Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Telecommunication Engineering Graduate Program

Techno-Economic Feasibility of Hybrid Energy System Versus Grid for a Different Level of Grid Reliability at Cellular Base Stations: A case of Ethio telecom

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Declaration

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

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

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Abstract

The rapid growth of cellular technology needs a significant attention to energy consumption in cellular networks. This is especially crucial in developing countries like Ethiopia, where the electric supply and grid power distribution are unreliable. In Ethio telecom, grid as the primary energy source for its communication infrastructure. Approximately 70% of the Base Transceiver Stations (BTS) are connected to the grid. Some BTS operate with grid and backup batteries, while others have standby diesel generators and backup batteries. Due to frequent grid outages, some sites are working with diesel generators for a long time whereas the other site service is disrupted, and increased operational costs, increase fuel consumption, degraded Quality of Service(QoS), Quality of Experience(QoE), and reduced the revenue.

This study focuses on the techno-economic feasibility of Grid connected PV hybrid energy system(HES) to provide a reliable and cost-efficient energy solution for BTS. The sites are classified based on grid outage frequency, maintenance time, climatic zones and 54 sites are represented for study . Input parameters are obtained from Ethio telecom's Network Ecosystem(NetEco) and Power Engineering Department, as well as solar radiation and temperature data from the National Aeronautics and Space Administration (NASA).To design the optimal hybrid energy system and components, optimization techniques and energy control strategies are employed, by utilizing the Hybrid Optimization of Multiple Energy Resources (HOMER) Pro software tool. The aim is to minimize the Net Present Cost (NPC) and Cost of Energy (COE) of the hybrid energy system by considering different power configurations. The results indicate that the proposed Grid/PV/BSS and Grid/PV/DG/BSS configurations have lower NPC and COE compared to the conventional power system. Grid/PV/DG/BSS configuration is feasible for frequent grid interruptions, and took long time grid maintenance and the proposed hybrid power system saved fuel consumptionqof the site from 5,393 to 61,843L/yr.

Keywords— Hybrid Energy system(HES), HOMER Pro, BTS, grid Outage, Net Eco, NASA, NPC, Quality of Service (QoS), and Quality of Experience (QoE).

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List of Acronyms

3G	Third Generation
4G	Fourth Generation
AC	Alternative Current
AC-DC	Alternative Current to Direct current Converter
AGM	Absorbant Glass Mat
ATN	Aeronautical Telecommunication Network
BB	Big Battery
BBU	Base Band Unit
BS	Base Station
BSS	Battery Storage System
BTS	Base Transceiver Stations
CC	Capital Cost
CC	Cyclic Charge
CN	Core Network
COE	Cost of Energy
CRF	Capital Recovery Factor
DC	Direct Current
DC-DC	Direct Current to Direct current Converter
DG	Diesel Generator
E_UTRAN	Evolved Universal Terrestrial Radio Access Network
eNodeB	Evolved Node B
EPC	Evolved Packet Core
ESS	Energy Storage System
ET	Ethio telecom
GHI	Global Horizontal Irradiation

GSM	Global System for Mobile Communication
GSMA	Global System for Mobile Communication Association
HES	Hybrid Energy System
HOMER	Hybrid Optimizations' Model for Electric Renewable
HRES	Hybrid Renewable Energy System
ICT	Information and Communication Technology
IP	Internet Protocol
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LF	Load Following
LiFePO4	Lithium Iron Phosphate
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advance
MILP	Mixed-Integer Linear Programming
MNOs	Mobile Operators
MSC	Mobile Switching Center
NASA	National Aeronautics and Space Administration
NetEco	Network Ecosystem
NMA	National Metrology Agency
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
O&M	Operational and Maintenance
OPEX	Operational Expenditure
PV	Photo Voltaic
QoE	Quality of Experience
QoS	Quality of Service

RAN	Radio Access Network
RC	Replacement Cost
RES	Renewable Energy System
RF	Radio Frequency
RF	Renewable Fraction
RNC	Radio Network Control
RRU	Radio Receiver Unit
RTN	Routing Transmission Network
SOC	State of Charge
STC	Standard Test Condition
SV	Salvage Value
TEA	Techno-Economic Analysis
UMTS	Universal Mobile Telecom System
VRLA	Valve-Regulated Lead Acid

Chapter 1: Introduction

1.1 Background of the Study

The mobile telecommunication sector is one of the fastest-growing sectors of global business industry. The ever-increasing demands of mobile telecommunication services in developing countries are driving this significant profitable growth [1]. In cellular networks, the access network part substantially Base transceiver station (BTS) accounts for 80% of the total energy consumed by the entire network structure and energy consumption [2][3]. A result, network drivers have to pay a large portion of their operating expenditure for energy costs. Accordingly, the hunt for energy-effective coming-generation' True ' green communication networks has come one of the hot exploration motifs for moment's communication experimenters [2].

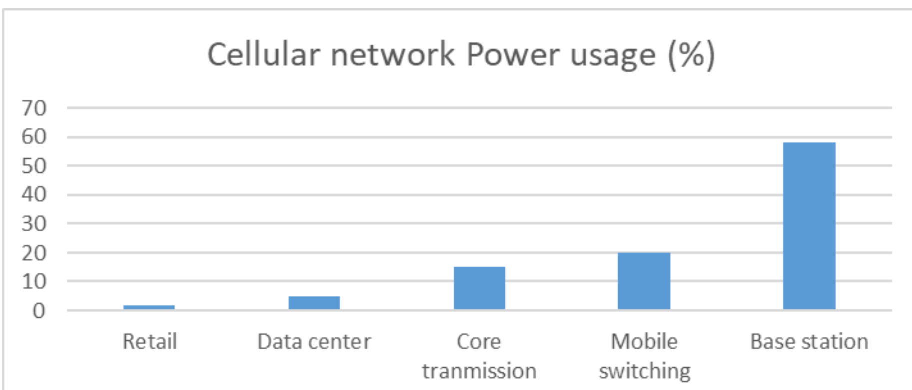

Figure 1 Power consumption of a typical wireless cellular network [4].

According to Figure 1, cellular network power consumption Base stations are highly energy consumed and wasted cellular network infrastructure, it needs optimal and efficient power system design to decrease operational cost, power wastage, and decrease environmental pollution.

In the telecommunications industry, Mobile Network Operators (MNOs) are facing challenges in finding energy solutions that are both reliable and cost-effective for their networks. The efficiency of energy usage has emerged as a crucial performance indicator for the upcoming 5G networks. Sustainability and environmental friendliness are primarily built upon the foundations of energy effectiveness and the utilization of renewable energy sources [4].

MNO drivers tend to maximize their gains by minimizing system time-out grounded on dependable operation and planting cost-effective systems for BTS. The power system planning and optimized power operation for BTS spots is under consideration of high sustainability, low cost, and, reduced environmental impacts [5].

Hybrid renewable energy system (HRES) technology plays a significant part in promoting green mobile communication. A strong energy system consists of two or further energy sources used together to give increased system effectiveness as well as greater balance in energy supply [6].

HRES are designed for the generation of electrical power using a number of power generation devices such as wind turbines, PV, micro-hydro, and/or other conventional generators [7]. Standalone renewable energy sources and /or RES with the conventional energy sources are the excellent alternates to goes a green cellular communication for access layer [8].

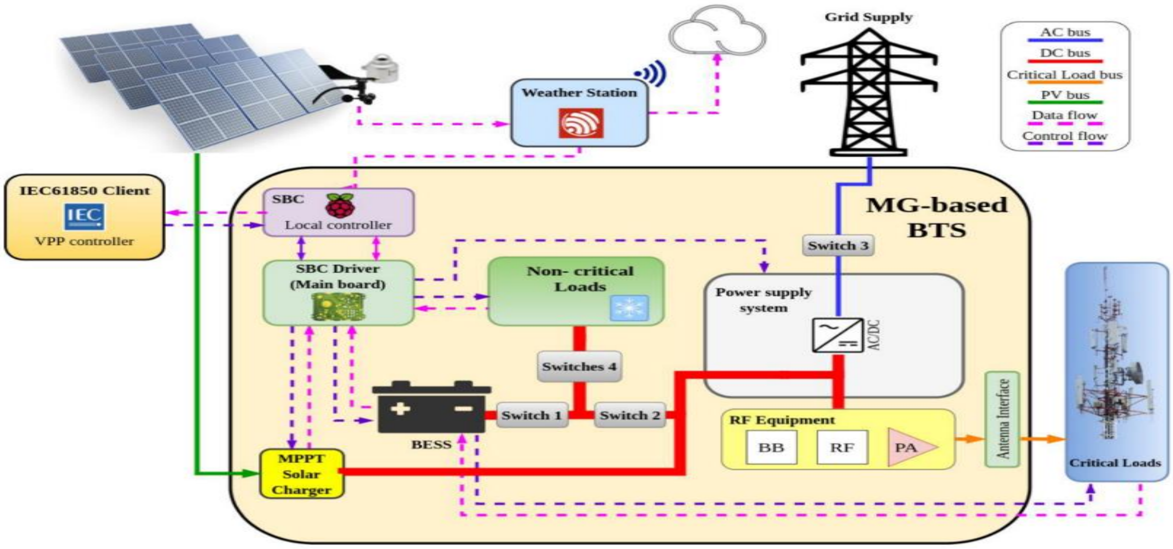

Figure 2 Hybrid power system structure for BTS [9].

Figure 2, indicates that Grid connected BTS with solar energy based on a micro grid architecture, the energy flow controller is design in locally, and PV system controlled by Maximums Power Point Tracke(MPPT).

In most developing countries, the electricity supply is highly unreliable. Ethiopia is one of the least developed countries in the world and the existing power distribution system of the country has encountered frequent power interruptions. During the interruption, diesel generators supplied the critical load of most industries in the country [10].

Ethio telecom is one of the telecom operators in Ethiopia that provides both wireless and wired telecommunication technology. Cellular technology is vastly growing up in the world as well as in Ethiopia, to expand the network all over the countries; it was invested in a huge Infrastructure. Currently around 70% BTS sites are connected to grid. The common power solution type selection criteria during the deployment of new BTS, network expansion, and optimization, are based on grid availability, grid availability hour, road access as per season, space availability, area clearance, and site service type.

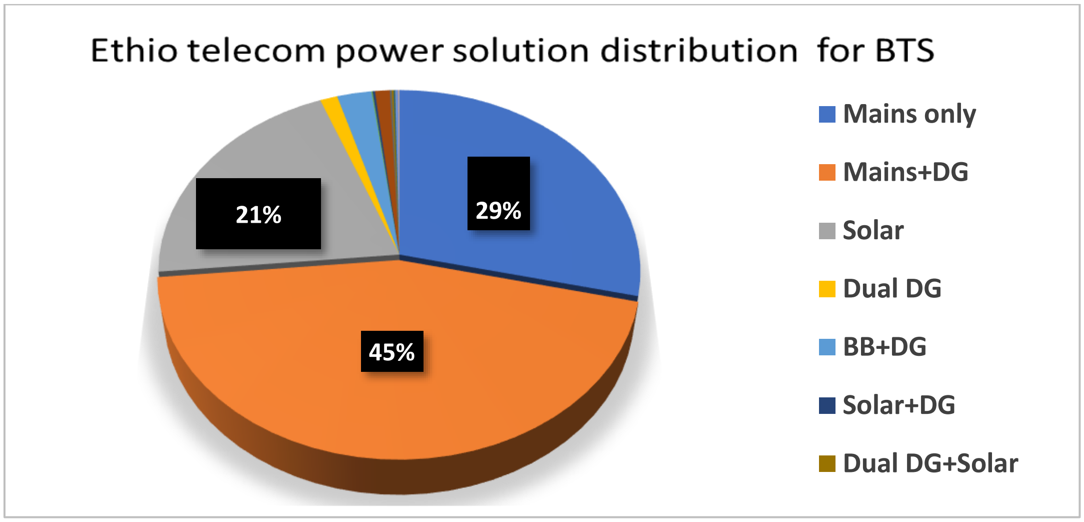

Figure 3 Ethio telecom BTS power system distribution (ET).

According to the figure 3 the power source for Ethio telecom BTS are grid, grid with DG and solar system. About 74% of the sites are connected to grid, so to provide reliable power system and reduce operation cost, optimal cost-efficient power system designing is required.

With Safaricom entering Ethiopia's telecom market, there will be increased competition in the industry. Ethio telecom, being the first telecom provider in Ethiopia, is responsible for providing the necessary infrastructure to support Safaricom's operations. In order to meet the demands of this competitive market, Ethio telecom needs to ensure the provision of a reliable, cost-effective, and environmentally friendly power system. This can be achieved by implementing an optimal power solution system that addresses the specific requirements and challenges of the telecom industry in Ethiopia.

1.2 Statement of the Problem

Currently the biggest challenge for mobile operators is high- energy consumption, high CO2 & CO emission due to fossil fuel, and the supply of interrupted and low-quality power to BTS located in pastoral areas. Numerous telecom halls are present in pastoral areas where electric grid power is unreliable or not available at all.

The performance index of various developed and existing energy systems are evaluated based on economy or cost of energy (COE), power system reliability, energy throughput, and emission reduction targets [1].

In developing countries like Ethiopia grid is not reliable with different reason. Most Ethio telecom BTS sites are connected to the grid. Due to frequent and longtime grid interruption, some sites services are interrupted, whereas as the sites are DG run for a long time, so the operational expenditure (OpEx), fuel consumption, and environmental pollution increases, in the other hand degrades quality of service(QoE) and quality of experience(QoE).

According to the Ethio telecom annual fuel consumption report in 2017/2018, the fuel consumption of standby DG for 3,171 BTSs was around 169 million birrs. The annual fuel consumption report for standby DG is shown in the table 1.

Table 1 Annual Fuel consumption in the year 2017/18 [11].

Site Location	No. of Sites	Fuel Consumption in /L	Fuel consumption /Birr
Regional	2,380	8,241,317	135,157,608
Zonal	791	2,054,601	33,592,730
Total	3,171	10,295,918	168,750,338

In general the main gaps are:

- Due to frequent grid interruption BTS sites are supplied by DG and increase the OpEx of the company and the other case if the sites doesn't standby DG, the service interrupted, it become reduce revenue, QoE, and QoS.

Grid and DC unavailability ET BTS data of 2022 ;

- 1478 BTS yearly grid outage is 1,281,399hr and total DC unavailability of 1257 BTS is 335, 285hr(725 Grid only sites is 251, 142hr and Grid with DG sites 83,139hr).
- The 2019 to 2022 fuel consumption report for 1221 BTS is 19,690,104 liters**.**

- Renewable hybrid energy system is reliable and cost efficient for energy source for mobile station. However Ethio telecom, PV hybrid energy system isnot used as the main power during planning and designing.
- When proposing an energy system, the focus is often primarily on assessing the initial cost, while the operational and replacement costs are not thoroughly examined.

Ethiopia has abundant solar energy in all over the country, so optimally sizing solar hybrid system is feasible for BTS power system.

1.3 Objective

1.3.1 General Objective

The primary goal of the study is to create a grid-connected PV hybrid power system specifically designed for Ethio telecom BTS sites, and study the techno-economic feasibility proposed PV hybrid energy system to the conventional.

1.3.2 Specific Objectives

The specific objectives are:

- Analayze grid outage of BTS sites and classify as per grid outage behavior
- Asses technical and economical parameters for designing hybrid power system
- Asses the solar potential of the study area

- Configure optimal hybrid power system for BTS
- Evaluate the techno-economic feasibility of a hybrid power system

1.4 Methodology

In this study, Ethio telecom BTS sites are the specific locations where the research is conducted. The study utilizes two types of data sources: primary and secondary data. Primary data is obtained from the Network Ecosystem (NetEco), while secondary data is gathered from sources such as the National Aeronautics and Space Administration (NASA) and Ethiopia Electric Utility (EEU). To design a hybrid energy system, the study employs a theoretical approach in the modeling process.

1.4.1 Related Works Review

The literature review for this study is conducted by gathering information from various sources such as Google Scholar, IEEE Xplore, and other research repositories. The review encompasses several key areas, including the examination of energy sources for BTS (Base Transceiver Station), the analysis of hybrid power systems, optimization techniques for hybrid power systems, energy management strategies of hybrid power systems, and the assessment of the techno-economic feasibility of hybrid power systems.

1.4.2 Data Collection and Analysis

The required data for the study contains the primary and secondary data, The primary data is hourly load profile, grid outage, and other power data from NetEco, power equipment technical and economic data from Power and Environment department. The secondary data (solar radiation, wind speed, temperature) from NASA. This data is analyzed by using microsoft excel.

1.4.3 Identification of Study Area

Site identification was done, sites which are affected by frequent grid outage, and they need improvement in operational cost, reliability, revenue, NPC, QoS and QoE due to frequent grid outage.

- Categorize (Classify) sites as per grid outage frequency, site load capacity, site type and accessibility for maintenance.

1.4.4 Evaluate Techno-Economic Feasibility of the Proposed Hybrid System

Techno-economic evaluation is the main metrics to design hybrid power system. To design hybrid power system, the required input parameters, constraints and objective functions are defined. The main objective is to minimize NPC, and COE by sizing optimal component and using renewable energy system. The selected optimization and simulation tools to design optimal hybrid power system and evaluate techno economic feasibility is Homer Pro software tools.

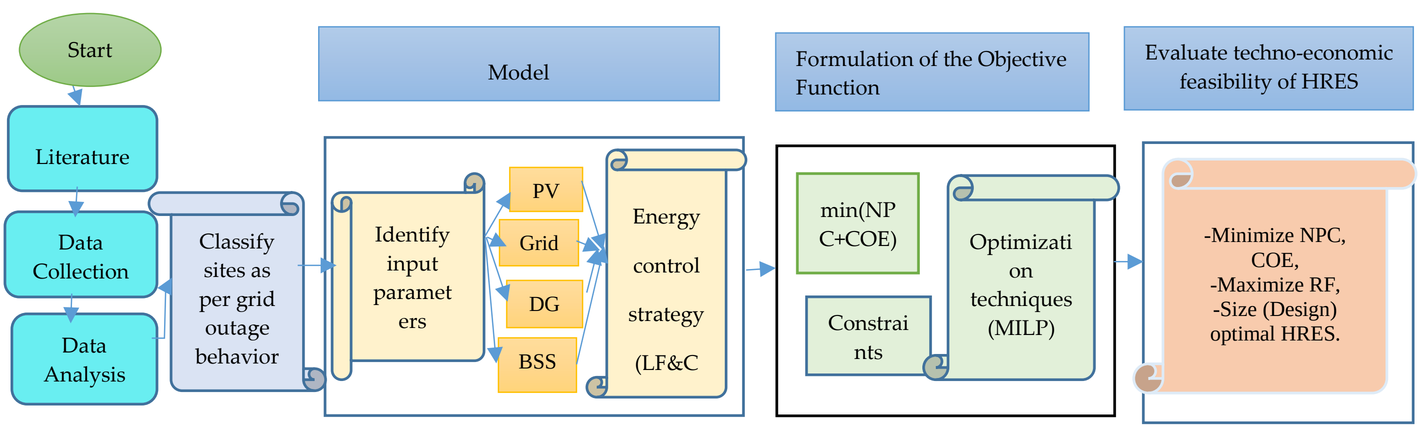

Figure 4 General methodology.

1.5 Related Work

Numerous studies have examined and analyzed the reliability and cost-effectiveness of hybrid power systems in various sectors; including industries, residential areas, commercial establishments, and small enterprises. These studies have explored different power configurations, optimization techniques, and energy management strategies to assess their effectiveness. Additionally, the techno-economic feasibility of various renewable hybrid power systems has been evaluated as part of these research efforts.

The author in[12] The study determined the optimum size and technical criteria for a stand-alone solar/battery power system that ensures 100% energy autonomy, long-term energy balance for solar-powered GSM base stations and evaluate techno economic feasibility, and compared the proposed solar power system.Optimization tool to design HES is Homwer Pro software tools, and analyzed the initial capital, replacement, operations, maintenance, and total net present costs for various solar-powered base stations.Annual OpEx savings of up to 65.45% in urban areas and 63.95% in remote areas.

