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TITLE: **Design and Analysis of an Off-grid Hybrid Renewable Energy System to Supply Electricity in Small Industries: A Case of Tanzania.**

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DECLARATION

I, Kaare MANYAMA, hereby declare that this thesis represents my personal work, realised to the best of my knowledge. I also declare that all information, material and results from other works presented here have been fully cited and referenced in accordance with the academic rules and ethics.

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CERTIFICATION

This is to certify that the thesis entitled “**Design and Analysis of an Off Grid Hybrid Renewable Energy System to Supply Electricity in Small Industries: A Case of Tanzania**” that is being submitted by Kaare MANYAMA, Masters student, Registration number PAUWES/2016/MEE01, in partial fulfillment for the award of Masters in Energy Engineering to the Pan African University Institute of Water and Energy Sciences (Including Climate Change) is a record of bonafide work carried out by him. This thesis has been submitted with my approval as the supervisor.

Professor Alexander POGREBNOI

Signed: 25th July 2018.

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DEDICATION

This work is dedicated to all who contributed immensely to the success of this study. Special dedication to my late Parents Mr & Mrs Manyama Jacob, may their soul rest in peace.

ABSTRACT

The off-grid hybrid power systems were attracting to supply electricity to small companies and interprices in different aspects like reliability, sustainability and environmental protections. Hybrid power system with various combinations based on renewable sources could be applied simultaneously to cater energy in the form employed in an off-gird supporting with battery storage and diesel generator as backup systems. In this thesis wind turbine, photovoltaic, battery bank and converter sytem have been simulated and optimized for the Bellaview Fresh Fruit Processing Industry Ltd in Rombo, Kilimanjaro region in Tanzania. Electric load demand of 1600 kWh/day, peak load of 184 kW was involved during optimization of the power system. Well known HOMER modeling tool have been used to design the off-grid system. Wind and solar energy are considered as primary sources to supply electricity directly to the load and to charge battery bank when excess generation is happened however in peak demand. The Industry's load has been suggested for running machines, lighting, water pumping, etc. During the design of this power system setup, the simulation and optimization were done based on the electricity load, climatic data sources, economics of the power components and other parameters in which the net present cost (NPC) has to be minimized to select an economic feasible power system. Moreover other parameters like capacity shortage, renewable fraction, excess of electricity, cost of electricity (COE), diesel fuel consumption was also considered to check the technical capability so as to select a system that is sound in techno-economic aspects. Some approaches were used as comparison measurements to select one power system from the selected options giving due merit to one of the measuring instruments (low cost of energy).

HOMER simulation result displayed the most economical feasible system sorted by NPC from top to down, the prime system ranked first has renewable fraction of 100% containing of 8 unit wind turbines with 100 kW each rating power, 189 kW photovoltaic panel, 487 unit batteries, and 142 kW converter. Sensitivity analysis was also performed for the system, different sensitivity cases were used such as; 2 values of primary loads, 3 cases of diesel prices and 2 cases of minimum renewable fractions.

Keywords: HOMER, Wind Speed, Solar radiation, off-grid power System, Hybrid wind-photovoltaic-diesel generator-battery system, Electricity load.

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LIST OF ABBREVIATIONS

AMR	Automatic Meter Reader
COF	Cost of Energy
DBSA	Development Bank of Southern Africa
EWURA	Energy Water Utility Regulatory Agency
FELISA	Farming for Energy for Better Livelihoods in Southern Africa
FYDP	Five years national development plan
HOMER	Hybrid Optimization Model for Electric Renewables
JBIC	Japan Bank for International Cooperation
JICA	Japan International Cooperation Agency
NPC	Net Present Cost
MEM	Ministry of Energy and Minerals
MTPY	Metric Tons Per Year
NEP	National Energy Policy
NORAD	The Norwegian Agency for Development Cooperation
POS	Point of Sale
PSMP	Power System Master Plan
PV	Solar Photovoltaic
REA	Rural Energy Agency
REF	Rural Energy Fund
SSMP	Sustainable Solar Market Package
TANESCO	Tanzania Energy Supply Company
TGDCL	Tanzania Geothermal Development Company Limited
TPDC	Tanzania Petroleum Development Corporation

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND

In the present world, every country is giving important place on energy security and sustainable development; hence role of renewable energy has become ever more significant. With the expectation of promoting electricity generation based on non-conventional renewable energy The rapid industrialization and growth of Tanzania human population have resulted in the unprecedented increase in the demand for energy and in particular electricity. Depletion of fossil fuels and impacts of global warming caused widespread attention using renewable energy sources, especially wind and solar energies. Energy security under varying weather conditions and the corresponding system cost are the two major issues in designing hybrid power generation systems.

The design of hybrid Renewable energy system is an important issue in small industries to increse productivity. Through this thesis it is expected to give concern about development of hybrid power generation systems for small Industries in Tanzania. The selected Industry is going to be analyzed using a software tool. Hybrid Optimization Model for Electric Renewables (HOMER) software will be used to analyze the data, the software is a micro-power optimization model for both off-grid and grid connected power systems in a variety of applications.

1.2 RESEARCH QUESTIONS

- Can developing countries like Tanzania be successful in industrialization without depending too much in fossil fuel?
- What is the suitable energy system design for off-grid electrification for small industry?
- Is the hybrid power system being able to solve the electricity problem in Tanzania especially for industrial sector?
- Is it feasible to shift from using fuel generator to renewable energy due to rising of oil price which increase the operation costs?

1.3 OBJECTIVES

1.3.1 Main objective

Design of an off-grid hybrid renewable energy system that can generate and provide cost effective electricity to the targeted industries (processing and manufacturing industries).

1.3.2 Specific objectives

- Estimating electricity load required for a targeted industry.
- Simulation and optimizing the hybrid power system to be applied to specific industry via solar PV, solar thermal, battery storage, convertor, diesel Generator and wind turbine.
- Comparing power systems based on certain criteria to select the techno-economic feasible systems beyond the net present cost (NPC).
- Analysis of the power system sensitivity.

1.4 PROBLEM STATEMENT AND MOTIVATION OF THE STUDY

Despite the abundant renewable energy resources in Tanzania, many Industries still live and operate under low adequite supply of electricity either from the utility grid or independent renewable energy generated electricity. There is a challenge to supply electricity to the Industries because of two reasons. First there is no enough power generation to fulfill the current power demand. Second, even if there is enough power generation, installation of grid system to each industrry is challenging due to their geographical locations and economic constraints.

Electrifying all areas by extending transmission lines from the utility grid to each and every industry is very labor, time and capital intensive. Certain fundamental services that should be provided to particular Industrry are electricity, water supply, communication and transportation; are some mandatory needs for any Industry to escalate high production, thus supply of reliable and adequite electricity is prerequisite to cater this all services. The demand as well as the energy exploitation is rising in Tanzania for however from two source mainly hydro and natural gases. To fulfill the ever increasing demand of the country especially in Industrial sector, the power generation system has to expand to exploit the renewable sources. Hybrid renewable energy systems are the possible means of electricity generating for Small Industries.

1.5 METHODOLOGY

The hybrid energy system integrates numbers of renewable resources components such as solar, wind, diesel generator, invertors, and batteries. The criteria of selecting the best hybrid energy component, combination for a proposed case study is based on the trade-off between cost, sustainability, maturity of technology, efficiency and minimum use of diesel fuel. The methodology which will be applied in this study is listed below:

- A literature review on hybrid systems applicable for Small Industries and the physics of renewable energy systeams will be conducted.
- The different hybrid configuration topologies will be considered.

- The cost data for each of the power system components will be thoroughly searched from different websites and publications.
- The climatic data (solar and wind) energy sources will be found by direct personal contact with my suppervisor, staff member of each targeted small Industries also data from
  - ✓ NASA Satellite Surface Meteorology and Solar Energy;
  - ✓ Wind and solar data available in Meteorological Department in Tanzania;
  - ✓ Wind and solar data available in Tanzania Energy Authority.
- Hybrid Optimization Model for Electric Renewable (HOMER) algorithm tool will be used to design the off-grid power system.
- Microsoft office excel.
- Different scenarios to select techno-economic hybrid energy system architecture were developed and compared.
- Electricity load demand for each section of the Industry will be calculated accordingly.
- Physical observation/Survey sites.

1.6 BOUNDARIES AND SCOPE OF THE STUDY

Different numbers of scenarios will be considered during System design and optimization for configurations of power schemes with less Net Present Cost and minimum cost of energy will supposed to be selected with the idea of cost effective system.

- PV-Wind turbine-battery bank (scenario A).
- Solar PV-wind turbine-generator-battery bank (scenario B).
- Wind-battery bank (scenario C).
- Wind turbine- generator-battery bank (scenario D).

Again my thesis will be based only under Bellaview Fresh Fruits Processing Industry Limited as a case study also the time will be within three months as a scope.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 TANZANIA CONTEXT

2.1.1 Geography and climate

The United Republic of Tanzania is the largest country in the eastern Africa region with an extension of 945,000 km^2, including mainland and the Zanzibar islands. It has a tropical climate with regional variations. The north and east of the country have two wet seasons, from October to December and from March to May, while the rest of the country has one wet season from October to April/May. Tanzania is endowed with abundant natural resources, including river basins and forests, but it is already experiencing vulnerability to climate change and extreme weather events. Droughts have recently affected the country and undermined its hydroelectric capacity, while the world famous glacier on top of Kilimanjaro Mountain is disappearing at an impressive speed. According to the UNDP climate change profle, temperatures are forecasted to rise between 1.5 ^oC to 4.5 ^oC by 2090, and rainfall is expected to increase in areas with two wet seasons and decrease in the centre and south of the country **[1]**.

2.1.2 Socio-economic demographic context

Tanzania has a total estimated population of 53 million. The current rate of population growth is 2.9% per year. If this trend continues, the population will reach 64 million by 2025 and 83 million by 2035. However, the growth rate is expected to slow as economic development progresses. Today, about three-fourths of Tanzanians live in rural areas; by 2035, it is projected that urban populations will have increased, although rural dwellers will still constitute the majority of residents.

