Optimal Sizing of Grid-PV Hybrid System for ethio telecom Access Layer Devices and Its Economic Feasibility

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This is to certify that the thesis prepared by Rihana Mohammed, entitled: Optimal Sizing of Grid-PV Hybrid System for ethio telecom Access Layer Devices and Its Economic Feasibility, submitted in partial fulfillment of the requirements for the degree of Master of Sciences (Energy Technology) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

In Ethiopia, conventional grid power is primary source for base stations with backup from diesel generator and/or battery. Unstable diesel price; huge expenses of fuel and its transportation; and high carbon emissions are the main problems associated with fuel energy. Mindful of these facts, countries move to renewable energy sources. The work behind this paper is to determine the optimal size of grid connected solar power system for powering base stations and compare its performance with the existing system.

The study included 138 base stations that are found in Addis Ababa. They are categorized in to five based on their technology – GULC, GUC, GUL, GU and UO. To estimate the size of PV module, real time power consumption data was collected from ethio-telecom Network Operating Center (NOC) for a period of about one year (Dec. 01, 2015 to Nov. 30, 2016) - 7,860 records for each site. In addition, hourly metrological data, specifically global horizontal, diffuse solar radiation, temperature and wind speed, were collected from National Metrological Agency. The proposed hybrid model comprises of PV-Grid-Battery. This project employed linear programming as optimization method and MATLAB program was used to compute hourly DC electric power output and to solve the developed optimization model.

The finding showed that the highest power consumption was nearly 6KWs in GUC and GULC technologies, while the lowest was found to be in UO technology – around 1 KW. The number of PV modules in the hybrid system for UO technology is lower, which shows it can be implemented in all areas; while the other two technologies, GUL and GU, required green field /outdoor base stations.

In addition the simulation output revealed that the system automatically chose the grid in case where subsidized/current cost of electricity was considered, while the model builds PV system to supply its energy need when the real electricity cost was utilized. This implied that PV's economic competence was hindered by local policy. Moreover, life cycle cost comparison of PV and DG showed that photovoltaic systems are more economical than diesel generator systems.

As this evidence has several ramifications, it is better to promote PV to be used in any power design of BS. Promoting competitive PV market is also important to avail sufficient generation capacity to cover the local need.

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Contents

List of Acronyms

0-9

1G	First Generations
2G	Second Generations
3G	Third Generations
3GPP	3rd Generation Partnership Project
4G	Fourth Generations
5G	Fifth Generations

A

AC	Alternating Current
ADSL	Asymmetric Digital Subscriber Line
Ah	Ampere-Hour
AMPS	Advanced Mobile Phone System

B

BS	Base Stations
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Transceiver Station

C

C	Total Cost
CDMA	Code Division Multiple Access
CI	Capital Costs
COE	Cost Of Energy
COM	Operation and Maintenance Cost
CPE	Customer Premises Equipment
CR	Replacement Costs

D

DC	Direct Current
DG	Diesel Generator
DOD	Depth Of Discharge

E

EDGE	Enhanced Data Rate for GSM Evolution
EEU	Ethiopian Electric Utility

EGPRS	Enhanced GPRS
EOT	Equation of Time
ETC	Ethiopian Telecommunications Corporation
EVDO	Evolution Data Optimized
F	
FDMA	Frequency Division Multiple Access
G	
GMSC	Gateway MSC
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
GU	GSM and UMTS
GUC	GSM, UMTS and CDMA
GUL	GSM, UMTS and LTE
GULC	GSM ,UMTS ,LTE and CDMA
H	
HES	Hybrid Energy System
HOMER	Hybrid Optimization Model Electric Renewable
I	
ICT	Information Communication Technology
IMEI	International Mobile Equipment Identity
IMSI	International Mobile Subscriber Identity
IMT	International Mobile Telephone
ISDN	Integrated Service Digital Network
ITU	International Telecommunication Union
K	
Kbps	Kilo bit Per Second
KWh	Kilo Watt hour
L	
LAC	Levelized Annual Cost
LCC	Life Cycle Cost
LOLP	Loss of Load Probability
LP	Linear Programming
LTE	Long Term Evolution

M

MAP	Mobile Application Part
MCIT	Ministry of Communications and Information Technology
MMS	Multi Media Messaging Service
MS	Mobile Station
MSAG	Multi Service Access Gateway
MSAN	Multi Service Access Node
MSC	Mobile Service Switching Center

N

NMT	Nordic Mobile Telephones
NOC	Network Operating Center
NPV	Net Present Value
NSS	Network Switching Subsystem
NTT	Nippon Telegraph And Telephone

O

OFDMA	Orthogonal Frequency Division Multiple Access

P

PIN	Personal Identity Number
PSTN	Public Switched Telephone Network
PUK	Pin Unblocking Key
PV	Photovoltaic

R

RET	Renewable Energy Technologies
RRU	Remote Radio Unit

S

SIM	Subscriber Identity Module
SMS	Short Message Service
SPSS	Statistical Package for Social Sciences
ST	Solar Time
STC	Standard Test Conditions

T

TACS	Total Access Communication Systems
TDMA	Time Division Multiple Access

TWh	Tera Watt hours

U

UMTS	Universal Mobile Telecommunication System
UO	UMTS Only

V

V	Volt
VPN	Virtual Private Network

W

W	Watt
WCDMA	Wideband CDMA
WLAN	Wireless Local Area Network
Wp	Watt Peak

List of Symbols

δ	Declination Angle
γ	Temperature Coefficient of the Peak Power (W/K^0) of the Module
A_D	The Diesel Consumption Per Year (Liter)
C_D	Diesel Cost Per Liter Taken ($/Liter)
Ci_b	The Cost of Energy Storage Depending on Energy Rating ($/Kwh)
Ci_{b1}	Capital Cost of Storage Unit Depending on Power Rating ($/W)
CI_D	Capital Cost of Diesel Generator
Ci_{pv}	Capital Cost of Renewable PV ($/Watt)
COM_b	The NPV of Annual Operation and Maintenance Cost of Battery
COM_D	The NPV of Annual Operation and Maintenance Cost of DG
COM_{pv}	The NPV of Annual Operation and Maintenance Cost of PV Module
CS_D	The NPV of Diesel Generator Service Cost
d	Discount Rate (%)
e	Inflation Rate (%)
E_{bo}	The Energy Storage Capacity of the Storage Unit.
E_{gr}	Energy From the Grid
$E_s(t)$	The Instantaneous Energy Stored In the Battery
$fpv(t)$	Normalized Output Power Profile of the PV Module Source
I_t	Module Irradiance
N	Life Time (Yr)
n_b	Life Time of Battery
n_g	The No. of Times the Generator is Serviced During the Lifetime of *N* Years
n_r	The Number of Battery Replacements In N Number of Years
P_{DC}	DC Power Output of Representative Module
P_{gr}	Power rating of the Grid
$P_g(t)$	Instantaneous Powers Delivered By the Grid
Pgr_{max}	Limits on Maximum Rating from the Grid
$P_L(t)$	Instantaneous Load at a Site
Ppv_{max}	Limits on Maximum Rating of the PV Modules

P_{pvo}	Power Ratings of the PV Module
$P_{pv}(t)$	Instantaneous Powers Delivered by PV Module
P_{so}	Power Ratings of the Storage Unit
Ps_{max}	The Maximum Power Rating of the Storage Unit
$P_s(t)$	Instantaneous Powers Delivered By the Storage
r	The Diesel Generator Service Period (Yr)
T_{mod}	Module Temperature
ω	Hour Angle

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CHAPTER ONE: INTRODUCTION

1.1. Background

Telecommunication industry is one of the fastest growing industries in the world. The unexpected increase in subscribers and demand for telecommunication services led to tremendous growth in telecommunication networks. Wireless communications, by any measure, is the fastest growing segment of the communications industry, in particular. Among the wireless networks, cellular phones have experienced exponential growth over the last decade, and this growth continues unabated worldwide. In 2014, the number of worldwide mobile users including both business and consumers will reach over 5.6 billion. By the end of 2018, International Telecommunication Union (ITU) expects the number of worldwide mobile users to over 6.2 billion. Roughly 84% of the world population will be using mobile technology by year-end 2018 [1].

Indeed, cellular phones have become a critical business tool and part of everyday life in most countries, and wireless local area networks are currently poised to supplement or replace wired networks in many businesses and campuses. Also many new applications, including wireless sensor networks, automated highways and factories, smart homes and appliances, and remote telemedicine, are emerging [2].

In Ethiopia, ethio telecom was established in November 2010 by replacing the previous name of the company Ethiopian Telecommunications Corporation (ETC). The operator has passed through different names since 1894 E.C at the governance of Emperor Menelik II when the 407 Km telegraph line between the cities of Harar and the capital Addis Ababa was constructed [3].

Currently ethio telecom is the sole service provider of telecom technology in the entire country with comprehensive plans in place to meet the requirements set out by the Ministry of Communications and Information Technology (MCIT). The Federal Government of Ethiopia owned and controlled all telecommunications services, except selling of Customer Premises Equipment (CPE) [4]. To provide reliable and secured communication services at affordable price throughout the country, the company has developed extensive mixed-capability

Information Communication Technology (ICT) infrastructure that provides a blended coverage of 85% of the country's population, with the potential to serve 90% of its population. Over 500 cities have been connected to fixed-line Internet and every regional capital municipality has fiber connectivity [5].

Like most countries, the telecommunication network architecture of ethio telecom has four layers, namely: service layer, control layer, transport layer and finally access layer. Each layer has different function and contains various network equipments [2].

Among other services, the company offers fixed line telephone, Fax, Internet, data, mobile post-paid, mobile roaming, mobile internet, fixed wireless broad band (Aironet), Evolution Data Optimized (EVDO), fixed broadband Asymmetric Digital Subscriber Line (ADSL), virtual private network (VPN), videoconference and Tele conferencing [5]. Mobile service in Ethiopia has existed since 1999 G.C and at that time the network coverage was limited to Addis Ababa with a network capacity not more than 60,000 subscribers. According to September 18, 2012 press release, the subscription of mobile reached 17.26 million at the end of 2011 [3].

To provide mobile service, ethio telecom uses Base Transceiver Station (BTS) that help to connect the service provider with the customer [6, 7]; which is placed in access layer of the integrated network structure. It is one of Base Station Subsystem (BSS) element that is used to connect Mobile station (MS) to the network through air interface on one side and Network Switching Subsystem (NSS) on the other side [6-8].

In providing mobile services throughout the country, two vendors (ZTE and HUAWEI) signed a contract with ethio telecom; to this end, BTS is installed with the inventory of these two companies. BTS, depending on people density, could be located in city, regions, villages, hill stations and remote areas; and are positioned either in Ground bases or Roof-top of towers [5].

Nationally, there are about 4,000 BTS sites in rural and urban areas; of these, above 700 of them are found in the capital city, Addis Ababa [5].

Ethio telecom holds a variety of telecom devices that needs consistent power source to be operational. The company got this power mainly from the national grid, and uses this power source alone or with generator and/or batteries as backup. In addition for off grid or remote areas, the company uses commonly generator and battery, but in few places solar power is available.

1.2 Problem Definition

Developing countries like Ethiopia have serious energy crisis. Satisfying the power demand of the people for the fundamental necessities by itself is in much a bother situation. Hence, governments and peoples started looking towards permanent and never-ending sources of energy called renewable sources of energy such as solar and wind energy. The positive aspect of use of renewable energy sources in these countries is that they are available in plenty and also pollution free.

Although, vendors and operators of equipment for mobile communications in developing countries have been facing difficulty to meet certain challenges such as it costs much, expensive to run, uses much power and is difficult in deploying with limited electricity supply. For instance, many people in emerging markets like Ethiopia live in rural areas with limited access to the electricity grid; it becomes a significant barrier to expanding network coverage in these areas as mobile phone base stations rely on a secure supply of power. Even in areas connected to the grid, the power supply can be unstable and disrupt. And also due to the reach of mobile telephony among the people in remote villages, the service providers are stressed for finding a working solution to the energy crisis. Thus the provision to power the base stations for mobile operators with renewable energy is gaining importance steeply.

Like other mobile communication devices, BS devices required power to be operational. In Addis Ababa, Ethiopia, currently most of the BS gets power from commercial line of Ethiopian Electric Utility (EEU). In addition, these devices were using generator and/or battery as backup in situations when power is disrupted. Although, the national power provider EEU has accelerated its progress in connecting towns and supplying power, electrification rates remain low and are well known in its frequent interruption. The alternative sources, batteries and diesel generators, are unsuitable for long hours and expensive to operate, respectively.

On the other hand, if there is no adequate and continuous power supply for the BTS sites, it is difficult to ensure service continuity. As a result, all services supported by the respective devices will automatically be paused. These problems become more challenging in countries like Ethiopia, where power interruption from the grid is more common and where there is lack of reliable power supply for remote locations. Moreover, in rural areas energy consumption contributes most of the total network operating cost. Thus, this expenditure on energy as a result of the lack of grid availability highlights a potential barrier to the growth of the service delivered by the company and ensuring reliable services throughout the country.

Fortunately solar power is available in almost every location no matter how remote and can be used for low- and medium capacity sites. Apart from having very low environmental impact, solar-powered sites have the advantage of being very low maintenance, with a technical lifetime of about 35 years or more [9]. In addition it allows deeper penetration of mobile networks and much more reliable than diesel generator-powered systems. And also it can scales with the load, so the size of the solar installation can be matched to actual needs without unnecessary capacity. However the fact that solar photovoltaic (PV) technology is not yet commercially mature in developing countries [10].

Generally, using photovoltaic energy sources to power the sites has the potential to resolve the three key needs of the company, namely: reduction in diesel usage; expansion of telecom infrastructure to off-grid areas; and reduction in carbon emissions.

Despite Ethiopia receives abundant sunshine for around 365 days a year with a solar irradiation of 5000 – 7000 Wh/m^2 according to region and season, Ethiopia did not utilize the resource properly. Seasonally the radiation intensity in the country ranged from highest (5.55-6.25 kWh/m2/day) for areas around northern Ethiopia to lowest (4.25-4.55 kWh/m2/day) for the extreme western lowlands [11]. Amazingly, a total of 2.199 million Tera Watt hours (TWh) solar energy can be reserved annually in this country [12].

Thus, the possibility of using such renewable energy technology, solar photovoltaic, might be an option for Ethiopia, as the country is gifted with huge solar radiation. Aware of the aforementioned facts, this project investigates the techno-economic feasibility of solar system.

It presents real data obtained from an operational site and elaborates on how such a system could allow better energy management, reduce emissions and move towards sustainable energy. The proposed system is intended to ensure the service continuity through designing a photovoltaic system as alternative power source for base stations in ethio telecom; this includes assessing site type, site connectivity to the fixed network, site configuration, the power consumption of the site, site position, design of optimum PV sizing and evaluating its economic feasibility.

1.3 Significance of the study

The significance of this stydy is to ensure service continuity and reduce dependency on commercial line of Ethiopian Electric Utility (EEU) through an optimal sizing of Grid-PV hybrid system. In addition, the project shows that availability of alternative PV power source for telecom access layer devices and to minimize the power cost. Furthermore, this project encourages further studies that can be done to utilize available alternative power sources for other network equipments. Finally, the findings of this study will serve as a reference for other studies and decision makers for planning.

1.4 Research Question

This study is intended to answer the following Questions:

- *What amount of power is consumed by base stations that are found in Addis Ababa?*
- *What are the gaps in the existing power system of the base stations?*
- *What alternative power source do we have for the base stations?*
- *What will be the optimum size of the alternative power source?*
- *Is the alternative power source economically feasible?*

1.5 objective of the study

General Objective

The main objective of this stydy is to model and develop alternative power source for ethio telecom access layer devices, BTS towers, using Grid connected PV system and size the system using proper optimization method.

Specific objectives

The specific objectives to be undertaken to reach at the general objectives are to:

- *Assess the solar radiation of Addis Ababa*
- *Determine the DC power output of a single module at Addis Ababa*
- *Assess type, position and configuration of BTS sites and determine the load pattern of the BTS sites by each category*
- *Develop a model and formulate objective function and constraints*
- *Determine optimum sizing which can fit the required power using appropriate optimization method*
- *Determine the economic feasibility of the proposed system*

1.6 Limitation of the study

- The fact that the study was done only in Addis Ababa, it may limit its generalization of using the alternative power source nationally;

CHAPTER TWO: LITERATURE REVIEW

2.1 Mobile Telephony Network

Consumers seek communication at home or in the street, always using the mobile phone beyond the limitations imposed by cables. However, in order to be able to use a mobile phone at least one telephone wireless network is required. (More detail on mobile technology, definition of technical terms, and mobile evolution is given in Appendix A). The network shown in Figure 2.1 required different network devices to get the desired communication [13].

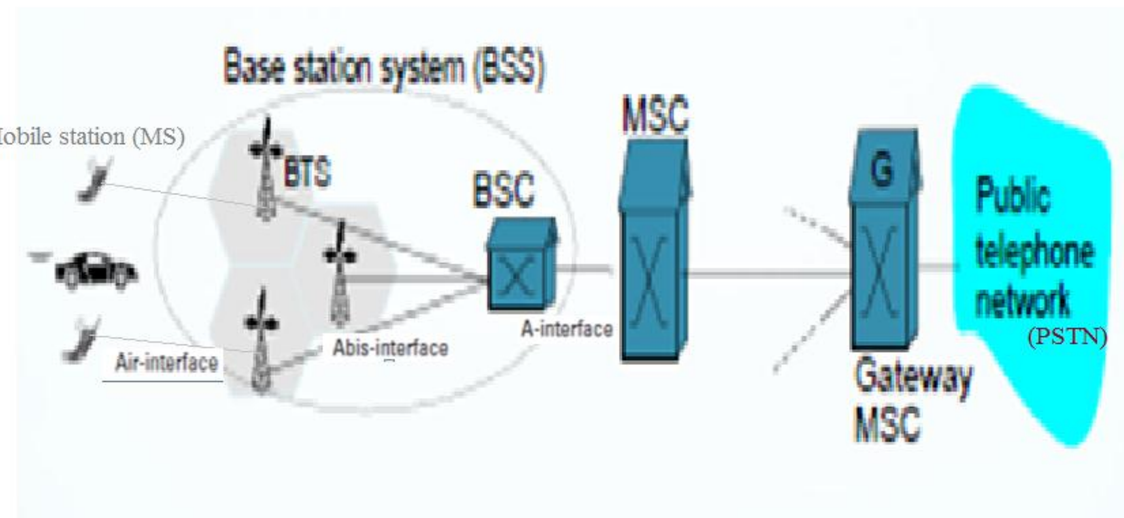

Figure 2.1 Structure of Mobile Network, [13]

A mobile telephony network is generally composed of the following:

Mobile station (MS): The MS includes all user equipment and software needed for communication with network. It consists of the subscriber identity module (SIM), which is a data base on the user side that stores all user-specific data [8, 14]. It contains many identifiers and tables, such as card-type, serial number, a list of subscribed services, a personal identity number (PIN), a PIN unblocking key (PUK), an authentication key Ki, and the international mobile subscriber identity (IMSI). And MS can be identified via the international mobile equipment identity (IMEI), a user can personalize any MS using his or her SIM, i.e., user-specific mechanisms like charging and authentication are based on the SIM, not on the device itself [8].

Base transceiver station (BTS): A BTS comprises all radio equipment, i.e., antennas, signal processing, amplifiers necessary for radio transmission. Also it provides the physical connection of MS to the network through Air-interface. On the other side, it is connected to the Base Station Controller (BSC) via the Abis-interface [8].

Base station controller (BSC): is a small digital exchange its function is to switch the incoming traffic channels through A-interface from the Mobile service Switching Center (MSC) to the correct Abis-interface channels. In addition it manages BTS's, reserves radio frequencies, handles the handover from one BTS to another within the Base Station Subsystem (BSS) and performs paging of the MS [8, 14].

Mobile services switching center (MSC): MSCs are high-performance digital integrated service digital network (ISDN) switches. They set up connections to other MSCs and to the BSCs via the A-interface, and form the fixed backbone network of a system. Typically, an MSC manages several BSCs in a geographical region. It also handles all signaling needed for connection setup, connection release and handover of connections to other MSCs [8].

Gateway MSC (GMSC) has additional connections to other fixed networks, such as public switched Telephone network (PSTN) and ISDN [8].

2.2 Cellular Base Stations (BS)

A base station is a wireless system situated at the heart of the cell (The area covered by base station signals); it includes an antenna, a controller and a number of transmitters and receivers. Usually, three antennas with hundred and twenty degrees are mounted on the top of the metallic tower to cover the specified region and connected to Remote Radio Unit (RRU) with cables. Though these antennas are operated at different frequencies they are well separated from each other to avoid interference of emitted power from each other [15, 16].