In[13] Studied by a group of Authors about the techno-economic performance of grid-integrated/PV/Wind power systems of Ethiopia's Industrial parks(IP)(Awassa, Adama, and Kombolcha).Existing power supply for IP grid with standby DG, but due grid interpprution DG supply critical load and run for along time, due to fuel consumption and fuel cost increment company revenue and customer satisfaction decreases.The study investigates the renewable energy(wind and solar) potential and grid interruption in the area. Model each hybrid compnents using technical and economical input parametrs to and designby Homer pro optimizer to get optimal power configuration.Solar energy potential is feasible in all three regions, wind energy is feasible only in Adama.. The result of grid/diesel is the lowest cost but highest in emission, based on the technical, economical, and environmental perspective grid/diesel/PV/battery system is feasible.

The author of [14] Study was focused on the Optimal Sizing of Grid-PV Hybrid systems for Ethio telecom access layer devices to improve the performance of the system. The existing power type is grid/DG or/and Battery, operator phase to expand their network due to unreliability power, reachability, and high operating cost. This study investigates Addis Ababa BTS their technology type, power consumption, morphology, and solar potential of the area. PV/grid/battery systems are modeled and sized optimal hybrid power systems by minimizing the System lifecycle cost (LCC) with a linear programming optimization algorithm with defined constraints using Matlab simulation tools. The Result indicates that the LCC of PV is lower than DG for all mobile technology, and the energy cost of the grid is very lower than PV because PV economic competence is trapped by national policy. The limitation of the study was not considering grid outage data and had not seen different configuration hybrid systems.

The authors in[15] Review different papers on how to size optimally, control, and manage HRES to build a modern electrical grid using several energy sources. This paper reviewed different research study about how to size, optimize, plan, control, and manage HRES. The three different optimization techniques (conventional, new generation, and hybrid) were evaluated as per their performance, capacity, and ability to apply. Conventional is more successful for economically but solve for limited parameters, whereas new generation and hybrid required high hardware, advanced design, and complex code to get a high-performance result. Sizing method used conventional and commercial approach, Conventional is easy to use and has speed but is restricted in performance and analysis. Control and energy management strategy focused on technical, economic, and techno economical. The result of this study shows that sizing, optimizing, controlling, and energy management are key parameters to size technical, economic, and environmental feasible HRES. Each method has its own advantages and disadvantages, depending on user's requirement, capacity, and input parameters.

The authors [16] in paper study design an optimal hybrid power system using different renewable energy by using a Homer simulator for Romica Volcea country with a load capacity of 218W. Three case study is proposed for investors, wind with a battery, solar with a battery, and, solar and wind with a backup battery. Wind energy, PV panel, and battery storage system are mathematically modeled input parameters (solar irradiation, wind speed, a load profile) technically and economically. The optimization tools to design optimal power system with low net present cost is homer. The result indicates that the third case Solar and wind with a backup battery system is the optimal solution for investors with minimum NPC and initial capital cost.

The authors [17] in, the paper investigates renewable energy system (RES) a popular energy system for both grid-tied and standalone energy systems for commercial, residential, and industrial areas. Since RES is intermittent in nature, an energy storage system (ESS) is required, and see different ESS systems. However, there is a big challenge to estimate the system component of HRES due to its intermittent nature and load variation. This study identifies key components, parameters, data, and methods to size a reliable and feasible system as per the constraints. The objective functions are technical, economical, and environmental, NPC, COE, total annualized cost (TAC), loss of power supply probability (LPSP), and Renewable Fraction (RF) with a constraint optimal generation and energy storage. This paper reviews different papers including types of ESS and different optimization techniques. The result indicates to size optimal HRES new heuristic optimization techniques are more efficient, whereas software tools such as Homer cannot address the multi-objective issue, but software tools are flexible to the designer to size efficiently.

In summary, the above studies lay about power solution type and providing reliable power systems for BTS, the study had seen different types of energy sources and different types of optimal designing methods. The study focuses on how to provide reliable, cost-efficient, and green energy demand for the commercial, industrial, and residential sectors, RES with grid-connected or standalone is recommended. The most common RES used for telecommunication are solar and wind. To provide a reliable, cost-efficient, and environmental friendly energy system, RES with on-grid and off-grid are recommended. Studies have seen different types of optimization techniques, sizing methods, and energy management strategies. In general, designing optimal HRES system is reliable and cost-efficient for telecommunication and other sectors.

1.6 Scope and Limitation

1.6.1 Scope of the Thesis

The primary objective of this research is to develop a grid-connected PV hybrid power system for outdoor Ethio telecom BTS sites monitored by NetEco . The study aims to evaluate the technical and economic viability of the proposed hybrid power system, considering both grid/PV/DG/battery and grid/PV/battery configurations, and compare them with conventional power systems.

1.6.2 Limitation of the Thesis

The study focuses configure optimal PV hybrid power system for Ethio telecom BTS sites, but some limitation of the study are:

- All BTS sites arenot accessed by system monitoring, and can't get all site logged grid outage and hourly load profile. The only data was taken sites monitored by NetEco.
- From the representative site two sites are Indoor ,but due to a compatability issue AC eaquipments power consumption profile can't access it.
- In order to incorporate solar energy into the hybrid power system, , to measure solar radiation and other required input parameters from the site. The remote locations of the sites and the absence of appropriate measuring tools make it challenging to gather such data locally. So solar radiation data ws obtained from NASA.

1.7 Contributions

Main contribution is to conduct and analysis grid outage behavior sites , aiming to enhance the reliability of power systems and decrease operational costs. The study assesses the solar potential of various climatic zones to identify which zones are more suitable for utilizing solar energy. It also identifies the necessary input parameters, optimization techniques, and tools required for designing optimal hybrid power systems. and the study evaluates the techno-economic feasibility of PV hybrid power systems for BTS. Techno-economic evaluation serves as the primary metric for designing and sizing hybrid power components and systems.

1.8 Thesis Organization/Layout

This thesis is organized into six chapters. The first chapter is deals with background of the study, statement of the problem, objectives, scope and limitation, literature review, methodology and contributions of the study. The second chapter was focused on overall cellular network, Base transceiver station components, power consumption of base transceiver stations, energy source of base transceiver, and solar energy potential in Ethiopia stations.

Chapter three explains the background of techno-economic and lifecycle cost analysis, detail techno-economic modelling of a hybrid power system, optimization and simulation tools and formulation of objective function. Chapter four explains the case study data analysis of BTS sites to classify BTS sites grid interruption, and their climatic zone. Identify the required input parameter for simulating a hybrid power system to analysis techno-economic feasibility of hybrid power system. . Chapter five presents detail results obtained from techno- economic hybrid power system and comparing NPC of different configuration. And the last one is chapter six, which summarize this thesis work with future research area direction.

Chapter 2: Overview of Base Transceiver Station Power System

2.1 Overview of Cellular Network

In the telecommunication industry, one of the fastest-growing technologies is the cellular network, which facilitates the economy and society of the world. In the past decades, cellular communications have had short-tempered growth due to the recent technological advancement of the cellular network and telephone industries [18]. The cellular network is network of numerous low-power transmitters that operate by dividing an area into cells, each of which is served by an antenna. Each cell is frequency served by a base station; it has a transmitter, receiver, and control unit, Cellular systems are designed to operate with groups of low-power radios spread out over the geographical service area [18] .The technology grows from first generation to sixth generation as per capacity, reliability, accessibility, and speed.

The cellular network system comprises three primary layers, namely the mobile station (user equipment), Radio Access Network (RAN), and Core Network (CN).

The mobile station refers to devices such as mobile phones, tablets, or computers that are capable of data and voice communication, serving as the end user's equipment.

The **RAN** consists of base stations and radio access controllers, which act as intermediaries between the mobile station and the core network. It oversees and manages the wireless connection for the entire network.

The **CN** serves as the central component of the cellular network and is responsible for routing and switching between networks. The architecture of the 3G UMTS network is derived from GSM, with certain improvements made to the core network elements [19].

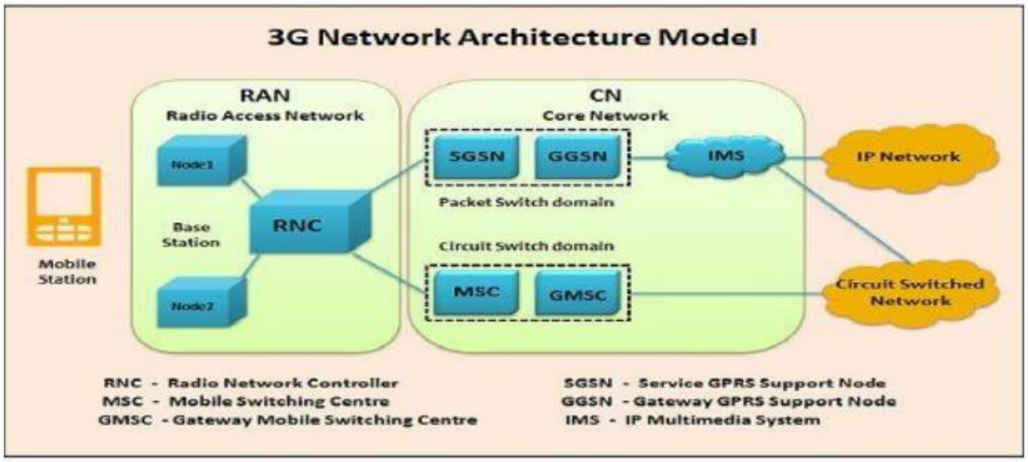

Figure 5. 3G network architecture model [18].

According to figure 5, 3G network, architecture RAN, CN and Mobile station, RAN contains RNC and BTS, RNC control multiple BTS ensure efficient utilization of radio resources and effective call handling by using packet and circuit switching.

In LTE and LTE advance, there is a network architectural advancement in 3G in all the three layers. The architecture layer is listed as follow:

User Equipment (UE) is any device capable of establishing communication functions like mobile phones, tabs, computers, etc. **Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) is** controls radio communication between user equipment and EPC. LTE mobile can connect with just one cell and one base station at a time. Main operations performed by EBS (Evolved Base Station). Evolved Packet Core (EPC): It communicates with internal and external packet data networks and IP multimedia subsystem [20].

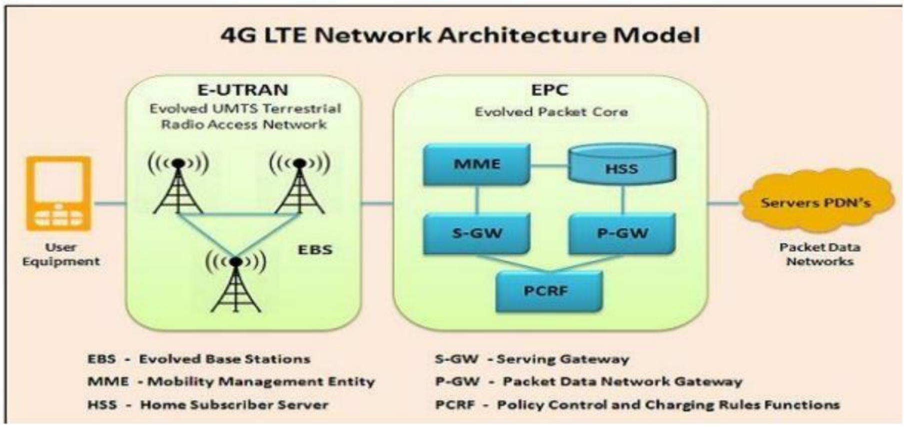

Figure 6 LTE (4G) architecture model [19].

According to figure 6 LTE and LTE-A network architecture are E_UTRAN, EPC and user equipment. E_UTRAN contains eNodeB and interface connecting network using internet protocol (IP) to EPC.

In general, all generations BTS works between the network and the mobile terminal and acting to provide the frequency interface between user and the network. BTS defines each cell that is in the geographical area coverage of the radio transmitter-receivers. It communicates with other parts of the cellular network, such as the Mobile Switching Center (MSC), to manage call setup, handover, and other network functions.

Multiple types of BTS are utilized to support various types of cells, including macro, micro, and small cells such as pico and femto cells. Each cell type differs in terms of coverage capacity, energy consumption, deployment arrangement, and associated costs [21].

2.2. Base Transceiver Station Components

The primary components of a BTS include transceivers (TRXs), power amplifiers (PAs), Base Band unit (BBU), Radio Frequency (RF) components, cooling system, AC-DC and DC-DC power supply, as well as alarm and monitoring systems [22] .

The BBU serves as the system responsible for digital signal coding and processing, handling transmissions over the network or from the Radio Receiver Unit (RRU). The RRU, in turn, is responsible for transmitting and receiving radio signals between the base station and mobile devices. The Antenna Unit plays a role in converting electrical signals into electromagnetic signals for RF transmission and reception. Transmission equipment, such as RTN&ATN, is utilized to transmit messages from the BTS to the Core network. Power Supply is a vital component that provides the necessary electrical power to BTS elements, comprising AC and DC power distribution units, rectifier systems, battery systems, and other backup power systems. Lastly, the Cooling System is employed to dissipate heat generated by the BTS components and maintain the operational temperature of the equipment.

2.3. Power Consumption of Base Transceiver Station

Small and micro cells base stations power consumption content and radiations are less as compared to macro base stations. Most of the electronic equipment requires cooling, therefore indoor Base stations are sheltered, and it requires air-conditioning system, this adds up to further power consumption [1].while core networks like MSC consume low power and also the mobile sations, which are mobile stations in nature and have indeed lower power consumption [23].

BTS has two types of power consuming equipment's; power amplifier, digital signal processing and transceiver are consumed DC power system, whereas cooling system (air conditioner) consumed AC power system.

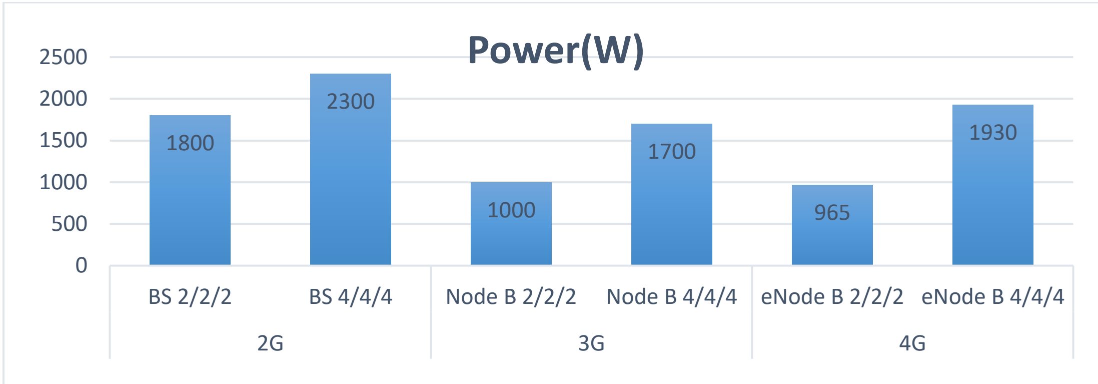

Figure 7 Power consumption for common cellular macro-BSs from different cellular generations [1].

Based on Figure 7, various cellular network configurations exhibit different power consumption levels, which also vary across different generations of technology. The graph illustrates a decline in power consumption as technology advances, highlighting the importance for wireless.

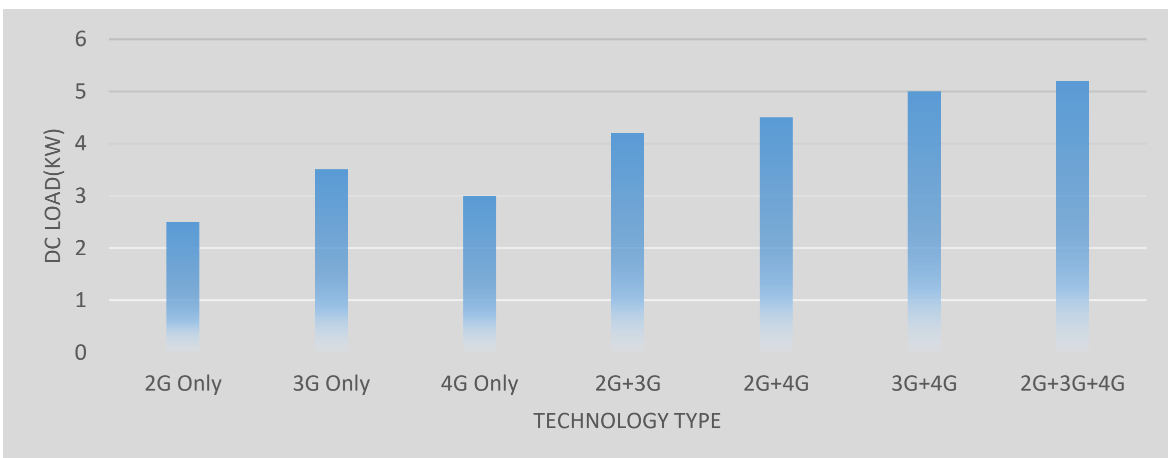

Figure 8 Average power consumption cellular BSs with the combination of generations [22].

Figure 8 demonstrates that standalone 3G technology exhibits higher power consumption in comparison to other technologies. Conversely, the two hybrid technologies display energy-saving characteristics for mobile stations.

2.4 Energy Source for Base Transceiver Station

BTS planning and network design is varies from operator to operator but do not consider detail power availability [17]. Improving energy efficiency also helps network operators reduce the operational cost by minimizing their energy cost and goes to green cellular network. Nowadays telecom Industries gives energy efficiency as one of the key performance indicators for cellular network design [24].

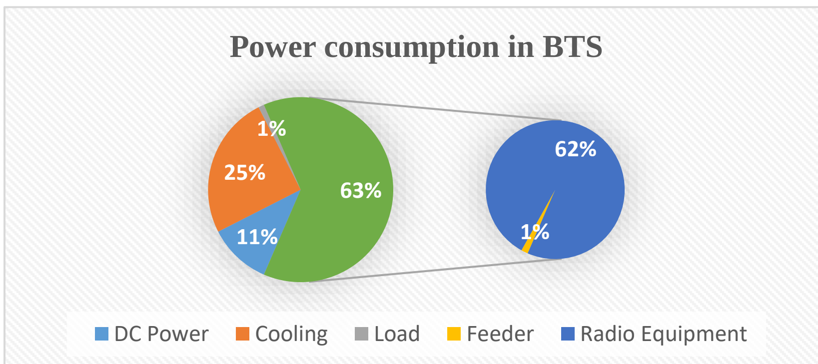

Figure 9 BTS sites load consumption per each equipment [21].

According to figure 9, in BTS, there are AC and DC power consumed equipment's. Radio, equipment's consume more than half of (62%) power of base station.

Ethio telecom has different types of power solutions in different scenarios, 45% of the sites power solution is a grid with standby DG and back battery, 29% grid with back battery, 21% PV with backup battery, and the rest 5% are Dual DG, Big Battery (BB)/ DG, PV/DG, Grid/PV, Grid/DG/Solar, and BB/DG/PV.

The common power solution criteria during the deployment of new sites are based on grid availability, grid availability hour within a day, site road access, space availability, area clearance. Power configuration types are listed below:

I. For towns, governmental service areas, investment locations, and downlink (Hub) sites situated up to 5 km away from the power grid, it is advisable to implement a power solution that combines grid power, diesel generator and Battery storage system (Grid/DG/BSS).

II. In rural areas and end, sites located up to 5 km away from the power grid, it is recommended to employ a power solution that incorporates grid power and Battery storage system (Grid/DG/BSS). This configuration is suitable for locations where there are no critical services in the vicinity.

III. For sites located between 5 km and 10 km away from the power grid, it is advised to implement a power solution that combines Big Battery Backup, and diesel generators (DG/BB). This configuration is recommended to meet the power requirements of such sites.

IV. For sites situated at distances greater than 10 km from the power grid, it is recommended to employ a power solution that combines Photovoltaic and battery storage system (PV/BSS). This configuration utilizing solar power is ideal for meeting the energy needs of such remote sites.

V. In case of In situations where frequent power interruptions pose challenges in terms of maintenance and refilling fuel, the power solution for sites may be transitioned to a configuration that combines Grid power, Photovoltaic and Battery storage systems (Grid/PV/BSS). However, it should be noted that there is no established design standard for this particular power solution.

2.4.1 Grid

In Ethio telecom, the power grid serves as the primary source of power for BTS. It supplies the sites with electricity if it is available, ensuring that the voltage and frequency fall within the permissible range required by the BTS equipment. The capacity of the grid requested from the utility is determined by considering the maximum power consumption of both the AC load and DC load, as well as the derating factor (utility factor).

