465	44237	0.000	6515	6515	1.000
October	171.7	177.8	49843	42391	0.000	6732	6732	1.000
November	174.3	191.1	53161	45679	0.000	6515	6515	1.000
December	183.8	208.3	58070	50662	0.000	6732	6732	1.000
Year	2188.3	2174.3	607053	519675	0.000	79260	79260	1.000

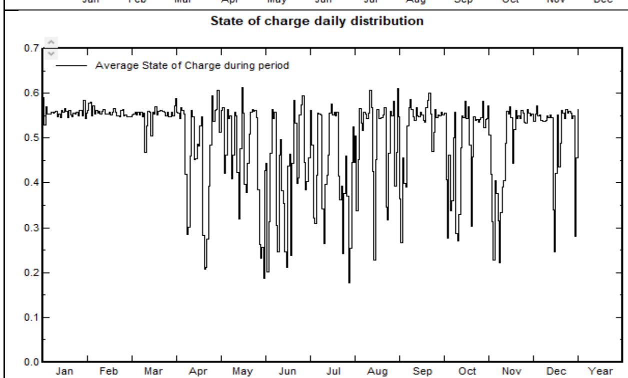
New simulation variant
Normalized Performance Coefficients

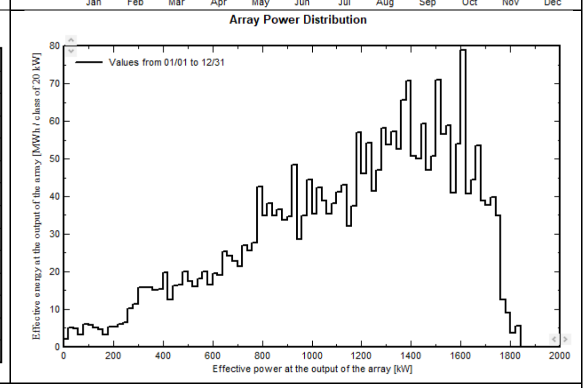
	Yr	Lu	Yu	Lc	Ya	Ls	Yf	PR
	kWh/m²/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	ratio
January	7.02	5.14	7.02	6.25	0.77	0.11	0.66	0.095
February	7.37	5.40	7.37	6.59	0.77	0.11	0.66	0.090
March	6.94	5.00	6.94	6.17	0.77	0.11	0.66	0.096
April	5.89	4.17	5.89	5.12	0.77	0.11	0.66	0.113
May	5.40	3.79	5.40	4.65	0.75	0.09	0.66	0.123
June	4.83	3.34	4.83	4.06	0.78	0.11	0.66	0.137
July	4.71	3.25	4.71	3.94	0.77	0.11	0.66	0.141
August	5.52	3.91	5.52	4.76	0.76	0.10	0.66	0.120
September	6.33	4.51	6.33	5.55	0.78	0.11	0.66	0.105
October	5.85	4.18	5.85	5.08	0.77	0.11	0.66	0.113
November	6.49	4.66	6.49	5.69	0.80	0.14	0.66	0.102
December	6.82	5.00	6.82	6.05	0.77	0.10	0.66	0.097
Year	6.09	4.36	6.09	5.32	0.77	0.11	0.66	0.109

Appendix E: Dolo Odo winning solar mini grid PV syst simulation result









New simulation variant
Balances and main results

	GlobHor	GlobEff	E_Avail	EUnused	E_Miss	E_User	E_Load	SolFrac
	kWh/m²	kWh/m²	kWh	kWh	kWh	kWh	kWh	ratio
January	195.6	215.9	363665	121374	0	234221	234221	1.000
February	189.8	199.9	335133	114486	0	211555	211555	1.000
March	207.4	204.5	343632	100023	0	234221	234221	1.000
April	171.6	158.8	268175	50907	17254	209412	226666	0.924
May	170.5	149.6	255587	33769	20157	214065	234221	0.914
June	151.5	129.6	222649	11977	22495	204171	226666	0.901
July	154.7	134.0	230397	15184	24545	209676	234221	0.895
August	172.7	156.1	267448	36525	11562	222659	234221	0.951
September	184.5	178.0	301943	72835	6062	220604	226666	0.973
October	166.8	170.9	290143	60342	12457	221764	234221	0.947
November	157.5	169.5	288147	62968	9642	217024	226666	0.957
December	178.9	199.1	336540	100056	7522	226699	234221	0.968
Year	2101.5	2065.8	3503458	780445	131696	2626072	2757768	0.952