The United Republic of Tanzania is a least developed country ranking 151st of 188 in the 2015 Human Development Index. Economic growth and development in the last decade led to the country setting the target of achieving middle income status by 2025: the second national Five Year National Development Plan (FYDP II) (2017-2021) accordingly prioritizes industrialization and human development. Structural gaps continue to limit the effectiveness of programmes, however, particularly at the local level. The Tanzania development vision 2025 calls for transformation to a semi-industrialized nation by building the economy and stabilizing livelihoods **[2]**.

2.2 RENEWABLE ENERGY POTENTIALS IN TANZANIA

Tanzania is blessed with abundant, high-quality renewable resources, which are largely untapped.

2.2.1 Wind energy sources

Several areas of Tanzania are known to have promising wind resources. In areas where assessments have been conducted, only Kititimo (Singida) and Makambako (Iringa) have been identifed as having adequate wind speeds for grid-scale electricity generation. At Kititimo wind speeds average 9.9 miles per second and at Makambako they averaged 8.9 miles per second at a height of 30 m. The Ministry of energy and minerals (MEM), in collaboration with TANESCO, is conducting wind resource assessments in Mkumbara (Tanga), Karatu (Manyara), Gomvu (Dar es Salaam), Litembe (Mtwara), Makambako (Iringa), Mgagao (Kilimanjaro) and Kititimo (Singida) **[3]**.

The Rural energy agency (REA) is supporting wind measurements on Mafia Island (coastal region). MEM and TANESCO will conduct wind resource assessments in Usevya (Mpanda). To date, four companies have expressed interest in investing in wind energy, namely Geo-Wind Tanzania Ltd. and Wind East Africa in Singida, and Sino Tan Renewable Energy, Ltd. and Wind Energy Tanzania, Ltd. in Makambako. These companies are considering investments in wind farms in the 50–100 MW range **[3]**.

2.2.2 Solar energy sources

Tanzania has high levels of solar energy, ranging between 2800-3500 hours of sunshine per year, and a global horizontal radiation of 4–7 kWh per m^2 per day. Solar resources are especially good in the central region of the country, and it is being developed both for off-grid and grid-connected solutions **[3]**.

2.2.2.1 Off-grid solar photovoltaics

To date, about 6 MWp (megawatt peak) of solar PV electricity has been installed countrywide for various applications in schools, hospitals, health centres, police posts, small telecommunications enterprises and households, as well as for street lighting. More than half of this capacity is utilised by households in peri-urban and rural areas. Government, through the REA and various donors, has supported a number of solar PV programmes that target off-grid areas where the cost of lighting from solar is less than from a diesel generator or kerosene. As an example, the Sustainable Solar Market Package (SSMP) is a contracting mechanism that bundles the supply, installation and maintenance of PV systems for public facilities (e.g. schools and clinics) with requirements and incentives for commercial sale to households, businesses and other nongovernmental customers in a defned geographical area **[4]**.

2.2.2.2 Grid-connected solar photovoltaics

In central Tanzania, 1 MWp of solar PV generates about 1,800 MWh per year (net of losses) and requires about 1 hectare of land. Theoretically solar PV could generate large shares of electricity. On the basis of a 20% constraint on total national production in 2025, the potential for grid-tied solar PV could be about 800 MW **[5]**. Given that large-scale, grid-tied solar PV installations are being undertaken in some countries for under US$1,750 per kWp, its prospects in Tanzania should be excellent In the short-term, the PSMP envisages 120 MWp of solar in the power expansion plan by 2018. Several private firms have expressed interest in investing in 50–100 MWp of solar PV. Next Gen Solawazi has signed an SPPA with TANESCO to supply 2 MWp of electricity from PV to an isolated grid. TANESCO has also signed a letter of intent for a 1 MWp isolated grid-tied PV project **[5]**.

2.2.2.3 Solar thermal

Solar thermal energy has been used for generations in Tanzania for drying crops, wood and salt. Currently, solar dryers are used in the agricultural sector to dry cereals and other farm products, including coffee, pyrethrum and mangos. Households and other institutions (*e.g.* hotels, hospitals, health centres and dispensaries) are the main-users of solar water heating systems in Tanzania. Despite the potential of solar thermal and the demand of heated water for both domestic and commercial applications, uptake is low. Lack of awareness, inability to mobilise financing, relatively lower priority given to such investments (*i.e.* water heating may not be a major cost relative to others) are some of reasons attributed to the low usage of solar thermal. Other more advanced solar technologies, such as concentrated solar power are not present in the country **[6]**.

2.2.3 Hydro energy sources

Tanzania has natural topographic features which provide the country with many opportunities for hydropower resources, to the magnitude of 4.7 GW in total only 12% of which is currently being tapped. It is a country of great lakes such as Lake Victoria and has rivers and basins such as river Rufiji (Rufiji basin), Pangani (Pangani basin) and Wami (Wami Ruvu basin). Over the years the power sector of Tanzania has been dominated by hydropower. However, poor rains in the past few years resulted in a shortage of water to the turbine generating electricity. This was further aggravated by agricultural activities that were going on upstream. As such, Tanzania embarked on a deliberated measure to forge an energy mix which will ensure reliable availability of power for the economy **[6].**

2.2.3.1 Large hydropower

Historically, hydropower has been the mainstay of Tanzania's national electricity system, with aninstalled capacity of 562 MW. However, intermittent river flows resulting from droughts have decreased its reliability as a power source. Another key challenge facing hydropower development in Tanzania is the regional mismatch between hydro sites and major demand centres. Hydro generation facilities are located primarily in the southwest, whilst major demand centres are in the north, northwest and east. To realise the full potential of hydropower, weak transmission systems must be strengthened. Tanzania intends to develop additional large-hydro capacity. Some of this capacity is located in areas currently set aside for wildlife conservation, as part of a national park. Estimates of potential additional capacity go as high as 4,000 MW, but the long-term reliability of the water flows has not been clearly established yet. The PSMP includes 16 projects with a combined capacity of 3,000 MW. With the proposed capacity additions, large hydropower is still expected to exceed 30% of generation capacity after 2025 thus risking a repeat of drought-related supply disruptions. Adding other renewable energy sources to the generation mix could mitigate this risk **[6]**.

Table 2.1: Tanzania large hydropower stations **[6]**.

Hydroelectric station	Region	Type	Capacity (MW)	Year completed	Name of reservoir	River
Mtera Power station	Dodoma	Reservoir	80	1979	Mtera	Rufiji River
Kihansi Power Station	Morogoro	Reservoir	180	2000	Kihansi	Kihansi River
Nyumba ya Mungu Power Station	Kirimanjaro	Reservoir	8	1967	Nyumba ya Mungu	Mt.Kirimanjaro Strem
Kidatu Power Station	Morogoro	Reservoir	204	1976	Kidatu Dam	Rufiji River
Pangani power station	Tanga	Reservoir	68	1994		Pangani River
Hale Power station	Tanga	Reservoir	21	1964		Pangani River
Kikonge Power Station	Ruvuma	Reservoir	300	2025		Ruhuhu River

2.2.3.2 Small hydropower

The assessed potential of small hydropower resources (up to 10 MW) is 480 MW. Installed, grid connected, small-hydro projects contribute only about 15 MW. Most of the developed small-hydro projects are owned by private entities and are not connected to the national electricity grid. Five sites in the 300 kW–8,000 kW range are owned by TANESCO. Faith-based groups own more than 1617 small hydro power stations with 15 kW-800 kW capacity and an aggregate capacity of 2 MW of the 11 projects for which SPPAs have been signed, four are mini-hydro projects, with a combined capacity of 20.5 MW, whilst the others are biomass powered **[6]**.

In addition, TANESCO has signed letters of intent for six small hydro projects with a combined capacity of 29.9 MW. Several small hydro projects are also being developed as isolated mini grids and the MEM is conducting small hydro feasibility studiesin eight regions: Morogoro, Iringa, Njombe, Mbeya, Ruvuma, Rukwa, Katavi and Kagera. Development partners are supporting several mini-micro grid projects throughout the country **[6]**.

2.2.4 Geothermal energy sources

Tanzania has signifcant geothermal potential that has not yet been fully quantifed. Estimates using analogue methods indicate a potential exceeding 650 MW, with most prospects located in the East African Rift System. Most geothermal prospects have been identifed by their on-surface manifestation, mainly hot springs. Surface assessments started in 1976 and, to date, more than 50 sites have been identifed. Geothermal sites are grouped into three main prospect zones: northeastern (Kilimanjaro, Arusha and Mara regions), southwestern (Rukwa and Mbeya regions) and the eastern coastal belt (Rufji Basin), which is associated with rifting and magmatic intrusions. Only the southwestern zone has undergone detailed surface exploration studies **[6]**.

In 2006 and 2010, MEM, in collaboration with the Geological Survey of Tanzania, the German Federal Institute for Geosciences and Natural Resources and TANESCO, carried out surface exploration and conducted detailed studies in the NgoziSongwe prospect in the Mbeya region. Geothermometers showed that the reservoir temperature exceeds 200 °C (Figure 2.1). Recognising the potential of geothermal resources and their contribution to energy diversifcation, government formed a National Task Force on Geothermal Development. Its main task is to advise government on national geothermal resource development. Government intends to prepare a Renewable Energy Policy and Geothermal Energy Act to expedite and scale up geothermal development in the country **[6]**.

The SREP program in Tanzania will make a substantial contribution to the development of geothermal energy. Public-sector support will be targeted at overcoming the higher-risk phases of exploration anddevelopment. It will also go towards a development project developed mainly by the private sector that could help catalyse the generation of about 100 MW, thus making geothermal energy a reliable low-cost and signifcant contributor to Tanzania’s electric power supply **[7]**.