2.4.2 Diesel Generator

DG is utilized in various capacities, such as standby, backup, and continuous (prime power), depending on the requirements of the BTS. In off-grid sites, DG is commonly used as the primary power source for BTS, while in on-grid sites; it serves as a standby and backup power solution. When there is a grid interruption or the grid voltage falls below or exceeds the acceptable range, the DG supplies power to all AC and DC load equipment in the BTS.

When configuring DG for the sites, several factors are taken into account. These factors include the total site load demand, the derating factor of the DG, and the working factor of the DG. By considering these factors, an appropriate DG configuration can be determined to meet the power requirements of the site effectively.

2.4.3 Solar Energy

Solar Energy is a technology that directly converts sunlight into electricity through the use of photovoltaic (PV) cells. These cells are typically composed of silicon or other semiconductor materials that absorb sunlight and generate an electric current. Solar energy can be categorized into two parts: extraterrestrial solar energy, which is sunlight above the Earth's atmosphere, and global solar energy, which is the sunlight reaching the Earth's surface.

In the field of telecommunications, solar systems are commonly deployed to provide power to continuous loads, ranging from small 1W single terminals to larger kW base stations and repeaters. These systems are especially useful in areas where there is no access to the electricity grid, such as rural regions. The panels used for converting solar energy into electrical energy offer several significant advantages, including:

- Independence from reliance on oil, gas, and the utility grid,
- Effective economic operation and low running costs,

- Long lifespan,
- Environmentally friendly with no pollution, noise, or dirt emissions [25].

The array refers to a grid-like arrangement of solar panels that are interconnected in a series-parallel configuration based on design requirements. The interconnection of solar panels within the array involves both series and parallel connections. Series connections are utilized to increase the voltage, while parallel connections are used to increase the current. Solar cells provide a constant current and generate voltage for impedance matching.

V_A and I_A be array output voltage and current, respectively. Power delivered to load is then:

$$P_L = V_A I_A \quad (2.1)$$

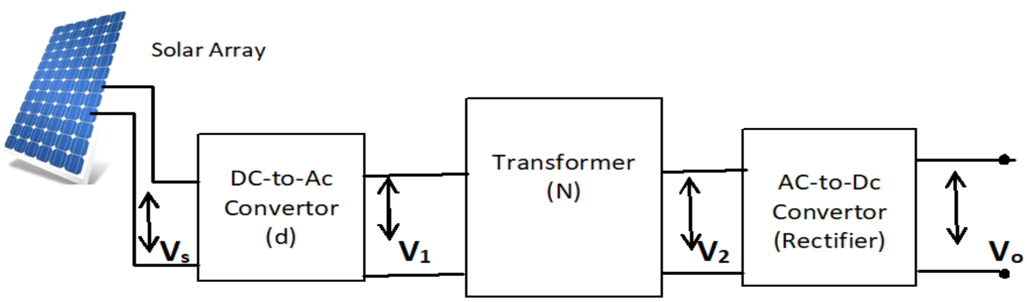

Figure 10 Solar voltage adjustment using transformer and DC-DC Converter [25].

In Figure 10, the voltage generated by the solar array is influenced by various factors, and to mitigate this variability, a transformer is used to increase the overall system voltage. In a BTS rsystem, the voltage requirement is 48V DC. To ensure a consistent load voltage, a DC-to-DC

current produced by the solar array is solely determined by the intensity of sunlight it receives. When the solar irradiance varies from its maximum to minimum levels, the array's output voltage exhibits characteristic operating points. Specifically, as the irradiance increases, the current generated by the array also increases, while the voltage decreases in an inverse relationship [25].

When designing a solar array, increasing the number of panels connected in series results in an increase in the output voltage capacity. On the other hand, increasing the number of parallel connections of solar panels leads to an increase in the system's current. However, this increase in parallel connections also results in a reduction in the current supplied by the solar array, which can be advantageous for reducing the size of the required cabling.

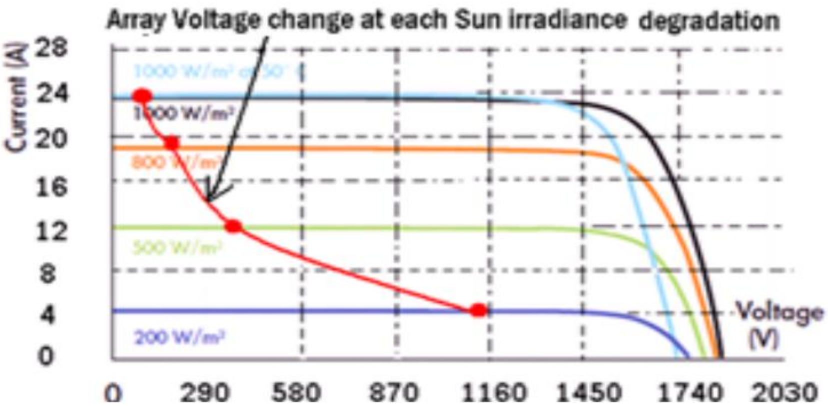

Figure 11 Effect of sun irradiance degradation on the solar array output voltage operation point [24].

Based on the information presented in Figure 11, it can be observed that as the solar radiance decreases, the current generated by the solar array also decreases. However, in contrast, the voltage produced by the array actually increases during this decrease in solar radiance.

2.4.4 Battery Storage System

BSS is a technology that allows power system operators and utilities to store energy for future utilization. This system utilizes an electrochemical device to collect energy from the grid or another power source and subsequently releases stored electrical energy as needed. Batteries are constructed using various battery chemistries, chosen based on factors such as their intended use, capacity, cost, and manufacturing standards. Examples of battery chemistries include lithium-ion, lead-acid, and redox flow batteries. Different battery chemistries possess distinct technical characteristics, with advancements in technology and manufacturing capacity contributing to their continuous improvement. Notably, lithium-ion chemistries have experienced a significant price reduction of over 70% between 2010 and 2016 [26] .

The main characteristics of battery storage systems include:

- **Rated power capacity** is the maximum instantaneous discharge capability of the system, measured in kilowatts (kW);

- **Energy capacity** is the maximum amount of energy that can be stored in the system, measured in kilowatt-hours (kWh);
- **Storage duration** is the period of time during which the storage system can discharge at its power capacity before depleting its energy capacity;
- **Life cycle/lifetime** is duration over which a battery storage system can consistently provide charging and discharging cycles before experiencing a decline in performance or failure;
- **Self-discharge** is the stored energy of the battery diminishes due to internal chemical reactions, such as internal resistance and other chemical processes;
- **Round-trip efficiency** is a measure of efficiency and is expressed as a percentage ratio of the energy charged into the battery to the energy discharged from the battery [26].

In telecommunications, high-capacity batteries are employed due to their durability, compact design, efficiency, long lifespan, and improved power output. There are two main types of batteries commonly utilized in telecommunications: lead acid batteries and lithium-ion batteries. Lead acid batteries are compact, easily deployable, and cost-effective. They offer fast response times for charging and discharging operations and have a lead usage recycling rate of 80%.

There are two types of lead-acid batteries:

Flooded lead acid battery is a type of battery where the electrolyte is exposed and not contained.

V**alve-regulated lead acid (VRLA) battery**, the electrolytes are sealed within the battery. On the other hand, lithium-ion batteries(LiFePO4) employ advanced battery technology, offering advantages such as longer float life compared to VRLA batteries, improved energy density, high-rate performance, better temperature tolerance, and the absence of ventilation requirements. However, there are concerns regarding the safety, reliability, and service life of modular energy systems using LiFePO4. In lead acid batteries, there is a 50% reduction in float life for every 10°C increase in operating temperature, whereas lithium-ion batteries tolerate 70% of their original capacity under similar conditions [27].

Presently, **LiFePO4** battery technology is widely employed in telecom equipment. While the technology has proven to be reliable and safe, its higher cost is attributed to its specific chemistry. However, there is currently a significant global shift towards adopting this battery chemistry, leading to a rapid reduction in prices [28].

The BTS battery system serves as a backup power supply in situations where the primary power sources, such as the grid, solar, and wind, experience interruptions. In some cases, the battery system also functions as the primary energy source when used in conjunction with a diesel generator (DG). The battery is charged using surplus power from various sources, including solar, grid, DG, wind, and other energy resources.

In the context of Ethio telecom BTS sites, the battery system is primarily utilized as a backup power solution. The backup duration varies depending on the power source configuration. For example, the backup duration can be 8 hours when using the grid and a battery storage system (BSS). In the case of a combination of grid, DG, and BSS, the backup duration can be 3 hours. Alternatively, when employing solar power in conjunction with a BSS, the backup duration can be extended up to 72 hours.

2.4.5 Hybrid Energy System

A HES refers to the integration of two or more energy sources, whether conventional or renewable, along with an energy storage system. This combination aims to enhance energy efficiency, reliability, and overall capacity. Common examples of renewable energy sources utilized in hybrid systems include wind power, solar power, hydroelectric power, and biomass. By integrating these diverse energy sources, hybrid energy systems offer a more sustainable and resilient solution for meeting energy needs.

The existing energy infrastructure requires significant transformation in response to the ongoing increase in fossil fuel prices and the environmental issues associated with pollution. Renewable energy sources offer a potential solution by reducing electricity costs and providing sustainable alternatives. However, designing an energy storage system for hybrid power generation is a complex task that necessitates intuitive energy management. This management involves the application of various optimization techniques to ensure efficient and effective utilization of different energy sources in the hybrid system [29], [30].

Renewable energy such as solar systems with diesel improves cellular network service by supplying base station sites [31].

2.5 Solar Energy Potential in Ethiopia

Ethiopia has one of the lowest per capita electricity consumption rates in Africa. The country's current energy consumption stands at approximately 40,000 GWh, with domestic appliances accounting for about 92% of the total, followed by the transport sector at 4%, and industry at 3%. To tackle the challenges related to energy supply and utilization, Ethiopia has implemented the National Energy Policy since 1994. This policy focuses on prioritizing the development of hydrological energy resources. In 2013, a second national energy policy was drafted, which further emphasized the importance of incorporating additional Renewable Energy (RE) sources as key players in the country's future energy development [32].

"Ethiopia is located in the East of Africa and lies between 3° to 15°N latitude and 33° to 48°E longitudes, has abundant solar energy and its solar irradiation ranges from 4.5 $kWh/m^2/day$ to 7.5 $kWh/m^2/day$" [32]. Solar energy is abundant energy all over Ethiopia and sunny time per day is long. Solar technology improve efficiency, capacity, and decrease investment cost. It is used as standalone, or hybrid energy system combined with other energy sources.

Chapter 3: Method of Evaluating Techno-Economic Feasibility of the Hybrid Power System

3.1 Techno-Economic and Lifecycle Cost Analysis

Techno-economic analysis (TEA) and life cycle cost analysis (LCCA) is valuable tools for driving efficient resource utilization; TEA is identifying the way of development efficient technology and how to deploy profitable technology, TEA measures OpEx) and capital (CapEx) expenditures and intensely rely on technological development. Whereas LCCA show the cost-effectiveness of the project with its lifetime [33],[34].

At TEA contains the integration of engineering design, modeling and economic evaluation using a method of defining the technology level, identifying the system, analyzing market, cost and feasibility profitability, risk analysis and recommendation [35].

LCCA considers different factors such as the time value of many, and economic uncertainty factors. It uses a method of defining a problem and objectives, cost analysis, cash flow, risk, and uncertainties by considering all costs (capital cost, operating cost, replacement cost, and salvage cost) [35]. To study techno-economic feasibility of a hybrid power system, common metrics are improved reliability, minimized NPC, COE, and carbon emission. So LCCA method are proposed for this study.

Figure 12 Lifecycle cost analysis [35].

Figure 12 illustrates that, the initial cost is lower compared to the LCC, with the primary expenses lying in O&M costs and service costs. Therefore, when designing the LCC, it is crucial to consider the key technical and economic metrics to ensure the deployment of a reliable and cost-effective project or system.

Telecommunication is the backbone of the economic and social interaction of the world. MNO tries to provide reliable and reachable service. One of the biggest challenges to providing reliable service is the power system, reachability, reliability, and sustainability. Common power sources for telecom equipment's are utility grid, solar, DG, wind, and hybrid system.

The rapid power demand growth of the ICT industry is not only affecting the public utility grid but also increase environmental pollution. To solve the above issue renewable hybrid energy system is recommended.

3.2 Techno-Economic Modeling of a Hybrid Power System

Techno-economic modeling integrates both technical and economic aspects of a system in a single mathematical formulation and solution. "The technical model computes the power generated and consumed by the system, while the economic model estimates the effective cost of the generated power. These two models are linked by a common denominator. The techno-economic approach considers the effect of variables from both aspects co-currently. This model will be used to evaluate the overall viability of the HES" [13].

3.2.1 Technical Modeling

Many researches have focused on conducting techno-economic analyses, feasibility studies, and evaluations of hybrid energy systems. These studies utilize technical, economic, and environmental metrics to assess the viability and potential of such systems. In particular, researchers have employed LCCA method to evaluate the techno-economic aspects of HES. The objective is to develop reliable and cost-efficient energy systems that can address grid interruptions experienced by BTS. The design of the proposed PV hybrid power system requires input parameters such as PV panels, DG, grid, and BSS. Each component can be modeled according to its specific application and requirements to achieve the desired output of HES.

Power balance of HES is calculated with eqn.(3.1),

$$P_L^{(t)} = P_{PV}^{(t)} \pm P_{BSS}^{(t)} \pm P_{DG}^{(t)} \pm P_{Grid}^{(t)} \quad (3.1)$$

I. Modeling of Photovoltaic System

PV panels generate electricity by converting solar irradiance emitted by the sun. It's important to note that these solar energy resources are intermittent in nature and do not generate electricity during nighttime when solar irradiance is not available.

The power output of the PV array is determined by the level of radiation that reaches its surface. To calculate the total solar radiation incident on the PV array's surface, two parameters are considered: the slope and azimuth of the PV array's orientation. Solar resource data provides information on the average solar radiation that reaches a horizontal surface at the Earth's atmosphere for each time interval. The clearness index, which is the ratio of surface radiation to extraterrestrial radiation, is used to quantify the amount of solar radiation reaching the PV array's surface.The clearness index to display monthly average global radiation statistics from the National Renewable Energy Laboratory (NREL) using geographical coordinates information [36].

The Clearness index defined by the eqn.(3.2) is,

$$K_T = \frac{G}{G_o} \quad (3.2)$$

Wher: G is the global horizontal radiation on the earth's surface [kW/m2], and G_o is the extraterrestrial horizontal radiation [kW/m2].

The input required for modeling PV power systems are solar irradiance (in W/m2), and temperature (in °C) [37],[38].

To calculate the output of PV array by using eqn.(3.3),

$$P_{PV} = P_{pv(rated)} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) \left[1 + \alpha_p (T_C - T_{C,STC}) \right] \tag{3.3}$$

Where: $P_{pv(rated)}$ is the rated capacity of PV module (kW), f_{PV} is PV derating factor (%), G_T is solar radiation incident on the PV array in the current time step [kW/m^2],$G_{T,STC}$ is solar incident radiation at standard test condition [1 kW/m^2],α_p is the temperature coefficient of power [%^{o}C], T_C is the PV cell temperature in the current time step [^{o}C], and $T_{C,STC}$ is the PV cell temperature under standard test condition [25^{o}C].

II. Modeling of a Battery storage system

Determining the maximum charge power is crucial when making decisions related to the utilization of surplus renewable power or determining the appropriate output of a cycle charging generator. The maximum charge power is not constant and varies from one time step to another based on factors such as the state of charge and the recent charging and discharging patterns of the storage bank. To charge the BSS for a specific time step, the required power can be calculated,[37].

The present value of the state of charge (SOC) determines the allowable charging and discharging of the BSS. The SOC of the BSS anatomy time (t)

$$SOC_{(t)} = SOC_{(t-1)}\left(1 - \delta_{Batt(t)} + \frac{P_{Batt(t)}}{V_{bus}} * \eta * \Delta t\right) \quad (3.4)$$

Where: Δt is the time step for the iteration (one hour), δ is represents the hourly self-discharge factor, η is the battery efficiency (considered 100%), V_{bus} is the voltage of the dc bus (V), and N_{bat} is the total number of batteries in BSS.

BSS discharging is halted if SOC is reached. The P (t) represents the charging and discharging power of BSS according to required and available power, respectively.

The required power to charge the BSS for one-time step (hour) is by eqn.(3.5),

$$P_{Batt(t)} = \left(\frac{SOC - SOC_{(t)} * C_{Batt} * N_{Batt}}{\Delta t}\right) \quad (3.5)$$

P(t) is the maximum power that BSS can continuously deliver (discharge) before reaching the SOC limit.

$$P_{Batt(t)} = \left(\frac{SOC - SOC_{(t)} * C_{Batt} * N_{Batt}}{\Delta t}\right) \quad (3.6)$$

Where: C_{Batt} is the rated capacity of battery,and N_{Batt} number of battaries.

By using equation 3.5 and 3.6 we calculate state of charge at time step t,

$$SOC_{(t)} = SOC_{(t-1)} + \left[P_{Charge(t)} - P_{discharge(t)}\right] * \frac{\Delta t}{C} \quad (3.7)$$

The formula specifically computes the variation in State of Charge (SOC) during the time interval Δt. It does so by comparing the power entering the battery (Pcharge(t)) with the power being discharged from the battery (Pdischarge(t)). By multiplying these power values by Δt, they are converted into an energy quantity. This energy value is then divided by the battery capacity (C) to determine the change in SOC.

III. Convertor Modeling

The power supply for base stations involves the use of both AC-DC and DC-DC converters. This is because the network equipment requires DC power. PV and BSS are connected to the utility grid through a DC bus. The DC-DC converter is responsible for performing maximum power point tracking (MPPT) control, while the bi-directional charger of the BSS manages the flow of DC power in both directions [25].

The capacity of the converter is determined based on factors such as the peak rated demand of the load, as well as the efficiency of the inverter and rectifier.

If P_{PL} is the peak load demand of the system and η_{Inv} is the efficiency of the inverter, the output power of the inverter (PInv) (in kW).

$$P_{conv} = \frac{P_{PL}}{\eta_{Conv}} \tag{3.8}$$

Where: P_{conv} is the output power of the converter in (kW), P_{PL} is the peak rated load demand in (kW), and η_{Conv} is efficiency of the converter.

IV. Diesel Generator Modeling

The DG serves as both a backup and primary source of energy for BTS. It is activated in situations where the Grid, PV, and BSS are unable to generate enough power to meet the load requirements. The output power of the DG is influenced by factors such as its efficiency-rated power and derating factors.

$$P_{DG} = P_r * N_{DG} * \eta_{DG} \tag{3.9}$$

Where: P_r is the rated power of the generator (kW), $\eta_{DG}$is the efficiency generator, and N_{DG} is number of generators.

A diesel generator is an ancillary component of the existing supply system, and it consumes diesel fuel to produce electricity. The fuel consumption of the generator is depend on the capacity of the generator and the load when the generator is operating. Fuel efficiency curve is the amount of fuel consumed to produce electric power, and set by manufactures and differ by manufacturer, model, and engine. To calculate the slope and intercept of fuel curve by using linear regression method, [13].

To model the fuel usage (Fc) of a DG in liter/kWh.

$$F_c = AP_r + BP_{out(t)} \tag{3.10}$$

Where: A is fuel curve intercept, B is fuel curve slope, P_r is power rated and $P_{out(t)}$ is output power within a time.

V. Grid Power Modeling

The grid provides electricity when the demand exceeds the power generated by PV energy sources, and it consumes electricity when there is surplus power from PV sources.

The cost of grid electricity is determined by two factors: the price at which electricity is purchased from the grid, and the price at which excess power is sold back to the grid. The equations below are utilized to represent and analyze the exchange of energy with the grid [37].

The grid maintains the balance between power supply and consumption. The load requirement is calculated as:

$$P_{G(t)} = R_{G(t)} * P_{L(t)} \tag{3.11}$$

The $R_G(t)$ is the reserve margin coefficient using the eqn.(3.11),

$$P_{G(t)} = \begin{cases} B_{G(t)} * P_{L(t)}, & B_{G(t)} > 0 \\ 0 & B_{G(t)} = 0 \end{cases} \tag{3.12}$$

Where: $B_{G(t)}$is a binary variable that describes the state of the grid at a specific hour. The value for $B_{G(t)}$ is determined according to the actual load-shedding schedule imposed by the grid operator.

3.2.2 Cost Modeling

LCC is total cost owning and operating of a hybrid energy system over its entire lifetime system. It includes capital cost, operational &maintenance costs, replacement costs and salvage value of the project.The key economical parameters for evaluating the economic feasibility of the project are the nominal discount factor, inflation rates, and project lifetime.