New simulation variant
Normalized Performance Coefficients

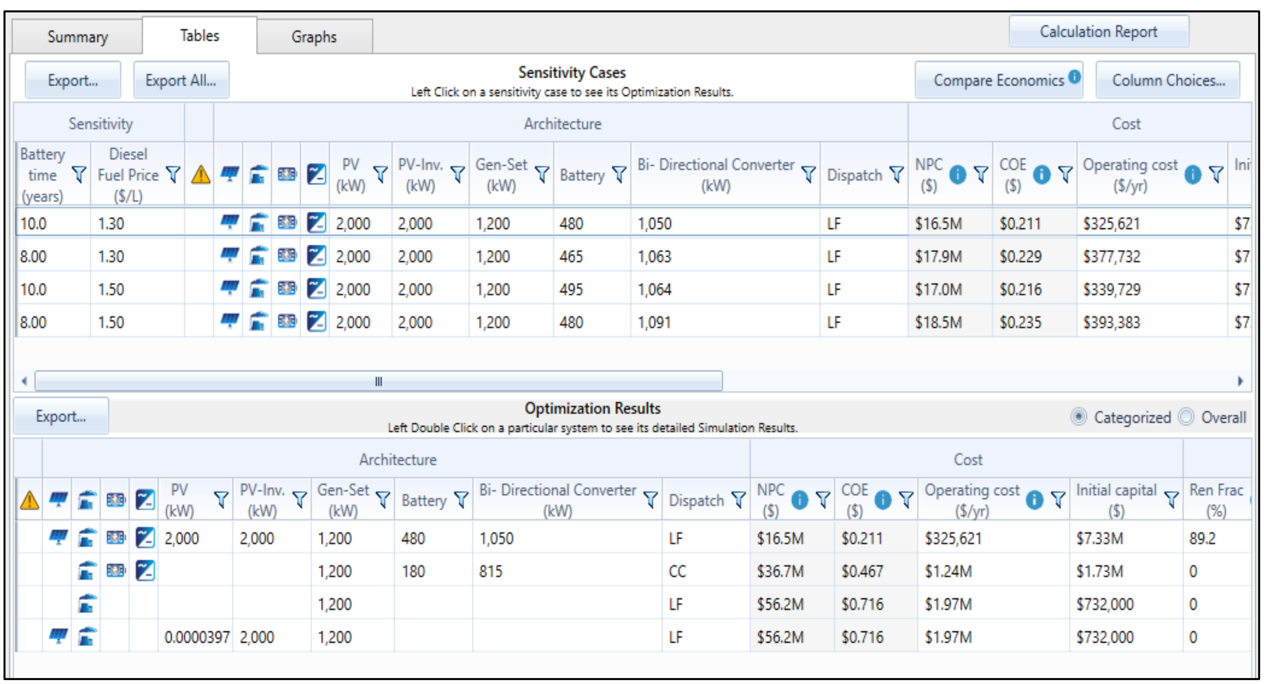
	Yr	Lu	Yu	Lc	Ya	Ls	Yf	PR
	kWh/m²/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	ratio
January	7.09	1.95	7.08	3.02	4.06	0.29	3.77	0.532
February	7.26	2.04	7.26	3.17	4.09	0.33	3.77	0.519
March	6.73	1.61	6.73	2.64	4.08	0.31	3.77	0.560
April	5.43	0.85	5.43	1.65	3.78	0.30	3.48	0.642
May	4.97	0.54	4.97	1.24	3.73	0.29	3.44	0.693
June	4.46	0.20	4.46	0.79	3.66	0.27	3.39	0.762
July	4.46	0.24	4.46	0.83	3.62	0.25	3.37	0.757
August	5.17	0.59	5.17	1.29	3.88	0.30	3.58	0.693
September	6.06	1.21	6.06	2.08	3.98	0.31	3.67	0.605
October	5.62	0.97	5.62	1.75	3.87	0.30	3.57	0.635
November	5.75	1.05	5.75	1.84	3.91	0.31	3.61	0.628
December	6.53	1.61	6.53	2.55	3.98	0.33	3.65	0.559
Year	5.78	1.07	5.78	1.90	3.89	0.30	3.59	0.620

Appendix F: Dolo Odo town population projection

Population Projection of Ethiopia for all regions at wereda Level from 2014 – 2017 G.C from Federal Democratic Republic of Ethiopia Central Statistical Agency (CSA) the values are in household; one household have 7 family members.