Also at the bottom of the tower a small house of electronic circuits often called a shelter is found, contained power amplifiers that are used to generate strong signals and they are connected to RRU with fiber. The base station also has additional components within a shelter include digital signal processing unit, microwave link, rectifier, air conditioning elements (for indoor base station) and lighting. Also many base stations have a Direct Current (DC) power back up system in the form of batteries connected either in series or parallel [16].

2.2.1 Power Consumption of BS

Base stations can be classified as Macro cell, Micro cell, and Small cell (Pico and Femto) base station based on the amount of area covered. Small cells cover the smallest area and they are deployed in a room, offices or shopping malls, metro stations etc. Micro cells can cover blocks of buildings in densely populated urban locality and cover area more than Small cells. Macro cells cover the largest area among all the cells and generally they are deployed in rural areas or on high ways. The number and type of components for each type of BS are different as shown in Figure 2.2 below [17].

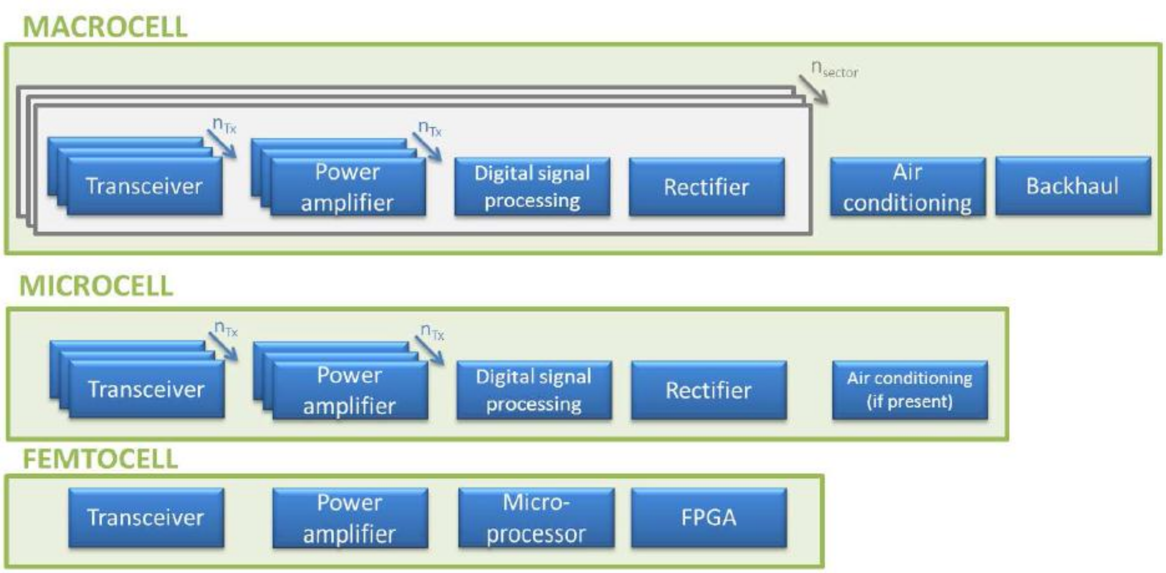

Figure 2.2 Architecture of the Macro cell, Microcell, and Femto cell base station, [18]

The base station's power consumption can be determined by the sum of the power consumption of all those components. However, as shown in Figure 2.2, some of the components are used multiple times depending on the configuration of the base station. The power consumption of these components should thus be multiplied by their number of occurrences. The type and the number of the required components depend on two factors: the number of sectors and the number of transmitting antennas. The term sector represents sub-area in a given cell, which is an area covered by base station [17, 18].

Each sector is covered by one antenna and needs therefore one rectifier, one digital signal processor, one transceiver, and one power amplifier. Therefore the power consumption of these components must thus be multiplied by number of sector. In addition multiple transmitting antennas are used per sector, for each transmitting antenna, one transceiver and one power amplifier are needed. This means that the power consumption of these two components must not only be multiplied by number of sectors but also by the number of transmitting antennas [17, 18].

Each of the base station's components has a typical power consumption value. The power consumption of the backhaul connection and the rectifier(s) is assumed to be constant throughout time. The power consumption of the air conditioning is not influenced by the time but rather by the temperature inside and outside the base station cabin [17, 18].

The power consumption of the digital signal processing, the transceiver, and the power amplifier can fluctuate during time due to variations in load on the base station. The load represents the number of active users or the number of calls at that time and the requirements of the services they use in the base station cell, the higher the load, the higher the base station's power consumption [17].

2.2.2 Power Sources for BS

BS primarily powered by electrical power from the grid in urban areas with a back-up by battery and/or a diesel generator. The grid power must be available for 24 hours a day to give reliable service for the customers. But electrical grids are not available or are unreliable in most locations of developing countries; therefore cellular network operators rely on diesel powered generators to run a base station.

The idea of using diesel generators as a primary or back-up power supply has become less favorable due to the challenges linked to their reliability, high operational and maintenance costs, and their considerable environmental impacts [19]. Therefore adding several base-stations for service providers can only multiply this destructive environmental impact, unless these base-stations are supported by a sustainable alternative energy sources. Hence renewable energy sources such as solar, wind and fuel cell energy or hybrid solution seem to be more practicable options to reduce the overall difficulties [19, 20].

These solutions have been strong choices for powering BSs due to their abundant availability in a wide range of geographical locations around the world. Additionally, the components in solar- and wind-based systems are usually modular, which makes the design, expansion, and installation of these types of systems for the BS sites very practical and feasible. However, due to the unpredictable and irregular nature of wind and solar, the systems running on these sources typically need to be integrated with other means of renewable or non-renewable power supply and/or energy storage solutions in order to ensure the continuity of power supply in a BS site [19, 20].

Implementing Renewable Energy Technologies (RET) for a particular telecom site requires a comprehensive understanding of that technology. The relative characteristics, advantages and limitations of solar photovoltaic technology are discussed below.

Solar Photovoltaic

Enabling distributed power generation and emission-free power source makes solar photovoltaic technology a desired option for backup power. However, the dependency on sunshine and the space requirement limits the scope of deployment. Geographic parameters including daily average energy incidents, the duration and availability of sunshine and also solar power density across different geographic locations, influence the scope of solar photovoltaic deployment [21].

In recent times, the two types of applications deployed at telecom tower sites are stand-alone and hybrid solar photovoltaic. The application types were chosen based on the site load profile, grid outage scenarios, space availability at the site and other configuration aspects including average sunshine availability throughout the year and the power storage configuration for non-sunshine hours [21].

Generally, a solar photovoltaic power system for a telecom site is designed in combination with the appropriately sized battery bank, or used to offset the operation of a backup power system like a diesel generator for approximate hours per day when sunlight is available. In addition detailed evaluation of the load profile of the site, weather conditions at the site throughout the year, battery efficiency, charge controller efficiency, power loss due to dust accumulation and available area for installation of the solar photovoltaic panels should be considered [20].

2.3 Components Used in Hybrid Model

Photovoltaic (PV) Cells, Panels and Arrays

A PV cell is a semiconductor device that can convert solar energy in to DC electricity through the photovoltaic effect. The PV generated electricity is 'silent', low in maintenance and does not need fuel or oil supplies. However, PV energy is only available when enough radiation is accessible.

A PV panel consists of several connected PV cells. The power rating of a panel is specified at standard test conditions (STC) which include a defined cell junction temperature, (usually 25^0C) and irradiance (usually $1000W/m^2$) and is the maximum power output in this state expressed in peak watt (Wp), also it depends on its cell area and efficiency. PV panels are available in wide variety of ratings, in some cases up to 300 Wp each are manufactured. Also developments are under way to produce Alternating Current (AC) PV panels by including an inverter in to the panel setup to enable easy and modular AC bus connections [22].

If higher voltages or currents are required from a single module voltage and current, modules must be connected into arrays. Series connections result in higher voltages, while parallel connections result in higher currents. When modules are connected in series, it is desirable to have each module's maximum power production occur at the same current. When modules are connected in parallel, it is desirable to have each module's maximum power production occur at the same voltage [23].

Since PV arrays produce power only when illuminated, PV systems often employ an energy storage mechanism so the captured electrical energy may be made available at a later time.

Most commonly, the storage mechanism consists of rechargeable batteries. When a battery storage mechanism is employed, it is common to also incorporate a charge controller into the system, so the batteries can be prevented from reaching either an overcharged or over discharged condition. It is also possible that some or all of the loads to be served by the system may be ac loads. If this is the case, an inverter will be needed to convert the dc from the PV array to ac [23].

Figure 2.3 Buildup of a solar PV array from cell to module to panel to final array, [23]

It is also possible that the PV system will be interconnected with the utility grid. Such systems may deliver excess PV energy to the grid or use the grid as a backup system in case of insufficient PV generation [23].

Energy Storage Battery Bank

Now a day's energy storage system has taken a huge part in case of power generation including hybrid power system. It makes the system much more reliable and efficient. Energy storage system has dual advantage; (1) whenever power deficit occurs; it helps to transfer the stored energy to the system. (2) In case of excess energy supply from resources, the system will store the surplus energy in the storable form of energy. To this end, storage system has remarkable importance in renewable energy sources, wind and Solar PVs in particular; as they are intermittent sources.

Battery characteristics

Battery is described in terms of four main characteristics: Battery capacity, Battery voltage, Cycle depth and autonomy [24].

Battery capacity: is the amount of energy, the battery can store. Temperature, rate of discharge, battery age and battery type determines the amount of energy extracted from a fully charged battery. The three main ratings to specify the capacity of a battery are: *(1) Ampere-hour (Ah)*: the amount of current at which the battery can discharge their stored energy over a fixed interval of time. (2)Reserve capacity: the time length in minutes when the battery can manage to produce a specified level of discharge. (3)KWh capacity: the amount of energy required to charge a depleted battery (not fully discharged batteries).

Battery voltage: is that of a fully charged battery. It depends up on the number of cells and voltage per cell.

Cycle depth: Fully discharging batteries can cause an adverse effect regarding to the life of the battery. Deep cycle batteries can discharge up to 15%-20% of their capacity. This gives a depth of discharge (DOD) of 85% - 80%.

Autonomy: the ratio of restorable energy capacity to the maximum power discharge. It indicates the maximum amount of time in which the system can extract its energy.

Grid Power source

The grid is a dispatch-able power source. Any amount of power can be drawn from the grid at any time and it does not have a startup, shutdown, minimum or maximum run time. The power that can be purchased from the grid to supply the load depends on its availability [25].

2.4 Economic Model Based on Life Cycle Cost (LCC)

The life cycle cost of a component consists of procurement cost and operation and maintenance cost. Some costs involved in the procurement and operating of a component are incurred at the time of an acquisition (includes costs of purchasing equipment and their installation), and other costs are incurred at later times (includes costs of fuel if exists, operation and maintenance). The later costs may occur on regular or/and at irregular basis. In order to compare two similar items, which may have different costs at different times; it is convenient to refer to all costs to the time of acquisition [26].

Two phenomena affect the value of money over time and shall be considered when evaluating in economic terms:

- *The inflation rate (e):* is a measure of decline in value of money.
- *The discount rate (d)*: relates to the amount of interest that can be earned on the principal that is saved in a certain account.

The concept of LCC is used for cost analysis in this study. The LCC of the system is composed of Net Present Value (NPV) of initial capital cost of all the model components, annualized operation and maintenance costs and replacement costs.

The economic dispatch problem is to determine the optimum scheduling of generation at any given time that minimizes the system LCC while completely satisfying the demand, operating limits and constraints. For this study, system LCC is calculated by the following formula [26]:

$$LCC = C_{gr} + C_{pv} + C_b \qquad \textit{(Eq. 2.1)}$$

Where total cost (C) and the corresponding subscripts gr, pv and b stands for grid, photovoltaic and battery respectively. More briefly Eq 3.2 could be written in the following:

$$LCC = C_{gr} + CI_{PV} + COM_{PV} + CI_b + COM_b + CR_b \qquad \textit{(Eq. 2.2)}$$

Where: capital costs (CI), the operation and maintenance cost (COM) and replacement costs (CR).

Initial Capital Cost [27]:

- The cost associated with getting energy from the grid is modeled as:

$$C_{gr} = Ci_{gr1} \times P_{gr} + Ci_{gr} \times E_{gr} \qquad \textbf{(Eq. 2.3)}$$

Where $\mathbf{E_{gr}}$ is the energy drawn from the grid; $\mathbf{P_{gr}}$ is the peak power drawn from the grid, and

Ci_{gr} is cost of grid electricity ($/kwh)

- The initial capital costs of the renewable PV and storage unit are modeled as:

$$CI_{PV} = Ci_{pv} \times P_{pvo} \quad \text{(Eq. 2.4)}$$

$$CI_b = Ci_{b1} \times P_{so} + Ci_b \times E_{bo} \quad \text{(Eq. 2.5)}$$

Where P_{pvo} and P_{so} are the power ratings of the PV module and storage unit, respectively, and E_{bo} is the energy storage capacity of the storage unit.

Ci_{pv} is capital cost of renewable PV ($/watt), $Ci_{b1}$is capital cost of storage unit depending on power rating ($/kw) and Ci_b is the cost of energy storage depending on energy rating ($/kwh)

Operation and Maintenance Cost [26]:

- The NPV of annualized operation and maintenance cost of the PV module is assumed as percentage F1 of initial capital cost and can be calculated by using the following relation:

$$COM_{PV} = F1 \times CI_{PV} \times \left\{ \sum_{i=1}^{N} \left(\frac{(1+e)}{(1+d)^i} \right)^{i-1} \right\} \quad \text{(Eq. 2.6)}$$

Where: COM_{PV}: is NPV of annualized operation and maintenance cost of PV module

e is the inflation rate, ***d*** is the discount rate and ***N*** is the lifetime of the system.

- Similarly, the operation and maintenance cost of the battery storage is given by the following expression:

$$COM_b = F1 \times CI_b \times \left\{ \sum_{i=1}^{N} \left(\frac{(1+e)}{(1+d)^i} \right)^{i-1} \right\} \quad \text{(Eq. 2.7)}$$

Replacement Cost [26]:

- In most system design, the life time of the system is equal to that of PV module; therefore the replacement cost of PV is zero.
- The replacement cost of battery bank is given by the following expression:

$$CR_b = F2 \times CI_b \times \left\{ \sum_{i=1}^{n_r} \left(\frac{(1+e)}{(1+d)^{n_b i}} \right)^{n_b (i-1)} \right\} \quad \text{(Eq. 2.8)}$$

Where n_r is the number of battery replacements in N number of years: $n_r = abs\left[(N - n_{b)}/n_b\right]$

n_b is the life time of the battery

Substitute all expressions in equation (2.2) and rearranging, the final LCC equation become:

$$LCC = K1 \times P_{gr} + K2 \times P_{pvo} + K3 \times P_{so} + K4 \times E_{bo} + K5 \times E_{gr} \qquad \textbf{(Eq. 2.9)}$$

Where: K1, K2, K3, K4 and K5 constants calculated from expressions shown in Appendix D.

LCC of Diesel Generator [26]:

LCC of diesel generator is given by:

$$LCC_G = CI_D + COM_D + CS_D + CF_D \qquad \textbf{(Eq. 2.10)}$$

Where CI_D: the initial cost of diesel generator, given by

$$CI_D = C_k \times P_{DG} \qquad \textbf{(Eq. 2.11)}$$

COM_D: The NPV of annual operation and maintenance cost is computed by the following equation. Here F3 is percentage of initial generator cost.

$$COM_D = F3 \times CI_D \times \left\{ \sum_{i=1}^{N} \left(\frac{(1+e)}{(1+d)^i}^{i-1} \right\} \qquad \textbf{(Eq. 2.12)}$$

The NPV of diesel generator service cost is calculated according to the following relation.

$$CS_D = F4 \times CI_D \times \left\{ \sum_{i=1}^{n_g} \left(\frac{(1+e)}{(1+d)^{ri}}^{r(i-1)} \right\} \qquad \textbf{(Eq. 2.13)}$$

Where n_g is the number of times the generator is serviced during the lifetime of *N* years computed by:

$$n_g = abs(N/r) \qquad \textbf{(Eq. 2.14)}$$

r is the diesel generator service period and F4 is percentage of initial generator cost.

The NPV of annual diesel cost is simulated by the following equation:

$$CF_D = C_D \times A_D \times \left\{ \sum_{i=1}^{N} \left(\frac{(1+e)}{(1+d)^i}^{i-1} \right\} \qquad \textbf{(Eq. 2.15)}$$

Where A_D is the diesel consumption per year and C_D is the diesel cost per liter taken.

2.5 Optimization Method

Optimization is the act of obtaining the best result under given circumstances. Optimization can be defined as the process of finding the best solution that maximizes or minimizes a given objective function under given constraints. The obtained solution is called the optimal solution. The constraints which the objective function can be subject to are in most cases categorized as boundary, equality and inequality constraints. However, some objective functions are not subject to any constraints [28].

2.5.1 Linear Programming (LP)

Linear Programming is one type of optimization method but not a programming language like C++, Java, or Visual Basic; however it can be defined as [29]:

"A mathematical optimization method to allocate scarce resources to competing activities in an optimal manner when the problem can be expressed using a linear objective function and linear inequality constraints."

A linear program consists of a set of variables; a linear objective function indicating the contribution of each variable to the desired outcome; and a set of linear constraints describing the limits on the values of the variables. The "answer" to a linear program is a set of values for the problem variables that results in the best (largest or smallest) value of the objective function and yet is consistent with all the constraints.

Formulation: is the process of translating a real-world problem into a linear program. Once a problem has been formulated as a linear program, a computer program (like MatLab) can be used to solve the problem. The hardest part about applying linear programming is formulating the problem and interpreting the solution.

The linear program consist the following elements [29, 30]:

(a) ***The Decision Variables:*** are a set of quantities that need to be determined in order to solve the problem in a linear program; i.e., the problem is solved when the best values of the variables have been identified.

(b) ***The Objective Function***: the objective of a linear programming problem is to maximize or to minimize some numerical value. The *objective function* indicates how each variable contributes to the value to be optimized in solving the problem. It takes the following general form:

$$\textit{Maximize or minimize} \quad \sum_1^n C_i X_i \qquad \text{(Eq. 2.16)}$$

Where C_i= the objective function coefficient corresponding to the *i*th variable, and

X_i = the *i*th decision variable.

The general objective function written above indicates that there is a coefficient in the objective function corresponding to each variable. Of course, some variables may not contribute to the objective function. In this case, you can either think of the variable as having a coefficient of zero, or you can think of the variable as not being in the objective function at all.

(c) ***The Constraints:*** *constraints* define the possible values that the variables of a linear programming problem may take. They typically represent resource constraints, or the minimum or maximum level of some activity or condition. They take the following general form:

$$\textit{Subject to} \quad \sum_1^n a_{ij} X_i = b_j \qquad \text{(Eq. 2.17)}$$

Where X_i= the *i*th decision variable,

a_{ij}= the coefficient on *Xi* in constraint *j*, and

b_j= the right-hand-side coefficient on constraint *j*.

Note: the *index j* runs from 1 to *n*, and each value of *j* corresponds to a constraint. Thus, the above expression represents *m* constraints (equations, or, more precisely, inequalities) with this form. Although the constraint above is written as equal, it can also take a less-than or equal constraint or greater-than or equal constraints.

2.5.2 Optimization Solver and Algorithm

The constrained linear optimization problem can be solved using the “linprog” solver in Matlab. The program linprog.m is used for the minimization of problems of the form linear program. The general form of calling linprog.m is [31, 32]:

[X , fval] =linprog (F, A, b, Aeq, beq, lb, ub, x0, options)

Where: the input and output arguments shown in Table 2.1

Table 2.1 Input, output arguments and their description

Input Arguments	**Description**
F	coefficient vector of the objective function
A	Matrix of inequality constraints
B	right hand side of the inequality constraints
Aeq	Matrix of equality constraints
Beq	right hand side of the equality constraints
Lb	lb ≤ x : lower bounds for x, no lower bounds use [ ]
Ub	x ≤ ub : upper bounds for x, no upper bounds use [ ]
X0	Start vector for the algorithm, if known, else [ ]
Options	Options are set using the optimset function; they determine what algorism to use.
Output Arguments	**Description**
X	optimal solution
Fval	optimal value of the objective function

Algorithms under linprog

There are three types of algorithms that are being implemented in the linprog.m [32]:

- Simplex algorithm;
- Active-set algorithm;
- Primal-dual interior point method.

The simplex and active-set algorithms are usually used to solve medium-scale linear programming problems. If any one of these algorithms fails to solve a linear programming problem, then the problem at hand is a large scale problem. Moreover, a linear programming problem with several thousands of variables along with sparse matrices is considered to be a large-scale problem, by default, the parameter 'Large Scale' is always 'on'.

For this paper ''linprog'' as optimization solver and the default interior point algorithm was used.