For constructing a hybrid power system that depends on annual load growth; a longer project lifecycle has hurdles to consider in terms of economic and technical aspects. Other likely factors include reliance on the weather, a decline in their annual efficiency, and changes in their O&M costs.

I. Capital Cost or Initial Cost

Capital cost (CC) is the initial cost of purchase and the installation of the equipment used for a hybrid power system.

$$C_C = C_G + C_{PV} + C_{DG} + C_{BSS} + C_{conv} \quad (3.13)$$

Where: C_C is the total capital cost of the proposed hybrid power system, C_G is the total capital cost of the grid power system, C_{PV} is the total capital cost of a PV panel, C_{DG} is the total capital cost of a diesel generator, C_{BSS} is the total capital cost of the battery storage system, an C_{conv} is the total capital cost of the inverter.

II. Operational & Maintenance Cost

It contains all the expenses, which are system operations during the lifetime of the project. Operational costs include preventive and proactive maintenance, fuel cost, utility cost, and labor cost; and these costs determine by subtracting the total yearly cost from the capital investment. These costs contain O&M of hybrid power system components PV, grid, DG, BSS, and convertors, $C_{O\&M}$ is calculated as:

$$C_{O\&M} = \frac{\sum_{n=0}^{N} C_{O\&M,PV}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{O\&M,Grid}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{O\&M,DG}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{O\&M,Conv}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{O\&M,BSS}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{Fuel}}{(1+i)^n} \tag{3.14}$$

III. Replacement Cost

Replacement Cost (RC)is the cost spent for the equipment replacement when, their service time is end or their performance is degraded up to the project's lifetime, Total replacement of the hybrid system, C_{RC} is calculated as:

$$C_{RC} = \frac{\sum_{n=0}^{N} C_{RC,PV}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{RC,DG}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{RC,Conv}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{RC,BSS}}{(1+i)^n} \tag{3.15}$$

IV. Salvage Value

Salvage value is the remains value of the system or the components at the end of the project lifetime. It represents the amount of money that can be recovered from selling the system or its components as scrap or for reuse after the end of their useful life [12].

The return value of the component or salvage(S_V) is calculated as:

$$S_V = C_{rep}\left(\frac{R_{rem}}{R_{comp}}\right) \tag{3.16}$$

Where: C_{rep} is replacement cost, R_{rem} is the remaining life of the component at the end of the life of the project and is indicated by:

$$R_{rem} = R_{comp} - (R_{Proj}) \tag{3.17}$$

R_{comp} is the time for the replacement cost of the components, and it is calculated as:

$$C_{rep} = R_{comp} \frac{R_{proj}}{R_{comp}} \tag{3.18}$$

Where: C_{rep} is component replacement cost, R_{comp} is the lifetime of the component (year), R_{Proj} is the lifetime of the project (year).

3.3 Energy Management Strategy

Energy management strategies are used to maximize the efficiency and reliability of energy systems while minimizing costs and environmental impacts. This can be achieved through various techniques such as load balancing, demand response, energy storage, and renewable energy integration cycle charging strategy and to ensure optimum energy flow concentrates on techno-economic objectives.

The optimizer starts by doing a precise optimization assessment for each hybridization case, calculating cost savings, reliability gains, and pollution reductions Cycle charge (CC) or Load following (LF) strategies [39].

3.3.1 Load Following Strategy

At LF method, PV supply the load demand at the same time charge the battery system, when the PV doesn't enough power to supply the load, the battery starts to supply the load. DG produce sufficient power to meet the required load only when both PV and battery system cannot produce enough energy [40].

When, P_{PV} < P_L, P_G=0 and SOC <SO Cmin, DG meets net load demand and formulated as:

$$P_{DG(t)} = P_{L(t)} \quad (3.19)$$

3.3.2 Cycle Charging Strategy

In cycle charging method, DG works to produce sufficient power to meet the required load and battery charging when the battery state of charge is below the minimum state of charge. This strategy is when the PV system and Grid can't have enough power for the load. The DG works at rated power and the excess power charge the battery system.

If the load cannot be supplied by the energy source i.e. the power of the PV panels is insufficient to supply the load and the battery is at its minimum SOC, then the diesel generator will be used to supply the load and charge the battery [41],[40],[42].

$$When, P_{PV} < P_L, P_G = 0, and\ SOC < SOC_{min}$$

DG runs at rated capacity supply to load and battery.

$$P_{DG(t)} = P_{L(t)} + P_{batt,ch(t)} \quad (3.20)$$

3.4 Optimization Techniques and Simulation Tools

3.4.1 Optimization Techniques

Mathematically sizing a hybrid power system can be complex, the complexity of sizing a hybrid power system can be addressed by using a combination of mathematical modeling and simulation tools, expert knowledge, sensitivity analyses, and iterative optimization. The most difficulties encountered are the evaluation of real load and step time accurately, intermittency of renewable energy, and fuel cost variation.

Optimization of integration of renewable sources in coherent energy more complex, because of the problem is nonlinear, non-convex, and has multiple local optima [43].

In the field of research, various optimization techniques have been employed to design HRES based on their performance metrics. These techniques can be broadly classified into three categories: traditional (conventional) and new generation (meta-heuristic) and hybrid approaches [44], [45].

To apply a conventional method to design optimal configuration by using the least square method, iterative and probabilistic approaches, linear and mixed integer linear programming. The non-conventional method used for large engineering optimization problem get the optimum solution of a computational method with natural evolution or social behavior of the species. Whereas hybrid techniques use two and more combination of optimization techniques and solve multi problems, but it has complex code and takes a long time to get local maxima and minima[44].

In order to investigate the techno-economic feasibility of grid-connected PV hybrid power systems, the necessary data is gathered as per the problem statement. The collected data consists of both continuous and discrete variables. The continuous data includes parameters such as solar irradiance, which represents the intensity of sunlight, and load demand, which indicates the amount of power required by the system.

On the other hand, the discrete data affects to the sizing of various components within the system. This includes determining the appropriate capacities for PV panels, DG, and BSS. Additionally, the data also encompasses information regarding of grid outages.

To solve this problem as per data behavior Mixed Integer Linear Programming (MILP) optimizer is selected. MILP optimization algorithm was developed using the Matlab at software to compute the optimal solution of the problem [46].

The MILP solver would then optimize the system design and operation by adjusting the decision variables to minimize the objective function subject to the constraints, and formulating the constraints as linear equations or inequalities, the user can ensure that the optimization problem is feasible and meets any additional requirements or limitations [47].

The MILP domain allows for a certain degree of modeling flexibility but inherently is limited by the requirement of linearity. Non-linear and highly complex processing systems are often simulated using flow sheeting software or purpose-built industry-specific tools.

To evaluate the techno-economic feasibility of a hybrid power system using MILP, the user would define the decision variables, objective function, and constraints that represent the system under consideration [46].

To evaluate the techno-economic feasibility of the component and system, most researchers used a HOMER optimization and simulation software tools. Optimization methodologies that do not rely on commercial software can be based on different algorithms

3.4.2 Simulation Tools

Homer Pro is a software tool developed by the National Renewable Energy Laboratory (NREL) in the United States; it is an optimization and sensitivity analysis to simulate different system configurations taking different technology costs and availability of energy sources [36].

It is widely used for the design off-grid and on-grid hybrid power systems and standalone power systems. It is predicting and ensures the long-term performance of hybrid power systems by understanding the energy production of configuration [48].It simulates different configuration that satisfies the technical constraint of the at lowest net present cost under the range of input parameters [49].

Homer is one of the tools used to design renewable energy systems for mobile base stations by Global System for Mobile Communications Association (GSMA) [50].

Based on the research findings, **Homer Pro** employs various optimization and simulation methods to develop and assess hybrid power systems ranging from large-scale power plants to independent small-scale systems based on specific demand requirements. For my study, I have chosen to utilize Homer Pro as the primary tool. This preference stems from the fact that Homer Pro encompasses both component and system-level sizing, takes into account technical and economic limitations, provides pre-defined input parameters, and incorporates methodological data that is inter linked with NASA and NREL. Additionally, Homer Pro offers diverse energy management strategies and has the capability to solve MILP optimization problems.

3.5 Formulation of Objective Function

The aim of this study is to develop an objective function that achieves a dependable and cost-effective design for a grid-connected HRES for BTS. The hybrid power system is designed to minimize the levelized cost of energy (COE), minimize the net present cost (NPC), enhance reliability, and increase the proportion of renewable energy in the system.

The objective function is to minimize NPC, COE, of grid/PV/DG/BS hybrid energy and other configuration:

Objective Function:

$$\min\,(\mathrm{NPC} + \mathrm{COE}) \tag{3.21}$$

To minminzie the total cost mean minimzing intial cost, O&M cost and replacement cost of the system . formulated as eqn.(3.22).

$$minNPC = \min\left(C_{cap} + C_{O\&M} + C_{rep} - C_{SV}\right) \tag{3.23}$$

Input Variables are energy demand, energy sources (Grid, PV, and DG), BSS, system efficiency, capital cost, operational cost, lifetime of components, and discount rate.

The **constraints** to consider designing a hybrid power system to be feasible are:

Energy Balance Constraint: the requirement of energy generated by the system to satisfy the load demand. In a hybrid power system, it ensures the total energy generated and the equilibrium between energy consumption within the system.

$$P_L^t = P_{grid}^t \pm P_{battery}^t \pm P_{PV}^t \pm P_{DG}^t \quad (3.24)$$

Energy Storage Constraint: avoids any overcharging or over-discharging of the batteries and ensures optimal utilization of the battery system, SOC is set bettewn minimum SOC and maximum SOC and formulated as eqn.(3.25),

$$SOC_{Batt}^{min} \leq SOC_{Batt} \leq SOC_{Batt}^{max} \quad (3.25)$$

Component size: minimum and maximum sizes of the component, the number of componets is affect the total performance of the system aswellas the cost [37].

$$N_i^{min} \leq N_i \leq N_i^{max} \quad (3.26)$$

3.5.1 Net Present Cost

The NPC is the sum of initial capital, operational & maintenance, replacement, and fuel costs over its entire lifetime, discounted to reflect the time value of money less the salvage cost at the end of the project's life cycle [48].

Total Annual Cost (Cann, tot) is the total annualizing cost of all power system components including capital, O&M, replacement, and fuel cost.

$$C_{ann,tot} = \sum_{i=1}^{n} C_{(C,i)} + \sum_{i=1}^{n} O\&M_{(C,i)} + \sum_{i=1}^{n} R_{(C,i)} + \sum_{i=1}^{n} F_{(C,i)} \quad (3.27)$$

NPC is the LCC of the project or system, which includes capital cost, operational and maintenance cost, replacement cost, and fuel cost of the system with the lifetime of the project [51], [52]. To calculate NPC, by dividing total annual cost to recovery factor of the project, formulated as eqn.(3.28),

$$NPC = \frac{C_{ann,tot}}{CRF_{(i,Rproj)}} \quad (3.28)$$

Where: NPC is the net present cost, $C_{ann,tot}$ is the total annual cost in ($/year), and$C\ RF_{(i,Rproj)}$ is the recovery factor with Rth lifetime of the project in years.

Each component capaital, O&M, and replacement cost is calaculated in the below eqn.(3.29),(3.30), and(3.31),

$$\mathrm{C_C} = \sum \mathrm{N_{PV}Cc_{PV}} + \sum \mathrm{N_{DG}Cc_{DG}} + \sum \mathrm{N_{BSS}Cc_{BSS}} + \sum \mathrm{Cc_{Grid}} + \sum \mathrm{N_{Conv}Cc_{conv}} \quad (2.29)$$

$$\mathrm{C_{O\&M}} = \sum \mathrm{N_{PV}C_{O\&M,PV}} + \sum \mathrm{N_{DG}C_{O\&M,DG}} + \sum \mathrm{N_{BSS}C_{O\&M,BSS}} + \sum \mathrm{C\ _{O\&M,Grid}} + \sum \mathrm{N_{Conv}}C_{\mathrm{O\&M,conv}} \quad (3.30)$$

$$\mathrm{C_R} = \sum \mathrm{N_{PV}C_{RPV}} + \sum \mathrm{N_{DG}C_{R,DG}} + \sum \mathrm{N_{BSS}C_{R,BSS}} + \sum \mathrm{C_{R,Grid}} + \sum \mathrm{N_{Conv}C_{R,conv}} \quad (3.31)$$

To calculate the NPC from cash flow, you need to discount the cash flow values over time to account for the time value of money; The net cost or net value of the project after considering the time value of money, is calculated as eqn.(3.32),

$$\mathrm{NPC} = \mathrm{C_{FO}} + \frac{\mathrm{C_{F1}}}{(1+\mathrm{i})^1} + \frac{\mathrm{C_{F1}}}{(1+\mathrm{i})^1} + \frac{\mathrm{C_{F2}}}{(1+\mathrm{i})^2} + \frac{\mathrm{C_{F3}}}{(1+\mathrm{i})^3} + \cdots \frac{\mathrm{C_{FN}}}{(1+\mathrm{i})^{\mathrm{N}}} \quad (3.32)$$

$$NPC = C_{FO} + \sum_{r=1}^{N} \frac{C_{FN}}{(1+i)^N} \quad (3.33)$$

Where: C_{FO} is the initial capital cost, and C_{FN} is the cash flow of N- year.

$CRF_{(i,Rproj)}$ is the function to calculate the coefficient of return on investment (ROI) is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows) [51].

$$CRF_{(i,N)} = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (3.34)$$

Real discount rate (interest rate) from the input data of the nominal discount rate and expected inflation rate. It is calculated as eqn.(3.35),

$$i = \frac{i' - f}{1 + f} \quad (3.35)$$

Where: i is the real discount rate (%), i' is the nominal discount rate (%), f is the expected inflation rate (%), and N is the number of periods (years).

3.5.2 Cost of Energy

COE is the critical metrics for comparing the hybrid system's economic parameters. It is the average cost of HES by the total served electricity (kWh)over the lifetime, or the total system cost over total the tolal energy production cost [53], [39]. It is calculated using eqn. (3.36),

$$COE = \frac{Total\ system\ cost}{Total\ Energy\ generated} = \frac{C_{ann,tot}}{E_{Served}} \quad (3.36)$$

Where: E_{Served} is the total energy generated (kWh/year).

The total system Cost of HES is total cost of components, calculated as eqn.(3.37),

$$C_{HES} = C_{PV} + C_{BSS} + C_{DG} + C_{Conv} \quad (3.37)$$

The total Energy is energy generated by PV& DG, Grid, and battery. it calculated as eqn.(3.38)

$$E_{HES} = E_{PV} + E_{DG} + E_{Grid} \quad (3.38)$$

3.5.3 Renewable Fraction

The renewable fraction(RF) is the fraction of the energy delivered to the load that originated from renewable power sources. The increasing of RF decrease NPC. It calaculated as eqn.(3.39),

$$RF = 1 - \frac{E_{nonren}}{E_{served}} \quad (3.39)$$

Where: E_{nonren} is nonrenewable electric production (kWh/yr.), and E_{served} is the total electrical load served (kWh/yr).

Chapter 4: Deployment and Simulation of Hybrid Power System

4.1 Data Collection and Analysis

The data necessary for the study includes the frequency of grid outages lasting one year, the duration of grid outages, the average duration of daily grid outages, and one-year hourly consumption of BTS data from NetEco. Additionally, technical, economic and related data site power equipment is obtained from the power and environment engineering department, while meteorological data such as solar radiation and temperature for the sites is sourced from NASA.

2,880 BTS are gathered from NetEco, and these data points are subjected to analysis utilizing microsoft excel. Out of the total dataset, 1,433 BTSs contain information regarding grid outages spanning one year, hourly load consumption, and other power-related data.

In order to examine the grid outage patterns and solar energy potential of a specific area, the sites are categorized based on several factors. These factors include urbanization (whether the site is urban or rural), grid outage characteristics (including frequency, duration, and maintenance time), power consumption capacity, and climatic zone type. The grid outages exhibit different behaviors. Some sites experience frequent grid interruptions, but the recovery time is relatively short. On the other hand, certain sites encounter fewer grid interruptions, but grid recovery time is longer.

4.1.1 Site Classification Based on Grid Outage Frequency

The frequency and duration of grid outages have an impact on the time required for battery charging. When grid interruptions occur frequently within a short span of time, the battery may not have sufficient time to fully or partially charge. As a result, the battery is unable to supply power to the load.

When studying grid outage frequency, the primary parameter considered is the battery charging time(T), is calculated as follows:

$$T = \frac{C}{I_{charge}} \tag{4.1}$$

Where: C is Battery Capacity in(AH) and I_{charge} is Battery Charging Current in(A)

Battery charge and discharge rates are controlled by the C Rates associated with the battery. The C Rate represents the time required to charge or discharge the battery and is subject to variation depending on the battery manufacturer and its specific chemistry.

For Absorbent Glass Mat(AGM) batteries, a standard bulk charging rate is typically 0.1C. This value implies a charging rate that adds 10% of the battery's full capacity every hour. In simpler terms, this rate would charge a battery from empty (20%) to full (100%) within a span of 10 hours. This information is relevant when considering AGM battery charging rates, currents, and times[54].Identifying the sites whose grid outage is **frequent,** or **few** is depend on battery charging time. Most BTS sites' Battery C rate is 0.1C, the charging time of 10hr, the battery is fully charged with 10hr.

To calculate grid interruption frequency is below or above battery charging time.

Let **x** is battery charging time =10hr

a is a variable which is the ratio of yearly hours to a number of grid interruptions per year (the grid interruption duration gap).

$$\mathbf{a} = \frac{\mathbf{365days*24hr}}{\mathbf{No\ of\ grid\ interruption\ per\ year}} \tag{4.2}$$

If x>=a, the grid outage is a **frequent** interruption,and x<a, the grid outage is a **few** interruptions**.**

4.1.2 Site Classification as per Grid Outage Duration and Maintenance Time

If the duration of a grid outage exceeds the battery backup time or discharging time, it results in an interruption of the site's power system. Ethio telecom set a battery backup time of 8 hours standard for their grid-connected sites.

When daily average grid outage duration is above 8 hours, it indicates a long maintenance time for the grid. Conversely, when the grid outage duration within a day is below 8 hours, it implies a short maintenance time for the grid. In such cases, the sites remain unaffected by grid outages, and the site power is restored through the use of batteries. Therefore, the determination of short or long maintenance time is based on the battery backup time available at the respective sites.

The classification of sites is based on their urbanization, grid outage frequency, and maintenance time:

- **Urban areas categories**: Few power interruptions and short maintenance time; Few power interruptions and a long maintenance time; Frequent power interruptions and short maintenance time; Frequent power interruptions and long maintenance time.
- **Rural areas categories**: Few power interruptions and short maintenance time; Few power interruptions and a long maintenance time; Frequent power interruptions and short maintenance time and Frequent power interruptions and long maintenance time.

Table 2 The number of BTS sites cluster into their grid outage frequency and maintenance time.

Site category as per grid outage	Max. Power consumption		Min. Power consumption		Avg. Power consumption	
	Capacity (W)	Site ID	Capacity (W)	Site ID	Capacity (W)	Site ID
Urban_Few_Short			920	151535	6215.00	131989
Rural_Few_Short			1000		3145	121851
Urban_Few_Long	no					
Rural_Few_Long		151211			-	
Urban_Frequent_Short	10580	111212	1880	171879	4600	141809

Urban_Frequent_Long						
Rural_Frequent_Short	11658.1	141595	480	161875	3000	131897
Rural_Frequent _Long	6000	171510	1000	161460	2600	171486

4.1.3 Representative Site Selection

Representative sites are selected as per power consumption and climatic zone using analytical analysis.

a) Power Consumption Capacity

Ethio telecom deploys different types of mobile station as per traffic capacities, technology, and infrastructure, so their power consumption is different. The study identifies which power consumption is more feasible for deploying a hybrid power system.

As per power consumption capacity, the representative sites are statistically selected as per minimum, average, maximum power consumption capacity.

Table 3 The number of BTS sites cluster into their grid outage frequency and maintenance time.