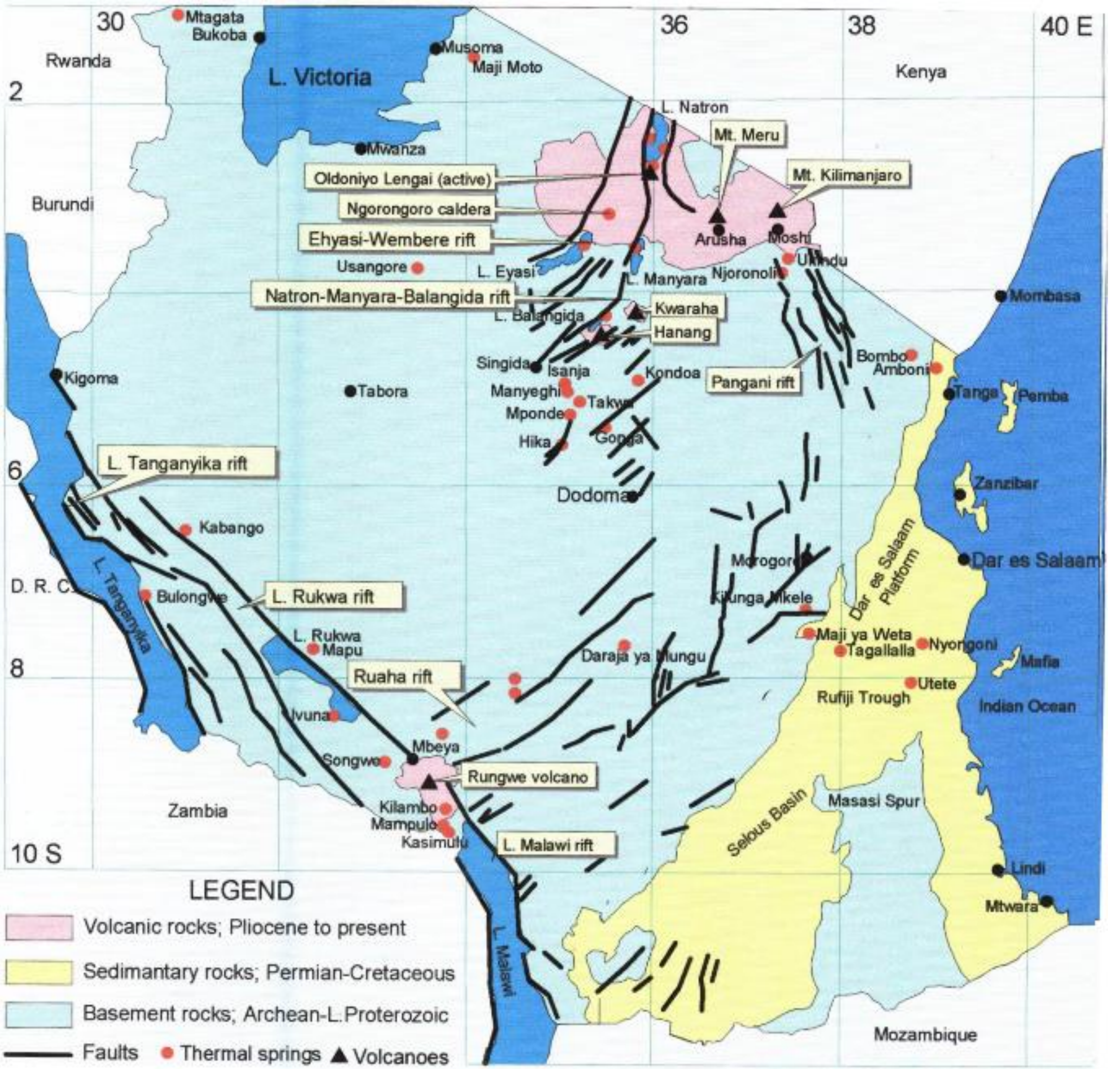


Figure 2.1: Distribution of geothermal prospects **[7]**.

2.2.5 Bio energy sources

2.2.5.1 Biomass

Biomass is Tanzania's single largest energy source, although much of it is produced in traditional and unsustainable ways. It is primarily used in the domestic sector. The sector is a major employer, an estimated 1 million people in the informal sector are engaged in charcoal preparation and supply. Because of weak enforcement and lack of awareness, much biomass from forests is harvested unsustainably. A 2010 World Bank report on charcoal in Tanzania reveals that

- ✓ Some 100,000–125,000 hectares of annual forest loss is attributable to unsustainable charcoal production and
- ✓ The government of Tanzania is losing about US$100 million in annual revenue, biomass is presently used for grid generation (around 18 MW) and by the agro-industry to generate its own electricity (about 58 MW estimated) **[8]**.

The potential for modern biomass uses is high, considering that the raw material available is abundant and includes: sugar bagasse (1.5 million MTPY), sisal (0.2 MTPY), coffee husk (0.1 MTPY), rice husk (0.2 MTPY), municipal solid waste (4.7 MTPY) and forest residue (1.1 MTPY). Further supplies can be obtained through sustainably harvested fuelwood from fast-growing tree plantations. Small-scale uses of biomass for energy generation in rural areas are taking off. Under the SPPA programme, two biomass power projects are supplying power to TANESCO: TPC, a major sugar producer with an SPPA for 9 MW of power **[8]**, and TANWATT, a tannin producer with an SPPA for 1.5MW. A third SPPA for 1 MW, the Ngombeni project, was commissioned in February 2014 to supply power to TANESCO's isolated grid on Mafa Island. TANESCO has signed SPPAs for three additional biomass projects with a total capacity of 9.6 MW. Various development partners are supporting biomass-sector development **[8]**.

2.2.5.2 Biofuels

Biofuels are liquid or gaseous fuels produced from biomass that are generally high in sugar (such as sugarcane, sugar beet, sweet sorghum), starch (such as corn and cassava) or oils (such as soybeans, rapeseed, coconut, sunflowers, and palms). The two most commonly used biofuels are ethanol and biodiesel. Biofuels are mostly used as a transportation fuel. Gel based biofuels can be used for cooking. There is potential for the sugar sector in Tanzania to produce ethanol or ethanol gel as a cooking fuel that could serve as a replacement for kerosene or charcoal. TaTEDO examined these options. The draft MEM Liquid Biofuels Policy is expected to be released in the near future **[8]**.

2.6 OCEAN ENERGY RESOURCE

Up to date in Tanzania mainland (Tanganyika) there is no ocean energy but Zanzibar is considering the possibility of turning Indian Ocean currents and waves into electric power to make the utmost of its geological position as an archipelago off east Africa. If the initial study proves viable, the Zanzibar Utilities Company will build a power plant on the Pemba Island, one of the three major islands consisting the archipelago, which enjoys a history of strong currents and tidal waves. The company expects to resort to power generated from tidal waves or ocean currents to turn the table against its loss-making situation. It now spends an average of 200 million Tanzanian shillings ($200,000) per month to generate power via gas turbines whereas it collects 60 million shillings ($60,000) for its power supply **[8]**.

Ocean energy constitutes to a large unexploited source of renewable energy and wave power therefore commands a good economic potential. The Zanzibar Utilities Company will wait for the initial study to decide on whether to benefit from the wave power or the tidal power, which dictate two different energy converters to transform wave energy or tidal energy into electricity. With prices of non-renewable natural gas rising in many countries around the world as readily accessible supplies dwindle, those countries which have a suitable stretch of coastline **[8]**.

2.7 CLIMATE CHANGE RISKS AND OPPORTUNITIES FOR RENEWABLE ENERGY

The country prepared a National Adaptation Program of Action in 2007, highlighting the vulnerability of the energy sector and proposing risk reduction strategies **[9]**. Hydroelectricity and biomass are vulnerable to changes in rainfall, extreme weather events and rising temperatures. In Tanzania rainfall has fallen off overall, whilst the frequency of below-average rainfall has risen. Meteorologists have observed an intensifed severity of extreme weather events, including dry and wet spells. This makes predicting seasonal weather patterns increasingly challenging **[9]**. The World Bank, with United Kingdom Department for International Development (DFID) co-funding, is carrying out the Tanzania Hydropower Vulnerability Assessment. The study is evaluating recent hydrology trends and the potential impact of both climate change and non-climate change factors, such as watershed management. Adaptation and risk mitigation measures for the energy sector include: diversifying energy sources; improving biomass energy conversion efciency; increasing the adoption of end-user, energy-efcient technologies (lamps, cook-stoves etc.); and protecting hydropower water catchments **[9]**.

2.8 SOLAR PHOTOVOLTAIC SYSTEMS

Photovoltaic system is the most well-known method of converting solar energy directly into electrical energy using semiconductor cells. Today's photovoltaic cells are mainly manufactured from a semiconductor material called crystalline silicon, which is available abundantly in the earth's crust and is free of toxicity. Modules made of by combining crystalline silicon cells are very durable, reliable; noise free and fuel free equipment's to produce electricity. Solar energy is the solitary source to power PV which is infinite. Photovoltaic cells have the capability of transforming 1/6 of solar resources into electric energy. PV systems are free of moving parts and are also environmental friendly. The lifetime of PV cells can end with greater than 30 years **[10]**. PV systems provide electricity to remote areas where there is no access to utility grid, thus elevates the life value of the community. In a PV cell there are two doped semiconductor layers, P-type (holes) and N-type (electrons) which are separated to each other by a junction. A spontaneous electric field is developed at the boundary which defines the direction of the current flow across the junction. In order to get electricity from a PV, the sunlight should penetrate a glass cover and antireflection coating. The model developed to harness solar energy was basically from the western, planed constructing centralized electricity generation and transmitting electricity by transmission wires to the consumers. Energy efficiency of solar photovoltaic is calculated as the power output from the PV divided by the solar radiation emitted to the solar array area.