Dolo Odo			
2007	6757	**2024**	10397.68
2008	6970	**2025**	10611.88
2009	7185	**2026**	10826
2010	7399	**2027**	11040.28
2011	7613	**2028**	11254
2012	7827	**2029**	11468.68
2013	8042	**2030**	11682.88
2014	8256	**2031**	11897.08
2015	8470	**2032**	12111
2016	8684	**2033**	12325.48
2017	8898	**2034**	12539.68
2018	9112	**2035**	12753.88
2019	9327	**2036**	12968.08
2020	9541	**2037**	13182.28
2021	9755	**2038**	13396
2022	9969	**2039**	13610.68
2023	10183	**2040**	13824.88

Appendix G: Dolo Odo proposed solar mini-grid HOMER PRO simulation result


Summary | Tables | Graphs | Calculation Report

Export... | Export All... | Compare Economics | Column Choices...

Sensitivity Cases

Left Click on a sensitivity case to see its Optimization Results.

Battery time (years)	Diesel Fuel Price ($/L)	PV (kW)	PV-Inv. (kW)	Gen-Set (kW)	Battery	Bi- Directional Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Ini
10.0	1.30	2,000	2,000	1,200	480	1,050	LF	$16.5M	$0.211	$325,621	$7
8.00	1.30	2,000	2,000	1,200	465	1,063	LF	$17.9M	$0.229	$377,732	$7
10.0	1.50	2,000	2,000	1,200	495	1,064	LF	$17.0M	$0.216	$339,729	$7
8.00	1.50	2,000	2,000	1,200	480	1,091	LF	$18.5M	$0.235	$393,383	$7

Export...

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Categorized | Overall

PV (kW)	PV-Inv. (kW)	Gen-Set (kW)	Battery	Bi- Directional Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
2,000	2,000	1,200	480	1,050	LF	$16.5M	$0.211	$325,621	$7.33M	89.2
		1,200	180	815	CC	$36.7M	$0.467	$1.24M	$1.73M	0
		1,200			LF	$56.2M	$0.716	$1.97M	$732,000	0
0.0000397	2,000	1,200			LF	$56.2M	$0.716	$1.97M	$732,000	0

Appendix H: Dolo Odo Solar resource estimation

No	n_d	δ	ω_s	N	n	n/N	H_o ($kWh/m^2/d$)	a	b	Estimate H ($kWh/m^2/d$)
1	15	-21.27	89.97	12.00	6.35	0.53	9.595	-0.093	1.443	6.44
2	45	-13.62	89.98	12.00	6.82	0.57	10.093	-0.080	1.416	7.32
3	74	-2.82	90.00	12.00	6.39	0.53	10.454	-0.092	1.441	7.06
4	105	9.41	90.01	12.00	5.41	0.45	10.389	-0.118	1.498	5.79
5	135	18.79	90.02	12.00	5.22	0.43	10.005	-0.123	1.509	5.33
6	166	23.31	90.03	12.00	5.05	0.42	9.707	-0.128	1.519	4.96
7	196	21.52	90.03	12.00	4.97	0.41	9.792	-0.130	1.523	4.90
8	227	13.78	90.02	12.00	5.48	0.46	10.148	-0.116	1.494	5.74
9	258	2.22	90.00	12.00	5.82	0.48	10.367	-0.107	1.474	6.30
10	288	-9.60	89.99	12.00	5.37	0.45	10.167	-0.119	1.500	5.61
11	319	-19.15	89.98	12.00	5.01	0.42	9.691	-0.129	1.521	4.91
12	349	-23.34	89.97	12.00	5.66	0.47	9.407	-0.111	1.483	5.54
									Average	5.825481419

month	NMA	NASA	Error
Jan	6.44	6.31	0.13
Feb	7.32	6.78	0.54
Mar	7.06	6.69	0.37
Apr	5.79	5.72	0.07
May	5.33	5.5	-0.17
Jun	4.96	5.05	-0.09
Jul	4.90	4.99	-0.09
Aug	5.74	5.57	0.17
Sep	6.30	6.15	0.15
Oct	5.61	5.38	0.23
Nov	4.91	5.25	-0.34
Dec	5.54	5.77	-0.23