Site category as per grid outage	Max. Power consumption		Min. Power consumption		Avg. Power consumption	
	Capacity (W)	Site ID	Capacity (W)	Site ID	Capacity (W)	Site ID
Urban_Few_Short			920	151535	6215.00	131989
Rural_Few_Short			1000		3145	121851
Urban_Few_Long	no					
Rural_Few_Long		151211			-	
Urban_Frequent_Short	10580	111212	1880	171879	4600	141809
Urban_Frequent_Long						
Rural_Frequent_Short	11658.1	141595	480	161875	3000	131897
Rural_Frequent _Long	6000	171510	1000	161460	2600	171486

b) Representative Sites as per Climatic Zone

The availability and potential of solar energy are influenced by factors such as latitude and altitude. At higher altitudes, the atmosphere is thinner, resulting in higher solar irradiance levels.

Additionally, there tends to be less cloud cover and air pollution at higher altitudes. Conversely, at lower altitudes, the atmosphere is denser, leading to lower solar irradiance levels and potentially more cloud cover and air pollution.

In the context of Ethiopia, the country is traditionally divided into five climatic zones based on altitude, rainfall patterns, and average annual temperatures. These zones are known as Wurch, Dega, Weynadega, Kola, and Bereha. By classifying sites according to these climatic zones, it becomes possible to study and assess the solar potential of each specific location, taking into account the corresponding climatic characteristics associated with altitude, rainfall, and temperature patterns.

Table 4 The number of BTS sites cluster into their grid outage frequency and maintenance time.

Zone	Altitude(meter)	Rainfall (mm/yr.)	Average annual temperature(^{0}C)
Wurch(Upper highlands)	>=3200	>2200	<11.5
Dega(highlands)	2300 - 3200	1200 - 2200	17.5/16.0 – 11.5
Weynadega(midlands)	1500 - 2300	800 - 1200	20.0 – 20.0
Kola(lowlands)	500 - 1500	2000 - 800	27,5 – 20.0
Bereha (desert)	<500	<200	>27.5

As per climatic zone 41 sites are selected for minimum, average, maximum, and median location per altitude.

Table 5 Representatives sites as per climatic zone.

Site category as per grid outage	Wurch	Dega	Wenadega	Kola	Bereha
	Site ID	Site ID	Site ID	Site ID	Site ID
Urban_Few_Short	_	112116,111131, ,111685	151535, 111188,113155	131816, 141538,141539	151717, 131810, 131811, 131810
Rural_Few_Short	131632, 171517	171461,131675	131698,121896,131607	131968,181621	132026,131534

Urban_Few_Long	_	_	_	_	_
Rural_Few_Long	_	_	141886	_	_
Urban_Frequent_Short	_	111121, 141809,111182	151532, 181695,141886	181580	132001
Urban_Frequent_Long	_	_	_	181370,181580	_
Rural_Frequent_Short	_	161484, 161473	141719, 173088, 141911,141837	131897, 161464, 132001,161463	_
Rural_Frequent _Long	_	173130, 171510	171486	161460	_

4.2 Power Configuration Type

4.2.1 Existing Power Configuration Type

The power configurations for representative sites consist of two types: Grid with backup storage battery (Grid/BSS) and Grid with standby DG and backup storage (Grid/DG/BSS).

Sizing of these power systems is determined based on various factors, including the load demand, required battery backup hours, expected running time of the DG, and the average daily grid interruption experienced in the vicinity. The information about the daily average grid interruption is obtained through verbal inquiries made to customers.

However, this design criterion is unreliable and not cost-effective; it is not considering the visible impact of grid interruptions.

4.2.2 Proposed Power Configuration Type

To develop reliable and cost efficient optimal hybrid power system that integrates renewable energy sources such as solar to the existing power system, it is crucial to take into account a range of factors. The capacity, efficiency, finial cost equipment's and project lifetime is main parameters to design optimal components and systems. Homer Pro-optimizers tool, which assists in accurately determining the optimal configuration and sizing of the system's components by using a search space.

The recommended hybrid power system include the PV/Grid/DG/BSS and PV/Grid/BSS configurations. These setups integrate existing components such as the grid, DG, and BSS, while incorporating new elements like PV panels and converters. However, the existing DG and BSS systems may not be suitable for the hybrid power system configuration due to limitations in capacity, cost, or efficiency. In such instances, alternative capacities are evaluated and optimized to achieve the most favorable outcomes for the system configuration.

4.3 Required Input Parameters

The configuration of a hybrid power system requires various input parameters categorized as technical, economic, and meteorological. The technical parameters encompass the hourly load profile, technical specifications of the system components, including PV, DG, Converter, and BSS, economic parameters consist of variables such as inflation rate, discount rate, project lifetime, grid purchasing price, demand rate, schedule grid outage data (mean outage frequency and repair time), and the capital cost, operational cost, and replacement cost of the system components (PV, DG, Converter, BSS).

The meteorological parameters, specifically, the annual average solar radiation (kWh/m2/day) and clearness index are obtained from NASA. And hourly load profile and grid outage data are sourced from the NetEco system, In the data of from World Bank, the 2021 inflation rate of Ethiopia is noted to be 26.8%, the discount rate utilized by Ethio telecom is 10% and the project lifetime is set at 25 years.

Table 6 Required technical and economic input data for configuring hybrid power system.

System component	Parameter	Measuring Metrics	Remark
PV panel	PV model	Generic	
	PV model capacity		
	Operational lifetime	25 years	
	Derating factor	0.85	
	System tracking		
	Capital cost	1.2/W	
	Replacement cost	$1/W	
	Operation and maintenance cost/year	$0.05/W	
Grid	Energy purchase price	$0.0221/kWh	
	Demand charge	2.732$/kW/Month	
	Mean grid outage frequency(1/yr)	per site data	
	Mean grid outage repair time(h)	per site data	
	Grid outage repair time variability (%)	30%	
DG	Model	Cummins	
	Capacity	10kW/15kW/20kW/ 25kW/30kW/40kW	
	Efficiency	0.8	
	Running lifetime(hour)	15,000	
	capital cost	$550/kW	
	Replacement cost	$500/kW	
	O&M($/op.hour)	0.5	
Battery	Model	Lithium	VRLA
	Capacity	100Ah150Ah/12V	300Ah/400Ah 500Ah/600Ah800Ah/1000Ah
	Initial SOC (%)	100	
	Minimum SOC (%)	(15-20)	
	Round trip efficiency	80% -97%	80% -97%
	Operating lifetime(hour)	15	10
	Capital cost	$(1100-1396)/unit	$(400-1000) unit
	Replacement cost	$(1000-1200)/unit	$(300-950) unit
	O&M cost/year	$5/unit	$5/unit
Converter	Model		
	Capacity		
	Efficiency (%)	95	
	Operating lifetime	15 years	
	Capital cost	$300/kW	
	Replacement cost	$300/kW	
	Operation and maintenance cost/year	$10/kW	

4.3.1 Hourly Load Profile of Base Transceiver Station

All of the representative BTS sites are categorized as outdoor sites, and consume a DC power. The loads present at these sites consist of BBU, RRU, ATN, aviation lights, site monitoring units, and air conditioning systems. The equipment system voltage is a -48V DC. The power consumption varies during high and low traffic hours. In addition, varies from site to site based on technology type, number subscribers, and services provided type. To capture this variability, data on the 24-hour load profile was collected for each site on an annual basis to facilitate simulation. The peak power consumption ranges is from 1.33 kW to 7.16kW.

Table 7 presents data that demonstrates the hourly power consumption of a sample BTS. The peak power demand is observed between 15:00 and 20:00 hours, while the lowest power demand is recorded between 02:00 and 06:00 hours.

Table 7 BTS site 24-hour power consumption data.

Start Time	DC Load Energy Consumption per Hour(kWh)
00:00:00	2.66
00:00:01	2.60
00:00:02	2.58
00:00:03	2.54
00:00:04	2.51
00:00:05	2.54
00:00:06	2.62
00:00:07	2.76
00:00:08	2.81
00:00:09	2.90
00:00:10	2.93
00:00:11	2.97
00:00:12	2.94
00:00:13	2.93
00:00:14	2.92
00:00:15	2.97
00:00:16	3.02

00:00:17	3.07
00:00:18	3.07
00:00:19	3.04
00:00:20	3.09
00:00:21	3.05
00:00:22	3.00
00:00:00	2.66
00:00:01	2.60

Daily, monthly and year load profile get from simulation result

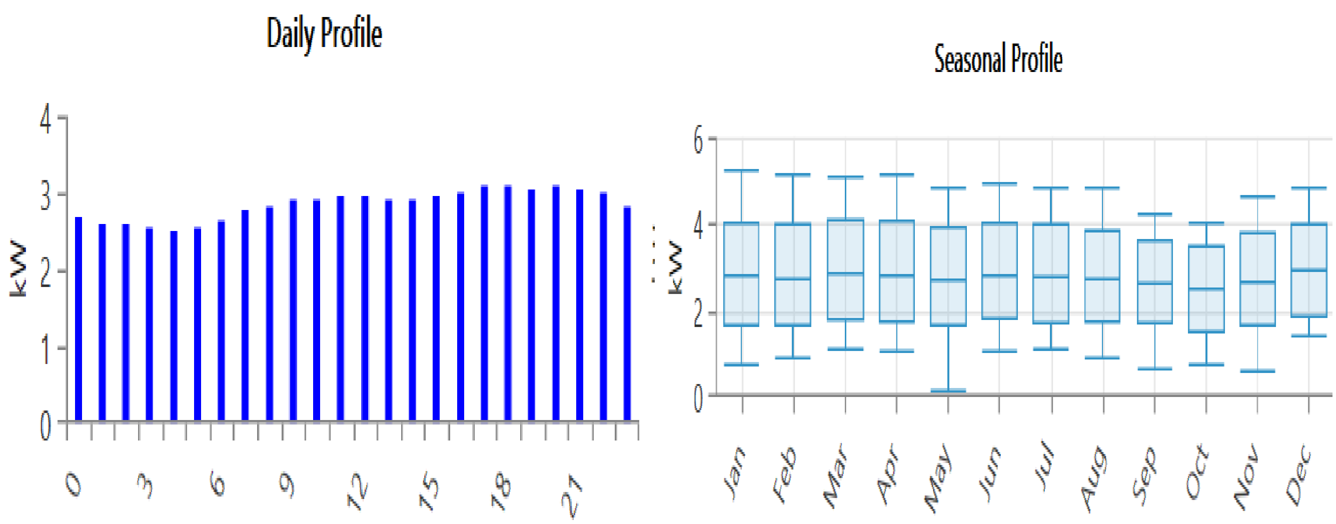

Figure 13 Daily and monthly load profile distribution.

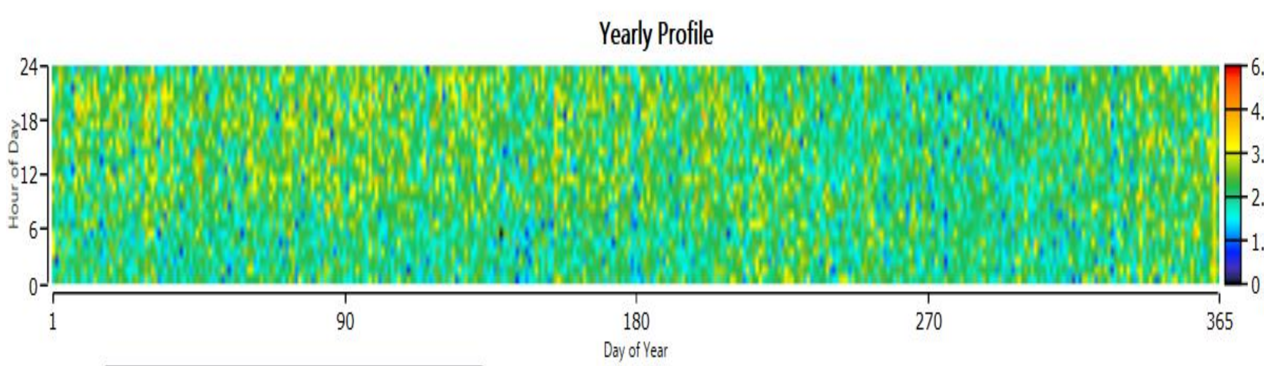

Figure 14 Yearly load profile distribution.

Figure 12, 13 and14 shows that, the simulation results of daily, monthly, and yearly load profiles. These profiles represent the variations in electrical load of BTS over different times. The daily load profile shows the changes in load throughout a typical day, indicating the peak and off-peak periods. The monthly load profile reflects the load patterns observed over a month. Finally, the yearly load profile represents the load characteristics over an entire year

4.3.2 Solar Energy Resource

The solar energy potential at a specific location can vary based on geographic Location, solar Insolation, climate and weather, seasonal variations, shading and obstructions, solar system efficiency, and tilt and orientation. Solar Global Horizontal Irradiation (GHI) measures the total amount of solar radiation received on a horizontal surface at a specific location on earth and the clearness of the atmosphere.

The solar radiation data is collected from NASA and the average annual solar irradiation of representatives is in a range of (5.68 to 6.88) kWh/m²/day.

Table 8 Daily average solar radiation and clearness index of a year from NASA.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Clearness index	0.66	0.66	0.614	0.58	0.603	0.589	0.568	0.564	0.584	0.62	0.67	0.67
Daily average radiation (kWh/m²/day)	5.9	6.34	6.29	6.1	6.27	6.03	5.83	5.86	6	6.06	6.07	

Table 8, provides information on the average monthly solar radiation, which demonstrates month-to-month variations. The lowest solar radiation levels are observed in July and August, while the highest levels are recorded in February and March. Additionally, the table indicates that the average annual solar radiation is 6.05 kWh/m²/day.

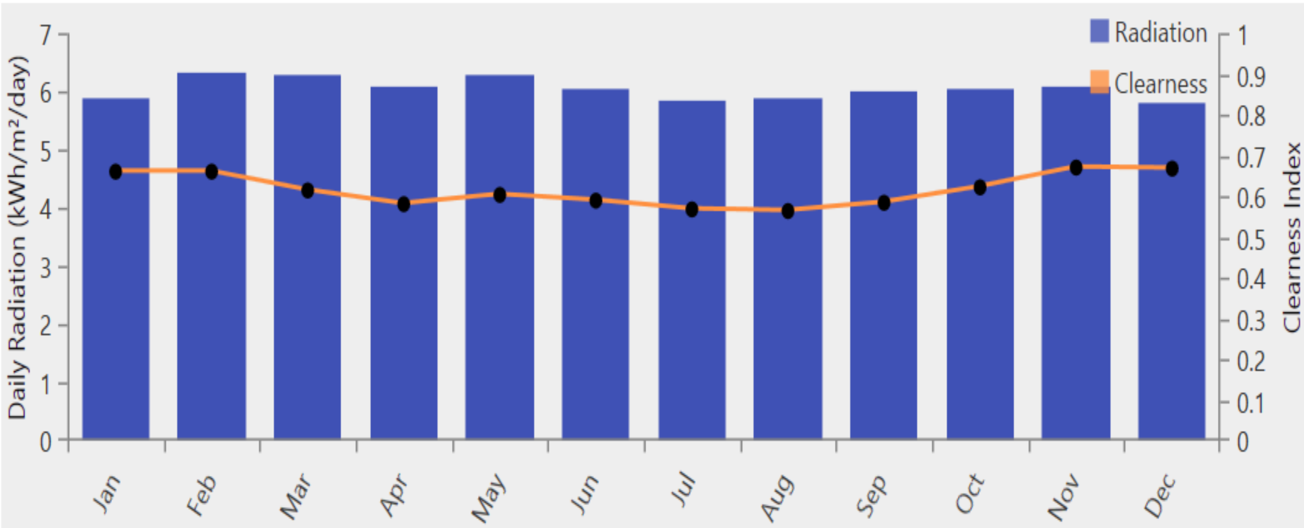

Figure 15 Daily solar radiation and clearness index.

Figure 15, show daily solar radiation and clearness index, he clearness index indicates how clear or cloudy the sky is in relation to the maximum possible solar radiation, the higher clearness index is at December and November is highest, because in most location of Ethiopia located a dry season, there minimum rainfall and cloud cover.

Chapter 5: Simulation Result and Discussion

5.1 Simulation Result

Once all the input variables are introduced, the Homer Pro software is executed continuously to determine the optimal and reliable system configuration and size its components to meet the load demand. The primary objective of the software is to minimize the NPC and achieve an optimal power configuration. The simulation results are presented in terms of the optimal systems identified and sensitivity analysis.

During the optimization process, the software explores various configurations by minimizing the NPC and COE within the defined search space. It simulates each system using different combinations of system elements (configurations) and evaluates their performance based on energy balancing at each time step throughout the year.

Homer Pro also facilitates sensitivity analysis by modeling the impact of variables that may not be known during the initial design phase. These variables include factors such as fuel cost, inflation, grid outages, and variations in solar radiation. By incorporating these variables into the analysis, Homer allows for a more comprehensive assessment of the system's performance under various scenarios and conditions.

5.1.1 Power Configuration Optimization Result

The simulation results encompass various power configurations suitable for mobile systems power systems. The four feasible configurations identified are Grid/PV/DG/BSS, Grid/BSS, Grid/DG/BSS, and DG/BSS. The results provide detailed information on the power components involved, including NPC, COE, Renewable RF, fuel consumption, energy production, and economic measurements such as capital cost, O&M cost, replacement cost, and salvage cost. Additionally, the cash flow of the system is analyzed.

For each site, a specific optimal power configuration is determined, and the simulation results provide predefined output measurements. The table presents the optimal power configuration and associated results for a particular site, outlining the various parameters and performance metrics obtained from the simulation.

The simulation result has different power configurations; the four configurations feasible for mobile systems power systems are Grid/PV/DG/BSS, Grid/ BSS, Grid/DG/BSS, and DG/BSS using two energy controlling dispatch strategies (LF&CC).

The result contains power components, NPC, COE, RF, fuel consumption, energy production, economic measurement (capital cost, O&M cost, replacement cost, and salvage cost) and cash flow of the system. Each sites have different power configuration with predefined measuring output result. The table describe one site optimal power configuration result.

Table 9, Optimal power configuration result one sample site.

Power Configuration Type	Architecture /PV (kW)	Architecture	Architecture/Power	Architecture/Converter	Architecture	Cost/NPC ($)	Cost/COE ($)	Cost/Operating cost ($/yr.)	Cost/Initial capital ($)	System/Ren Frac (%)	System/Total Fuel
Grid/PV/DG/BS	6.09	10	24	1.13	LF	-58,212.9	-0.03386	-327.339	25,608.67	75.91	1.20
Grid/DG/BSS		10	24	3.25	CC	-24,197.8	-0.01947	-168.842	19,037.50	0	11.67
Grid/PV/BSS	4.81		24	0.99	CC	106,747.8	0.066345	346.4704	18,027.13	73.04	0
Grid/BSS			48	2.18	CC	201,404.2	0.162124	699.5799	22,262.92	0	0

Table 9 result indicates that, Grid/PV/DG/BS power configuration has minimum **NPC (-$58,212.9)** and **COE (-$0.03386),** the negative value of NPC shows that the project or investment being evaluated is financially beneficial. The project is expected to generate more revenue or savings over its lifetime than the costs incurred. Similarly, a negative COE implies that the cost of producing energy from the project is lower than the revenue or savings generated by the energy produced.

5.1.2 Energy Production for Hybrid Power System

Hybrid energy system has different energy sources, PV, DG, Grid, and BSS. Each energy source generates energy depend on the energy source availability, load demand, and economical evaluation of the system.

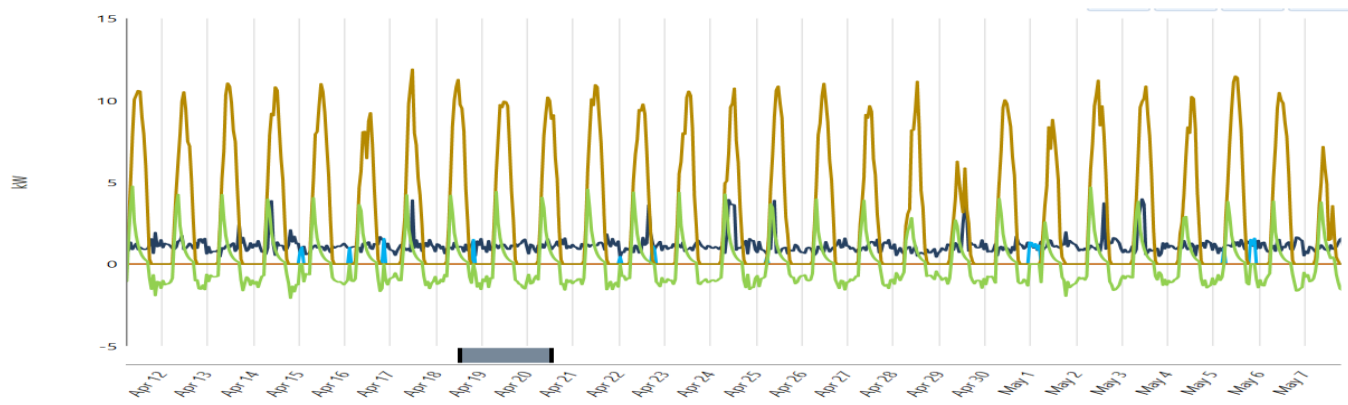

Figure 16 Daily energy production of proposed hybrid power system.