2.6 Related Works

Solar power for powering BS

There are several works which have used solar power energy for powering base stations that are on or off grid sites. A study conducted in West Arsi, Oromia region presented the solution to utilizing a hybrid of photovoltaic (PV) solar and wind power system with a backup battery bank to provide reliable electric power for a specific remote mobile base station. The result indicated that the hybrid energy systems can minimize the power generation cost significantly and can decrease CO_2 emissions as compared to the traditional diesel generator [33].

Study done by *Firas Shaher* [34] showed that it is possible to supply the communication towers in remote areas by using PV systems as a hybrid with existing diesel generators. The study also showed that, it is possible to design and select the size of PV modules which are applicable to supply the tower loads during 24 hours/day.

Ani, Vincent Anayochukwu, et al. [35] determined the optimal size of stand-alone PV/diesel hybrid power system for BTS site located in rural Nigeria. In same study, Hybrid Optimization Model Electric Renewable (HOMER) software was used to design the system. The result showed that the PV/diesel hybrid system has a lower net present cost and the amount of carbon dioxide production was also found to be lower.

In 2014 *Salih et al.* [36] a study was done based on minimized capital and operation costs of system components without compensation of meeting the load demand. The study used three different system configurations (system efficiency and performance, Cost of Energy (COE) and environmental emissions) for assessment and comparison; and the analysis was carried out by HOMER software. Generally, the study showed the use of a PV/wind/Diesel and battery hybrid system for powering remote BTS sites.

Subodh Paudel et al. [37] discussed a feasibility assessment and optimum size of PV array, wind turbine and battery bank for a standalone hybrid Solar/Wind Power system at remote telecom station of Nepal. In the study feasibility analysis was carried through HOMER and mathematical models were implemented in the MATLAB environment. At last the simulation results for the existing and the proposed models were compared.

All the above studies showed that PV hybrid with other power sources can be used for powering remote/off grid base stations. While this study demonstrated how PV hybrid system can be used for both grid connected and off grid base stations.

Renewable Energy Hybrid with Grid

A study done in Nigeria by *Okundamiya et al*. [38] examined the viability of a grid-connected hybrid energy system (HES) for domestic electricity. The HES consists of the grid power supply, wind energy conversion, power electronics, and storage units. The study showed that the power system could bring benefits of cost saving and improve power reliability, but the range of financial benefits depends on the geographical coordinates.

Another study done by *Khatib, et al*. [39] presented an optimum PV power system design for JAWWAL's (mobile) base station in order to solve the problem of the frequent power cut offs in Gaza. The study proposed PV system work in parallel with the main electricity source as a hybrid system to charge additional backup batteries for the BTS, and that finally increase the up-time of the stations operation, which already suffers from frequent power cut offs, due to the unreliable electricity generation in Gaza.

C.S. Supriya et al. [40] conducted a research on the optimal design of a hybrid wind-solar power system for either autonomous or grid-linked applications. The study was designed to accomplish minimum cost, reliable source for the load and to reduce the power purchased from the grid. This was achieved by finding the optimum number of PV modules and wind turbines using quadratic programming techniques. The result showed that the hybrid systems had considerable reductions in carbon emission and cost of the system.

Panagiotis et al. [41] published a remarkable research in 2013 on how a hybrid solar-wind-diesel/electricity grid system could efficiently feed the load of a BTS. The study presented the techno-economical optimization of the proposed hybrid system, through the development of a time-step simulation model, which takes into account the loss of load probability (LOLP) and levelized annual cost (LAC). Finally, the case-study was installed in the Greek island of Kea, showed that a combination of photo-voltaic, wind, diesel generators, batteries and electricity grid, for a grid-connected BTS, is the most cost-effective solution.

The most related study done by *Nikum et al.* [42] presented techno-economic analysis of hybrid power system with cost minimization. The renewable sources, wind and solar energy connected with battery, grid and diesel generator, which are used as backup in the study, and their economic feasibility was compared. The data from location of Mumbai, Maharashtra assessed and calculated by HOMER. The result showed that the cost with highest renewable fraction to reduce the emission and fulfill the load demand significantly. Finally the study concluded that the grid plays an important role of power backup component in the hybrid system, when the renewable energy resources are not enough to meet the load.

Here some of the above studies used the PV hybrid system for other purpose other than powering base stations; while this study employed it for base stations. Moreover, in some of the studies, the PV hybrid system included diesel generator where it doesn't allow excluding the effect of diesel generator such as cost and environmental pollution.

Linear Programming (LP) Used as Optimization Method

There are various studies used LP as optimization method for single or multi objective functions. For instance a study done by *Chedid, R. and Rahman, S.* [43] used a technique to design and analyze a hybrid wind-solar power system for either autonomous or grid linked application. Linear programming optimization method was used to minimize the average production cost of electricity while meeting the load requirements in a reliable manner.

Kusakana et al. [44] provided an energy system for rural and isolated areas in developing countries. The study presented a mathematical formulation of the renewable hybrid sources connected together in order to build an economical system. Linear Programming was used for the objective function that to minimize the capital investment cost of renewable energy components subject to energy resources, size of components and energy demand. Finally a numerical example was done by combined PV, wind and Hydro kinetic energy system.

Khatib [45] studied that a renewable energy system consisting of a PV and a wind energy source was proposed to be connected to electricity grid of Nablus city in Palestine. The proposed system was optimally designed taking into consideration maximum system productivity and inverter size. The optimum inverter sizing ratio was obtained using a liner programming optimization method. The study concluded that the use of PV energy sources was more feasible as compared to wind energy sources in Nablus and a grid-connected system consisting of PV array only as an energy source was recommended.

The study conducted by *Huneke et al.* [46] used linear programming methods for optimal configuration of the electrical power supply system followed by characteristic restrictions as well as hourly weather and demand data was found. From the model, the optimal mix of solar- and wind-based power generators combined with storage devices and a diesel generator set was formed. Finally, the result showed that the optimized capacity of the diesel generator remains nearly constant; its contribution to the total power generation is being substituted by renewable energy sources.

All the above studies used linear programming for optimization method however the objective function varied. The studies used to minimize capital investment cost, or to minimize production of electricity, while this study used to minimize life cycle cost of the system.

CHAPTER THREE: METHODOLOGY

3.1 Description of ethio-telecom (Study Company)

Ethio telecom was established in November 2010 by replacing the previous name of the company ETC, owned and monopolized by government. All telecommunication services are provided by this company. Among others, internet, mobile, fixed line telephone, data communication, e-video, international connectivity and teleconferencing are the services provided by the telecom. In delivering these aforementioned services, the company uses diverse communication equipments including BTS, media gateway devices, wireless antennas, Micro waves, routers, switches and etc.

BTS is the device used to link the provider (ethio-telecom) with the customers (SIM cards). According to ethio telecom report, the Company has more than 4000 Base stations (BS) across the country; of these around 20% of base stations are available in Addis Ababa, capital city of Ethiopia. All telecom base stations are connected to national as well as local networks either through fiber and/or microwave links. Each base station serves the entire customers that are found in the surrounding area.

Telecom BS have similar design, principle of work, and equipment that it consists of; however, it is broadly categorized in to two based on the equipment placement: (1) indoor position – where the tower is situated in the compound of around 150 square meter area of green field and all other telecom equipment, electrical boards, racks, air conditioners and batteries are placed in room next to the tower. (2) Outdoor position –as the name implied, the towers, all telecom equipment, battery banks and etc are sited on the roof top of buildings. (See Figure 3.1 and Figure 3.2, respectively)

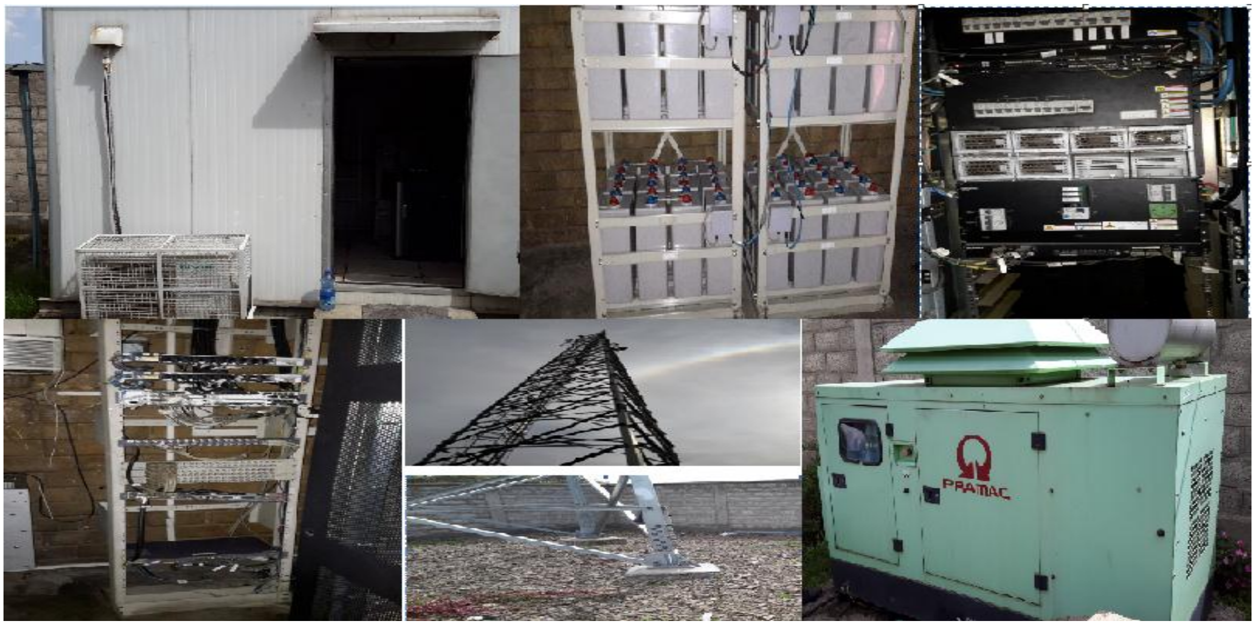

Figure 3.1 indoor position base station a camera picture (Sarbet, AA, January 2016)

Figure 3.2 outdoor tower and equipment a camera picture (Sarem Building AA, January 2016)

Electrification of Existing Base Stations in ethio-telecom

Base station equipment needs stable electric source to be operational. They are categorized in to three based on their power configuration or the type of electric supply system; described under here:

Main sites: these sites are usually either VIP sites such as sites connected to Minister Offices, Hotels, Embassies and Security Offices or sites which have linkage with other towers. Continuous power supply is mandatory for this category; as a result these sites are supplied by three alternative sources: (1) the main source is AC power from grid networks; (2) first backup system from diesel generator; and (3) battery system as second backup system.

Tower serving small areas: usually it is the dead end which doesn't have linkage with other towers. It is supplied by two power sources with main source of AC power from grid networks and backup of battery system.

Towers in remote (off grid) areas: are sites that are far from utility grids. Its main source is diesel generator and/or with additional solar source in some areas and battery system as backup.

3.2 Study Area

Ease of accessibility of data; availability of several types of technologies; ease of demonstration or piloting of proposed designs; and having greater proportion of users in the region were some of the reasons that obliged us to select Addis Ababa as a study area. At the same time, design considerations for remote towers are the same as that of the urban. But in urban systems, assessing the impact of the national energy policy on the use of the PV technology can also be taken into account by comparing cost of operation using the subsidized electricity services via-a- vis the solar PV energy storage. Taking the case of Addis Ababa will provide us more comprehensive scenarios that enable us to examine the potential for prosumer market.

Addis Ababa is one of the two city Administrations of Federal Democratic Republic of Ethiopia which covers an area of about 530.14 square kilometers, located at 9°1′48″N 38°44′24″E at the center of Ethiopia and lies an elevation of 2,300 meters (7,500 ft). It has 10 sub cities (kifle ketemas) and 99 woredas (kebele's) with estimated total population of 3.35 million with 817,561 households (2007 E.C census projection).

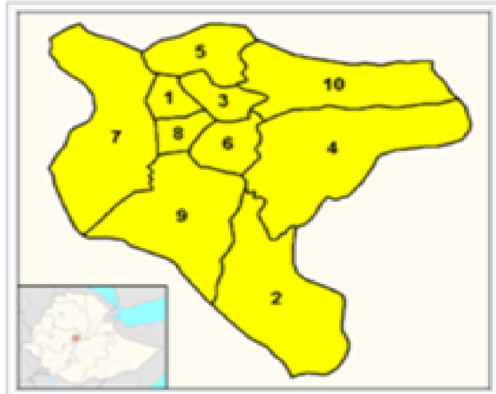

Figure3.3 District Map of Addis Ababa, [47]

According to the 2008 E.C ethio telecom report, around 728 base stations are available across all woredas. All the stations are powered from utility grid; at a time of grid interruption battery and/or generator is used as backup power source.

3.3 Specification of PV module and Battery

PV module and battery should be selected for the system simulation. To select these equipment local markets were surveyed. The selection criteria were availability and cost of equipment; and existence of full data sheet. Based on the criteria, 150Wp module and a COPEX solar battery with 150Ah and 12V have been selected. The data sheet for the selected equipment and their cost is annexed in Appendix H.

3.4 Metrological data

One year hourly metrological data specifically global horizontal radiation, diffuse solar radiation, wind speed and average temperature, were collected from National Metrological Agency; sample hourly collected data and monthly average data are annexed in Appendix I. The hourly data was used to simulate hourly DC power output generated by a single selected PV module.

3.5 Determination of hourly DC Power Output

Hourly simulation of the PV output was performed following, a method developed in [48, 49]. The flow diagram given in Figure 3.4 summarizes the hourly DC electric power output using Matlab program.

The details formulae used in each step are given in Appendix B (from Eq. B1 to Eq. B11). Primarily metrological data including wind speed, solar radiation and ambient temperature were read and values of parameters were set from PV specification and standards. Using these data, solar time (ST) and Equation of Time (EOT) were computed. Then, declination angle (δ) and Hour angle (ω) were calculated.

Figure 3.4 Flow Chart to find DC Power Productionof a Module

Following this, global irradiance and module temperature were determined. Finally, the hourly DC electrical output from a single selected module was obtained using the following expression [49]:

$$P_{DC} = [\ I_t \div 1000w/_{m2}] \times [W_p + \gamma * (T_{mod} - 25^{oC})] \qquad \textbf{\textit{(Eq. 3.1)}}$$

Where P_{DC}=calculated DC power output of representative module

I_t = Module irradiance

W_p= Watt peak of selected module

γ= Temperature coefficient of the peak power (W/K^0) of the module

T_{mod}= module temperature

Once hourly data was computed using the above algorithm, the hourly DC power generation of a single module was simulated using Matlab. The corresponding MatLab Code for this part is presented in Appendix C.

3.6 Base Stations (BS)

3.6.1 Factors Affecting Power Requirement of Base Stations

Base stations represent the main contributor to the energy consumption of a mobile cellular network. Several factors can affect the base station power consumption. These include the traffic load (which varies as a function of time), the density of population and building of an area that is morphology, the type of technology or combination of technology used at the base station, number of hub linked to a specific base station, availability of microwave link, normally the BS is linked to the respective backbone through fiber link; however, some BSs may not have access to fiber link, as a result microwave connection will be used. In some cases, both may occur at a time. The other factors are configuration and whether the site is indoor (BTS housed in a shelter) or outdoor. Description of the characters presented in Table 3.1 below:

Table 3.1 Power Consumption factors description and their Classification

Category	Description	Classification
Technology	Single or a combination of access technologies implemented on the site	GULC, GUL, GU, UO and GUC
Morphology	classified based on the density of population and buildings; number of customers and height of buildings	Urban, sub-urban and Dense urban
Position	denotes the place where the BS devices are located	Indoor (inside the room) and outdoor (green field areas)
Configuration	signifies both the technology type and the total number of sectors of the base station	
Hub number	shows the number of base stations that are linked to a specific base station	The number ranged from 1 to 14.
Microwave link	The availability of micro wave link and its capacity	Different capacity exists

In light of these variables, it is unrealistic to create one load profile for all cell tower power system configurations. For that reason, analyze the relation of energy consumed by BTS sites in ethio telecom to these factors we used IBM Statistical Package for the Social Sciences (SPSS) software.

SPSS is a package of programs for manipulating, analyzing, and presenting data. It makes statistical analysis more convenient for users. Simple menus and dialog box selections also make it possible to perform complex analyses without typing a single line of command syntax and can take data from almost any type of file and use them to generate tabulated reports, charts, and plots of distributions and trends and descriptive statistics [50].

We used the analysis to categorize the base-stations based on consumption for better estimation of the required and available hourly power at specific BTS for which the aspired power supply is to be designed.

3.6.2 BTS Site Selection and Site Background

There are around 728 base stations in the city of Addis Ababa; of these, 545 of them were accessible from central data center. From these base stations, nearly a quarter (138) stations were included in the study sample. The sample sites were from all 10 sub-cities and Zones (according to Ethio telecom structure). The sample sites were characterized by their technology type, morphology, position, configuration, hub number and microwave link connection availability.

Description of sample sites selected is given as revealed in Table 3.2. Majority (80%) of the sites were found to be out door. Regarding the technology, two third of the sites were using either GU or UO. Urban was the dominant type of morphology constituting 46% of the sites; followed by sub-urban and dense-urban in 32% and 22% respectively. Almost all (98%) of the sites were using at least one microwave link. A fifth of the sites were used as an intermediate link between two other sites or site with backbone.

Table 3.2 Description of Selected BTS sites, Addis Ababa, Ethiopia, March 2016

Characteristics	No.	%
Technology (n= 138)		
GULC	10	7%
GUC	5	4%

GU	48	35%
UO	42	30%
GUL	33	24%
Position(n= 138)		
Indoor	28	20%
Outdoor	110	80%
Morphology (n= 138)		
Urban	63	46%
Sub-urban	44	32%
Dense Urban	31	22%
No of Microwave link (n= 138)		
None	3	2%
One	112	81%
More than one	23	17%
No of Hubs(n= 138)		
One	110	80%
More than one	28	20%

3.6.3 Description of BTS Load Profile

The power rating of each site is important to estimate the size of PV module. Accordingly, the data was collected from ethio-telecom. Ethio-telecom Network Operating Center (NOC) collects real time power consumption data using NetEco software, developed by HUAWEI Company. Thus, primarily hourly power consumption data for each 138 sites was obtained from NOC. The data was collected for a period of about one year (December 01, 2015 to November 30, 2016). For each of the 138 BTS sites, hourly power consumption data (7,860 records for each site) was read.

3.7 Model Design

3.7.1 Proposed Model

Towards overcoming the national power shortage and ensuring service continuity, a model was proposed in this study. The proposed hybrid model comprises of PV-Grid-Battery as shown (Figure 3.5). The main components to supply the demand are the Grid and PV module; while the battery is used as a back-up energy source. This is due to the fact that, normally PV is not reliable as the solar irradiance is intermittent in nature and the grid will also be interrupted;

therefore, battery is used as a storage device that can deliver power at the time of shortage in energy for load. The PV module and batteries are giving the DC power output which is going to the DC link.

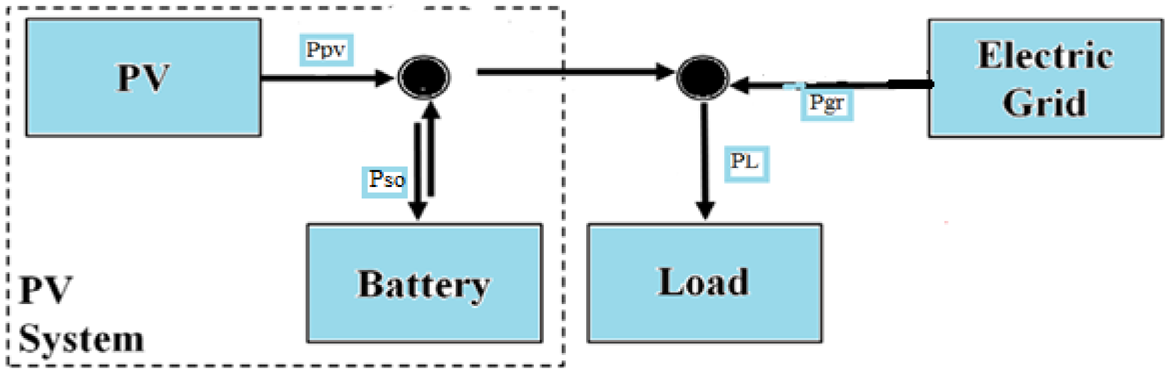

Figure 3.5 proposed model

When the proposed system starts to operate, to fulfill the power demand the grid, PV array and battery are working in one of the following ways:

- *When the total power generated by PV arrays and utility Grid are greater than the load demand, the surplus energy will be stored in the batteries. However, when the battery becomes full, the remaining energy will be either dumped or can be sold to the utility.*
- *When the total power generated by PV arrays and/or Grid are less than the load demand, the battery will be used as a backup source.*

3.7.2 Modeling the Proposed Model in Terms of LP

Our proposed model has linear objective function and constraints it is suitable to use linear programming as optimization method. For our model an optimal solution is one with the lowest system lifecycle cost, as modeled by equation (2.9). This cost depends on the ratings $\boldsymbol{P_{gr}, P_{pvo}, P_{so}, E_{bo}\ and\ E_{gr}}$ which are the decision variables. These ratings depend upon the power drawn by the BTS load as a function of time $P_L(t)$, as well as the design constraints and the power flow control methodology [27].