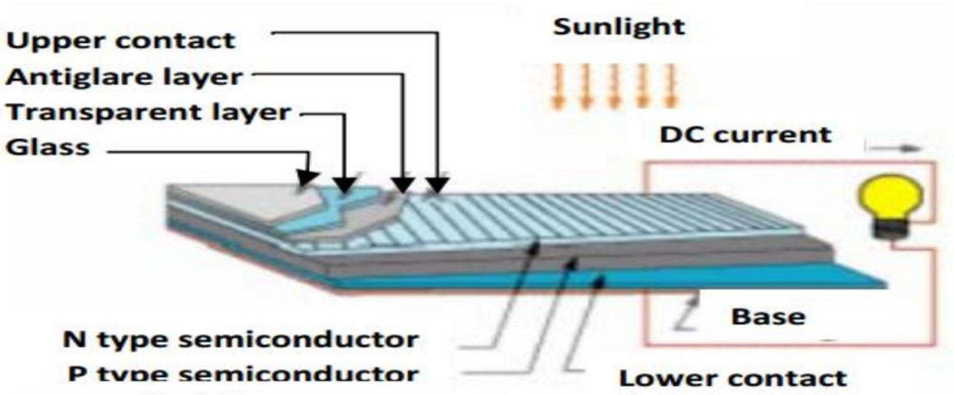


Figure 2.2: Typical PV cell **[10]**.

2.8.1 Types of solar PV cells

Different materials are used to make PV cells, with silicon obtained from sand is being the main material used for and it is available in the earth's crust. The electricity generation depends on the size of the PV cell, the conversion efficiency, and sunlight intensity of the local area. Based on the material from which it is made and the means of manufacturing, PV cells of silicon material are classified into the following.

Mono-crystalline PV Cells: are made from uncontaminated silicon single crystals, cut-off from ingots. It has a dark color and along all its corners is trimmed; this is one clear difference from the poly-crystalline panels. This type of PV cell is the efficient one since it is made from one crystal but the most expensive too. It functions better in areas where low energy sources are required. This technology is the first generation of all PV cells and has high heat resistant ability. The disadvantage with this technology is that it consumes more time to manufacture. The means of production of mono-crystalline silicon is first heating high purity of silicon into super saturated state, second inserting seed crystal into the molten silicon. Then lastly slowly pulling the seed crystal out of the melted mono-crystalline with the aid of Czochralski mechanism to get silicon ingot; moreover, slicing the crystal in to pieces to make the cells then to modules and arrays. This technology has the ability to convert 1000 W/m^2 solar radiation to around 140 W of electricity in PV cell surface area of 1 m^2 **[10]**.

Polycrystalline PV Cells: It is made from combination of smaller quantities of silicon crystal blocks. They are considered as the most widely used cells nowadays. Such PV cells are inefficient than the single crystalline cells due to the reason that they are not grown from single crystals but from a combination of many crystals. They perform better than the mono-crystalline in slightly shaded conditions. This technology hasthe ability to convert 1000 W/m^2 solar radiation to around 130 W of electricity in PV cell surface area of 1 m^2 **[10]**. The production of this type of cells is more efficient than mono-crystalline. Molten silicon has to be placed into blocks, which are then cut into slabs to make the crystals. Size of poly-crystalline solar panel is larger than mono-crystalline panel to get the same wattage because mono-crystalline is more efficient per area than multi-crystalline. So when comparing the two PV panels in terms of size to get high power output, single crystalline is good in usefulness.

Thin Film PV Cells: These types of cells are not made from real crystals rather the silicon is deposited on stainless steel, plastics or glass to form the solar module. These types of PV cells are much less efficient than the above two but the production process costs less. The inefficiency shows that larger panels of this type required producing same power as the mono or polycrystalline panels. They have efficiency from 5% to 13% and their lifespan is about 15-20 years **[10]**.

2.8.2 The PV module and PV array

Individual PV solar cells are the fundamental building blocks of the solar panel. In general PV cells are smaller in size and produce about one watt power. An individual solar cell produces a voltage of 0.5 to 0.6V. In order to get sufficient output voltage, PV cells are connected in series to form a PV module. PV systems are frequently functioned at multiples of 12 volts; modules are usually designed for optimal operation in these systems **[11]**. While PV cells are connected in series, the output current remains the same but the output voltage will be the total summation of all cells formed the module. Schematic diagram on how PV cells connect to form module as well as modules to form array is shown in Figure 2.3.

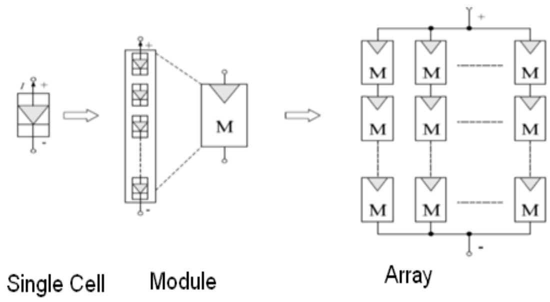


Figure 2.3: Schematic diagram for cell, module and PV array **[11]**.

The power rating of solar panel depends on the number of solar cells and the size of the panel. When the PV cells are assembled as module, they can be illustrated as having a nominal operating cell temperature. NOCT is the temperature of PV cell when operating at an open circuit at a temperature of 20 with air mass of 1.5, irradiance G = 800 W/m^2 and a wind speed less than 1 m/s **[12, 13]**. When large voltages or currents than single module are required, modules have to be connected together to form an array as indicated in Figure 2.4. Arrays connected in series result higher voltages where as the ones connected in parallel has higher current. When modules are connected in parallel they produce large power at the same voltage due to the increment of current, in a similar fashion when modules are connected in series; it is enviable to provide each module maximum power production at the same current due to the increment of voltage. When deciding to install solar panels, it is important to take into consideration the shading effects faced to the panels during the peak sun hours. The shading effect causes to the reduction of power production and it may even damage the cells. Generally, it is advisable to install PV panels free of trees, buildings, and other obstacles.

The second important parameter to consider during solar panel installation is temperature. The heating up of solar panels cause a loss of power because solar cells efficiency is decrease as temperature increases. The mounting system of the panels should allow the air circulation system during the hot sun hour to cool the solar panel.

2.8.3 Solar PV installation methods

Solar energy exploitation depends on the tracking system that mounts the PV panel. The tracking system is basically applied to direct the panel to the direction of the sun light which enhances the radiation that strikes the surface of the PV module. Most PV arrays are typically mounted with no tracking systems. There is possibility to track the radiation of the sun for the power output maximization. Solar tracking systems are basically categorized according the number of axes of tracking and the time with which the adjustment is to be made. Below are the techniques to be considered during the design of the PV system **[14, 15]**.

No tracking: Photovoltaic panels are mounted at a fixed slope and azimuth; moreover it is the simplest and cheapest method. Preferable to orient the panel to the equator (south in the northern hemisphere) usually the angle of tilt is equal to the latitude of the specific site under study. A small increase and decrease from the latitude will be better for the winter and summer sun tracking respectively. Horizontal axis monthly adjustment: This type of tracking system, it rotates horizontally from east to west direction. The angle of inclination of the PV is adjusted on the beginning of every month so that the beam strikes at 90 to the PV panel when sun is overhead **[14, 15]**.

Horizontal axis weekly adjustment: This type of mounting system, its axis of rotation is from east to west direction. The PV angle of tracking (slope) is adjusted on the first day of the week, thus solar radiation is at 90 to PV at noon of the corresponding day. The PV module slanted towards parallel the ground.

Horizontal axis daily adjustment: Axis of rotation is about a horizontal east-west direction to track the solar radiation. The slope is adjusted each day so that the sun's rays are at 90 degree to PV at noon of the corresponding day.

Horizontal axis continuous adjustment: It is a type of PV mounting system in which slope of photovoltaic is adjusted continuously and rotation is about a horizontal east-west axis. The slope is adjusted continually in order to minimize the angle on incidence.

Vertical axis continuous adjustment: PV axis of rotation is about a vertical with respect to the ground surface. The slope is fixed, but the azimuth is continually adjusted to minimize the angle of incidence.

Two axes: The panels are rotated about both to east-west and from north-south having two pivots to rotate. However, it is the most expensive method.

2.8.4 Solar terminologies

According to Dan Chiras **[16]**, the solar energy reached each year to the earth's surface is roughly 10k times the total energy consumed by human. As sunlight passes through the earth's atmosphere some of it absorbed, some is scattered and some passes through the molecules in the atmosphere. Solar energy that reaches the earth surface is solar radiation. Nuclear reactions occur in the sun as a result hydrogen is converted into helium with a process called fusion. This reaction caused for the release of large amount of radiation, where its temperature reaches about 15 million degree Celsius **[17]**. It is part of this energy that strikes the earth's surface. The magnitude of solar irradiance which strike on the surface of the earth depends on latitude, climatological location parameters like air pressure, cloudiness, etc. Some of the direct applications of solar energy are to heat, to pump, and to desalinate water. Solar energy can be converted in to electricity using different conversion technologies, among which photovoltaic and solar thermal are the basics. Photovoltaic technologies convert the incoming solar insolation directly into electricity. Whereas, solar thermal technologies initially heats water then directs to mechanical systems such as steam turbines to generate electricity. This technology uses mirrors to concentrate the incoming solar energy, it captured in the form of heat. Taking an account for the PV systems and sunshine, it is necessary to take a note of the following important concepts.

Irradiance: It is the power density of the sun, measured in W/m^2. At night and on sunrise times, irradiance is often zero and increases respectively then reaches at its highest value around noon. It again decreases from noon to sunset and dropping to zero at night.

Irradiation: it is the time integral of power density of the sun (irradiance), measured in kWh/m^2.

Air mass: A parameter that influences the quantity of irradiance that is incident on the earth's atmosphere.

Solar constant: The amount of solar radiation incident on the earth's atmosphere at a vertical angle of air mass (AM=0), and its magnitude is about 1367 W/m^2.

Global solar radiation: The total summation of the sunbeam and diffuse radiations. In case of horizontal laid surfaces, global solar radiation is the summation of vertical radiation and diffuse radiation. This is part of the constant solar radiation that hits the ground.