Legends

- Total Electrical load served
- Grid purchases
- Generic 10kW fixed capacity genset power output
- Generic flat plate PV power output
- Energy system power safe OPzV420 Input power

Figure 15 illustrates the daily power production of different power sources, with the PV system generating the highest energy output compared to the other power sources. Additionally, the energy supplied to the battery exceeds the energy consumed by the load.

5.1.3 Power Configuration Result as per Grid Outage Behavior

The primary objective of this study is to examine the consequences of grid interruptions on BTS operations, including increased operational costs and decreased power system reliability. The behavior of grid interruptions varies across different BTS sites and over time. Some sites experience frequent but short-duration interruptions, while others encounter fewer interruptions with longer times.

Individual optimization and simulation processes are carried out for 54 BTSs with the goal of determining the most efficient and effective power configuration for each unique location.

I. Power configuration for rural sites with few interruptions and long maintenance time (Rural_Few_Long)

According to the selection criteria, two BTS sites are grouped. These sites have a relatively few grid interruptions, occurring from 26 to 65 times per year. Moreover, the average daily grid outages at these sites are 17.23 hours to 17.28 hours. The result indicates that, the optimal power configuration is Grid/PV/DG/BSS with LF energy control strategy.

Table 10 Simulation result and required power data of Rural_Few_Long sites.

Site ID	Climatic Zone	Daily Avg Outage Duration (h)	Mains Outage Times	Annual Average solar radiation(kWh/ m2/day)	Peak load(kW)	Proposed Power configuration type	Energy dispatch strategy type	NPC ($)	COE ($)	Initial capital cost ($)	Total Fuel Consumption(L /yr)	Ren Frac (%)
141886	Weynadega	17.23	65	6.09	2.1	Grid/PV/DG/ BSS	LF	-168,625	0.041	22,843	1.2	79.1
151211	Weynadega	17.28	26	6.2	2.1	Grid/PV/DG/ BSS	LF	-60,499	-0.036	21,801	1.2	61.4

II. Power configuration for rural sites with frequent interruption and long maintenance time (Rural_Frequent _Long)

Based on the selection criteria, 4 BTS sites are grouped. These sites experience a relatively frequent grid interruptions range of (883 to 1304) times per year. Additionally, the daily average grid interruptions range of (8.32to 15)hours. The result indicates that, the optimal power configuration for all 4 sites is Grid/PV/DG/BSS.

Table 11 Simulation result and require power data of Rural_Frequent _Long sites.

Site ID	Climatic Zone	Daily Avge. grid Outage Duration (h)	Grid Outage frequency/yr	Daily Annual Average solar radiation	Peak (kW)	Proposed Power configuration type	Energy dispatch strategy type	NPC ($)	COE ($)	Initial capital cost ($)	Total Fuel Consumption	Ren Frac (%)
161460	Kola	15.00	940	6.27	2.46	Grid/PV/DG/BSS	CC	-148,260.00	-0.044	45,797.10	13.93	98.01
171486	Weynadega	11.12	972	5.90	2.1	Grid/PV/DG/BSS	LF	-43,576.30	-0.030	34,955.52	5.98	95.44
171510	Dega	9.60	1284	5.80	2.1	Grid/PV/DG/BSS	CC	-21,961.00	-0.016	37,471.36	20.32	95.34
173130	Dega	8.32	1304	5.93	2.1	Grid/PV/DG/BSS	LF	-29686.2	-0.021	35691.43	9.56	94.98

III. Power configuration for rural sites with few interruptions and short maintenance time (Rural_Few_Short)

According to the selection criteria, 12 BTS sites are grouped. These sites have few grid interruptions, with a range of (4 to 869) times per year. Furthermore, the average daily grid outages varies from (0.11 to 5.64) hours. The result indicates that, the optimal power configurations are (1 sites Grid/DG/BSS, 3 sites Grid/PV/DG/BSS and the rest 8 sites are Grid/PV/BSS).

Table 12 Simulation result and require power data of Rural_Few_Short sites.

Site ID	Climatic Zone	Daily Avg Outage	Mains Outage Times	Annual Average solar	Peak load(kW)	Proposed Power configuration	Energy dispatch	NPC ($)	COE ($)/kwh	Initial capital cost ($)	Total Fuel Consumption	Ren Frac (%)
121884	Dega	0.11	29	6.04	1.33	Grid/DG/BSS	LF	-42,311	0.02720	18,308	1.20	
121896	Weynadega	1.65	64	6.09	2.82	Grid/PV/DG/BSS	LF	-29136.3	-0.00823	13,429	1.20	52.22

131534	Dega	5.41	438	6.1	1.39	Grid/PV /BSS	CC	832,526	0.14400	219,050	0	89.40
131607	Weynadega	4.01	14	6.14	2.13	Grid/PV /BSS	CC	61,248	0.02350	18,714	0	63.70
131632	Wurch	1.87	641	6.14	3.85	Grid/PV /DG/BSS	LF	14,191	0.00263	30,209	16.70	59.50
131675	Dega	1.43	228	6.03	2.03	Grid/PV /BSS	CC	117,533	0.04660	17,062		60.40
131698	Weynadega	3.21	384	5.96	1.75	Grid/PV /BSS	CC	118,929	0.06020	18,628		58.90
131968	Bereha	0.95	149	6.03	1.72	Grid/PV /BSS	CC	119	0.06020	18,628	0	58.90
131977	Weynadega	3.35	160	6.25	1.33	Grid/PV /BSS		98,503	0.05880	16,738		79.60
132026	Bereha	0.12	69	6.1	1.33	Grid/PV /BSS	CC	97,780	0.05900	17,033	0	81.90
171517	Wurch	5.64	628	5.99	2.90	Grid/PV /BSS	CC	135,204	0.08370	29,474		99.80
121851	Weynadega	0.74	178	6.16	4.49	Grid/PV /BSS	CC	38,390	0.00844	20,080	0	

IV. Power configuration for rural sites with frequent interruption and short maintenance time (Rural_Frequent_Short)

Based on the selection criteria, 11 BTS sites are grouped. These sites experience a high frequency of yearly grid interruptions, ranging from 707 to 1424 times per year. Additionally, the daily average duration of grid outages at these sites varies from 3.09 hours to 6.63 hours. The result indicates that, the optimal power configuration is Grid/PV/DG/BSS.

Table 13 Simulation result and require power data of Rural_Frequent_Short sites.

Site ID	Climatic Zone	Daily Avg Outage	Mains Outage Times	Annual Average solar	Peak load(kW)	Proposed Power configuration type	Energy dispatch strategy type	NPC ($)	COE ($)/kwh	Initial capital cost ($)	Total Fuel Consumption(L/)	Ren Frac (%)
132001	Bereha	3.73	988	6.14	3.23	Grid/PV/ DG/BSS	LF	26,217.00	0.006	31,499.00	7.17	82.00
141595	Weyna dega	3.72	924	6.05	1.89	Grid/PV/ DG/BSS	LF	-50,309.60	-0.021	29,036.83	2.39	81.67
141719	Weyna dega	4.94	1344	6.09	6.29	Grid/PV/ DG/BSS	LF	78,351.00	0.281	49,402.00	153.00	85.30

141911	Weyna dega	3.28	1062	6.05	2.14	Grid/PV/ DG/BSS	LF	-58,212.90	-0.034	25,608.67	1.20	75.91
161464	Kola	3.49	1177	5.82	2.10	Grid/PV/ DG/BSS	LF	-74255.7	-0.0446	24997.45	3.585	94.94
161473	Dega	3.82	1015	5.9	3.73	Grid/PV/ DG/BSS	LF	32,649.00	0.006	42,818.00	11.70	74.50
161484	Dega	3.09	1424	5.9	2.10	Grid/PV/ DG/BSS	LF	-56,906.60	-0.036	27,145.57	1.20	78.74
161875	Dega	3.58	969	6.05	4.49	Grid/PV/ DG/BSS	CC	116,658.00	0.021	32,349.00	5.12	64.70
171461	Dega	6.63	707	6	4.49	Grid/PV/ DG/BSS	LF	81,727.00	0.016	49,710.00	20.30	79.10
173088	Weyna dega	5.34	1031	5.99	4.49	Grid/PV/ DG/BSS	LF	-224,411.00	-0.044	61,892.80	22.78	83.65
131897	Kola	5.35	1297	6.14	4.49	Grid/PV/ DG/BSS	LF	120,518.00	0.026	65,285.00	4.78	98.5

V. Power configuration for urban sites with few interruptions and short maintenance time (Urban_Few_Short)

According to the selection criteria, 11 BTS sites have been grouped. These sites experience few grid interruptions, ranging from (13 to 701) times per year. Moreover, the daily average duration of grid outages at these sites varies from (0.07 to 3.08) hours. The result indicates that, the optimal power configurations are(5 sites Grid/PV/DG/BSS and 5 sites Grid/PV /BSS).

Table 14 Simulation result and require power data of Urban_Few_Short sites.

Site ID	Climatic Zone	Daily Avg Outage Duration (h)	Mains Outage Times	Annual Average solar radiation	Peak load(kW)	Proposed Power configuration type	Energy dispatch strategy type	NPC ($)	COE ($)/kwh	Initial capital cost ($)	Total Fuel Consumption(	Ren Frac (%)
111685	Dega	0.6	259	6.09	4.53	Grid/PV/ DG/BSS	CC	165584.1	0.0274	32,840.39		66.97
112116	Dega	0.87	218	5.81	4.53	Grid/PV/ DG/BSS	LF	23,105.0	0.0041	26,407.00	1.2	43.20
113155	Weyna dega	2.7	206	5.81	7.12	Grid/PV/ DG/BSS	LF	332,029.0	0.0288	57,771,00	0	60.30
121461	Weyna dega	1.03	169	6.09	3.71	Grid/PV/B SS	CC	99,485.0	0.0210	19,435,00	0	50.20
131810	Kola	3.08	701	6.10	3.93	Grid/PV/ DG/BSS	LF	31178.4	0.0057	35,178.55	13.15	65.81

131989	Weyna dega	2.09	330	6.03	3.57	Grid/PV/DG/BSS	LF	2,024.0	0.0004	27,549.00	4.78	56.90
141538	Berha	0.34	227	6.05	5.16	Grid/PV/DG/BSS	LF	27,081.0	0.0039	30,156.00	1.20	54.30
151535	Weyna dega	1.18	583	6.12	7.16	Grid/PV/DG/BSS	LF	102,388.0	0.0112	33,160.00	2.05	48.20
151717	Bereha	0.83	429	6.88	4.49	Grid/PV/BSS	CC	169,614.0	0.0381	27,787.00		61.70
111131	Dega	0.07	13	6.09	2.1	Grid/PV/BSS	CC	115732.5	0.0730	20,021.77		72.16
111188	Dega	1.06	220	5.81	7.16	Grid/PV/BSS	CC	191,507.0	0.0064	101,690.00		53.30

VI. Power configuration for urban sites with frequent interruption and short maintenance time (Urban_Frequent_Short)

Based on the selection criteria, a total of 14 BTS sites are grouped. These sites experience a high frequency of yearly grid interruptions, ranging from 880 to 1641 times per year. Additionally, the daily average duration of grid outages at these sites varies from 0.75 hours to 7.51 hours.

The result indicates that, the optimal power configuration is Grid/PV/DG/BSS for all.

Table 15 Simulation result and require power data of Urban_Frequent_Short sites.

Site ID	Climatic Zone	Daily Avg Outage Duration (h)	Mains Outage Times	Annual Average solar radiation (kWh/m2/day)	Peak load(kW)	Proposed Power configuration type	Energy dispatch strategy type	NPC ($)	COE ($)	Initial capital cost ($)	Total Fuel Consumption	Ren Frac (%)
111121	Dega	0.75	1089	5.68	6.09	Grid/PV/DG/BSS	LF	237,339	0.0249	86,139	74.95	17.72
131811	Kola	2.64	798	5.96	4.53	Grid/PV/DG/BSS	LF	28,659	0.0044	38,100	65.98	29.89
131816	Beha	2.72	792	5.96	4.43	Grid/PV/DG/BSS	LF	41,166	0.0067	37.486	32.30	66.60
141808	Weynadega	2.76	882	6.05	3.74	Grid/PV/DG/BSS	CC	3,634	0.0077	36,591	5.970	70.20
141809	Dega	2.66	880	6.05	3.94	Grid/PV/DG/BSS	LF	13,682	0.0026	38,850	7.17	70.50
151532	Weynadega	4.32	1043	6.12	5.4	Grid/PV/DG/BSS	LF	173,743	0.0232	52,965	0.724	77.70
151715	Weynadega	2.92	834	6.12	7.16	Grid/PV/DG/BSS	LF	120,312	0.0127	59,542	8.42	69.70

171879	Weynadega	2.68	894	6.00	2.89	Grid/PV/DG/BSS	CC	89,344	0.0249	23,961	0	64.60
181370	Kola	1.5	941	5.70	5.18	Grid/PV/DG/BSS	LF	54,97	0.0078	33,394	6.62	51.70
181580	Kola	7.51	1641	5.76	2.1	Grid/PV/DG/BSS	LF	52,015	0.0381	102,156	47.80	94.10
181621	Kola	3.77	1271	5.71	2.9	Grid/PV/DG/BSS	LF	41,286	0.0122	50,435	5.97	94.30
181695	Weynadega	3.84	1622	5.84	4.49	Grid/PV/DG/BSS	CC	116,493	0.0230	57,906	7.70	82.60
111182	Dega	0.92	1350	6.09	6.86	Grid/PV/DG/BSS	CC	-159,477	-0.0195	41,982	12.66	55.55
111212	Weynadega	2.12	1061	5.81	7.16	Grid/PV/DG/BSS	CC	-104211	-0.0108	49506.99	17.72	55.35

5.2 Discussion

5.2.1 Proposed Power Configuration Type as per Site Classification

The power configuration type for each site is determined based on the simulation results, specifically by selecting the configuration type that yields the minimum NPC and COE.

I. Power Configuration for Rural Sites with Few Interruptions and Long Maintenance Time (Rural_Few_Long)

Sites classified as Rural_Few_Long face long grid maintenance periods from17.23 to 17.28 hours, with a relatively low number of interruptions occurring 26 to 65 times per year and have a high daily average annual solar radiation ranging from 6.09 to 6.2 kWh/m2/day. The optimization results indicate that the most optimal power configuration is Grid/PV/DG/BSS with LF energy control strategy. This configuration demonstrates the lowest NPC and COE compared to other setups such as Grid/PV/BSS, Grid/DG/BSS, and Grid/BSS.

The findings suggest that the extended grid outages directly affect the battery's lifespan, increase fuel consumption, operational costs, and equipment replacement expenses. Therefore, the

Grid/PV/DG/BSS power configuration is considered the most cost-effective solution, especially when faced with the challenges posed by prolonged grid outages.

II. Power configuration for rural sites with frequent interruption and long maintenance time (Rural Frequent _long)

The Rural_Frequent_Long sites experience long grid maintenance periods spanning from 9.6 to 15 hours, as well as frequent grid interruptions from 924 and 1304 times per year, and receive an average daily annual solar radiation ranging from 5.8 to 6.27 kWh/m2/day. The results suggest that the Grid/PV/DG/BSS power configuration, coupled with LFand CC energy controlling strategy, demonstrates the lowest NPC and COE for this group of sites. The Grid/PV/DG/BSS power configuration optimal for sites with frequent grid interruptions since the battery system's lifespan and efficiency are impacted by these interruptions. By reducing the battery discharging, it helps to sustain the system's battery life.

III. **Power Configuration for Rural Sites with Few Interruptions and Short Maintenance Time (Rural_Few_Short)**

The sites classified as Rural_Few_Short grid experience short grid maintenance periods from 0.11 to 5.64 hours, with a few interruptions 14 and 641 times per year, and receive daily average annual solar radiation ranging from 5.96 to 6.25 kWh/m2/day. Among the three power configuration types, namely Grid/PV/DG/BSS, Grid/PV/BSS, and Grid/DG/BSS, the minimum NPC and COE are observed for 2 sites using the Grid/PV/DG/BSS configuration, 9 sites using the Grid/PV/BSS configuration, and 1 site using the Grid/DG/BSS configuration.

Based on the results, the Grid/PV/BSS optimal power configuration exhibits the lowest NPC and COE for the majority of the sites, making it a feasible option. However, there is one site characterized by a very low grid outage frequency of 26 times per year and a short maintenance time of 0.11 hours. In this particular case, the Grid/DG/BSS configuration is considered viable.

IV. Power configuration for rural sites with frequent interruption and short maintenance time (Rural_Frequent_Short)

The sites categorized as Rural_Frequent_Short encounter short grid maintenance times, ranging from 3.09 to 6.63 hours, with frequent grid interruptions from 14 to 641 times per year, and daily average annual solar radiation ranging from 5.82 to 6.14 kWh/m2/day. The analysis indicates that optimal power configuration that yields the lowest NPC and COE for this group is Grid/PV/DG/BSS.

The results for this group align with those for sites that experience frequent grid outages with long maintenance times. Both categories share the characteristic of extended grid maintenance times, which subsequently affect battery life time and increase the operational costs of the system.

V. Power Configuration for Urban Sites with Few Interruptions and Short Maintenance (Urban_Few_Short) Time

The Urban_Few_Short category includes sites that have short grid outage maintenance time ranging from 0.07 to 3.08 hours, few grid interruptions of 13 to 429 times per year, and dail average annual solar radiation of 5.81 to 6.88 kWh/m2/day.Based on the optimization results, it has been determined that the optimal power configuration type of Grid/PV/BSS, Grid/PV/DG/BSS and provides the lowest NPC. and COE.

VI. Power Configuration for Urban Sites with Frequent Snterruption and short Maintenance (Urban_Frequent_Short) Time

The Urban_Frequent_Short category sites have a short grid outages maintenance time with ranging from 0.075 to 7.51 hours, frequent interruptions with ranging from 792 to 1641 times per year,and daily average annual solar radiation of 5.68 to 6.12 kWh/m2/day.

According to the optimization results, the optimal power configuration type of Grid/PV/DG/BSS offers the lowest NPC, and COE for all 14 sites in this category. This finding is consistent with the results obtained for the Rural_Frequent_Short group. Based on the data analysis, it can be observed that in urban area sites grid outages behavior is few, frequent and short maintenance time.The grid interption recover within short time.

The findings indicate that the most suitable power configuration for frequent grid interruptions and long maintenance time is Grid/PV/DG/BSS. However, for sites with minimal interruptions and short maintenance durations, both Grid/PV/BSS and Grid/PV/DG/BSS configurations are recommended. Specifically, Grid/PV/BSS is suitable for sites with few grid interruptions and short maintenance time. Out of the 54 sites studied, 39 of them have the optimal power configuration of Grid/PV/DG/BSS.

5.2.2 Solar Radiation Potential as per Climatic Zone

In the Wunch climatic zone, the daily average annual solar radiation varies between 5.99 to 6.14 kWh/m2/day, in Dega zone, it ranges from 5.68 to 6.1 kWh/m2/day, Wenadega zone experiences range of 5.81 to 6.15 kWh/m2/day, Kola zone experiences range of 5.7 to 6.27 kWh/m2/day, and Bereha zone with a range of 5.96 to 6.88 kWh/m2/day. Overall, there are no significant variations in the daily average annual solar radiation levels observed across all the climatic zones, relatively Bereha climatic zone has higher daily average annual solar radiation.

5.2.3 Electric Energy Production

The proposed hybrid power system incorporates a combination of the grid, DG, and PV panels as sources of energy generation. The findings suggest that, in hybrid power systems, the PV panel serves as the main source of energy generation. The energy production levels differ among sites and are influenced by system capacity, efficiency of PV and BBS, daily solar radiation, and grid interruptions.