Objective function of the model:

LCC of the system is used as an objective function of the model and given by the expression from Eq. 2.9:

$$\textit{Minimize} \quad LCC = K_1 P_{gr} + K_2 P_{pvo} + K_3 P_{so} + K_4 E_{bo} + K_5 E_{gr}$$

Subject to following constraints:

(a) Equality constraints

Constraints are imposed by physical laws and the connections between the components; including the following from energy conservation:

Energy balance equation:

$$P_g(t) + P_{pv}(t) + P_s(t) = P_L(t) \qquad \textbf{(Eq. 3.2)}$$

At any time t, the sum of output power from grid, PV module and storage must be equal to the total amount of power required by the load.

Also the instantaneous power from the PV module satisfies:

$$P_{pv}(t) = P_{pvo} \cdot f_{pv}(t) \qquad \textbf{(Eq. 3.3)}$$

At any time t the output power from PV module must be equal to the product of total amount of power produced by the PV module P_{pvo} and the hourly normalized value.

Where $f_{pv}(t)$ is the normalized output power profile of the PV module source which varies between 0 and 1 due to variation of solar irradiation.

Also the energy in the storage unit is related to the power drawn from it by:

Storage Energy balance:

$$E_s(t) - E_s(t-1) = T \times P_s(t) \qquad \textbf{(Eq. 3.4)}$$

Where T is period

The energy and instantaneous power drawn from the grid are related as follows:

$$E_{gr} = \int_0^T P_{gr}(t)dt = T \times P_{gr}(t) \qquad \textbf{(Eq. 3.5)}$$

(b) Non-equality constraints

Constraints arise from the maximum power that can be drawn from the grid, Pgrmax, limits on the maximum rating of the PV modules Ppvmax, the maximum power rating of the storage unit, Psmax, can be expressed as:

$$0 \leq P_g(t) \leq P_{gr} \leq P_{grmax} \quad \text{(Eq. 3.6)}$$

$$0 \leq P_{pv}(t) \leq P_{pvo} \leq P_{pvmax} \quad \text{(Eq. 3.7)}$$

$$-P_{smax} \leq -P_{so} \leq P_s(t) \leq P_{so} \leq P_{smax} \quad \text{(Eq. 3.8)}$$

A constraint is required under the battery bank operation. the value of Es(t) could not be less than minimum allowable energy level which must be remain in battery banks $(E_{bo}\ Soc_{min})$ also while charging operation the value of Es(t) could not higher than maximum allowable energy level $(E_{bo}\ Soc_{max})$. Mathematically it can be expressed as:

$$E_{bo} Soc_{min} \leq E_s(t) \leq E_{bo}\ Soc_{max} \leq E_s max \quad \text{(Eq. 3.9)}$$

Where $P_g(t)$, $P_{pv}(t)$ and $P_s(t)$ are the instantaneous powers delivered by the grid, the PV module, and the storage unit, respectively; and $E_s(t)$ is the instantaneous energy stored in the storage unit.

3.7.3 Component Size

Here a PV-Grid-Battery power system is optimized with the help of linear programming. For the proposed system model, linprog Matlab function with interior point algorithm was employed. The main objective of optimization procedure was to reduce the life cycle cost of the system with the given constraints. To employ the optimization procedure, three scenarios were considered based on the amount of power contributed by the grid.

- **Scenario I:** Assuming the grid can provide up to **average** value of power demand.
- **Scenario II:** Assuming the grid can supply up to the **maximum** power demand.
- **Scenario III:** Assuming the grid **doesn't contribute** any power to fulfill the demand that is high solar scenario.

3.7.4 PV and DG Life Cycle Cost (LCC)

To compare the economic viability of photovoltaic powered systems and diesel generator powered systems the life time cost of PV and Diesel Generator was computed for over a 35 year period taking into account capital cost, operating and maintenance costs, replacement cost and fuel cost for each technology of BS using equations Eq.2.4, Eq.2.6 and Eq.2.10. The separate photovoltaic and diesel generator systems were compared with each other. Variables used to calculate these values are taken from Table 3.3.

3.7.5 Simulation Parameters

For this study design constraints with their assumed values and cost parameters are summarized in Table 3.3:

Table 3.3 Simulation Parameters

Variables	Values	Unit	Description
Ci_{pv}	1.597	$/watt	the initial capital cost of PV module (35birr/watt)
Ci_{b}	254	$/kwh	capital cost of the storage unit depending on energy rating
Ci_{b1}	0.254	$/w	capital cost of the storage unit depending on power rating
Ci_{gr}	0.03	$/kwh	Subsidized Cost of energy from the grid*
Ci_{gr1}	0	$/kw	Cost of power from the grid**
Cig_{real}	0.1	$/kwh	Real cost of electricity from the grid
e	9	%	inflation rate
d	10	%	discount rate
N	35	Yr	System life time
n_b	10	Yr	Battery life time
n_r	3	Yr	Number of battery replacement
F1	2	%	Percentage of investment cost to find O&M cost
F2	10	%	Percentage of investment cost to find replacement cost
F3	5	%	Percentage of investment cost to find O&M cost of generator
F4	5	%	Percentage of investment cost to find diesel generator service cost
K2	2.471	-	Coefficient of O.F calculated from Eq. D2
K3	0.503	-	Coefficient of O.F calculated from Eq. D3
K4	502.5	-	Coefficient of O.F calculated from Eq. D4

SOCmax	1		Battery maximum permissible state of charge
SOCmin	0.2		Battery bank minimum discharge level
η_b	0.85		Round trip battery efficiency
C_K	0.589	$/w	Initial cost of diesel generator
C_D	0.73	$/Lit	the diesel cost per liter (16birr/lit)
A_D	3160.9	Lit/yr	the diesel consumption per year (4.33lit/hr)
r	300	hr	the diesel generator service period
Note: 1USD=21.91 birr (collected from CBE on July 5, 2016)			

**Source: Ethiopian electric utility*

***Source: reference # 51, but this study done by Ashenafi, doesn't consider the transmission cost of electricity in computing the real cost of electricity in Ethiopia; this implies that the real cost will be higher than the calculated one when including transmission cost.*

CHAPTER FOUR: RESULT AND DISCUSSION

4.1 Simulation of DC Power Generated

The simulation output from a single selected module for 8,760 hours of power generation is displayed below in Figure 4.1. The output is used as an input for system unit sizing and the generation is assumed to be constant in each hour interval.

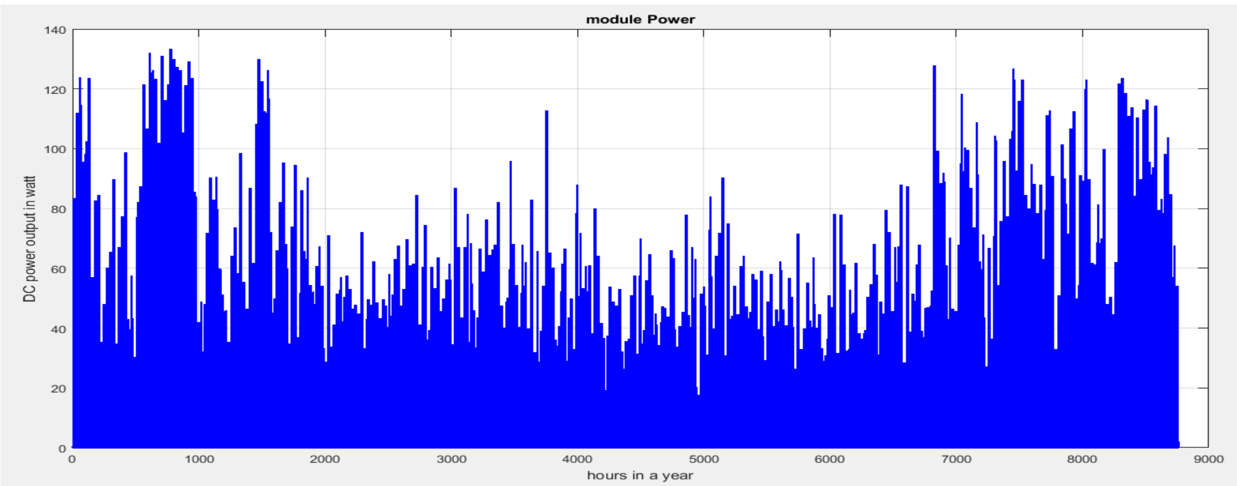

Figure 4.1 DC power generated at each hour of the year for Addis Ababa City

In addition total monthly DC power production was also computed to identify the worst month where the lowest power was produced. The peak months are December and January the lowest months are July and August in Addis Ababa. July was found to be the worst for PV power production as compared to other months of the year. Thus, system size was designed considering this lowest month, July. (Figure 4.2)

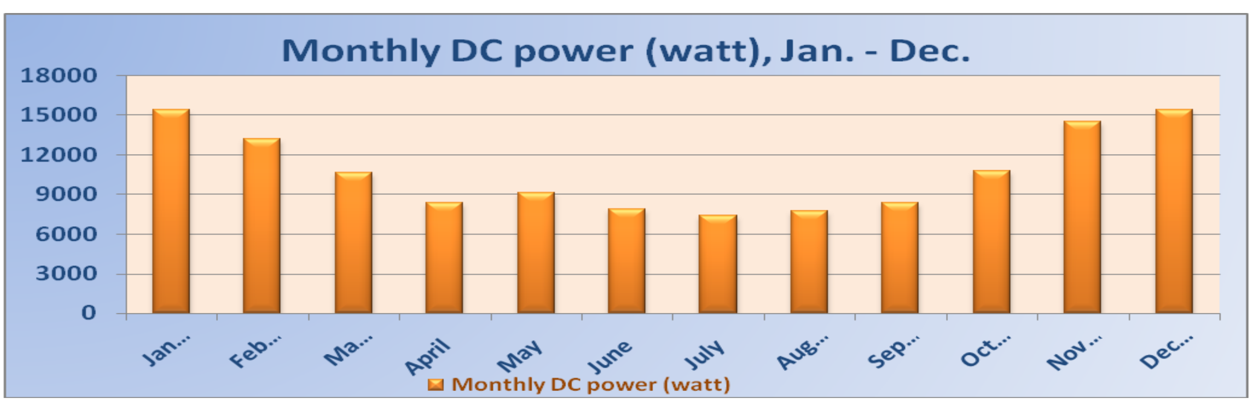

Figure 4.2 Total DC power output from single module for each month for Addis Ababa City

4.2 SPSS Regression Result

Linear regression analysis results for power consumption of BTS sties from SPSS revealed that sites with more technology combination consumed significantly higher power compared to sites with single technology. Likewise, configuration is also a significant predictor of power consumption; as the number of sectors increases, the power consumption also increases. Being outdoor position is associated with lower power consumption ($p<0.01$). Moreover, having higher number of hubs is associated with significantly higher power consumption ($p<0.05$). Conversely, sites that are found at urban area were significantly less likely to consume power than sites found in dense urban area. The remaining independent variables—number of microwave and microwave capacity —were not significant factors of power consumption. Regression output shown in Table 4.1:

Table 4.1: Regression result for power consumption

Variable	Before controlled		Controlled for other factors	
	t-statistic	*P*-value	t-statistic	*P*-value
Technology	17.86	**<0.001**	3.3	**<0.01**
MW-Capacity	2.87	**<0.01**	0.33	0.7
# of Microwave	0.84	0.4	-1.04	0.3
Morphology	6.16	**<0.001**	-2.56	**<0.05**
Configuration	22.1	**<0.001**	9.65	**<0.001**
Position	-9.57	**<0.001**	-3.1	**<0.01**
Hub_number	2.55	**<0.05**	2.26	**<0.05**

4.3 BTS Sites Load Profile Result

From the collected data hourly mean power consumption was calculated for each technology group; then this mean data was considered as hourly real power consumption. Taking the maximum value from the total 7,860 hourly records of one year data, normalization was done for each group. Further, this value was multiplied by the maximum value of power consumption set by ethio telecom. To this end, the maximum value for each of the 8,760 record was obtained for each group; using these data, time series graph was plotted (load versus time) as revealed below.

As depicted in following graphs, the highest power consumption was nearly 6KWs which is recorded in GUC and GULC technologies, while the lowest was found to be UO technology, around 1 KW.

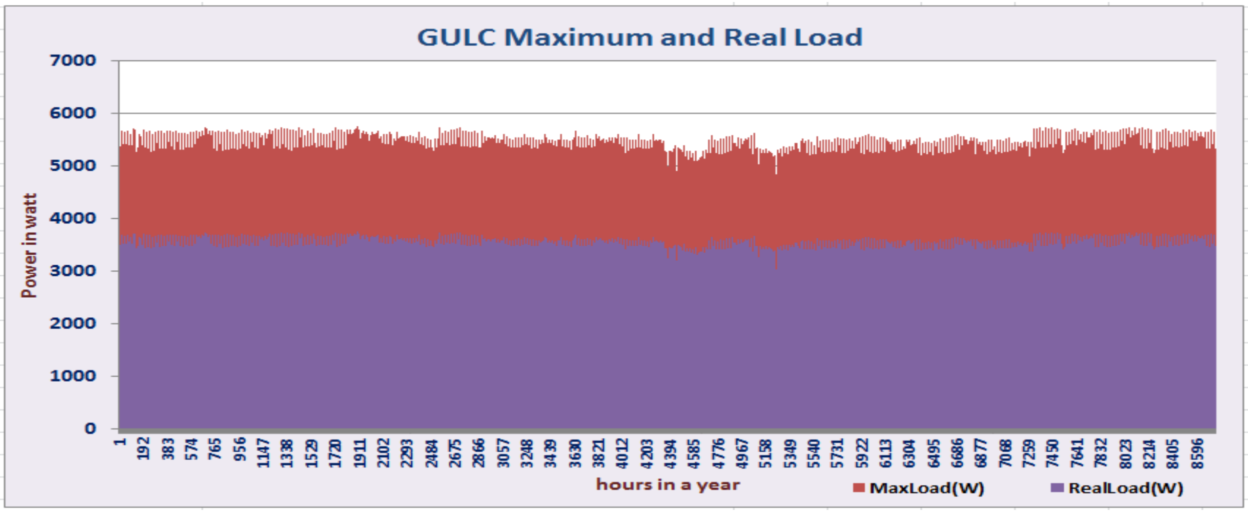

Figure 4.3: Maximum and Real Power Consumption of Technology Type GULC

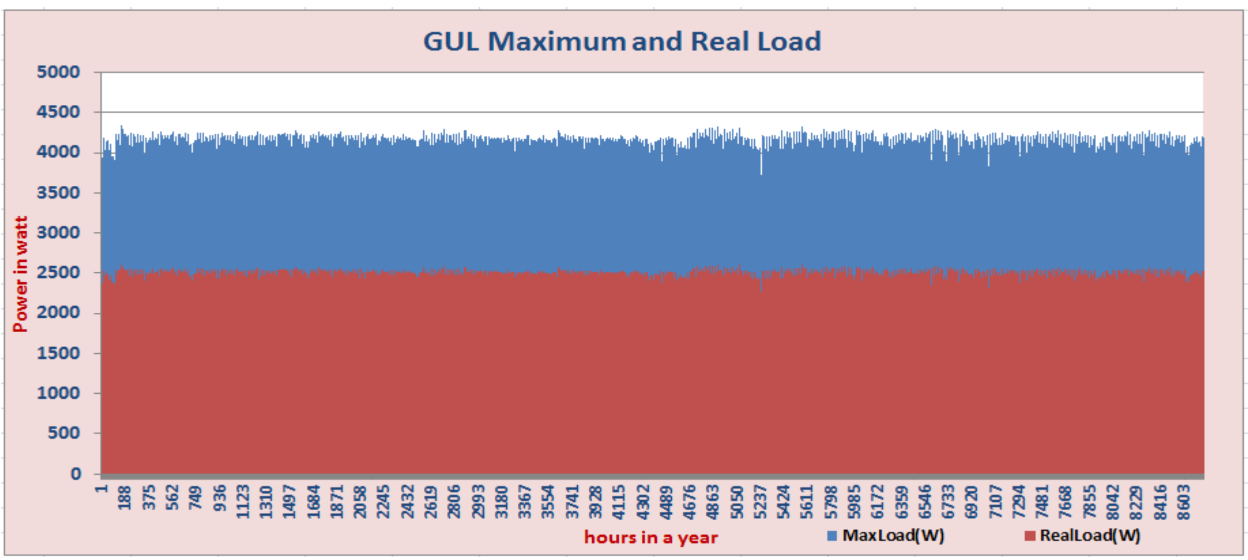

Figure 4.4: Maximum and Real Power Consumption of Technology Type GUL

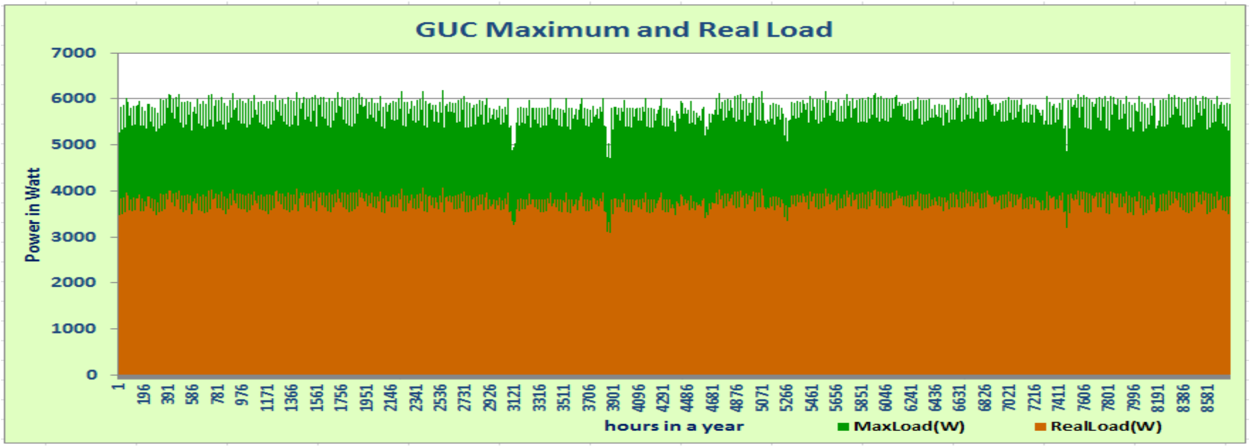

Figure 4.5: Maximum and Real Power Consumption of Technology Type GUC

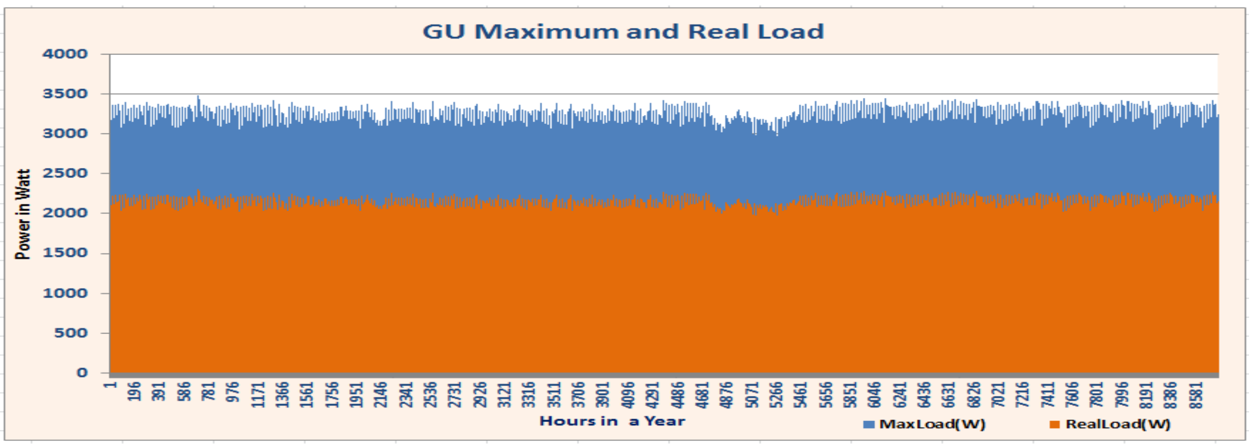

Figure 4.6: Maximum and Real Power Consumption of Technology Type GU

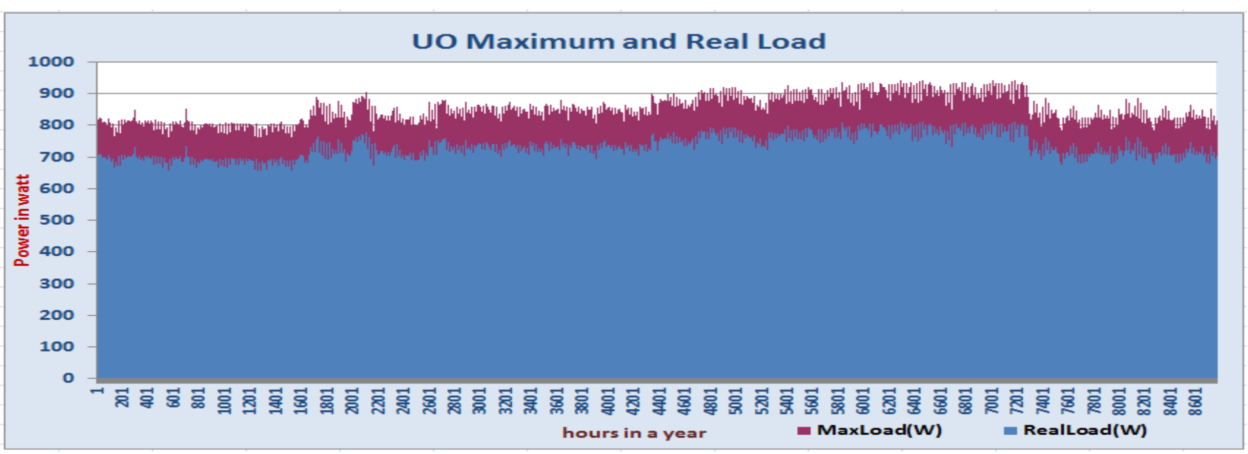

Figure 4.7: Maximum and Real Power Consumption of Technology Type UO

Note: to size the system, the maximum load of the base stations was taken.