Beam radiation: It is the sunbeam that reaches the earth right from the sun disk.

Diffuse radiation: It is the solar insolation that reaches the ground from the sky where its direction is changed by the atmosphere. The diffuse radiations magnitude depends on solar height, and atmospheric transparency. The higher the cloud in the sky is the higher the dispersed radiation.

Albedo radiation: It is the reflected sunlight from the ground.

Extraterrestrial normal radiation: Is the quantity of solar insolation that arrives on a surface perpendicular to the atmosphere.

Extraterrestrial horizontal radiation: is the quantity of solar radiation reaching on a flat surface positioned on top of the atmosphere. If the entire direct solar radiation source is converted into usable form of energy in the earth, it would be more than enough to supply the energy requirement of the world.

2.8.5 Incident radiation

The position of the sun, the slope and the orientation of the photovoltaic surface are the most important parameters for any solar system design. Photovoltaic power output affects by the amount of radiation reaching the surface area of the collector; however the irradiance that is incident is flat or horizontal. Thus the incident solar radiation in a tilted surface is inclined component of the radiation, which should be calculated from the global horizontal radiation. Figure 2.5 illustrates the orientation of photovoltaic system towards the sun. The angles involved in determining the amount of incident solar radiation on the surface of PV panel are described below.

Zenith angle (θz): Is the angle between the line drawn vertically and the line that connects to the sun from the vertical line. Usually this angle is 90º at sunrise and sunset times. Solar altitude **angle (αs):** It is an angle included between the line that directs to the sun and the line drawn perpendicular to this line. Its value remained at 0º during sunrise and sunset times. Solar **azimuth angle (γs):** It is an angle that draws from south direction to the line that indicates to the sun. Its value varies from 0º when sun is overhead, –90º at sunrise and 90º at sunset.

Angle of incidence (θ): It is the angle sandwiched between the line that draws normal to PV surface and the line that points to the sun. It is the critical angle in determining the incident radiation accordingly the photovoltaic power output. For the determination of this angle, it is basic to know the following angles too.

Hour angle (ω): is defined as the angular displacement of the sun, which is east or west, of the civil meridian time zone. The earth rotates 15º/hour; furthermore this shows that at 11am and 1pm, hour angle is –15º and 15º respectively. Surface azimuth angle (γ) is an angle that measures from south to the line that draws perpendicular to the PV panel surface. East and west orientations are negative and positive respectively. The azimuth specifies the direction towards which the panels slope. The direction into which the PV array faces is called azimuth. Zero degree azimuths depict south facing surface. So an azimuth of negative value results to a south-east facing surfaces, furthermore a surface oriented to an azimuth of 90° shows a surface facing to the west. Collector slope (β) is the angle of inclination of a surface between the PV and the horizontal plane. A, 0 and 90 slopes indicate the horizontal and vertical orientations of the PV array respectively. A slope roughly equal to the latitude will typically maximize the annual PV energy production. Declination (δ) is the angle formed between the line from the sun directed from equator and the line that directs straight to the equator. It varies by plus or minus 23.45 degrees during the year. Latitude (φ) is the angle measured from the line that draws to the center of the earth and the line directs to the equator.

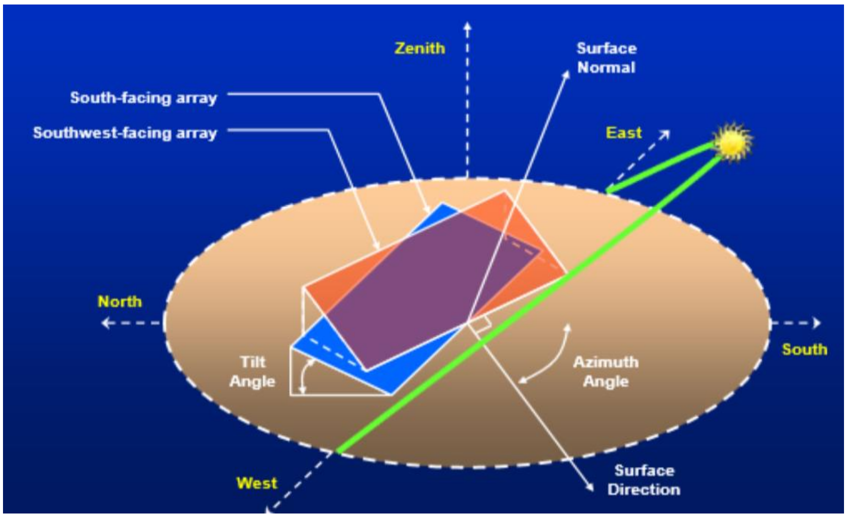


Figure 2.4: Orientation and slope of solar PV module **[18]**.

- The employment of PV array may describe with inclination or slope and azimuth of the PV surface. The latitude, the time and day of the year are also parameters that relates to the sun geometry. The time of year relates to the solar declination angle. Solar declination is the latitude at which the solar beams are at 90° to the earth's surface at solar noon. All of the following equations below are presented by different authors **[12, 15, 17, 19, 20]**. The declination angle, denoted by δ,

$$\delta = 23.45° \, sin\left(360° \frac{284+n}{365}\right) \tag{1}$$

varies seasonally due to the tilt of the Earth on its axis of rotation and rotation of the Earth around the sun [**17**], n: is the day of the year, 1st January as 1 through 365. All angles here and hereafter are measured in degrees.

- The sun location in the sky and hour angle which is used to describe the diurnal time are related in order to determine the hour angle. At solar noon hour angle is set as zero, while in the morning and in the afternoon it is set as negative and positive respectively. The following equation can be used to calculate the hour angle ω:

$$\omega = (t_s - 12hr) * 15°/hr \tag{2}$$

- At solar noon the value of is 12:00 hour and in 11/2 hour later its value is 13.5 hour. The 150 depicts the fact that the sun moves around the earth at 150 per hour. Solar radiation data and electric load data are measured with civil times or local standard times and this shows that the two parameters are local time dependent data's. Solar time can be calculated from civil time using the following equation:

$$t_s = t_c + \frac{\lambda}{(15°/hr)} - Z_c + E \tag{3}$$

where t_s: solartime (hr), t_c: the local time accounted to the center (middle) of the time step (hr), E: equation of time in hour, λ: Longitude (degree), Z_c: time region (zone) to east of Greenwich Meridian Time (GMT) (hr).

- The equation of time corresponds for the effects of the tilt of the earth's axis of rotation (23.45°) relative to the eccentricity of the earth's orbit and the plane of the ecliptic. The equation of time can be calculated as follows

$$E = 3.82(0.00075 + 0.001868cosB - 0.032077sinB - 0.014615cos2B - 0.04089sin2B \tag{4}$$

- Another parameter for a surface of any orientation is the angle of incidence, and it is defined as the angle between the sun's beam radiation and the line perpendicular to the PV surface, which is expressed mathematically using the following equation

$$cos\theta = sin\delta sin\emptyset cos\beta - sin\delta cos\emptyset sin\beta cos\gamma + cos\delta cos\emptyset cos\beta + cos\delta sin\emptyset sin\beta cos\gamma cos\omega + cos\delta sin\beta sin\gamma sin\omega \tag{5}$$

where θ: Angle of incidence, δ: Solar declination, Ø: latitude, β: llope of the tilted surface; γ: azimuth angle of the surface, ω: hour angle.

- The zenith angle has value of zero degree when the sun is at solar noon and 90° when it is at horizon. The zenith angle can be expressed mathematically as shown in equation below by letting β from equation

$$cos\theta_z = cos\delta cos\emptyset cos\omega + sin\delta sin\emptyset \tag{6}$$

where θ_z: the zenith angle.

- Extraterrestrial normal radiation is the quantity of radiation reaching at the top of the earth's atmosphere at 90° and would be expressed mathematically as in equation

$$G_{on} = G_{sc}\left(1 + 0.033\, cos\,\frac{360n}{356}\right) \tag{7}$$

where G_{on}: the extraterrestrial normal radiation (kW/m^2); G_{sc}: the solar constant = 1.367 kW/m^2.

- The extraterrestrial horizontal radiation can be expressed mathematically by the following equation

$$G_o = G_{on} cos\theta_z \tag{8}$$

where G_o: the extraterrestrial horizontal radiation (kW/m^2).

- The average extraterrestrial horizontal solar radiation can be calculated as follows.

$$\bar{G}_o = \frac{12}{\pi} G_{on}[cos\emptyset cos\delta(sin\omega_1 - sin\omega_2) + \pi\frac{(\omega_1 - \omega_2)}{180°} sin\emptyset sin\delta] \tag{9}$$

where $\bar{G}_o$:extraterrestrial horizontal radiation averaged over time intervals (kW/m^2); G_{on}: extraterrestrial normal radiation (kW/m^2); ω_1: hour angle at time t_1 (degree); ω_2: the hour angle at time t_2 (degree), δ: solar declination , Ø: latitude.

- Equation above depicts the average solar radiation reaching a flat surface at the top of the atmosphere. A parameter called clearness index is to define mathematically below in equation clearness index is the ratio of the solar radiation reached the earth's surface to the radiation striking the top of the atmosphere (extraterrestrial radiation).

$$K_T = \frac{\bar{G}}{\bar{G}o} \tag{10}$$

where $\bar{G}$: global horizontal radiation reached the earth's surface averaged over time interval (kW/m^2), $\bar{G}o$: extraterrestrial horizontal radiation averaged over time intervals (kW/m^2)

- The solar radiation that reaches the earth's surface is in the form of beam and diffuse radiation. The global solar insolation is obtained by summing up the diffuse and beam radiation which is given by the following equation.

$$\bar{G} = \bar{G}_b + \bar{G}_d \tag{11}$$

where $\bar{G}$: the global horizontal radiation on the earth's surface averaged over the time step (kW/m^2), $\bar{G}_b$: the beam radiation (kW/m^2), $\bar{G}_d$: the diffuse radiation (kW/m^2).