Table 16 illustrates, the energy production per source and load demand, with solar energy being the highest. The surplus energy can be utilized for selling to the grid or other customers.

Table 16 Electric production and load consumption of hybrid power system.

Production	kWh/yr.	%
PV Panel	39,978	86.0
Diesel Generator	1.58	0.00339
Grid purchases	6,532	14
Total	46,512	100
Consumption	**kWh/yr.**	**%**
AC primary load	0	0
DC primary load	24,324	83
Deferrable load	0	0
Grid sales	4,982	17
Total	29,306	100
Quantity	**kWh/yr.**	**%**
Excess Electricity	16,267	35
Unmet load	0	0
Capacity shortage	0	0
Renewable Fraction		77.7
Maximum renewable penetration		3.933

One benefit of the hybrid power system is its capability to generate excess energy that can be sold back to the grid. This presents an opportunity for financial gains through energy sales.

5.2.4 Fuel Consumption of Conventional verses Proposed Hybrid Power System

The main advantage of hybrid power system to reduce fuel consumption by using energy controlling sitrayegy that by praiotizin the energy supply source,PVpannel, grid, BSS, and last DG. The fuel consumption of new prposed and existing power system of some sites are listed in the below table.

Table 17 Fuel consumption of existing power system verses the proposed.

Site ID	Existing power		Proposed power		Saved fuel L/year
	Configuration Type	Fuel Consumption (L/yr)	Configuration Type	Fuel Comsumption (L/yr)	
112116	Grid/DG/BSS	23899.3	Grid/PV/DG/BSS	1.2	23898.1
131534	Grid/DG/BSS	4009	Grid/PV/DG/BSS	2.39	4006.61
151532	Grid/DG/BSS	61844	Grid/PV/DG/BSS	0.724	61843.276
161460	Grid/DG/BSS	2219.93	Grid/PV/DG/BSS	13.93128	2205.99872
161473	Grid/DG/BSS	5404.76	Grid/PV/DG/BSS	11.7	5393.06
161484	Grid/DG/BSS	6892.76	Grid/PV/DG/BSS	1.195	6891.565
181695	Grid/DG/BSS	1240.28	Grid/PV/DG/BSS	7.7	1232.58

Table 17 displays, the fuel consumption comparison between the existing power configuration (Grid/DG/BSS) and the proposed configuration (Grid/PV/DG/BSS) across different sample sites. The existing configuration results in an annual fuel consumption ranging from 1,240 to 61,844 liters per year, whereas the proposed configuration utilizing PV hybrid power leads to a significantly lower range of 0.724 to 2.39 liters per year. By implementing PV hybrid power systems, substantial fuel savings of 1,223 to 61,843 liters per year can be achieved for each site, resulting in a simultaneous reduction in carbon emissions.

5.2.5 Techno-Economical Comparison of Conventional to Proposed Power System

The economic assessment involves comparing the existing power systems with the proposed ones, considering factors such as NPC, capital cost; O&M cost, replacement and salvage cost. The existing power system configurations consists of Grid/DG/BSS and Grid/BSS, while the proposed configurations are Grid/PV/DG/BSS and Grid/PV/BSS.

The majority of cases show that the proposed hybrid power configurations exhibit lowest NPC, COE, and O&M costs when compared to the existing systems. However, the initial capital cost of implementing the proposed configurations is higher.

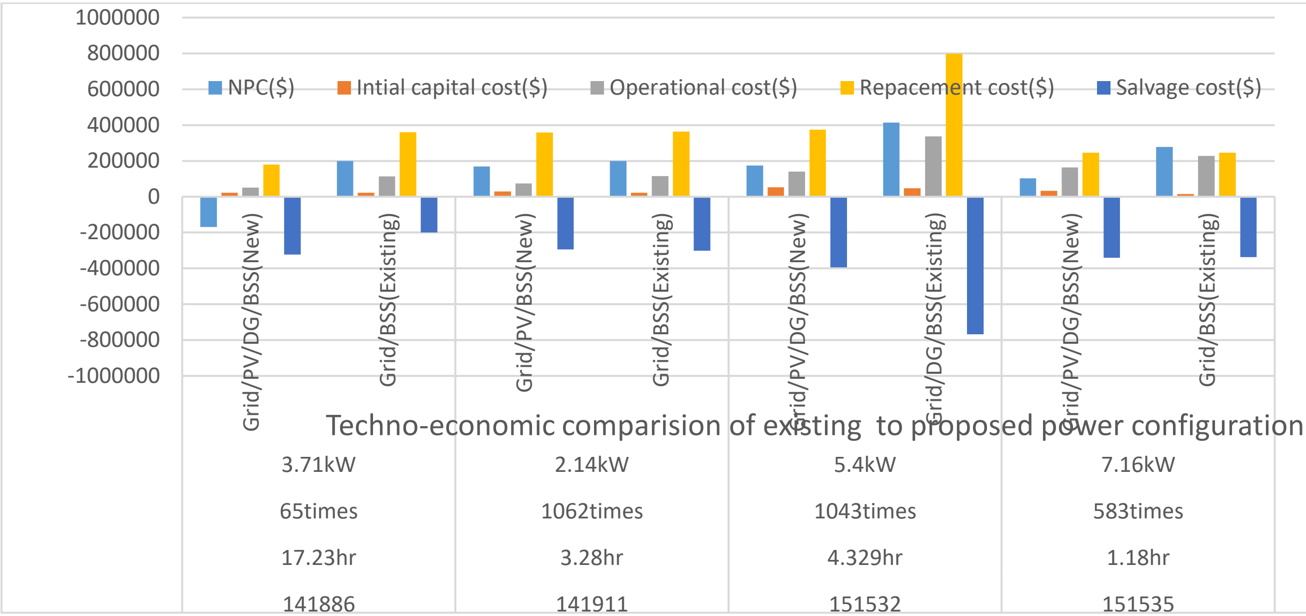

Figure 17 Economic comparison of convention power configuration to the proposed.

Figure 17 displays, power configurations for four BTS, including both existing and proposed setups. The NPC is impacted by the frequency of grid interruptions, as a higher frequent interruptions leads to an increase in both NPC and COE.

Sites 151532 has frequent grid interruptions, and high power consumption, In comparison to the proposed configuration, the existing power system at this site exhibits significantly higher values for NPC, replacement cost, and operational cost.

Chapter 6: Conclusion and Future Work

6.1 Conclusion

The primary obstacle faced by Mobile Network Operators (MNOs) is to ensure the availability of dependable, cost-effective, and eco-friendly energy for their mobile base stations. This study concentrates on evaluating 54 Ethio telecom BTS situated in diverse regions, each experiencing grid interruptions with different characteristics. Some sites encounter frequent grid interruptions but have shorter recovery times, whereas others have less frequent interruptions but longer recovery durations.

To propose a power system that is both reliable and cost-efficient, the sites are classified based on their level of urbanization, grid behavior, power consumption, and climatic zone type. This categorization enables a more focused approach in designing a suitable power system for each site. The design of a hybrid power system consideration of technical and economic parameters. The evaluation criteria for techno-economic analysis aim to minimize the NPC, COE and maximize RF.

In urban areas, the grid experiences frequent interruptions but recovers quickly. As a result, the battery backup autonomy time for BTS is relatively shorter compared to rural sites. However, for sites with frequent grid interruptions and varying maintenance times, the battery autonomy time increases. In such cases, the recommended hybrid power system with the lowest NPC is Grid/PV/DG/BSS. However, certain sites necessitate a configuration of Grid/PV/DG/BSS, whereas others can make use of Grid/PV/BSS.

Across all climatic zones, the average daily solar radiation ranges from 5.68 to 6.88 kWh/m2/day, suggesting that there is a considerable potential for solar energy in all climatic zones. The average daily solar radiation does not exhibit significant differences across the various climatic zones.

Additionally, due to the influence of grid outage behavior, it is challenging to assess the specific impact of the climatic zone on the proposed hybrid power configuration.

Ethiopia has the lowest energy costs in Africa. While the international standard cost of energy (COE) is $0.1/kWh, Ethiopia offers a subsidized COE of $0.02205/kWh for medium voltage consumers to COE of $0.07/kWh. This government grid cost subsidy has a significant impact on the expansion of solar energy in the country.

6.2 Future Work

Further research is required to design a hybrid power system by adding energy-saving strategies due to the intermittent nature of renewable energy sources and considering mobile traffic variation on peak hour and off peak hour.

Further investigation is needed to explore hybrid power components, specifically focusing on battery storage systems. This research involves determining the most suitable battery types for hybrid power systems and implementing efficient energy control strategies. Battery capacity and battery types is significantly affectes hybrid power system configuration and NPC.

The research conducted initially focused on outdoor BTS sites with DC load power. However, further investigation is required to explore indoor BTS sites that adds AC loads, as well as other exchange sites that encompass BTS, transmission, and fixed equipment. The objective is to analyze the impact of significant power consumption and high load fluctuations on hybrid power systems within these environments.

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Techno Economic Feasibility of Hybrid Energy System versus Grid for a Different Level of Grid Reliability for Cellular Base Station: In the case of Ethio telecom

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***Abstract*—For the rapid growth of cellular technology, there is a significant attention to energy consumption in cellular networks. This is especially crucial in developing countries like Ethiopia, where the electric supply and grid power distribution are unreliable. In Ethio telecom, grid as the primary energy source for its communication equipments. Approximately 70% of the Base Transceiver Stations (BTS) are connected to the grid. Due to frequent grid outages, Standby desiel generator is supply to BTS for a longe time and increase desiel fuel demand, OpEx, degraded quality of service(QoS), and experience(QoE).**

This study focuses on the techno-economic feasibility of a Grid connected PV hybrid energy system to provide a reliable and cost-efficient energy solution for BTS. Based on grid outage frequency, maintenance time, and climatic zone. 54 BTS are representd for study.To design the optimal hybrid Energy system (HES) and components, optimization techniques and energy control strategies are employed, by utilizing Hybrid Optimization of Multiple Energy Resources (HOMER) Pro software tool. The objective function is to minimize the Net Present Cost (NPC), Cost of Energy (COE) and design optimal HES for BTS. The results indicate that the proposed Grid/PV/BSS and Grid/PV/DG/BSS configurations have lower NPC and COE compared to the conventional power system. The Grid/PV/DG/BSS configuration is feasible for frequent grid interruptions, and took long time grid maintenance.

Keywords—Hybrid Energy system(HES), HOMER Pro, BTS, grid Outage, NetEco, NASA, NPC, Quality of Service (QoS), and Quality of Experience (QoE).

I. Introduction

The mobile telecommunication sector is one of the fastest-growing sectors of global business industry. The ever-increasing demands of mobile telecommunication services in developing countries are driving this significant profitable growth[1]. In cellular networks, the access network part substantially Base transceiver station (BTS) accounts around 80% of the total energy consumed by the entire network structure and energy consumption[2][3].

In the telecommunications industry, Mobile Network Operators (MNOs) are facing challenges in finding energy solutions that are both reliable and cost-effective for their networks. The efficiency of energy usage has emerged as a crucial performance indicator for the upcoming 5G networks[4].

Hybrid renewable energy system (HRES) technology plays a significant part in promoting green mobile communication. A strong energy system consists of two or further energy sources used together to give increased system effectiveness as well as greater balance in energy supply[5]. HRES is relieable, cost-effectient and envromentally friend, but it has complex to designing and planning due to the intermittent nature of renewable energy.

Cellular technology is vastly growing up in the world as well as in Ethiopia, to expand the network all over the countries; it was invested in a huge Infrastructure. The main energy source of Ethio telecom(ET) BTS are grid, solar,desiel generator with backup battery storage system(BSS).

Currently around 70% ET BTS sites are connected to grid, and 45% sites are Grid/DG/BSS. Due to frequent frequent and long time grid outage and most sites DG is working for a long time and increase fuel consumption and mentatince cost, whereas grid/BSS sites service is interrupted and degrades QoS, QoE and revenue. Grid and DC unavailability ET BTS data of 2022:

- 1478 BTS yearly grid outage is 1,281,399hr and total DC unavailability of 1257 BTS is 335, 285hr(725 Grid only sites is 251, 142hr and Grid with DG sites 83,139hr).
- The 2019 to 2022 fuel consumption report for 1221 BTS is 19,690,104 liters.

HRES is reliable and cost efficient for energy source for mobile station. However Ethio telecom, PV hybrid energy system isnot used as the main power during planning and designing.

The study is focus on design optimal reliable and cost effective hybrid power system and component for BTS, study techno-economic feasibilty of PV hybrid energy system, and compare the techno-economic of BTS by using technical and economical parameter.

II. RELATED WORK

Different papers are reviewed about BTS energy source with their reliability and effciency, hybrid energy type, techno economic feasibility, optimization techniques and energy controlling method to design hybrid energy system.

The author in[6] The study determined the optimum size and technical criteria for a stand-alone solar/battery power system that ensures 100% energy autonomy, long-term energy balance for solar-powered GSM base stations and evaluate techno economic feasibility, and compared the proposed solar power system.Optimization tool to design HES is Homwer Pro software tools, and analyzed the initial capital, replacement, operations, maintenance, and total net present costs for various solar-powered base stations.Annual OpEx savings of up to 65.45% in urban areas and 63.95% in remote areas.

In[7] Studied by a group of Authors about the techno-economic performance of grid-integrated/PV/Wind power systems of Ethiopia's Industrial parks(IP)(Awassa, Adama, and Kombolcha).Existing power supply for IP grid with standby DG, but due grid interppution DG supply critical load and run for along time, due to fuel consumption and fuel cost increment company revenue and customer satisfaction decreases.The study investigates the renewable energy(wind and solar) potential and grid interruption in the area. Model each hybrid compnents using technical and economical input parametrs to and designby Homer pro optimizer to get optimal power configuration.Solar energy potential is feasible in all three regions, wind energy is feasible only in Adama.

The result of grid/diesel is the lowest cost but highest in emission, based on the technical, economical, and environmental perspective grid/diesel/PV/battery system is feasible.

The authors in[8] Review different papers on how to size optimally, control, and manage HRES to build a modern electrical grid using several energy sources. This paper reviewed different research study about how to size, optimize, plan, control, and manage HRES. The optimization techniques (conventional, new generation, and hybrid) were evaluated as per their performance, capacity, and ability to apply. Conventional is more successful for economically but solve for limited parameters, whereas new generation and hybrid required high hardware, advanced design, and complex code to get a high-performance result. The result of this study shows that sizing, optimizing, controlling, and energy management are key parameters to size technical, economic, and environmental feasible HRES.

III. METHDOLOGY

The following methods are applied to achieve the objective of the study. The study utilizes two types of data sources, Primary data is obtained from the NetEco, while secondary data is gathered from NASA and Ethiopia electric utility (EEU). To design a hybrid energy system, the study employs a theoretical approach in the modeling process.

A. Data Collection and Analysis

2021 and 2022 G.C, 2880 BTSs grid outage data is collected from NetEco, 1433 BTSs have seven months and above grid status information,from this 909BTS Urban and 524 Rural.

Grid outage behavior is studied as per grid outage maintenance time(MT) and frequency(F).
MT depends on the battery discharging time; if MT< 8hr short MT, and MT>8hr long MT,F depends on battery charging time(10hr).

$$a = \frac{365\text{days}*24\text{hr}}{\text{No of grid interruption per year}} \qquad (1)$$

a is a time gap b/n grid outage comes;
If a> 10, the grid interruption is few,
a=<10, the grid interruption is frequent.

Table 1 indicates the number of BTS sites cluster by their grid outage frequency and maintenance time by using the above analysis in eqn. 1.

Table 1 Site classification as grid outage.

Site classification as per grid outage behavior	No of sites		Daily avg. Outage Duration (h)	Grid outage duration (h)/year	Grid outage time (frequency)/year
	Urban	Rural			
Few interruption-short maintenance time	893	439	0-7.85	0-2867	4-874
Few interruption-long maintenance time	0	2	17.23-17.28	6288-6305	26-65
Frequent interruption-short maintenance time	16	88	0.41-7.08	151-2739	876-1934
Frequent – interruption-long maintenance time	0	5	8.32-15	338-5475	883-1304

Representative sites are selected as per power consumption and climatic zone using analytical analysis:

- Power consumption capacity 13 BTSs.
- Climatic zone 41 BTSs.

B. Identify Input Parameters

Input parameters to model Grid-connected PV hybrid power system:

- Technical, economic, 26.8% of inflation rate, 10% of discount rate, 25yr project lifetime,and hourly power consumption.
- Metrological data from NASA.

Table 2 Technical and economic data of hybrid compomenets.

System component	Parameter	Measuring Metrics	Remark
PV panel	PV model	Generic	
	PV model capacity		
	Operational lifetime	25 years	
	Derating factor	0.85	
	System tracking		
	Capital cost	1.2/W	
	Replacement cost	$1/W	
	Operation and maintenance cost/year	$0.05/W	
Grid	Energy purchase price	$0.0221/kWh	
	Demand charge	2.732$/kW/Month	
	Mean grid outage frequency(1/yr)	per site data	
	Mean grid outage repair time(h)	per site data	
	Grid outage repair time variability (%)	30%	
DG	Model	Cummins	
	Capacity	10kW/15kW/20kW/ 25kW/30kW/40kW	
	Efficiency	0.8	
	Running lifetime(hour)	15,000	
	capital cost	$550/kW	
	Replacement cost	$500/kW	
	O&M($/op.hour)	0.5	
Battery	Model	Lithium	VRLA
	Capacity	100Ah150Ah/12V	300Ah/400Ah/ 500Ah /600Ah800Ah/1000Ah
	Initial SOC (%)	100	
	Minimum SOC (%)	(15-20)	
	Round trip efficiency	80% -97%	80% -97%
	Operating lifetime(hour)	15	10
	Capital cost	$(1100-1396)/unit	$(400-1000) unit
	Replacement cost	$(1000-1200)/unit	$(300-950) unit
	O&M cost/year	$5/unit	$5/unit
Converter	Model		
	Capacity		
	Efficiency (%)	0.95	
	Operating lifetime	15 years	
	Capital cost	$300/kW	
	Replacement cost	$300/kW	
	Operation and maintenance cost/year	$10/kW	

IV. MODELLING COMPONENTS OF HYBRID ENERGY SYSYEM

Techno-economic modeling integrates both technical and economic aspects of a system in a single mathematical formulation and solution. “The technical model computes the power generated and consumed by the system, while the economic model estimates the effective cost of the generated power. This model will be used to evaluate the overall viability of the HES”[7].

A. Technical Modeling

The design of the proposed PV hybrid power system requires input parameters such as PV panels, DG, grid, and BSS. Each component can be modeled according to its specific application and requirements to achieve the desired output of HES.

Power balance of HES is calculated with eqn.(2),

$$P_{L}^{(t)} = P_{PV}^{(t)} \pm P_{BSS}^{(t)} \pm P_{DG}^{(t)} \pm P_{Grid}^{(t)} \qquad (2)$$

1) *Modeling of photovoltaic system:*The power output of the PV array is determined by the level of radiation that reaches a horizontal surface at the Earth's atmosphere for each time interval. The clearness index to display monthly average global radiation statistics from the National Renewable Energy Laboratory (NREL) using geographical coordinates information[10].

The input required for modeling PV power systems are solar irradiance (in W/m2), and temperature (in °C)[11][12].

To calculate the output of PV array by using eqn.(3),

$$P_{PV} = P_{pv(rated)} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \alpha_p (T_C - T_{C,STC})] \quad (3)$$

Where: $P_{pv(rated)}$ is the rated capacity of PV module (kW), f_{PV} is PV derating factor (%), G_T is solar radiation incident on the PV array in the current time step [kW/m^2],$G_{T,STC}$ is solar incident radiation at standard test condition [1 kW/m^2],α_p is the temperature coefficient of power [%°C], T_C is the PV cell temperature in the current time step [°C], and $T_{C,STC}$ is the PV cell temperature under standard test condition [25°C].

*2) Modeling of battery storage system:*The maximum charge power is not constant and varies from one time step to another based on factors such as the state of charge and the recent charging and discharging patterns of the storage bank. To charge the BSS for a specific time step, the required power can be calculated[11].

The present value of the state of charge (SOC) determines the allowable charging and discharging of the BSS. The SOC of the BSS anatomy time (t)

$$SOC_{(t)} = SOC_{(t-1)} \left(1 - \delta_{Batt(t)} + \frac{P_{Batt(t)}}{V_{bus}} * \eta * \Delta t \right) \quad (4)$$

Where: Δt is the time step for the iteration (one hour), δ is represents the hourly self-discharge factor, η is the battery efficiency (considered 80%), V_{bus} is the voltage of the dc bus (V), and N_{bat} is the total number of batteries in BSS.