4.4 Optimization Result

4.4.1 Component Size

Scenario I

This scenario assumed a hybrid system that consists of battery, PV and grid power sources; where the system anticipated grid can supply up to the average power requirement of the BS. Optimization was conducted for each type of technologies and its simulation result is shown below, Table 4.2. Optimum amount of power generated by PV, Grid and battery; and life cycle cost were read from simulation output. Then, number of PV modules required for the system was computed based on the amount of power generated.

Table 4.2: PV size and LCC for Scenario I

Technology	Power (watt)			# of PV module (150wp)	LCC ($x10^4$) ($USD)
	Grid	PV	Battery		
GULC	5,250	8,990	440	**60**	64.7
GUC	5,360	12,300	2,220	**81**	187
GUL	4,020	6,710	303	**45**	65.6
GU	3,080	6,380	1,070	**42**	89
UO	815	1,930	367	**15**	30.2

Figure.4.8 below showed that 48 hours simulation output of hybrid system. During day time (7am to 1pm), the PV power source started to contribute to the system and at the same time it charged the battery. On the other hand, the amount of power consumed from the grid decreases. During night time (1pm to 7am), PV source doesn't contribute for the system; the load demand was fulfilled by battery and the grid. It is observed that, the load demand increases during night time and the battery addressed this demand. This figure is for technology – GU; same holds true for other technologies. (See Appendix E – graphs showed 744 hours run for all technologies).

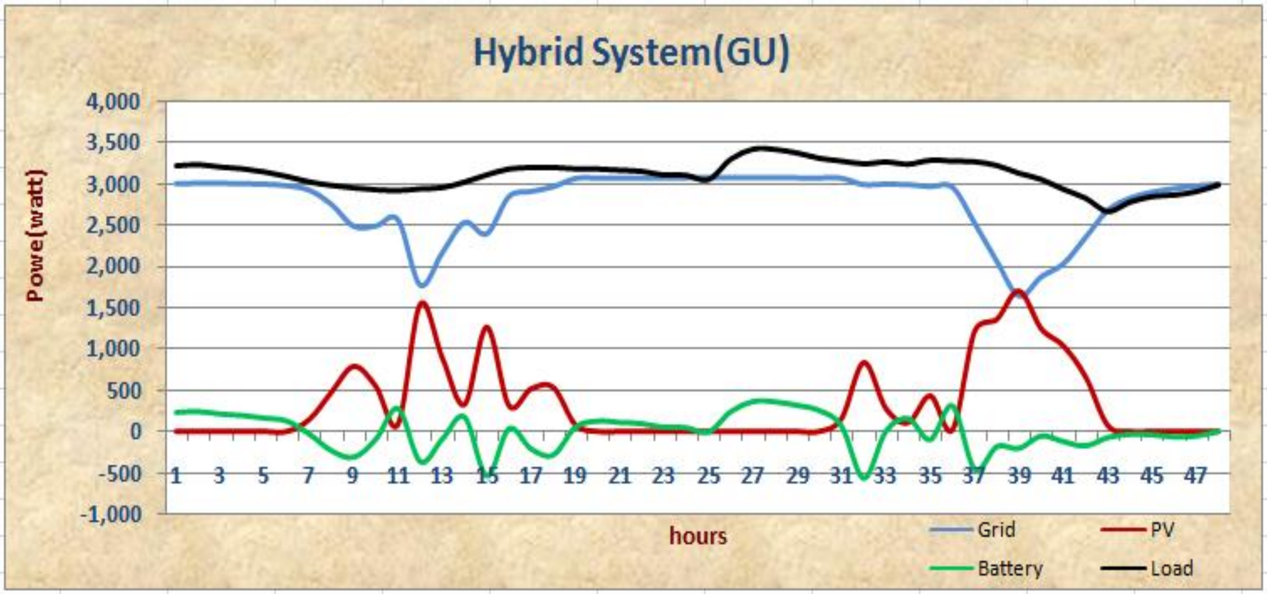

Figure 4.8: 48 hour Run for Hybrid System (GU)

Scenario II

System simulation was done here on hourly basis for each group of technology. It was assumed that the grid can supply up to the maximum power requirement of the load. This scenario further considered two cases: real and subsidized cost of electricity from the grid.

When the system is implemented using the real cost of electricity, the system included PV power; however, in case of subsidized cost, the grid power satisfied the load demand across all hours of the period as shown in Table 4.3 below. The simulation output that shows the contributions of power source for technology GU considering the two cases displayed in Appendix F.

Table 4.3: Effects of Cost of Electricity from the Grid

Technology	Real cost of electricity (0.1$/kwh)			Subsidized cost of electricity (0.03$/kwh)		
	Grid	PV	# of PV module (150wp)	Grid	PV	# of PV module (150wp)
GULC	5,750	8,300	57	5,752.3	0	0
GUC	6,180	8,780	60	6,183.14	0	0
GUL	4,340	6,560	45	4,339.91	0	0
GU	3,480	4,690	33	3,479.09	0	0
UO	942	1,350	9	941.71	0	0

Scenario III

Here the third scenario assumed that the grid doesn't supply any power to the system; this implied the system get 100% power from solar energy (high solar scenario). The corresponding simulation result shown in Table 4.4 revealed that high LCC and number of PV.

Table 4.4: High Solar Scenario

Technology	Grid	PV	Battery	# of PV module (150wp)	LCC ($x10^6$) ($USD)
GULC	0	69,300	38,400	462	79.8
GUC	0	72,800	40,300	486	83.4
GUL	0	54,300	30,100	363	61.8
GU	0	41,500	23,200	276	50.4
UO	0	11,500	6,390	75	13.2

On the other hand the system was designed for maximum load of BS; nevertheless, currently the system consumed real load of the BS. Therefore, there will be excess power production at a time; that is detailed in Table 4.5 below.

Table 4.5 Excess power produced

Technology	Power (KW)		
	Maximum Power generated	Real Power used	Excess Power
GULC	8.16	3.35	4.81
GUC	8.58	3.55	5.03
GUL	6.38	2.42	3.96
GU	4.88	2.04	2.84
UO	1.36	0.74	0.62

4.4.2 Life Time Cost of PV and DG

Table 4.6 summarized the LLC of PV and DG by technology type. As shown here, as the number of technology composition increases, the power consumption of the BS increases. During this situation, the LLC of DG becomes lower than PV at start but after few years the LCC of PV become lower. Conversely, for technologies with lower power consumption, the LLC of PV is lower than DG from the start, for example in case of technology UO.

Table 4.6 LCC of PV and Diesel Generator

Technology	power consumption (watt)	LCC ($x10^3$) ($USD)			
		Photovoltaic		Diesel Generator	
		Year 1	Year 35	Year 1	Year 35
GULC	5754	10.3	15.6	5.97	92.1
GUC	6184	11.1	16.8	6.24	93.8
GUL	4341	7.76	11.8	5.06	86.4
GU	3480	6.22	9.43	4.51	82.9
UO	943	1.69	2.55	2.89	72.6

4.5 DISCUSSION

Discussion on Scenario I

The number of PV modules that need to be installed required enough space. For each module about an area of 0.876 m^2 is required. As shown in the result section, Table 4.2, the number of PV modules in the hybrid system for UO technology is lower, which can be implemented in all areas including Addis Ababa. For the other two technologies, GUL and GU, implementation can be considered in green field base stations. However, the remaining two, GULC and GUC, required large space. Regarding the proportion of technologies, the popularity of them (88%) were UO, GUL and GU; however, only 12% of them were found to be GULC and GUC. Moreover, the later technologies are considered as obsolete, and ethio-telecom is expanding the first three technologies and other new ones.

Discussion on Scenario II

The system automatically chose the grid in case where subsidized cost of electricity was considered; this is due to the fact that, the case permits to get till maximum load requirement from the grid and also the grid has lowest cost (0.03$/kWh). However, when the real cost of electricity (0.1$/kWh) was considered, the system included the PV source even if the case permits all the required load demand from the grid. This implied that PV's economic competence was hindered by local policy. If the grid is sold with its real cost (not subsidized) and/or the PV system is subsidized, the two power sources will have comparable selling costs. Therefore, the system can take the required load demand from both sources equally. As a result PV can be used with the grid as backup, thus backup power supplies like generator will have no position. Further promote PV to be used in any design of BTS and promoting competitive PV market and adopting a policy that enhance distributed self-generation could provide multiple purpose to the industry.

The following graph (Figure 4.9) from simulation output revealed that the number of PV modules in other words the contribution of PV source gets the minimum when the grid considered the subsidized cost; while the reverse is true when the grid assumes real cost.

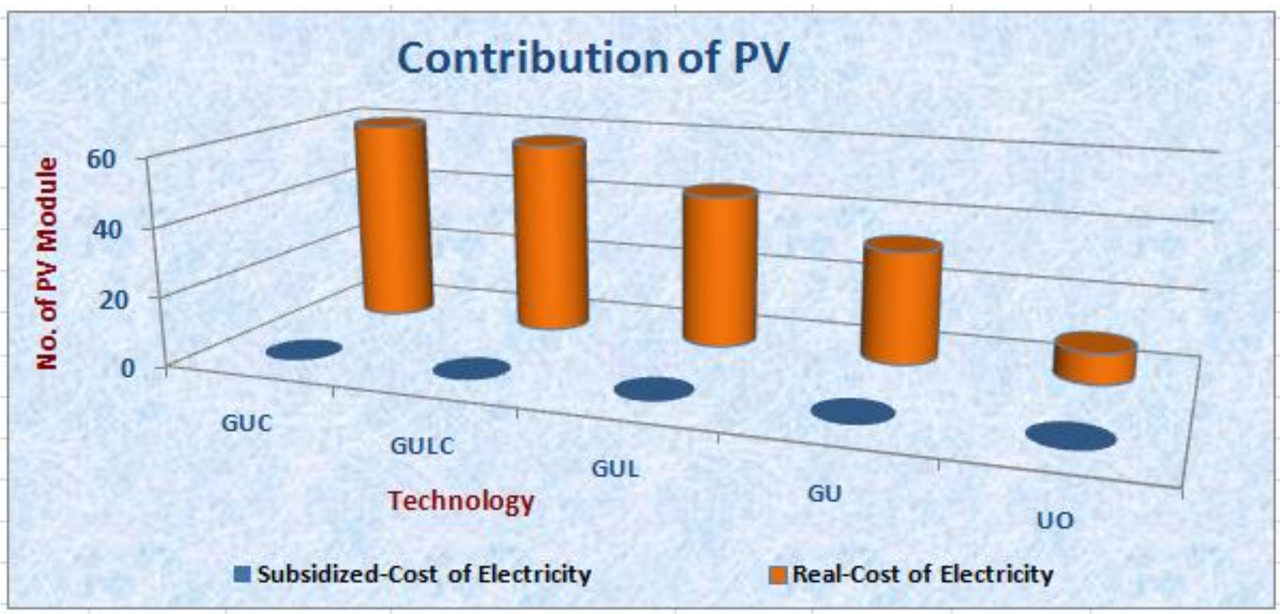

Figure 4.9 Number of PV Module for Subsidized and Real Cost of Electricity

Discussion on Scenario III

In general, the proposed system was designed considering the maximum power consumption of base stations. But, in the present actual setup, the real load doesn't reach at its maximum load. This implied that, there is excess power that will be released from the proposed system of each technology types. The amount of excess power produced for each technology versus the real and maximum power consumption is displayed in the following Figure 4.10.

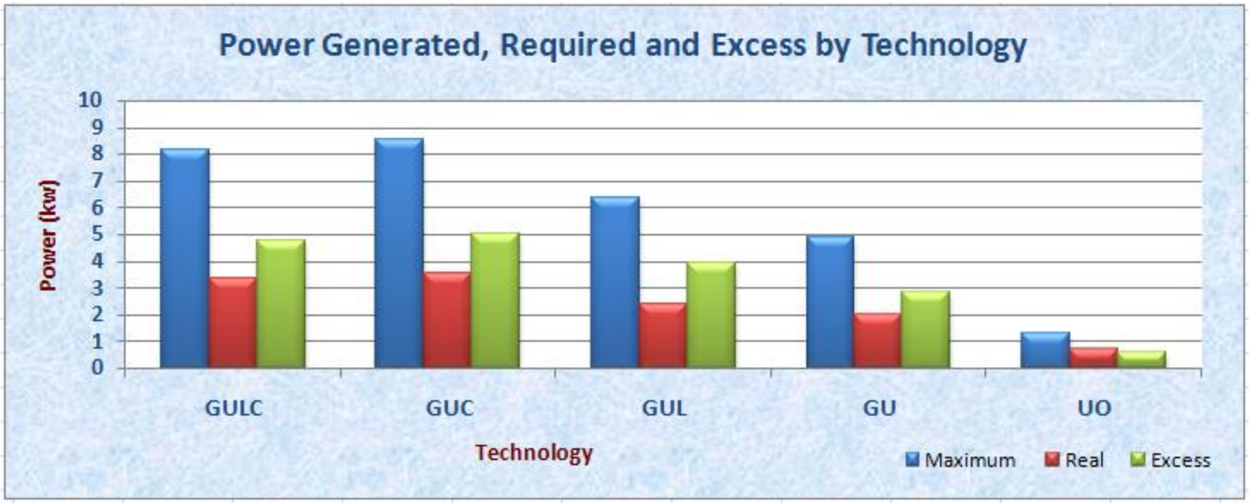

Figure 4.10 Power Generated, required and excess by technology

In addition, selling this excess power to utility grid will be one of the benefits of the proposed system. According to EEU the selling price will be 0.02$/Kwh. Therefore, if the company implements the proposed system off grid regions and if it is used for PV technology for other telecom devices, huge amount of excess energy will be produced, as a result it will be an additional source of income for the company.

Furthermore this study intended to compute the power share that the modeled PV system can contribute for the national grid. This power share was calculated based on the assumption given in scenario three; where the model used 100% of power from the solar system. There will be lots of constraints that will appear during implementation such as lack of adequate space; presence of unavoidable shadow; and installation cost of the system especially for the first four technologies; hence, this project assumed to implement for off grid BS with technology UO in different 500 places in the country. Based on this assumption, the power share was determined; the share of power produced by the model to that of the national power production is revealed below in (Table 4.7).

Table 4.7 Power Share of the Proposed Model

Technology	Total Power generation /site (Kw)	# of sites	Total Power generation (kw)	Total national Power Production
UO	1.36	500	680	1,839,000kW (42% of 4,380,000kW)
				0.04%

Accordingly, the power share was found to be 0.04%; which considered only one of telecom devices, BTS with one technology type. However, the power share will be maximized if the company implemented the proposed system for other technologies and if it applied PV technology for other kinds of telecom devices.

Discussion on PV and DG Life time cost

From Figure 4.11, for technology GUC the LCC costs within the first three years are similar for both PV and Diesel system. However the diesel generator LCC cost increases astronomically in subsequent years. Both PV and diesel LCC at three years are exactly the same, compared to the difference $77 thousand after 32 years. On the contrary for technology UO from the start the LCC of PV system ($1.69 thousand) is lower than that of diesel generator system ($2.89 thousand) as shown in Figure 4.12, and after that the LCC of diesel generator reached to $72.6 thousand after 35 years.

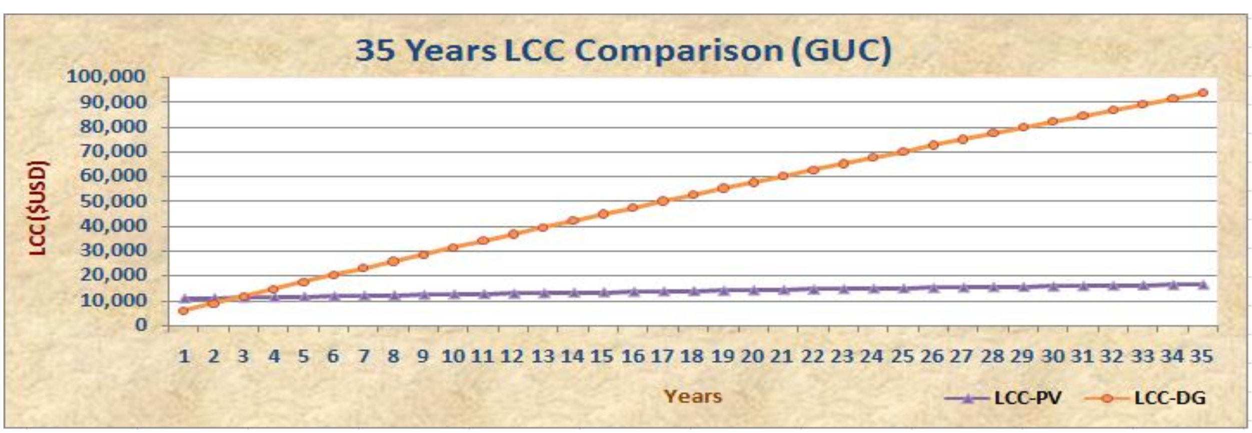

Figure 4.11 LCC Comparisons for PV and DG (GUC)

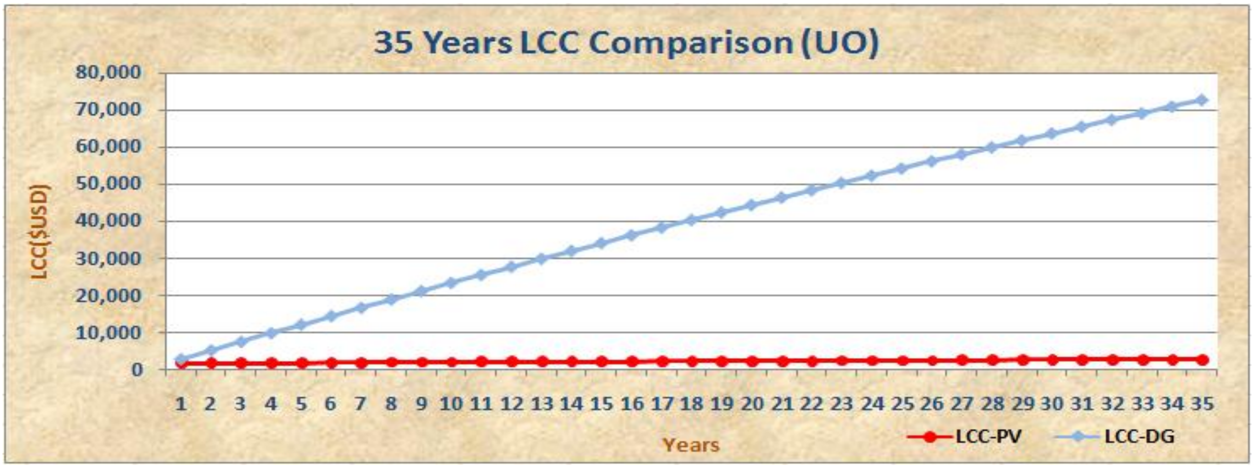

Figure 4.12 LCC Comparisons for PV and DG (UO)

The LCC of diesel generator increases at a high rate over the predicted project life times compared to a much smaller rate of the photovoltaic based system. This is because the need to replace the diesel generator after 7 to 10 years, high maintenance and fuel costs are believed to be responsible for the very high life cycle costs of diesel generator system despite the higher capital cost of the PV system. It is therefore fairly obvious from this result that on the basis of life cycle costing, photovoltaic systems are cheaper than diesel generator systems in the long term.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

Conclusion

This project assessed 138 BTS sites that are found in Addis Ababa, with the aim of developing alternative power source and sizing a Grid-PV hybrid system demonstrated that the model produced energy that will be used by BTS sites. The methodology for optimal sizing hybrid system with battery storage based on linear programming method has been presented in this paper.