- The global solar radiation that reaches the inclined surface of the PV panel can be calculated now by applying the following equations. Before going to the equations, defining the following three diffuse solar radiations is important. Isotropic diffuse solar radiation is a type of diffuse radiation which receives from all parts of the sky uniformly. Circumsolar diffuse radiation is a type of diffuse radiation which emanates directly from the sun. Horizon brightening diffuse solar radiation is the third type of diffuse radiation which emanates from the globe. The ratio of beam radiation reached on the tilted surface to beam radiation reached on the horizontal surface of the PV is given in the equation below

$$R_b = \frac{cos\theta}{cos\theta_z} \tag{12}$$

where Rb: ratio of tilted to horizontal beam radiations

- The anisotropy index is a parameter given to a measure how much the atmosphere can transmit beam radiation. The anisotropy index is an important factor for the estimation of the circumsolar diffuse radiation determination, and it is given by the following equation

$$A_i = \frac{\bar{G}_b}{\bar{G}_o} \tag{13}$$

where A_i: anisotropy index

- The final factor to be defined is the horizon brightening, diffuse radiation comes from the horizon is accounted to the cloudiness and is expressed by the following equation

$$f = \sqrt{\frac{\bar{G}_b}{\bar{G}}} \tag{14}$$

where f: the cloudiness index

- The global radiation striking on the PV array is given below.

$$\bar{G}_T = (\bar{G}_b + \bar{G}_d A_i)R_b + \bar{G}_d(1 - A_i)\left(\frac{1+cos\beta}{2}\right)\left[1 + fsin^3\left(\frac{\beta}{2}\right)\right] + \bar{G}\rho_g\left(\frac{1-cos\beta}{2}\right) \tag{15}$$

where $\bar{G}_T$:global radiation incident on the inclined surface, β: the slope of inclined (degree), ρg: the ground reflectance also called albedo (%)

2.8.6 Solar PV modeling

PV panels can be modeled using different approaches. The PV panel has two distinct parameters provided by the manufacturers such as short circuit current and open circuit voltage, commonly used to characterize PV cells. I-V curve of the panel should be accounted for when considering to model PV systems. I-V characteristics curve has three main factors to consider, like short-circuit current, the opencircuit voltage and the maximum power point

2.8.6.1 Equivalent electrical circuit of PV cell

The electrical circuit of typical PV cell characteristics is depicted in Figure 2.5. In the V-I characteristics curve it is shown that solar generated current, diode current, the shunt resistance and shunt-leakage current are connected in-parallel furthermore in series thru internal resistance developed in the circuit during the operation of the system.

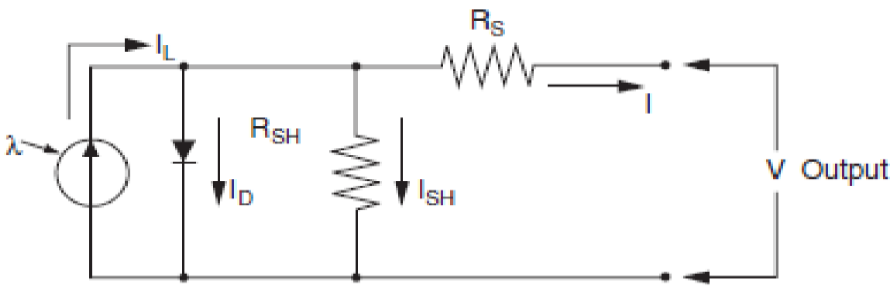


Figure 2.5: Equivalent circuit of solar PV cell **[12]**.

The different parameters of the photovoltaic cell indicated in the equivalent circuit are expressed by the following mathematical expressions **[12].**

$$I = I_L - I_d - I_{sh} \tag{16}$$

where I: PV output current (A), I_L: solar generated current (A), I_d: diode current (A), I_{sh}: shunt-leakage current (A)

The yield efficiency of PV panel can be greatly reduced by a small change of the internal resistance developed in the cell however there is no change of output voltage for any change of the shunt resistance **[12]**. Other mathematical expressions can be applied to determine the output current of the cell as follows.

$$I = D_L - I_O\left(e^{\frac{(Q.V_{OC})}{K.T}} - 1\right) - \frac{V_{oc}}{R_{SH}} \tag{17}$$

In actual operating times the last term which represents the shunt current is so small compared to the solar produced and diode currents, thus it can omitted **[13,19]**. Temperature variations of the cell are considered uniform in this kind of model **[21]**. The open circuit voltage and the diode current are being determined as follows respectively

$$V_{OC} = V + I.R_{SH} \tag{18}$$

$$I_D = I_O\left(e^{\frac{(Q.V_D)}{K.T}} - 1\right) \quad (19)$$

where Io: reveres saturation current of diode (A), Q: electron charge (C), K: Boltzmann's constant (J/K), V_D: voltage of the diode (V), T: cell junction point temperature (k), V_{OC}: cell open circuit voltage (V).

Similarly the short circuit current of the cell can be determined by setting the open circuit voltage as zero accordingly the short circuit and solar generated currents remained with the same magnitude. The diode saturation current (Io) is constant at constant temperature **[13]** and its mathematical determination is expressed as follows.

$$Io = \frac{Isc}{(e^{Q.Voc} - 1)} \quad (20)$$

If the short circuit current of the module is known from the data sheet of the cell therefore at any solar irradiance, the cell current is given as follows.

$$I_{SC} = \left(\frac{G}{G_0}\right) I_{SC}, G_0 \quad (21)$$

where I_{sc}: short circuit current (A), G: solar irradiance (W/m^2), I_{sc},G_0: short circuit current at standard test condition (A), G_0: solar irradiance at standard test condition (1000W/m^2)

The open circuit voltage can be determined by setting the output current to zero

$$V_{OC} = \frac{AKT}{Q} log\left(\frac{I_L}{I_0} + 1\right) \quad (22)$$

The quality of PV cell is measured by the parameter called fill factor. This shows that an efficient PV will have higher values of short circuit current, open circuit voltage, and filling factor. Any solar PVs fill factor depends on the design and technology of the panel. Whichever parameter or damage that influences the fill factor also disturbs the yield power by reducing maximum current or maximum voltage or both at the same time. The output power of PV can be calculated using equation given below **[11]**

$$P_{mp} = I_{mp} * V_{mp} \quad (23)$$

$$FF = \frac{VoB*Isc}{P_{mp}} \quad (24)$$

where V_{mp}: PV maximum potential voltage [V], I_{mp}: PV panels maximum current [V], P_{mp}: PV panels maximum power [V], FF: fill factor

Furthermore, the output power of the PV can also be determined by considering the effect of solar irradiation and environmental temperature at the site of interest. As the expression given in **[14]** the mathematical expressions for the maximum current and maximum voltage given in the equation below can be determined as follows.

$$V_{mp} = V_{mp}.ref * P_{V,OC}\ (Tc - Tc, ref) \tag{25}$$

$$V_{mp} = I_{mp}.ref * I_{SC}, ref\ (Tc - Tc, ref) \tag{26}$$

where $V_{mp.}$ref: potential voltage at standard condition (V), $P_{V,OC}$: open circuit temperature coefficient (Vov/k), Imp,ref: PV panels maximum current at standard conditions (A), I_{SC},ref: PV panels short circuit current at standard condition (A), Tc: cell operational temperature (K) Tc,ref: cell temperature at standard conditions (K)

A typical PV module with I-V and P-V characteristics curve is shown in Figure 2.6

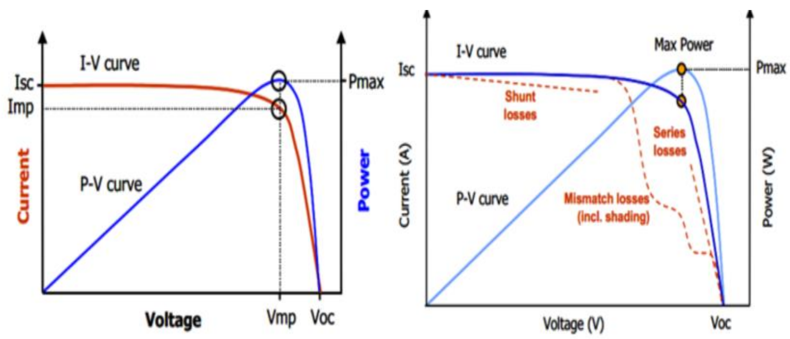


Figure 2.6:Variation of I-V characteristic curve of PV cell with categories of different losses **[15]**.

Referring into Figure 2.6 in the right graph, the series losses & shunt losses, and mismatch losses are resulted due to uniform soiling and non-uniform shadings of the solar PV system respectively.

2.8.7 Mathematical modeling

The mathematical modeling depicts a different approach for the design of a PV array. The performance of solar PV is needed to produce power in an efficient way as much as possible, thus the mathematical model described below is used to determine the optimal power generation characteristics. Having the inputs such as, incident solar radiation data, the local area ambient temperature data, and PV module data supplied by the manufacturers, the PV power output can be determined by the following equations **[22, 23]**.

$$P_{pv} = \eta * N * A_m * G_t \tag{27}$$

where P_{pv}: solar PV power output (W), η: generator efficiency (%), A_m: area of single module (m^2), Gt: global radiation (W/m^2), N: number of modules assembled in the system

The solar photovoltaic generator efficiency is represented by the following equation

$$\eta_g = \eta_r * \eta_{pt} \, [1 - \beta_t(T_c - T_r)] \tag{28}$$

where η_r: reference efficiency (%), η_{pt}: tracking system efficiency (%), T_c: PV cell temperature (K), T_r: PV cell reference temperature (K), β_t: temperature coefficient efficiency ranging from for silicon cells.

$$T_C = T_a + G_t(\frac{\tau\alpha}{U_1}) \tag{29}$$

$$\frac{\alpha\tau}{U_1} = \frac{NOCT-20}{800} \tag{30}$$

where Ta: site ambient temperature (K), U_l: overall heat loss (W/m^2), τ and α: photovoltaic transmittance and absorpitance coefficients respectively, η_{pt}, β_t, NOCT, Am: area parameters that depend on module type and this are obtained from solar module manufacturers.