*3) Modeling of convertor system:*The power supply for base stations involves the use of both AC-DC and DC-DC converters.

The DC-DC converter is responsible for performing maximum power point tracking (MPPT) control, while the bi-directional charger of the BSS manages the flow of DC power in both directions[15].

If $P_{PL}$is the peak load demand of the system and η_{Inv} is the efficiency of the inverter, the output power of the inverter (Pout) (in kW).

$$P_{conv} = \frac{P_{PL}}{\eta_{Conv}} \quad (5)$$

4) Desiel generator modeling:The DG serves as both a backup and primary source of energy for BTS. It is activated in situations where the Grid, PV, and BSS are unable to generate enough power to meet the load requirements. The output power of the DG is influenced by factors such as its efficiency-rated power and derating factors.

$$P_{DG} = P_r * N_{DG} * \eta_{DG} \quad (6)$$

Where: P_r is the rated power of the generator (kW), $\eta_{DG}$is the efficiency generator, and N_{DG} is number of generators.

To calculate the slope and intercept of fuel curve by using linear regression method[13].

To model the fuel usage (Fc) of a DG in liter/kWh.

$$F_c = AP_r + BP_{out(t)} \quad (7)$$

Where: A is fuel curve intercept, B is fuel curve slope, P_r is power rated and $P_{out(t)}$ is output power within a time.

5) Modeling grid system:The grid provides electricity when the demand exceeds the power generated by PV energy sources, and it consumes electricity when there is surplus power from PV sources.

The grid maintains the balance between power supply and consumption[11]. The load requirement power is calculated as:

$$P_{G(t)} = R_{G(t)} * P_{L(t)} \quad (8)$$

B. Cost Modeling

Lifecycle cost is total cost owning and operating of a hybrid energy system over its entire lifetime system. It includes capital cost, operational &maintenance costs, replacement costs and salvage value of the project.

Hybrid power system depends on annual load growth; a longer project lifecycle has hurdles to consider in terms of economic and technical.

1) Capital cost: is the initial cost of purchase and the installation of the equipment used for a hybrid power system.

$$C_C = C_G + C_{PV} + C_{DG} + C_{BSS} + C_{conv} \quad (9)$$

Where: C_C is the total capital cost of the proposed hybrid power system, C_G is the total capital cost of grid power system, C_{PV} is the total capital cost of a PV panel, C_{DG} is the total capital cost of a diesel generator, C_{BSS} is the total capital cost of the battery storage system, and C_{conv} is the total capital cost of the inverter.

2) *Operational & maintenance cost*: it contains all the expenses, which are system operations during the lifetime of the project. It include preventive and proactive maintenance, fuel cost, utility cost, and labor cost.

$$C_{O\&M} = \frac{\sum_{n=0}^{N} C_{O\&M,PV}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{O\&M,Grid}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{O\&M,DG}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{O\&M,Conv}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{O\&M,BSS}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{Fuel}}{(1+i)^n} \quad (10)$$

4) *Salvage Value*: is the remains value of the system or the components at the end of the project lifetime. It represents the amount of money that can be recovered from selling the system or its components as scrap or for reuse after the end of their useful life[12].

The return (salvage) value of the component is calculated as:

$$S_V = C_{rep}\left(\frac{R_{rem}}{R_{comp}}\right) \quad (11)$$

Where: C_{rep} is replacement cost, R_{rem} is the remaining life of the component at the end of the life of the project, and R_{comp} is the life time of the components.

3) *Replacement Cost*: is the cost spent for the equipment replacement when, their service time is end or their performance is degraded up to the project's lifetime.

The total replacement cost(C_{RC}) is calculated as:

$$NPC = C_{FO} + \sum_{r=1}^{N} \frac{C_{FN}}{(1+i)^N} \quad (19)$$

$$C_{RC} = \frac{\sum_{n=0}^{N} C_{RC,PV}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{RC,DG}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{RC,Conv}}{(1+i)^n} + \frac{\sum_{n=0}^{N} C_{RC,BSS}}{(1+i)^n} \quad (12)$$

V.FURMULATION OF OBJECTIVE FUNCTION

The objective function is to minimize NPC, COE, of grid/PV/DG/BS hybrid energy and other configuration:

Objective Function:

$$\min (NPC + COE) \quad (13)$$

To minminzie the total cost mean minimzing intial cost, O&M cost and replacement cost of the system . formulated as eqn.(3.22),

$$minNPC = \min\left(C_{cap} + C_{O\&M} + C_{rep} - C_{SV}\right) \quad (14)$$

Input Variables are Energy Demand, Energy Sources (Grid, PV, and DG), Energy Storage (BSS), System Efficiency, Capital cost, Operational cost, lifetime of components, and discount rate.

The **constraints** to consider designing a hybrid power system to be feasible are:

- **Energy Balance Constraint**: the requirement of energy generated by the system to satisfy the load demand.

$$P_L^t = P_{grid}^t \pm P_{battery}^t \pm P_{PV}^t \pm P_{DG}^t \quad (15)$$

- **Energy Storage Constraint:** avoids any overcharging or over-discharging of the batteries and ensures optimal utilization of the battery system[11]. SOC is set bettewn minimum SOC and maximum SOC and formulated as eqn.(16),

$$SOC_{Batt}^{min} \le SOC_{Batt} \le SOC_{Batt}^{max} \quad (16)$$

- **Component size:** minimum and maximum sizes of the component, the number of componets is affect the total performance of the system aswellas the cost[37].

$$N_i^{min} \le N_i \le N_i^{max} \quad (17)$$

To calculate NPC, by dividing total annual cost to recovery factor of the project [16][17].It is formulated as eqn.(18)

$$NPC = \frac{C_{ann,tot}}{CRF_{(i,Rproj)}} \quad (18)$$

Where: NPC is the net present cost, $C_{ann,tot}$ is the total annual cost in ($/year), and $CRF_{(i,Rproj)}$ is the recovery factor with Rth lifetime of the project in years.

$$C_{ann,tot} = \sum_{i=1}^{n} C_{(C,i)} + \sum_{i=1}^{n} O\&M_{(C,i)} + \sum_{i=1}^{n} R_{(C,i)} + \sum_{i=1}^{n} F_{(C,i)} \quad (20)$$

Where: C_{FO} is the initial capital cost, and C_{FN} is the cash flow of N- year and i the real discount rate.

Cost of Energy (COE): is the critical metrics for comparing the hybrid system's economic parameters, which is the total system cost over total the tolal energy production cost [13]14].It is calculated(3.36)

The total Energy is energy generated by PV& DG, Grid, and battery. it calculated as eqn.(21),

$$\mathrm{COE} = \frac{\text{Total system cost}}{\text{Total Energy generated}} = \frac{\mathrm{C_{ann,tot}}}{\mathrm{E_{Served}}} \qquad (21)$$

Where: E_{Served} is the total energy generated (kWh/year).

The total system Cost of HES is total cost of components, calculated as eqn.(22),

$$C_{HES} = C_{PV} + C_{BSS} + C_{DG} + C_{Conv} \qquad (22)$$

VI.SIMULATION RESULT AND DISCUSSION

Once all the input variables are introduced, the HOMER software is executed continuously to determine the optimal and reliable system configuration and size its components to meet the load demand.

A. *Power Configuration Optimization Result*

The simulation results encompass various power configurations suitable for mobile systems power systems

The four feasible configurations identified are Grid/PV/DG/BSS, Grid/BSS, Grid/DG/BSS, and DG/BSS. The results provide detailed information on the power components involved, including NPC, COE, Renewable RF, fuel consumption, energy production, and economic measurements such as capital cost, operation and maintenance (O&M) cost, replacement cost, and salvage cost.

The table describe one sample site optimal power configuration result.

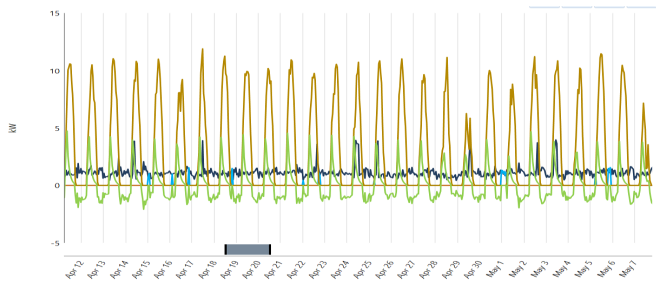
Table 3 Optimal power configuration result one sample site.

Power Configuration Type	Architecture /Dispatch	Cost/NPC ($)	Cost/COE ($)	Cost/Operating cost ($/yr.)	Cost/Initial capital ($)	System/Ren Frac (%)	System/Total Fuel (L/yr)
Grid/PV/DG/BSS	LF	-58,212.90	-0.03386	-327.339	25,608.67	75.91	1.2
Grid/DG/BSS	CC	-24,197.80	-0.01947	-168.842	19,037.50	0	11.67
Grid/PV/BSS	CC	106,747.80	0.066345	346.4704	18,027.13	73.04	0
Grid/BSS	CC	201,404.20	0.162124	699.5799	22,262.92	0	0

Table 3 result indicates that, Grid/PV/DG/BS power configuration has minimum **NPC (-$58,212.9)** and **COE (-$0.03386),** the negative value of NPC shows that the project or investment being evaluated is financially beneficial.

B. *Energy Production for Hybrid Power System*

Hybrid energy system has different energy sources, PV, DG, Grid, and BSS. Each energy source generates energy depend on the energy source availability, load demand, and economical evaluation of the system.



Legends
- Total Electrical load served
- Grid purchases
- Generic 10kW fixed capacity genset
- Generic flat plate PV power output
- Energy system power safe OPzV420

Figure 18 Daily energy production of proposed hybrid power system.

Figure 1 illustrates that PV system generating is the highest energy output compared to the other power sources. Additionally, the energy supplied to the battery exceeds the energy consumed by the load.

C. *Power Configuration Result as per Grid Outage Behavior*

Grid interruptions on BTS operations, including increased operational costs and decreased power system reliability. Grid interruptions varies across different BTS sites and over time.

1) Power configuration for rural_few_long:Two BTS sites are grouped, few grid interruptions, from 26 to 65 times per year, the average daily grid outages are 17.23 hours to 17.28 hours. The result indicates that, the optimal power configuration is Grid/PV/DG/BSS with LF energy control strategy.

2) Power configuration for rural_frequent _long: 4 BTS sites are grouped, frequent grid interruptions range of (883 to 1304)/yr, the daily average grid interruptions range of (8.32to 15)hr. The result indicates that, the optimal power configuration for all 4 sites is Grid/PV/DG/BSS.

3) Power configuration for rural_few_short:12 BTS sites are grouped few grid interruptions, with a range of (4 to 869)/yr, average daily grid outages varies from (0.11 to 5.64)hr. The result indicates that, the optimal power configurations are 1 site Grid/DG/BSS, 3 sites Grid/PV/DG/BSS and the rest 8 sites are Grid/PV/BSS).

4) Power configuration for rural_frequent_short:11 BTS sites are grouped, yearly grid interruptions, ranging from 707 to 1424 times/yr, the result indicates that, the optimal power configuration is Grid/PV/DG/BSS.

5) Power configuration for urban_few_short:11 BTS sites have been grouped, grid interruptions, ranging from (13 to 701) times per year, The result indicates that, the optimal power configurations are(5 sites Grid/PV/DG/BSS and 5 sites Grid/PV /BSS).

6) Power configuration for urban_frequent_short:14 BTS sites are grouped, yearly grid interruptions are from 880 to 1641 times, The result indicates that, the optimal power configuration is Grid/PV/DG/BSS for all.

The findings indicate that the most suitable power configuration for frequent grid interruptions and long maintenance time is Grid/PV/DG/BSS. However, for minimal interruptions and short maintenance durations, both Grid/PV/BSS and Grid/PV/DG/BSS. Specifically, Grid/PV/BSS is suitable for sites with few grid interruptions and short maintenance time. Out of the 54 sites studied, 39 of them have the optimal power configuration.

Table 4 Yearly fuel consumption b/n existing and the proposed.

Site ID	Existing Fuel Consumption (L/yr)	Proposed Fuel Consumption (L/yr)	Saved Fuel (L/yr)
112116	23899.3	1.2	23898.1
131534	4009	2.39	4006.61
151532	61844	0.724	61843.276
161460	2219.93	13.93128	2205.99872
161473	5404.76	11.7	5393.06
161484	6892.76	1.195	6891.565
181695	1240.28	7.7	1232.58

From table 4, The existing configuration results in an annual fuel consumption ranging from 1,240 to 61,844 liters per year, whereas the proposed configuration utilizing PV hybrid power leads to a significantly lower range of 0.724 to 2.39 liters per year. By implementing PV hybrid power systems, substantial fuel savings of 1,223 to 61,843 liters per year can be achieved for each site, resulting in a simultaneous reduction in carbon emissions.

Table 5 Power configuration type for Rural_Frequent, Few_Long, and Frequent_short maintenance time

Site ID	Site group per grid outage	Climatic Zone	Daily Avge. grid	Grid Outage	Daily Annual Average	Peak (kW)	Proposed Power configuration type	Energy dispatch	NPC ($)	COE ($)	Initial capital cost ($)	Total Fuel Consum	Ren Frac (%)
161460	Rural_Frequent _Long	Kola	15	940	6.27	2.46	Grid/PV/DG/BSS	CC	-148,260.0	-0.04	45,797.10	13.93	98.01
171486		Weynadega	11.12	972	5.9	2.1	Grid/PV/DG/BSS	LF	-43,576.30	-0.03	34,955.52	5.98	95.44
141886	Rural_Few _Long	Weynadega	17.23	65	6.09	2.1	Grid/PV/DG/BSS	LF	-168,625	0.041	22,843	1.2	79.1
151211		Weynadega	17.28	26	6.2	2.1	Grid/PV/DG/BSS	LF	-60,499	-0.04	21,801	1.2	61.4
132001	Rural_Frequent _short	Bereha	3.73	988	6.14	3.23	Grid/PV/DG/BSS	LF	26,217.00	0.006	31,499.00	7.17	82
141595		Weynadega	3.72	924	6.05	1.89	Grid/PV/DG/BSS	LF	-50,309.60	-0.02	29,036.83	2.39	81.67
141719		Weynadega	4.94	1344	6.09	6.29	Grid/PV/DG/BSS	LF	78,351.00	0.281	49,402.00	153	85.3
141911		Weynadega	3.28	1062	6.05	2.14	Grid/PV/DG/BSS	LF	-58,212.90	-0.03	25,608.67	1.2	75.91
111121	Urban_Frequent _short	Dega	0.75	1089	5.68	6.09	Grid/PV/DG/BSS	LF	237,339	0.025	86,139	74.95	17.72
131811		Kola	2.64	798	5.96	4.53	Grid/PV/DG/BSS	LF	28,659	0.004	38,100	65.98	29.89
141809		Dega	2.66	880	6.05	3.94	Grid/PV/DG/BSS	LF	13,682	0.003	38,850	7.17	70.5
151532		Weynadega	4.32	1043	6.12	5.4	Grid/PV/DG/BSS	LF	173,743	0.023	52,965	0.724	77.7
151715		Weynadega	2.92	834	6.12	7.16	Grid/PV/DG/BSS	LF	120,312	0.013	59,542	8.42	69.7

From the above table result indicates that;

- For frequent grid outages and long MT sites, the optimal power configuration is Grid/PV/DG/BSS,r and educe battery maintenance and replacement cost.
- For Urban &Rural_Few_short maintenance time, results optimal power configuration is Grid/PV/BSS, Grid/DG/BSS, and Grid/PV/DG/BSS but common and for more sites are Grid/PV/BSS. Grid/PV/BSS is suitable for few grid interruptions and short maintenance time.

D. *Techno-Economic Comparsion*

The economic assessment comparing the existing power systems with the proposed by considering NPC, capital ; O&M, replacement and salvage cost.The existing power system configurations are Grid/DG/BSS and Grid/BSS, while the feasible configurations are Grid/PV/DG/BSS and Grid/PV/BSS.

Figure below figure 17 displays, power configurations for four BTS, including both existing and proposed setups. The NPC is impacted by the frequency of grid interruptions, as a higher frequent interruptions leads to an increase in both NPC and COE. and result,151532 grid outages were frequent, and NPC, operational, and replacement costs were the highest.The higher frequent interruptions lead to an increase in both NPC and COE.

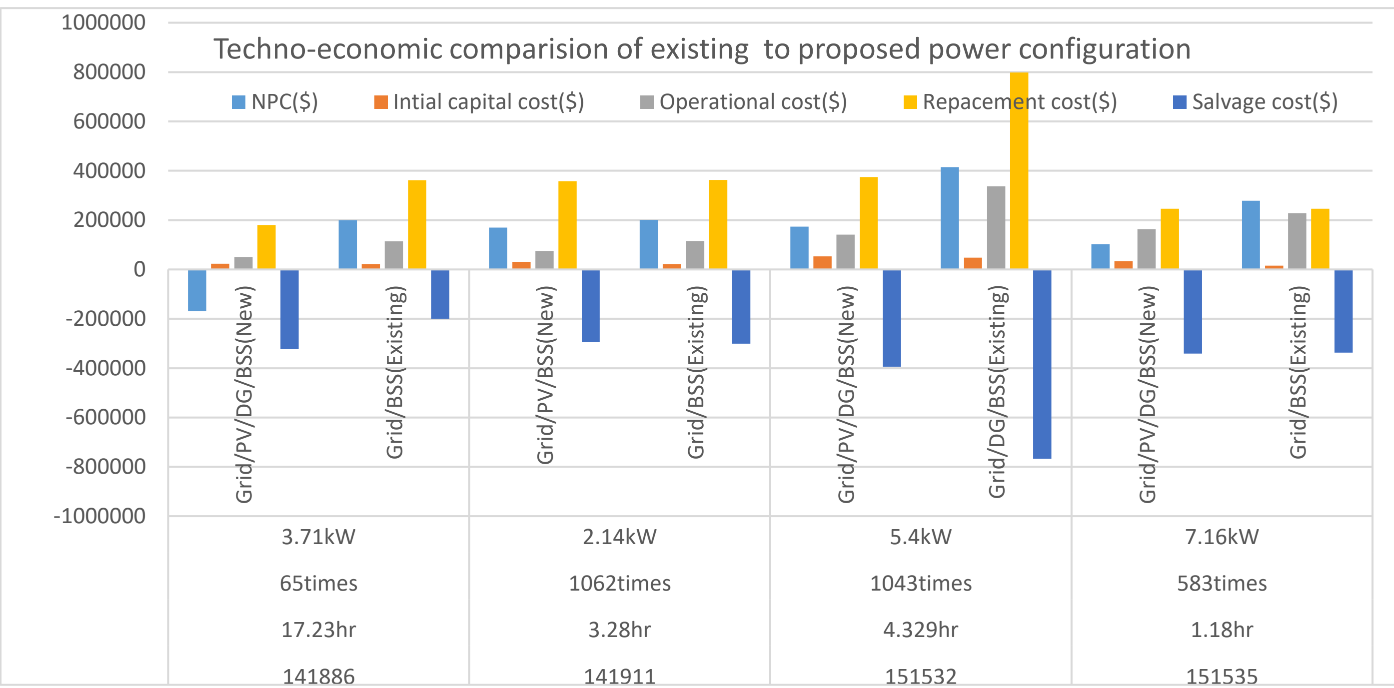


Figure 2 Techno economic compasrion of sample sites.

VII.CONCLUSION AND FUTURE WORK

A. *Conclusion*

In urban areas, few and frequent grid outages but have short maintenance time. Grid/PV/DG/BSS & Grid/PV/BSS offers the lowest NPC and is viable for a majority of sites. For frequent grid outages and long maintenance time sites, Grid/PV/DG/BSS is feasible.

31 sites have lower costs than grid COE($0.02205). Ethiopia's grid COE is the lowest. International COE is $0.1, but the proposed PV hybrid COE is (-$0.0475 to $0.032).

B. *Future Work*

Future research will include indoor BTS and exchanges(BTS, transmission, and fixed equipment), to consider AC load and different load patterns.

Battery storage system plays a crucial role in hybrid systems. Future studies will be assessing the viability of various battery technologies.

Mobile traffic varies from time to time, and the intermittent nature of renewable energy, design HERS using Energy-saving strategies.

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