The result showed that the proposed model has lower life time cost as compared to the existing Diesel Generator (DG) hybrid system; The LCC of PV was lower than DG for all technologies; therefore PV can be used either as backup (in the form of hybrid) or standalone (for off-grid areas). Beyond cost, the use of PV will contribute for the reduction of the negative effects of DG such as environmental pollution and emission through minimizing the number of DG implementation; this will save the extra budget. Additionally this will reduce dependency on commercial line of Ethiopian Electric Utility (EEU) and ensure continuous power supply; it will also contribute to reduce the national energy crisis as well. But, on the other hand, the cost of electricity from the grid affects the implementation of PV system. This finding suggests that PV's economic competence was trapped by local policy – there is large gap between cost of electricity from the grid and PV source.

The proposed system will also produce excess power that will be sold to the national grid, so that it will be a form of income generation for the company. Implementation of the proposed model will have invaluable merits including reduced operational cost due to no fuel consumption and low PV maintenance, increased operational life due to no use of generator set operating hours, environmentally friendly due to reduced emissions and noise pollution (quiet to operate), safe and clean.

Moreover, Ethiopia as a country has many opportunities to use PV including the abundant sunlight across the year; and the world is now shifting to renewable energy; and the negative effects of global warming are also push factors to shift to PV technology. Therefore, the suggested model can be implemented in BTS sites particularly, sites with UO, GU and GUL technologies.

Recommendation

Finally, the following points are recommended:

- The proposed model will be beneficial if it can be implemented in BTS sites particularly, sites with UO, GU and GUL technologies.
- There are emerging technologies for BTS sites, this model can be implemented for such technologies with few modifications as the power consumption of the new technologies are almost similar with GU.
- The project was undertaken in Addis Ababa, where its context is different from other towns especially considering weather condition; therefore, it will be good if further assessment is done in other areas.
- This project consider 150wp module available in the country, but using higher watt peak modules will decrease the number of module needed for the system. That implies space constraints mainly for high solar scenario will be minimized.
- Replace old equipment with energy efficient BTS equipments.
- PV's economic competence is limited due to the local policy on the subsidy of electricity. Thus it requires revision of the policy.
- In this project, the model is designed only for one type of access layer device, BTS; it is suggested to assess and design PV source for other telecom devices such as Multi-Service Access Gateway (MSAG) and Multi-Service Access Node (MSAN).

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APPENDIX

Appendix A: Evolution of Mobile Cellular technology

A.1 Definition of Important Terms

Multiplexing: describes how several users can share a medium with minimum or no interference and used to transmit multiple signals through a single medium. While, de multiplexing is obtained at the receiver side to detached the multiplex radio signals. It is an integral part of transmitter. For wireless communication, it can be carried out in four dimensions: space, time, frequency, and code [8, 52].

Frequency Division Multiple Access (FDMA): In FDMA scheme, the frequency band is allocated to each single user by separating the frequency band into further smaller bands. Senders using a certain frequency band can use this band continuously. There are also guard spaces that are needed to avoid frequency band overlapping [8, 52].

Time Division Multiple Access (TDMA)–The TDMA scheme uses the same frequency band for all users in different time intervals. Here a single channel is given the whole bandwidth for a certain amount of time, i.e., all senders use the same frequency but at different points. Guard spaces, which now represent time gaps, have to separate the different periods when the senders use the medium [8].

Code Division Multiple Access (CDMA): CDMA channel scheme makes a data transmission to multiple users through assigned code for each transmitter over the same channel. Channels use the same frequency at the same time for transmission and separation is achieved by assigning each channel its own code [52, 53].

Orthogonal Frequency Division Multiple Access (OFDMA): In OFDMA, the carrier signal is separated into different smaller subsets. For a single user this separated carrier signal subset is used to send data [53, 54].

A.2 Evolution of Mobile Technology

Mobile Cellular Technology evolution has been categorized in to 'generations' as shown in figure below.

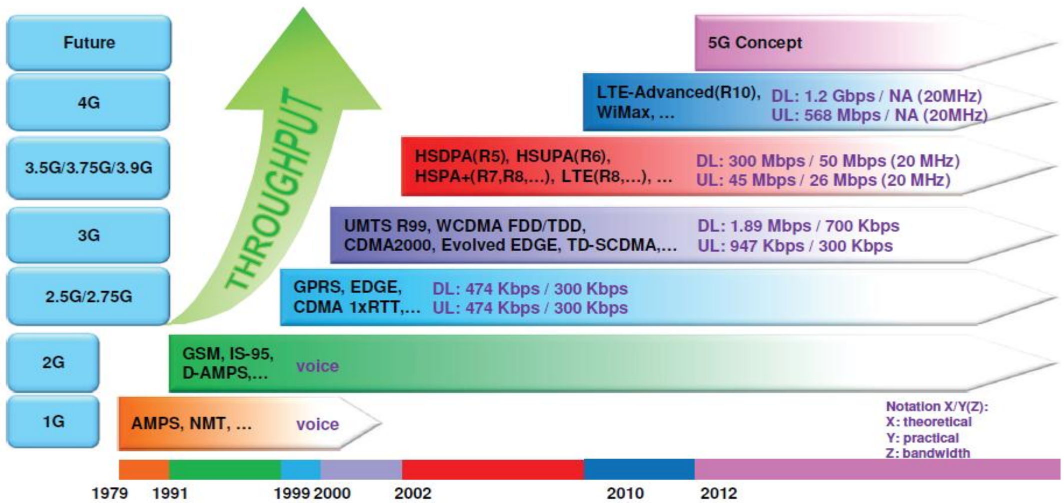


Figure A.1 Evolution of Mobile Cellular Technology, [55]

- **The First Generation (1G)**

Japan launched the world's first commercial cellular system in 1979, initially in the metropolitan area of Tokyo, which was developed and operated by Nippon Telegraph and Telephone (NTT). The system operates in the 800 MHz band. The channel bandwidth is 25 kHz and the signaling is at 300 bps [56].

Two years later, the cellular age reached Europe. The two most popular analogue systems were Nordic Mobile Telephones (NMT) and Total Access Communication Systems (TACS). Also in the United States, the Advanced Mobile Phone System (AMPS) was launched in 1982. The system was allocated a 40-MHz bandwidth within the 800 to 900 MHz frequency range [57].

1G systems were based on analog technology and frequency division multiple access (FDMA). Due to the nature of analog technology, 1G system provided very limited services and suffered from many limitations, such as poor communication quality, low capacity, poor voice links, and low frequency utilization. All of the systems offered handover and roaming capabilities but the cellular networks were unable to interoperate between countries. This was one of the inevitable disadvantages of first-generation mobile networks. Also at that time, there was no worldwide coordinating body to develop technical standards for the system [57, 58].

- **The Second Generation (2G)**

The second generation of mobile systems began to emerge in the early 1990s. Digital signal processing and transmission were introduced to replace the analogue transmission. Global System for Mobile Communication (GSM) is the most popular 2G cellular system standard. In its original form, GSM in the 900, 1800 and 1900 MHz frequency bands uses a Time Division Multiple Access (TDMA) scheme and offers a digitized speech and digital data at up to 9.6 Kbps. The introduction of Subscriber Identity Module (SIM) cards and the GSM Mobile Application Part (MAP) protocol enabled internetworking between different networks, allowing subscribers to roam worldwide [59, 60].

All 2G wireless systems are voice-centric. GSM includes short message service (SMS), enabling text messages of up to 160 characters to be sent, received and viewed on the handset. Most 2G systems also support some data over their voice paths, but at painfully slow speeds usually 9.6 Kb/s or 14.4 Kb/s. So in the world of 2G, voice remains king while data is already dominant in wire line communications [61].

GSM has been constantly upgraded and included the following Mobile technologies: General Packet Radio Service (GPRS), Code Division Multiple Access (CDMA), Enhanced GPRS (EGPRS) and Enhanced Data Rates for GSM Evolution (EDGE) [59].

- **The Third Generation (3G)**

The idea of 3G became evident with the need for more capacity, new frequencies, and higher bit rates. International Telecommunication Union (ITU) defined the demands for 3G mobile network with International Mobile Telephone 2000 (IMT-2000) standard. The data requirements for the next generation radio networks, referred to as the third generation, to 144 kbps at driving speeds, 384 kbps at pedestrian speeds, and 2 Mbps in indoor environment [63, 64].

CDMA2000 is considered one of the 3G standards in American that Provide a speed up to 2.4 Mbps. An organization called 3rd Generation Partnership Project (3GPP) has continued that work by defining a mobile system that fulfills the IMT-2000 standard. In Europe it was called Universal Mobile Telecommunication System (UMTS) [63].

3G Technology comprises also Wireless Local Area Network (WLAN), Bluetooth and also provides facilities such as Global Roaming Clarity in voice calls, Fast Communication, Internet, Mobile T.V, Video Conferencing, Video Calls, Multi Media Messaging Service (MMS), and 3D gaming [58].

- **The Fourth Generation (4G) (All IP)**

Fourth Generation mobile communication services started in 2010 but will become mass market in about 2014/15. The fundamental reason for the transition to the All-IP is to have a common platform for all the technologies that have been developed so far, and to harmonize with user expectations of the many services to be provided [57].

Different from the previous UMTS networks, Long Term Evolution (LTE) radio access is based on wideband CDMA (WCDMA) and it adopted orthogonal frequency division multiple access (OFDMA). It supported spread spectrum transmission of minimum 200Kbps. And the system supports mobile application include mobile web access, IP telephony, mobile on-line gaming services, high-definition mobile TV, video conferencing and 3D television [64].

- **Fifth Generation (5G) (future)**

The evolution of LTE does not end with LTE advanced rather continues to evolve into further releases. Each new release further enhances system performance and adds new capabilities with new application areas. From user point of view, apart from throughput, other factors that differentiate 5G from its predecessors and make its implementation essential are [58]:

- *Battery Consumption Alleviation*
- *Improved coverage range and higher data rate availability at cell edge.*
- *Multiple concurrent paths for data transmission and hand over.*

• Worldwide wireless web (WWWW), wireless-based web applications that include full multimedia capability beyond 4G speeds.

• Several Artificial Intelligence aided applications at high bandwidth with multiple sensors enabled mobile devices.

Appendix B: Sequence of Activities in Determining DC Power Output

Terms with definitions and appropriate equations that are used in the determination of hourly module DC power output for one year explained briefly in this section

Determination of Solar Time (ST) and Equation of Time (EOT)

There is a difference between real time and solar time. For a given point on the earth's surface in the Northern/Southern hemisphere, solar noon is denned as that time of day when the sun appears due South/North. Solar time is the time of day measured from solar noon. Solar time coincides with real time only at certain times of the year; e.g., when the earth is at the perigee or apogee of its orbit. At other times, real and solar time may differ by as much as ± 15 minutes. The difference between local solar time and local standard time (corrected for longitude) is called the equation of time EOT. The value of EOT can be determined from the equation [48].

$$EOT = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B) \text{ (Minutes)} \qquad \text{(Eq. B.1)}$$

Where: $B = 360(N - 81)/364$

N= day of the year

In terms of EOT, the solar time is related to standard time by the following equation [48]:

$$Solar\ Time = Standard\ Time + 4 * (L_{st} - L_{loc}) + EOT \qquad \text{(Eq. B.2)}$$

Where: L_{st}= the standard meridian for the local time zone (for Addis Ababa: 45^0)

L_{loc} = Longitude of the location in question in degrees west (for Addis Ababa: 38.5^0)

Determination of Solar Angles

Solar angles are several angles that can be obtained from sun earth geometry. These angles are responsible for the solar radiation that falls on the earth surface including PV module. Solar angles that are applied in this study are categorized as follows:

Latitude (ϕ): is the angle made by the radial line joining the given location to the center of the earth with its projection of the equatorial plane. The latitude indicates how far north or south the location is from the equator. By convention, latitude is measured positive for the northern hemisphere [65]. Addis Ababa's latitude is read as 9.02 degree.

Declination Angle (δ): is the angle made by the line joining the centers of the sun and the earth with its projection on the equatorial plane. It happens because the earth rotates about an axis, this varies from a maximum value of +23.45° on June 21 to a minimum value of -23.45° on Dec 21, zero on the two equinox days of March 21 and Sept 21 [66, 67].

$$\delta(in\ degrees) = 23.45 * sin\ [360(N + 284)/365] \quad \textbf{(Eq. B.3)}$$

Where, N = days of the year; for this study, the number of days ranged from 1 to 365.

Hour Angle (ω): is the angle measured in the earth's equatorial plane between the projections of the distance to the center of the earth and the projection of a line from the center of the sun to the center of the earth. It is an angular measure of time and is equivalent to 15° per hour, measured from noon, based on local solar time (LST) or local apparent time being positive in the morning and negative in the afternoon. It is given by the following equation [48].

$$\omega = \left(\frac{360^0}{Tday}\right) \times ST \quad \textbf{(Eq. B.4)}$$

Where: $Tday$: length of the day in second

ST: standard time

Collector Slope (β): is the angle made by the plane surface with the horizontal, taken to be positive for surfaces sloping towards the south and vice-versa. For this study the value of beta is taken as 9.02 degrees (9.02 *π/180rad).

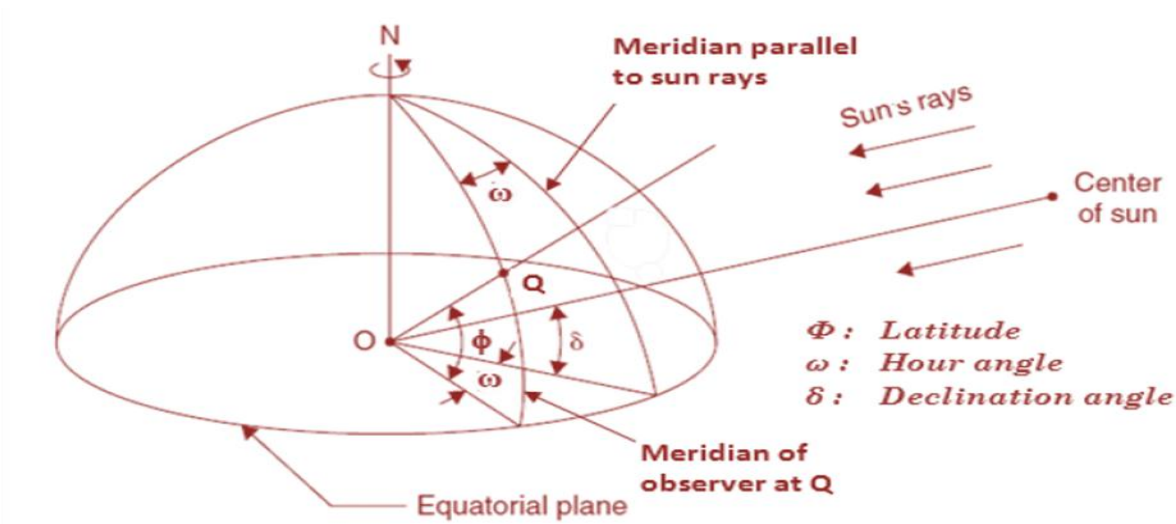


Figure B.1 Position of the Sun in the sky relative to the solar angles, [65]

Zenith Angle (θ_Z): is the complementary angle of sun's altitude angle. It is a vertical angle between the sun's rays and a line perpendicular to the horizontal plane through the point i.e. the angle between the beam from the sun and the vertical [65].

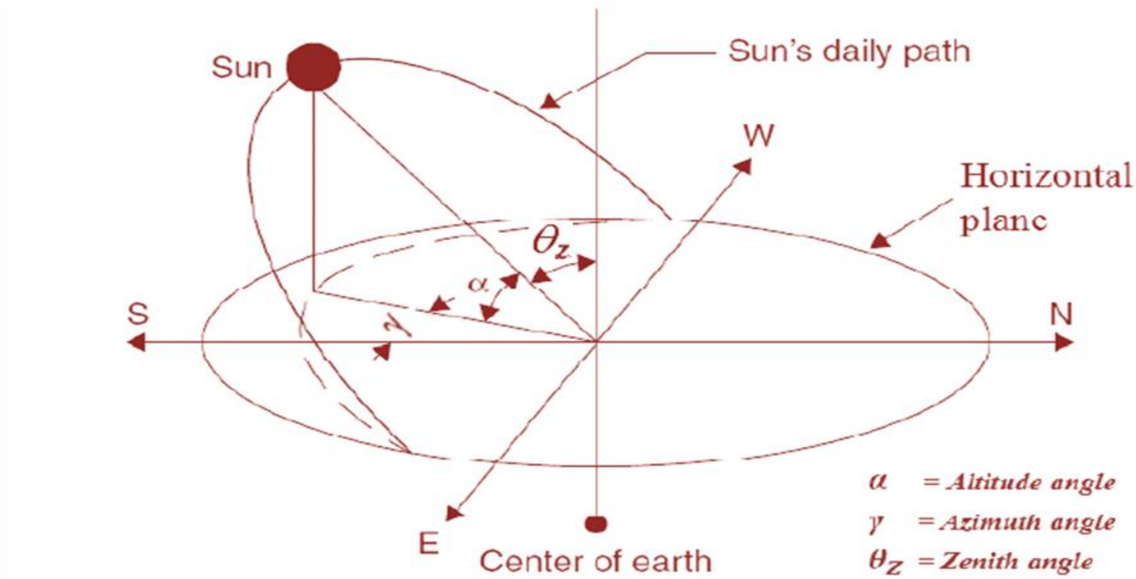


Figure B.2 Relative Position of the sun, [65]

Azimuth Angle (γ): is the solar angle in degrees along the horizontal east west of north or it is a horizontal angle measured from north to the horizontal projection of the sun's rays. Angle is positive when measured west wise. By convention, the azimuth angle is positive in the morning with the sun in the east and negative in the afternoon with the sun in the west [65].

Determination of Global Irradiance

In the computation of Global irradiance, readings from several types of solar radiations were used. Each of them is discussed below:

Beam Radiation: is often referred to as direct solar radiation. The solar radiation received from the sun that passes through the atmosphere without having been scattered or absorbed by particles or gases in the air [66, 67].

Diffuse Radiation: is referred as sky radiation or solar sky radiation. The solar radiation received from the sun after its direction has been changed by scattering by the atmosphere. The diffuse radiation on a collector is much more difficult to estimate accurately than it is for the beam.

Because, there are variety of components that make up diffuse radiation. Incoming radiation can be scattered from atmospheric particles and moisture, and it can be reflected by clouds. Some is reflected from the surface back into the sky and scattered again back to the ground [66, 67].

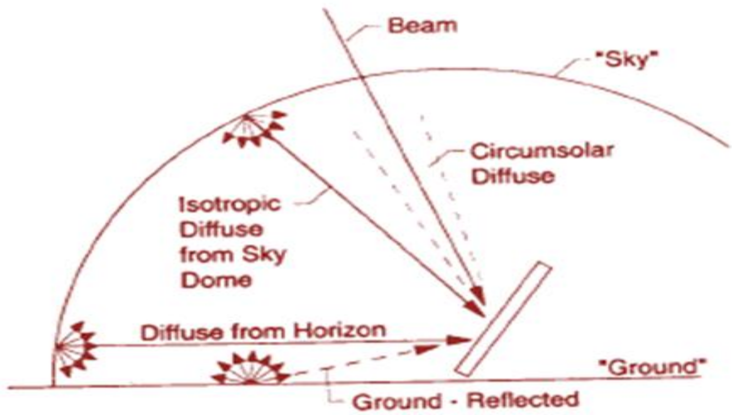


Figure B.3: Beam Diffuse and ground reflection radiation on a tilted surface, [67]

Total Solar Radiation: The sum of the beam and the diffuse solar radiation on a surface. The most common measurements of solar radiation are total radiation on a horizontal surface, often referred to as **global radiation** on the surface [66, 67].

Irradiance: The rate at which radiant energy is incident on a surface per unit area of surface. The symbol *I* is used for solar irradiance, with appropriate subscripts for beam, diffuse, or spectral radiation. It's unit is watt per meter square (W/m2) [66, 67].