2.9 WIND ENERGY CONVERTERS BASICS

2.9.1 Wind energy converters and regulation mechanisms

A physical configuration which produces uneven force on the wind flow stream tends to rotate, oscillate and power could be harnessed from the wind flow. Wind turbines are machines that produce electricity by using power from wind to drive an electrical generator. The wind energy conversion machines extract the wind kinetic energy from the swept area of the turbine blades making pressure differences across the blade and initiate the electrical generator to generate electricity. The wind turbine includes components like; tower, rotor, nacelle, and the turbine rotor control structure or yawing mechanism. The tower is thebuilding block of the wind turbine which supports the gear box and electric generator which are held in the nacelle. The yawing mechanism is an important component of wind turbines which is used to direct the turbine rotor to the wind flow direction in order to extract kinetic energy of the wind. The torque developed by the wind turbine transforms to the gear box accordingly to the electrical generator. The electrical generator produces electricity from the transformed mechanical energy. Figure 2.7 illustrate the general architectures of the two well-known wind turbine types.

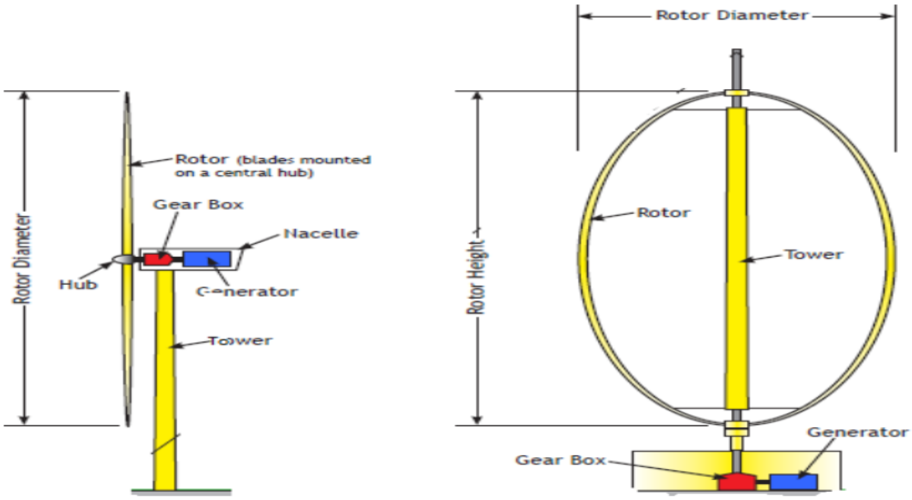


Figure 2.7: Architecture of typical wind energy converter **[24]**.

Wind turbines start to generate power when the wind speed flow passes the minimum wind speed (cut-in speed). The wind turbine power increases with the wind speed until it reaches the rated speed where it produces maximum power. The turbine does not produce power beyond the cut-off wind speed due to assembly of safety mechanisms that could stop turbine from producing power. There are two over speed or power control mechanisms needed to protect both load and turbine during high wind speed periods **[24]**.

Pitch regulation: It has an electronic control system or active control mechanism which reduces the aerodynamic efficiency of the wind turbine. The principle how it works is that, the blades are to be turned along their axis of rotation with the help of pitch control mechanism as wind speed tries to cross rated speed. When wind velocity is greater than the rated wind speed the regulation mechanism automatically changes the blade pitch. The modification in the angle of attack would reduce the capability of the rotor. To avoid the operation of wind turbine blades out of the feasible range, the controlling mechanism should 24 respond faster with wind speed variation. Pitch regulated turbines convert the wind speed more efficiently when wind flows in moderate range as blades set to its appropriate angle of attack. Referring in to Figure 2.8 the power output of the turbine is increasing until the rated wind speed but beyond that it remains constant power.

Stall regulation: In this power control mechanism the profile of the blade is designed to be aerodynamically adjusted along its longitudinal axis in order to increase the angle of attack and has no active control. The increment of the angle of attack causes air to stick on the upper side of the blade and these results in turbulence, thus this effect stops the lift force on the blades, leading to blade stall. Generally, the power output is controlled by the special design of the rotor blades to ensure that as the wind speed gets higher it produces turbulence on the side of the turbine blades as a result the aerodynamic efficiency of the turbine decreases. The power production, rotational speed, aerodynamic torque decreases with the raise of wind speed as illustrated in Figure 2.8.

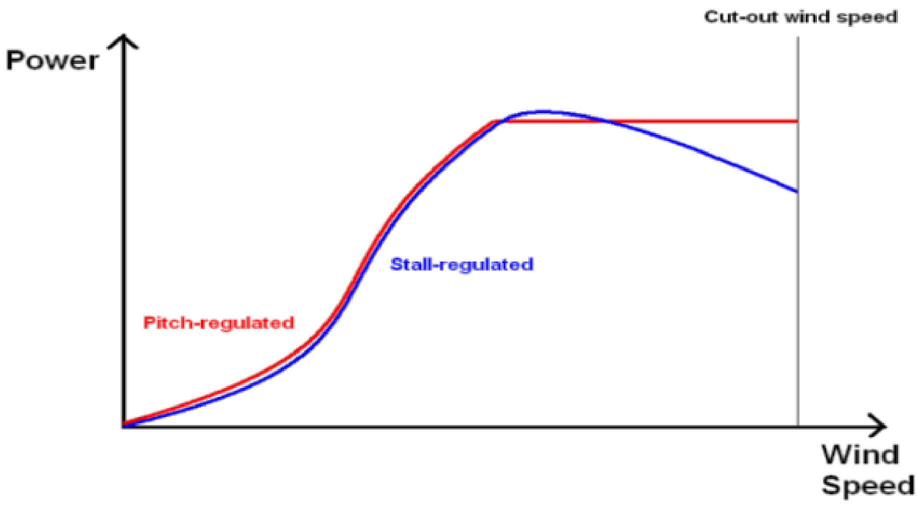


Figure 2.8: Wind turbine power control mechanisms **[24]**.

2.9.2 Classification of wind turbines

Wind turbine technologies can be categorized as turbines that depend on aerodynamic drag and lift forces. Wind machines that use aerodynamic lift force can also be grouped based on the arrangement of the axis of rotation, into horizontal axis and vertical axis machines (Darrieus turbines). Horizontal axis wind turbines are machines having axis of rotation parallel to the wind flow stream. The horizontal axis wind turbines consists the tower structure and the nacelle which contains the electrical generator, the gearbox and the rotor. In small wind turbines the nacelle and rotor directed to the wind direction with the aid of tail vane; whereas, on large wind turbines the nacelle and rotor directed electrically into or out-of the wind with the help of signal from the yaw **[25]**. These types of machines have low cut-in speed and they relatively have higher power coefficient. Horizontal axis wind turbines are categorized based on the application of the wind turbine; single bladed, double bladed, three bladed and multi bladed. Figure 2.9 shows the classification of wind turbines in different aspects.

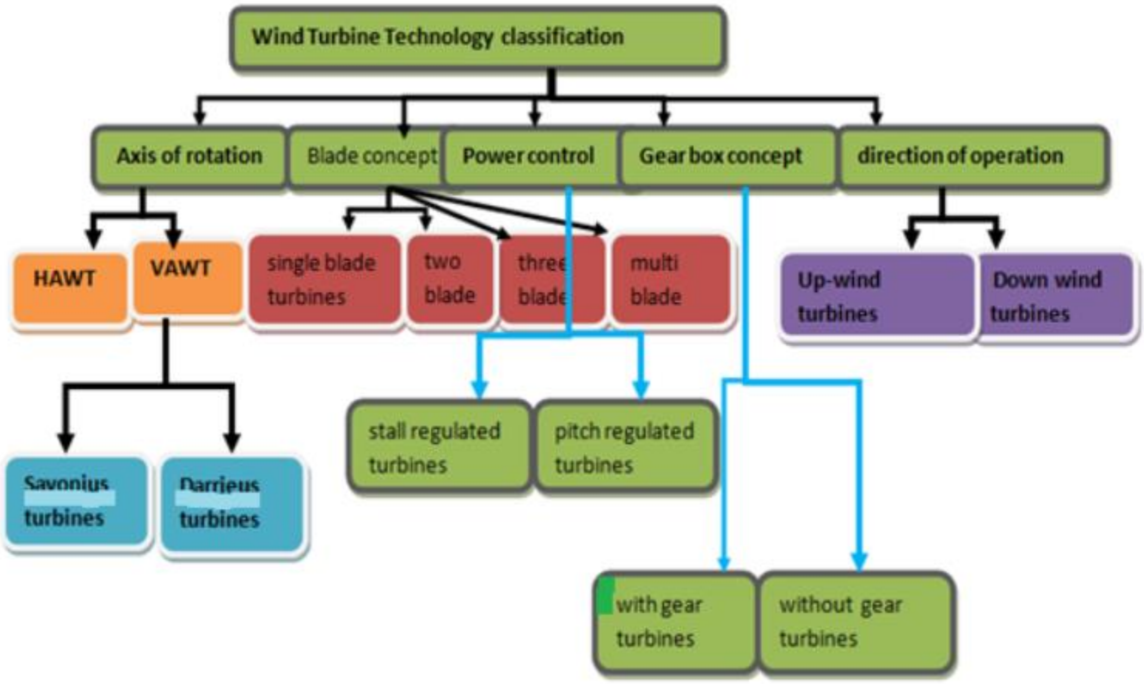


Figure 2.9: Block diagram showing classification of wind turbines **[25]**.