Total irradiance (I_t): is given by the standard expression [49]:

$$I_t = K(\theta) * I_b * cos(\theta) + [K(\theta_{eff}) * [I_d * 0.5 * (1 + cos(\beta))]] + [K(\theta_{effg}) * \rho * I_h * 0.5 * (1 - cos(\beta))]$$

(Eq. B.5)

Where:

I_d: diffuse solar radiation (*read from metrological data*)

I_h: Global horizontal irradiance (*read from metrological data*)

I_b: Direct normal irradiance ($I_b = I_h - I_d$)

ρ: is the reflectivity of the surrounding ground (it is 0.2)

Cos (θ_Z): Tilt angle factor and given by the expression [66, 67]:

$$\cos(\theta_z) = \cos(\phi)\cos(\delta)\cos(\omega) + \sin(\phi)\sin(\delta) \quad \textit{(Eq. B.6)}$$

Cos (θ): The factor that is the cosine of the incidence angle of the sun on the horizontal surface is represented as [66]:

$$\cos(\theta) = \cos(\delta)\cos(\beta)\cos(\beta - \phi) + \sin(\delta)\sin(\phi - \beta) \quad \textit{(Eq. B.7)}$$

$K(\theta)$ **:** Incidence angle modifier and given by [49]:

$$K(\theta) = \cos(\theta) * [1 + sin^3(\theta)] \quad \textit{(Eq. B.8)}$$

Where: θ is the solar angle of incidence to the plane of module

θ_{eff} **:** Factor for the direct beam contribution and given by [49]:

$$\theta_{eff} = 59.68 - 0.1388 * \beta + 0.001497 * \beta^2 \quad \textit{(Eq. B.9)}$$

θ_{effg} : Factors for the ground reflectance contribution and given by [49]:

$$\theta_{effg} = 90 - 0.5788 \times \beta + 0.002693 \times \beta^2 \quad \textit{(Eq. B.10)}$$

Where: β is the angle between the plane of module and horizontal

T_{mod} : Module temperature is given by [49] :

$$T_{mod} = T_{amb} + (I_t \div (U'_o + U'_1 \times V_{wind})) \quad \textbf{(Eq. B.11)}$$

Where: the two coefficients U'o=25W/m^2 K and U'1=6.8W/m^3 s/ K and V_{wind} : wind speed

Appendix C: MatLab Code for the DC Power Production from a single Module

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%the following MatLab code used for calculation of hourly DC power output
from a single selected module for one year at Addis Ababa
%===========================================================================
% parameter assignments
rho=0.2;                %Ground reflectivity factor
beta=(pi*9.02)/180;     %Collector  slope (south facing)
beta1= (pi*9.02)/180;   %Collector slope (south facing)
lamda=9.02*pi/180;      %Latitude  of Addis Ababa [ rad ]
Uo=25;                  % (W/m2k)
Ui=6.8;                 % (W/m3sk)
Wp=150;                 % the peak watt rating of the module (W)
gama=-0.238;            % Temperature coefficient of the peak power(W/K) (for
all crystalline silicon modules)
%===========================================================================
% locate and load the solar radiation and wind data collected from
metrological agency
load SolarDatafinal.m;
load winddat.m;
data=zeros(24,3,365);
wdata=zeros(24,365);

for j=1:365;
    data(:,:,j)=SolarDatafinal(j+(23*(j-1)):j*24,:);

end

for j=1:365;
     wdata(:,j)=winddat(j+(23*(j-1)):j*24);
end
%===========================================================================
% Calculation of EOT for each day of the year
  EOT=zeros(365);
  for n=1:365
    B=(pi/180)*((360*(n-81))/364);
    EOT(n)=9.87*(sin((2*B)))-(7.53*cos(B))-(1.5*sin(B));
  end

%===========================================================================
 %Calculation of hour angle for each hour of the day
  for jj=1:24
      ST=((jj-12)*60)+(4*(-45+38.5))+EOT(jj);
      omega1(jj)=(ST*360)/(24*60);
      omega(jj)=omega1(jj)*pi/180;
  end
%===========================================================================
% Calculation of declination angle for each day of the year.
  for n=1:365
    decl(n)=(pi/180)*(23.45*sin((2*pi/365)*(284+n)));

  end

%===========================================================================
```

```
% Calculation of a constant effective solar angle of incidence to the plane
of module
    tetaeff=59.68-(0.1388*beta1)+(0.001497*(beta1)^2);
%============================================================================
% Calculation of a ground reflectance contribution of solar angle of
incidence to the plane of module
    tetaeffg=90-(0.5788*beta1)+(0.002693*(beta1)^2);
%============================================================================
 % Incident angle modifiers ktetaeff and ktetaeffg

    ktetaeff=cos(tetaeff)*(1+(sin(tetaeff)^3));
    ktetaeffg=cos(tetaeffg)*(1+(sin(tetaeffg)^3));

%==============================Main Program==============================

 for i=1:365
     Idd=data(:,2,i);
     Ihh=data(:,1,i);
     Taa=data(:,3,i);
     Wii=wdata(:,i);
     for j=1:24
         Ih=Ihh(j);
         Id=Idd(j);
         Ta=Taa(j);
         Vw=Wii(j);
% Determination of hourly irradiance I
    costeta=(cos(lamda-
beta)*(cos(decl(i))*cos(omega(j))))+(sin(lamda)*(sin(lamda-beta)));
costetaz=(cos(lamda)*cos(decl(i))*cos(omega(j)))+(sin(lamda)*sin(decl(i)));
    kteta=costeta*(1+(sin(acos(costeta)^3)));
    I=(kteta*(costeta/costetaz)*(Ih-
Id)+(ktetaeff*(Id))*0.5*(1+cos(beta)))+(ktetaeffg*(0.5*rho*((1-
cos(beta))*Ih)));
% calculation of hourly module temperature

         Tmod=Ta+(I/(Uo+Ui*Vw));

% calculation of hourly dc power for a single module

        Pdcm=abs(I/1000*(Wp+gama*(Tmod-25)));

         Pdcm1(i,j)=Pdcm;

     end
 end
%============================================================================
 %plot declination angle Vs Days of the year
  kk=1:365;
  plot(kk,decl,'r-','linewidth',2);
  xlabel('Days in  a year')
  ylabel('Declination angle [rad]')
  title('Declination Angle')
  grid on
  pause
  clf
%============================================================================
```

```
% plot EOT Vs days of the tear
  ii=1:365;
  plot(ii,EOT,'b-','linewidth',2);
  xlabel('Days in a year')
  ylabel('EOT in minutes')
  title('Equation of Time')
  grid on
  pause
  clf
%============================================================================
 % plot hour angle Vs hours of the day
  rr=1:24;
  plot(rr,omega1,'c-','linewidth',2);
  xlabel('Hrs in a day')
  ylabel('Hour angle (w) in degree')
  title('Hour Angle')
  grid on
  pause
  clf
%============================================================================
 %plot Dc power generated at each hr of the year from a single module

  PDCF=transpose(Pdcm1);
  PDC=PDCF(:);
  jj=1:8760;
  plot(jj,PDC,'b-','linewidth',2);
  xlabel('hours in a year')
  ylabel('DC power output in watt')
  title('module Power')
  grid on
  pause
  clf

%============================================================================

   % extract the hourly dc power output of a single selected module for one
year to 'D:\exportedPdc_data.xls'
export_data1=PDC;
save  -ascii 'D:\exportePdc_data.xls'  export_data1
%============================================================================
```

Appendix D: Expressions for variables

The following expression used for determining the values of variables (constants) in Eq. 2.9.

K1= Ci_{gr1} **(Eq. D.1)**

$$K2 = Ci_{pv} + \left[F1 \times Ci_{pv} \times \left\{\sum_{i=1}^{N}\left(\frac{(1+e)}{(1+d)^{i}}^{i-1}\right)\right\}\right] \quad \textbf{(Eq. D.2)}$$

$$\text{K3=}Ci_{b1} + \left[F1 \times Ci_{b1} \times \left\{\sum_{i=1}^{N}\left(\frac{(1+e)}{(1+d)^{i}}^{i-1}\right)\right\}\right] + \left[F2 \times Ci_{b1} \times \left\{\sum_{i=1}^{n_r}\left(\frac{(1+e)}{(1+d)^{n_b i}}^{n_b(i-1)}\right)\right\}\right] \quad \textbf{(Eq. D.3)}$$

$$\text{K4=}Ci_{b} + \left[F1 \times Ci_{b} \times \left\{\sum_{i=1}^{N}\left(\frac{(1+e)}{(1+d)^{i}}^{i-1}\right)\right\}\right] + \left[F2 \times Ci_{b} \times \left\{\sum_{i=1}^{n_r}\left(\frac{(1+e)}{(1+d)^{n_b i}}^{n_b(i-1)}\right)\right\}\right] \quad \textbf{(Eq. D.4)}$$

K5= Ci_{gr} **(Eq. D.5)**

Appendix E: Simulation out Put for Scenario I

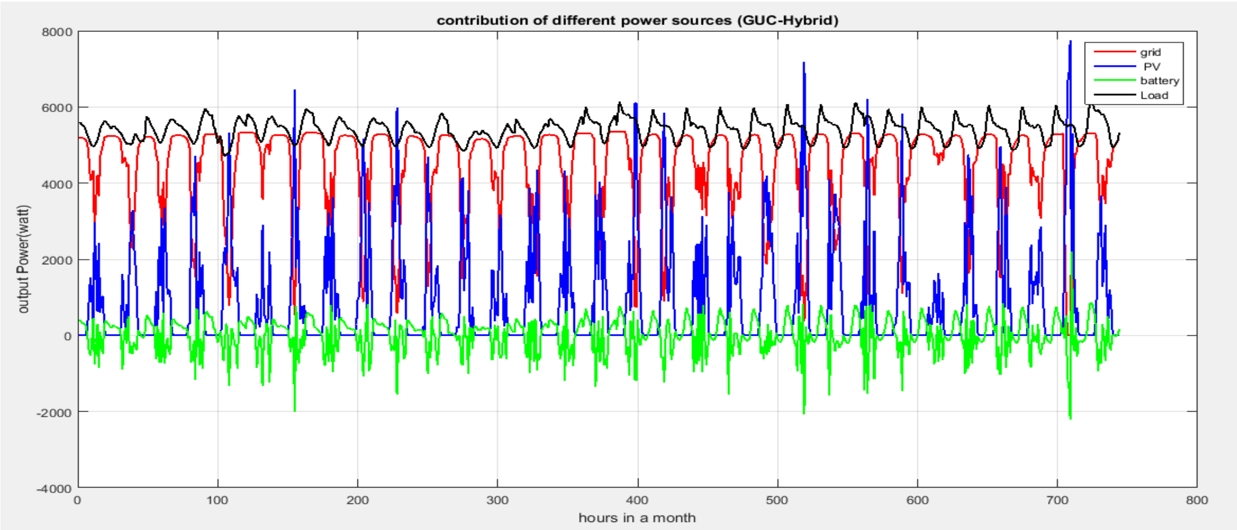


Figure E.1 Power contribution for hybrid system (GUC)

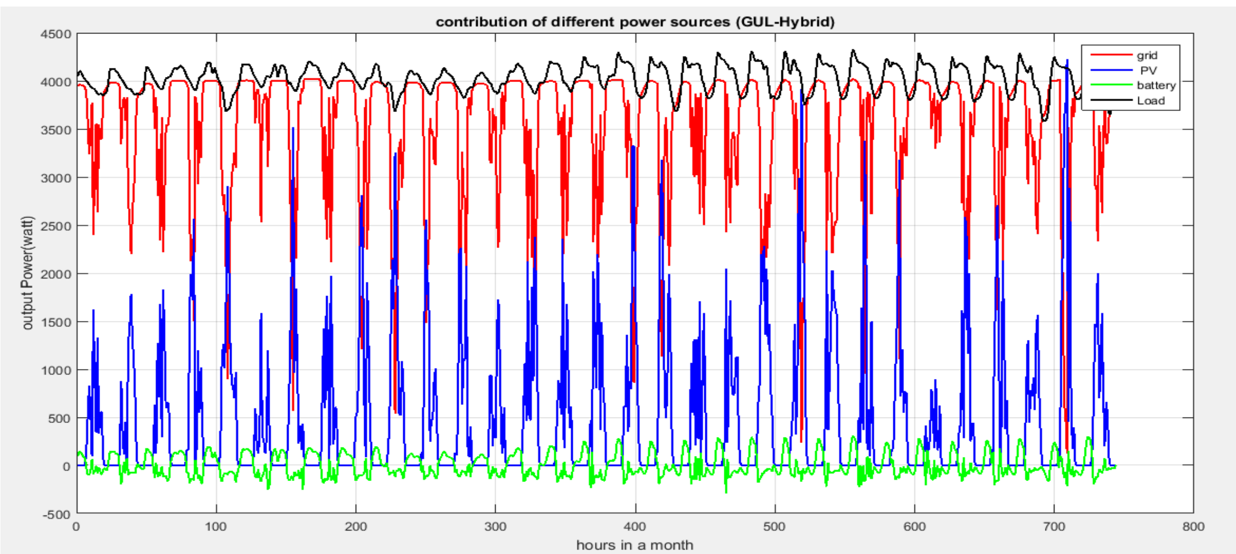


Figure E.2 Power contribution for hybrid system (GUL)

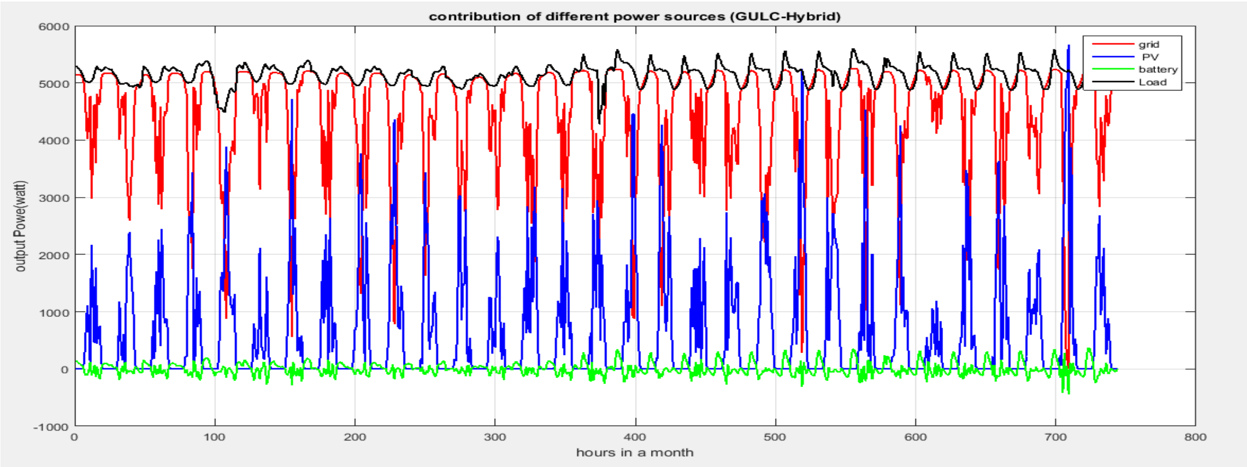


Figure E.3 Power contribution for hybrid system (GULC)

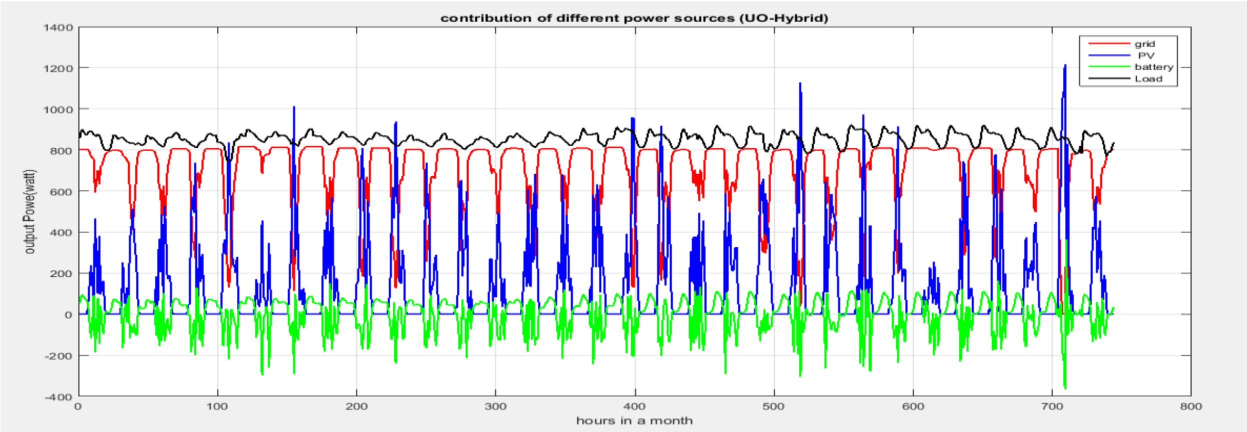


Figure E.4 Power contribution for hybrid system (UO)

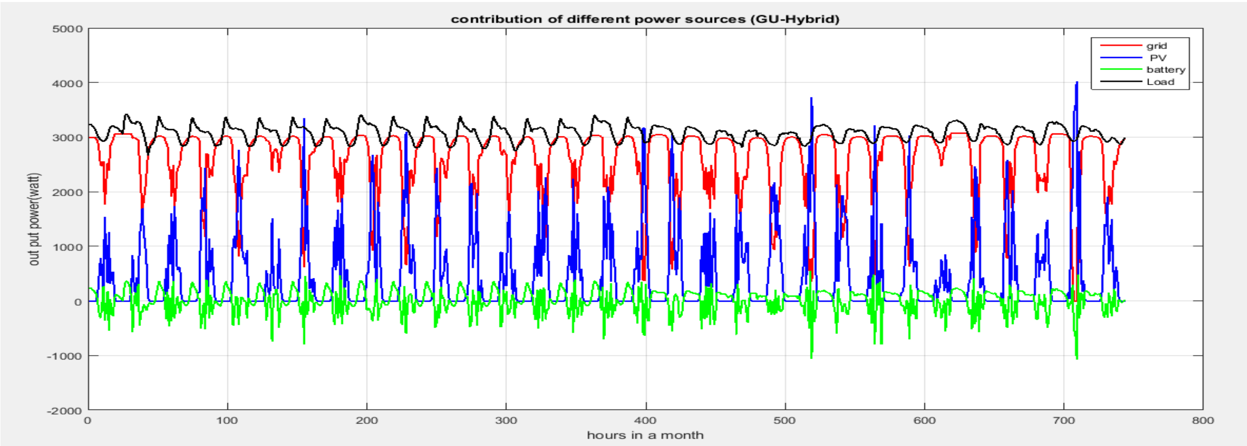


Figure E.5 Power contribution for hybrid system (GU)

Appendix F: Simulation Output for Scenario II

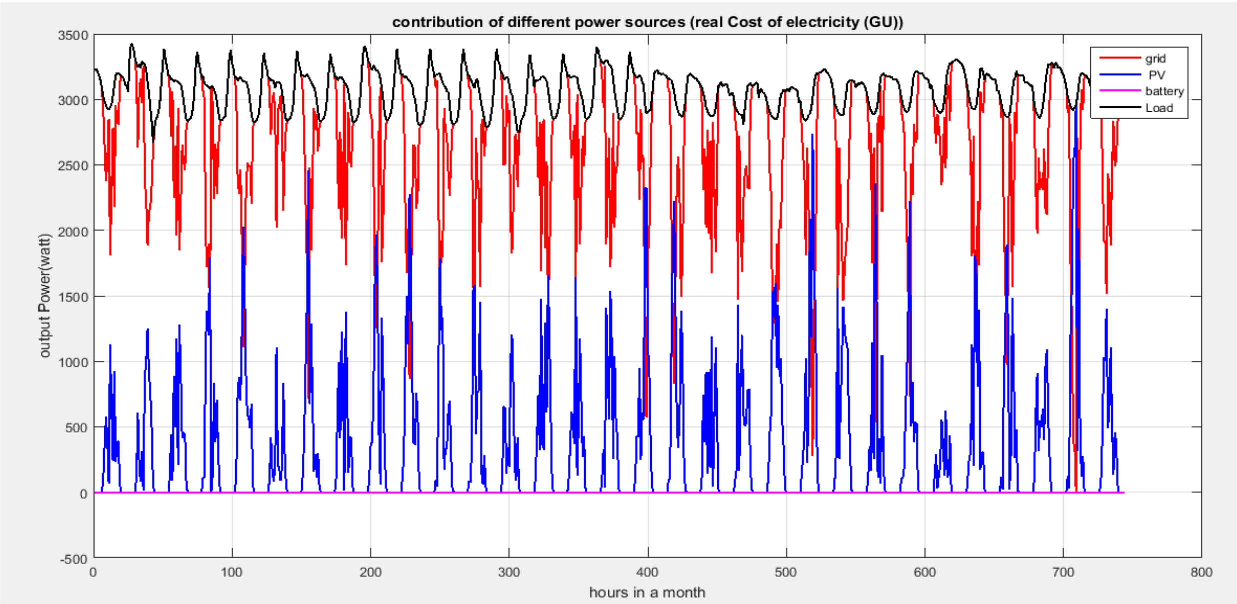


Figure F.1 Power Contribution for Real Cost of Electricity (GU)

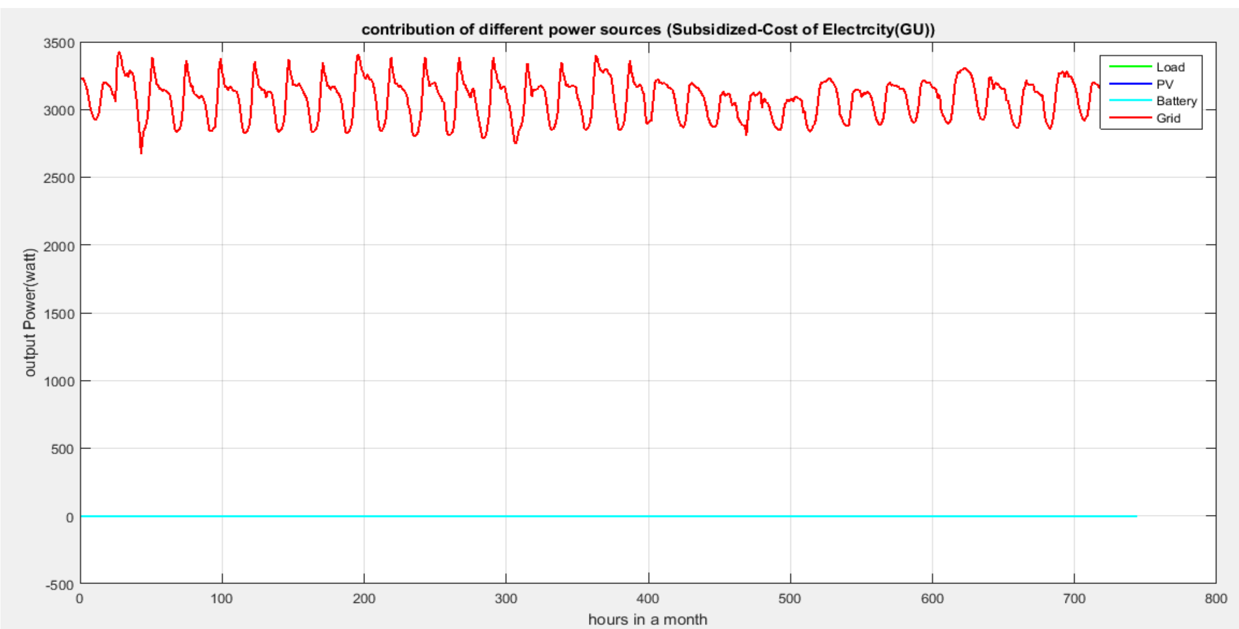


Figure F.2 Power Contribution for Subsidized Cost of Electricity (GU)

Appendix G: Pseudo Code for System Sizing

1. ***Load data***: locate and store in to array the normalized output of solar power for the worst month, July and the maximum and Real power consumption of BTS sites for each group
2. ***Declaring Variables***: declare a double type variables
3. ***Parameter Assignment***: constant values assigned and assumptions made
4. ***Build Objective Function (F):*** populate the matrix of objective function
5. ***Build Equality Constraint Matrices (Aeq and beq):***
   - Generate sub matrices for energy balance equation (Eq. 3.2), equation for instantaneous power from PV module (Eq. 3.3), storage energy balance equation (Eq. 3.4), and equation that relates the energy and instantaneous power from the grid (Eq. 3.5)
   - Generate sub matrices for the right hand side of equations from Eq. 3.2 to Eq. 3.5
   - Concatenate all sub matrices to build equality constraint matrices (Aeq and beq)
6. ***Build non-Equality Constraint Matrices (A and b):***
   - Build sub matrices for the minimum and maximum value of power from the grid PV module and the storage unit (Eq. 3.6 to Eq. 3.8)
   - Build sub matrices for maximum and minimum level of energy in the battery (Eq. 3.9)
   - Build the sub matrices of the right hand side of equations from eq. 3.6 to Eq. 3.9
   - Concatenate the sub matrices to build non equality constraint matrices (A and b)
7. ***Solve the LP:*** solve the linear program using a matlab function linprog

   ```
   [X,fval] = linprog (F,A,b,Aeq,beq,[],[],[]);
   ```
8. ***Plot:*** plot the power contribution of each source versus simulation time for different scenarios and extract the instantaneous power output from different power sources during simulation period.

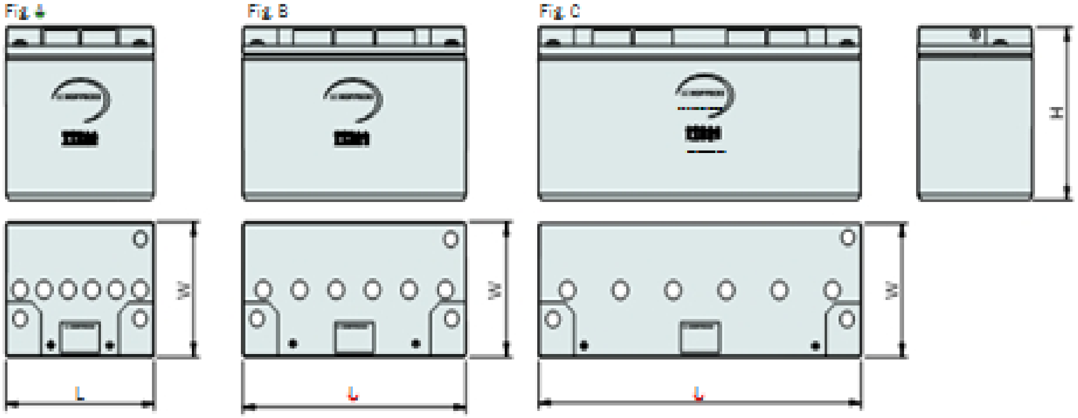
Appendix H: Battery and PV module Datasheet

Type overview

Capacities, dimensions and weights

Type	C10**/1.80 V Ah	C8/1.77 V Ah	C5/1.75 V Ah	C3/1.70 V Ah	C1/1.65 V Ah	C1/2/1.60 V Ah	Weight kg	Length L mm	Width W mm	Height H mm	Fig.
[illegible] SB 12V 50	52.7	51.5	49.2	41.8	35.8	25.3	28.0	229	177	230	A
[illegible] SB 12V 60	63.2	58.5	54.3	48.1	39.5	28.0	28.5	229	177	230	A
[illegible] SB 12V 80	80.4	78.5	75.0	63.7	54.5	38.8	37.5	344	177	230	B
[illegible] SB 12V 100	94.8	85.0	81.3	69.2	59.0	42.0	38.0	344	177	230	B
[illegible] SB 12V 110	111.1	108.0	103.5	88.1	75.5	53.7	52.0	498	177	230	C
[illegible] SB 12V 130	128.9	115.5	110.7	94.1	80.5	57.2	52.5	498	177	230	C
[illegible] SB 12V 140	142.2	127.5	122.1	104.0	89.0	63.2	54.5	498	177	230	C
[illegible] SB 6V 170	170.0	143.1	133.2	110.0	94.4	68.3	32.0	242	170	275	D
[illegible] SB 6V 220	220.0	185.2	172.4	142.4	122.2	85.8	41.0	308	170	275	D
[illegible] SB 2V 400	400.0	374.5	351.7	298.5	258.4	173.2	25.0	178	154	314	E

Fig. A Fig. B Fig. C

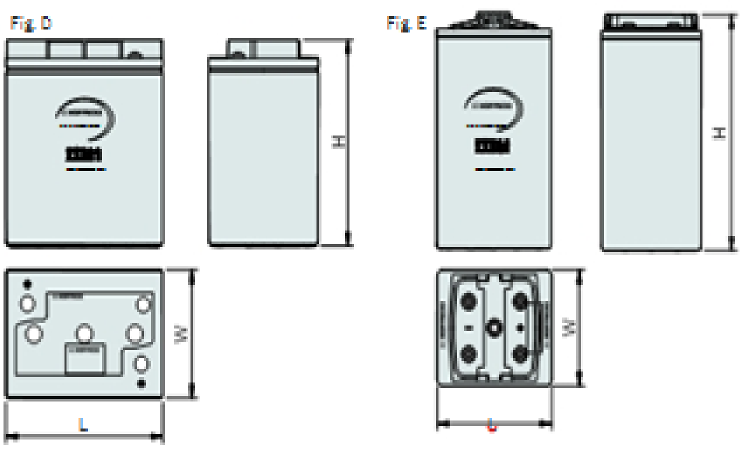


power.com SB 12V 50 - power.com SB 12V 60

power.com SB 12V 80 - power.com SB 12V 100

power.com SB 12V 110 - power.com SB 12V 140

Fig. D Fig. E



power.com SB 6V 170 - power.com SB 6V 220

power.com SB 2V 400

Life expectancy:
12 years (acc. to EUROBAT)

HOPPECKE Batterien GmbH & Co. KG
P.O. Box 1140 · D-59914 Brilon
Bontkirchener Straße 1 · D-59929 Brilon-Hoppecke

Phone: + 49 (0) 29 63 61-0
Fax: + 49 (0) 29 63 61-2 70
Email: info@hoppecke.com
Internet: www.hoppecke.com

HOPPECKE POWER FROM INNOVATION

Sunmodule SW 150 poly R6A

Produced in Germany,
the center for solar technology

TUV Power controlled:
Lowest measuring tolerance in industry

25 year linear performance warranty and
10 year product warranty

SolarWorld AG relies on Germany as its technology location, thereby ensuring sustainable product quality.

The TUV Rheinland Power controlled inspection mark guarantees that the nominal power indicated for solar modules is inspected at regular intervals and thus ensured. The deviation to TUV is maximum 2 percent.

With its linear performance warranty covering a period of 25 years SolarWorld guarantees a maximum performance degression of 0.7% p.a., a significant added value compared to the two-phase warranties common in the industry. Therefore, the service certificate offers comprehensive protection for your investment in the long term.

SOLARWORLD

We turn sunlight into power.

www.solarworld.com

Sunmodule SW 150 poly R6A

PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

		SW 150
Maximum power	P_{max}	150 Wp
Open circuit voltage	U_{oc}	22,5 V
Maximum power point voltage	U_{mpp}	18,3 V
Short circuit current	I_{sc}	8,81 A
Maximum power point current	I_{mpp}	8,27 A

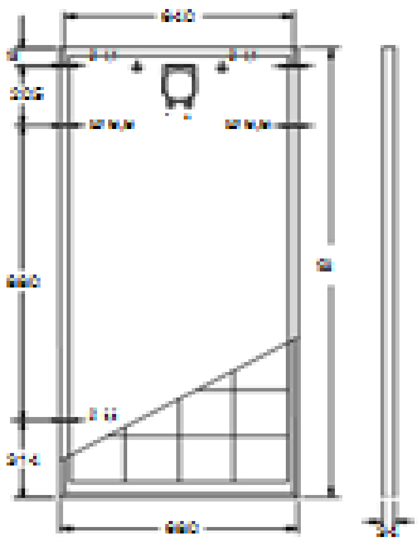
Measuring tolerance (P_{max}) traceable to TUV Rheinland: +/- 3% (TUV Power controlled)

*STC: 1000 W/m², 25°C, AM 1.5

PERFORMANCE AT 800 W/m², NOCT, AM 1.5

		SW 150
Maximum power	P_{max}	110,1 Wp
Open circuit voltage	U_{oc}	20,5 V
Maximum power point voltage	U_{mpp}	16,6 V
Short circuit current	I_{sc}	7,17 A
Maximum power point current	I_{mpp}	6,63 A

Minor reduction in efficiency under partial load conditions at 25°C: at 200 W/m², 100% (+/-2%) of the STC efficiency (1000 W/m²) is achieved.



DIMENSIONS

Length	1508 mm
Width	680 mm
Height	34 mm
Frame	Aluminum
Weight	[illegible] kg

COMPONENT MATERIALS

Cells per module	36
Cell type	Poly crystalline
Cell dimensions	156 mm x 156 mm
Front	tempered glass (EN [illegible])

THERMAL CHARACTERISTICS

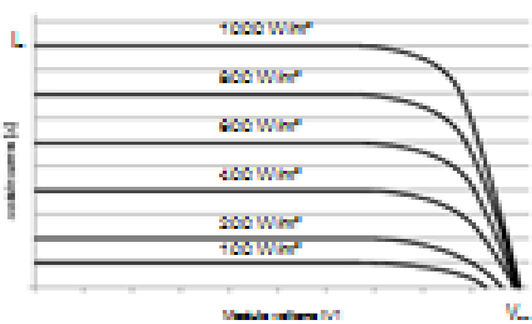
NOCT	[illegible] °C
TK I_{sc}	[illegible] %/K
TK U_{oc}	-0,37 %/K
TK U_{mpp}	-0,45 %/K

ADDITIONAL DATA

Power sorting	[illegible]
J-Box	[illegible]

PARAMETERS FOR OPTIMAL SYSTEM INTEGRATION

Maximum system voltage SC II	1000 V
Maximum reverse current	16 A
Load / dynamic load	5,4 / 2,4 kN/m²
Number of bypass diodes	2
Operating range	-40 °C to +85 °C



SolarWorld AG reserves the right to make specification changes without notice. This data sheet complies with the requirements of EN 50380.

SOLAR DEVELOPMENT

PROFORMA INVOICE

To: Kihana
Tel: +251 956 961 669

Date: 16/05/2016
Ref. No.:SD.Q/056/16

Project Name: Supply of Solar System

No.	Item Description	Qty	Unit Price ex. VAT	Total Price
1	Solar world module 80Wp	1	5,060.87	5,060.87
2	Solarworld Module 150Wp	1	5,739.15	5,739.15
3	Steca Charge Controller PR 2020,20A,12/24V	1	4,385.22	4,385.22
4	Phocos MPS 80, 80A Charge Controller	1	8,695.65	8,695.65
5	Phonix Inverter C12/1600W,230V	1	22,956.52	22,956.52
6	Copex Solar Battery 150Ah,12V	1	10,434.78	10,434.78
7	Hoppecke OPZS Solar battery 100Ah,12V	1	15,678.26	15,678.26
			Sub Total	68,930.43
			15% VAT	10,339.57
			Total Including VAT	79,270.00

Selling Conditions

1. Delivery Time: Directly from stock
2. Validity of Quote: 10 days
3. Payment Terms: 100% when stock is received
4. Warranty: 1 Year

PI prepared by: Marta Negussie

Signature:

Nefas Silk Lafto Sub City, Woreda 04, House No. 1823 - 1st Floor
E-mail: info.ethio@solar23.com | Tel: +251-113-712-377 | Fax: +251-113-712-376

Appendix I: Sample Metrological Data

Addis Ababa Temperature Data

NAME	EG_GH_ID	YEAR	MONTH	DAY	TIME	TEMPERATURE
Addis Ababa	SHADDI15	2013	1	1	0:00:00	9
Addis Ababa	SHADDI15	2013	1	1	0:15:00	9.3
Addis Ababa	SHADDI15	2013	1	1	0:30:00	9.5
Addis Ababa	SHADDI15	2013	1	1	0:45:00	8.5
Addis Ababa	SHADDI15	2013	1	1	1:00:00	7.9
Addis Ababa	SHADDI15	2013	1	1	1:15:00	8.1
Addis Ababa	SHADDI15	2013	1	1	1:30:00	8
Addis Ababa	SHADDI15	2013	1	1	1:45:00	7.7
Addis Ababa	SHADDI15	2013	1	1	2:00:00	7.4
Addis Ababa	SHADDI15	2013	1	1	2:15:00	7
Addis Ababa	SHADDI15	2013	1	1	2:30:00	7.5
Addis Ababa	SHADDI15	2013	1	1	2:45:00	7.5
Addis Ababa	SHADDI15	2013	1	1	3:00:00	6.1
Addis Ababa	SHADDI15	2013	1	1	3:15:00	6.4
Addis Ababa	SHADDI15	2013	1	1	3:30:00	6.2
Addis Ababa	SHADDI15	2013	1	1	3:45:00	5.7
Addis Ababa	SHADDI15	2013	1	1	4:00:00	6.1
Addis Ababa	SHADDI15	2013	1	1	4:15:00	6.6
Addis Ababa	SHADDI15	2013	1	1	4:30:00	7.8
Addis Ababa	SHADDI15	2013	1	1	4:45:00	9.9
Addis Ababa	SHADDI15	2013	1	1	5:00:00	12.1
Addis Ababa	SHADDI15	2013	1	1	5:15:00	13.9
Addis Ababa	SHADDI15	2013	1	1	5:30:00	14.5
Addis Ababa	SHADDI15	2013	1	1	5:45:00	15
Addis Ababa	SHADDI15	2013	1	1	6:00:00	15.6
Addis Ababa	SHADDI15	2013	1	1	6:15:00	16.4
Addis Ababa	SHADDI15	2013	1	1	6:30:00	17
Addis Ababa	SHADDI15	2013	1	1	6:45:00	17.5
Addis Ababa	SHADDI15	2013	1	1	7:00:00	18.1
Addis Ababa	SHADDI15	2013	1	1	7:15:00	18.6
Addis Ababa	SHADDI15	2013	1	1	7:30:00	19.4
Addis Ababa	SHADDI15	2013	1	1	7:45:00	19.8
Addis Ababa	SHADDI15	2013	1	1	8:00:00	19.8
Addis Ababa	SHADDI15	2013	1	1	8:15:00	20.3
Addis Ababa	SHADDI15	2013	1	1	8:30:00	20.8
Addis Ababa	SHADDI15	2013	1	1	9:30:00	21.8
Addis Ababa	SHADDI15	2013	1	1	9:45:00	22.3

Addis Ababa Solar Radiation Data

Country	Solar site	Latitude	Longitude	Altitude	Year	Month	Day	Hour	Global horizontal radiation (Wh/m2)	Diffuse horizontal component (Wh/m2)
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	1	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	2	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	3	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	4	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	5	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	6	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	7	5	3
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	8	138	48
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	9	344	92
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	10	536	145
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	11	693	107
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	12	699	212
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	13	840	180
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	14	832	161
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	15	671	183
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	16	556	145
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	17	369	79
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	18	96	52
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	19	3	2
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	20	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	21	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	22	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	23	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	1	24	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	1	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	2	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	3	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	4	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	5	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	6	0	0
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	7	3	3
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	8	131	44
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	9	365	74
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	10	612	98
Ethiopia	Addis_Ababa	8.59	38.48	2355	2014	1	2	11	791	114

Addis Ababa Wind Data

Country: Ethiopia				Latitude: 8.59
Wind site: Addis Ababa				Longitude: 38.48
Year: 2011				Altitude: 2355
Month	Day	Hour	Wind Direction degrees from north	Wind Speed (m/s)
1	1	00:00	0	2.5
1	1	00:01	0	2
1	1	00:02	0	1.5
1	1	00:03	0	1
1	1	00:04	0	0.5
1	1	00:05	0	0
1	1	00:06	0	0
1	1	00:07	0	2
1	1	00:08	70	4
1	1	00:09	70	3.7
1	1	00:10	70	3.3
1	1	00:11	150	3
1	1	00:12	150	3.1
1	1	00:13	120	3.1
1	1	00:14	210	3
1	1	00:15	140	1.5
1	1	00:16	140	3.2
1	1	00:17	110	5
1	1	00:18	110	4
1	1	00:19	110	3
1	1	00:20	80	2
1	1	00:21	80	2.2
1	1	00:22	80	2.4
1	1	00:23	110	2.5
1	2	00:00	110	2.7
1	2	00:01	110	2.3
1	2	00:02	80	2
1	2	00:03	80	2
1	2	00:04	80	2
1	2	00:05	330	2
1	2	00:06	330	1.3
1	2	00:07	330	0.7
1	2	00:08	0	0
1	2	00:09	0	1.3
1	2	00:10	0	2.7
1	2	00:11	190	4
1	2	00:12	190	6
1	2	00:13	190	8
1	2	00:14	0	10
1	2	00:15	0	8

Monthly Average Data's

Month	Global_horizontal_radiation_Wh/m2	Diffuse_horizontal_component_Wh/m2	Average Temperature	Wind_speed_m/s
January	234.292	65.339	16.234	3.783
February	245.826	79.792	17.811	4.441
March	245.558	106.692	18.855	4.452
April	223.564	121.949	18.392	4.341
May	198.977	125.211	17.784	4.169
June	237.425	113.976	16.463	3.191
July	225.446	118.800	15.271	3.082
August	240.720	118.371	14.791	2.723
September	193.206	126.272	15.746	2.629
October	249.305	98.515	15.945	4.987
November	254.415	70.614	16.226	4.681
December	238.184	64.633	15.618	4.641