The most popular ones for electricity generation are the horizontal axis turbines with three blades **[26]**. This is because its low cut-in wind speed, high power coefficient, easy curling and its stability. Turbines with even number of blades have stability problems because when the uppermost blade twists back, the lowermost one passes into the wind shade at the front of tower. Wind turbines with more than 20 blades are applied for water pumping purposes and are not applicable for electricity generation due to higher aerodynamic losses. The tip speed ratio and the number of wind turbine blades have an indirect relation. It is the ratio of the blade tip speed to the wind speed, which can be expressed mathematically in **[27]**.

$$\lambda = \frac{\omega R}{V} \tag{29}$$

where λ: tip speed ratio, ω: the frequency of distribution, R: rotor radius (m); V: wind speed (m/s).

The higher number of blades the lower tip speed ratio with high starting torque. Wind turbines with two or three blades owe high tip speed ratio. Horizontal axis wind turbines rotor can be placed upwind of tower and downwind of tower direction. The lift force is the driving component of the horizontal axis wind turbine machine. Vertical axis wind turbines are machines having axis of rotation perpendicular to the wind flow. Darrieus turbine is vertical axis type that functions independent of the wind flow direction. This type of machine receives wind power from any direction, meaning they do not need any yaw mechanism to adjust every time to the wind flow direction. They also do not have pitch regulation, the generator is placed at ground level which makes the structure simple and less costly but the huge problem with such type of machine, and it is not self-starter it needs some mechanism to rotate. Vertical axis wind turbines can be divided in to two main groups: those that use aerodynamic drag to harness power from the wind (cup anemometer) and those that use lift force **[28]**.

2.9.3 Wind shear

Apart from the availability of wind speed for an extended period of time, its distribution is an important factor in wind potential determination. The ground friction in relation to wind speed decreases with height from ground. Wind shear is the wind speed variations with height above ground level, thus it is also called wind speed profile. As wind turbine height increase length from ground the wind speed also increase and hence, power production also rises. This shows that the force acting on the turbine blade when it is in the top position is large. It is described by two methods, such as power law profile and logarithm profile. The wind speed at any height above ground level can be expressed either in exponential function or logarithmic function forms **[23, 29]**. The power law profile is given in equation.

$$\frac{V_2}{V_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{31}$$

where α: the power law exponent which depends on the elevation, the time of the day, the season, the terrain, the wind speed and the temperature of the site, V_2: wind speed estimated at hub height h2 (m/s), V_1: wind speed at reference height h1 (m/s), h_1: reference height above ground level (m), h_2: hub height (m).

Table 2.2: The power law exponent (α)

Terrain Type	Friction coefficient (α)
Lake, ocean, smooth hard ground	0.1
Foot-high grass on level ground	0.15
Tall crops and shrubs	0.2
country with many trees	0.25
Small town thru some trees and shrubs	0.3
City with tall buildings	0.4

Another method is the logarithmic function that is given below in equation . The logarithmic function adopts that the logarithmic height above ground surface is related to the wind speed

$$\frac{V_2}{V_1} = \frac{ln\left(\frac{h_2}{Z_0}\right)}{ln\left(\frac{h_1}{Z_0}\right)} \tag{32}$$

where z_0: surface roughness length factor [m], surface roughness length describes the roughness of the surroundings terrain.

Table 2.3: Surface roughness lengths **[15]**.

Terrain Description	Z_0 (m)
Very smooth, ice or mud	0.00001
Calm open sea	0.0002
Blown sea	0.0005
Snow surface	0.003
Lawn grass	0.008
Rough pasture	0.010
Crops	0.05
Few trees	0.10
Many trees, few buildings	0.25
Forest and woodlands	0.5

Figure 2.10 depicts wind speed variation profile with surface roughness factor of 0.01, indicating that the area is rough pasture. Thus, the higher the tower the higher the wind speed would be recorded.

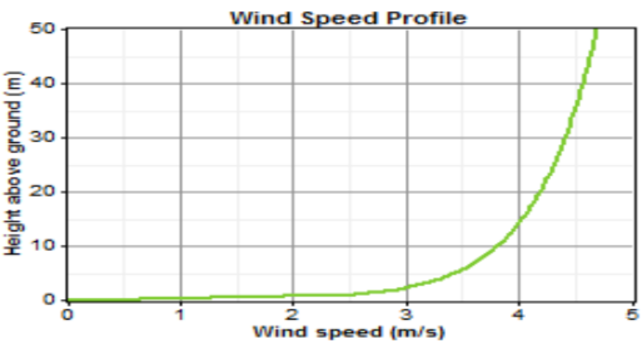


Figure 2.10: Wind speed variation with height above ground surface **[15]**.

2.9.4 Autocorrelation

Autocorrelation factor: Wind speed time series data show autocorrelation, which is defined as the degree of dependence at the previous values. Autocorrelation factor is a measure of the strength of wind speed at present time depends on the wind speed in the preceding time. This factor is dependent on topography features. Areas enclosed by uniform topography have values that vary from 0.9 to 0.97, while areas with complex topography have values range from 0.7 to 0.8 But then again it depends on weibull value. In this paper study the autocorrelation factor calculated by HOMER from the input data is 0.856.

Diurnal pattern strength: It is a measure of how strong the wind speed depends on time of day. Wind speed is affected by the availability of solar radiation; most sites indicate some diurnal pattern in wind speed. The diurnal pattern strength calculated again is about 0.309. Hour of Peak Wind Speed:

Hour of peak wind speed is the duration of the day in which wind speed is recorded higher or in short the windiest time of the day on average. In this paper the value of peak hour of 14 is obtained from HOMER after inputting the 10 minute wind speed data, anemometer high and altitude.

CHAPTER THREE

3.0 METHODS, METHODOLOGY AND DISCRIPTION OF CASE STUDY AREA

3.1 OVERVIEW

This chapter presents materials and methods that will be adopted in this study. It outlines the major techniques and methods to be used in collecting the data, information and statistics that will be gathered during the field survey of the study. It will also outline the techniques that will be used in the data analysis and in presenting the findings of the study.

3.2 CASE STUDY AREA DESCRIPTION

3.2.1 Introduction

Bellaview Fresh Fruits Processing Industry Limited (BFFPIL) is located in Mkuu Township, Rombo District in the Kilimanjaro Region of Northern Tanzania. The company is in the beverage manufacturing industry targeting to process bottled soft drinks such as fruit juices, soda, energy drinks and drinking water. Currently the company has successfully produced bottled drinking water under the brand name SEQUA and mango fruit juice under the brand name Bella.

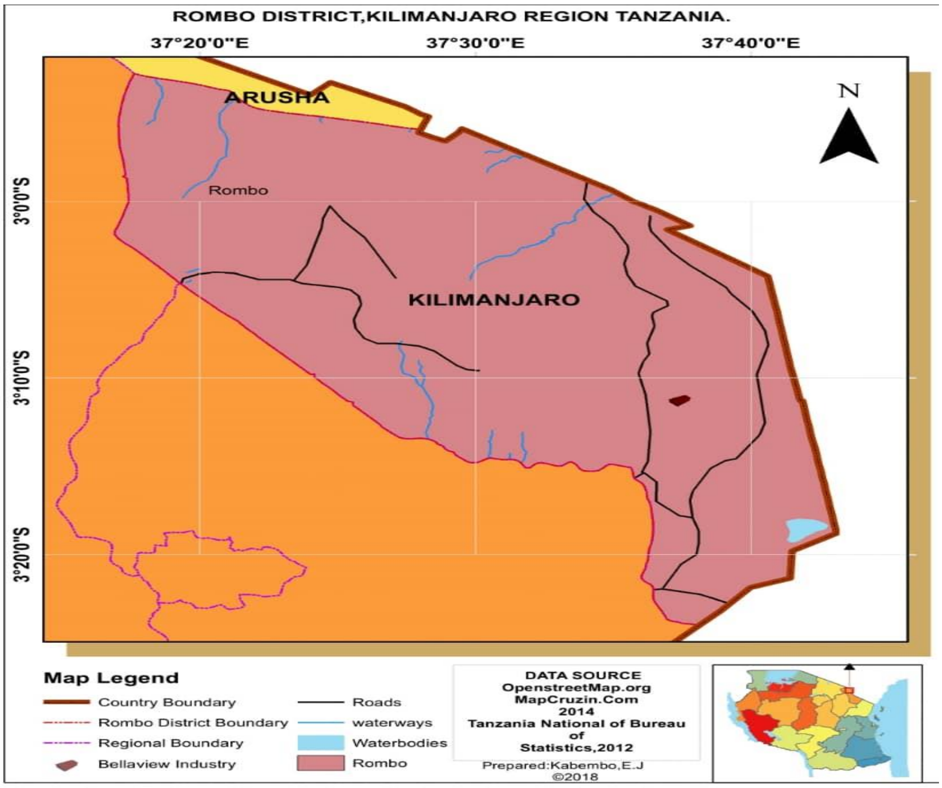


Figure 3.1: Location of case study area.

Figure 3.2: Bellaview fresh fruits processing industry limited.

3.2.2 Production capacity and processes

Belleview Fresh Fruits Processing Industry commenced manufacturing operations in July, 2012 by launching Sequa drinking water as its first product in the market. The second product of the factory was Bella Fresh Juice Product that was launched in July, 2014. Currently BFFPIL is only producing drinking water at slightly over 60% of its line capacity; equivalent to 60,000 cartons of 1.5 Litre (12x1) bottled drinking water per month. Working capital is a big constraint in expanding this capacity by working two shifts and ensuring there is enough inputs to support expanded activity. Production of fruit juice was stopped due to process control and management challenges that led to loses of revenue.

Figure 3.3: Products produced from Bellaview fresh fruits processing industry limited.

3.2.3 Climatic condition

Tanzania's climate ranges from tropical to temperate in the highlands. Average annual precipitation over the entire nation is 1042 mm. Average temperatures range between 17 °C and 27 °C, depending on location. Natural hazards include both flooding and drought. Within the country, altitude plays a large role in determining rainfall pattern, with higher elevations receiving more precipitation. In Rombo-Moshi, the climate is warm and temperate. When compared with winter, the summers have much more rainfall.The average temperature is 21.3 °C **[50]**.

Table 3.1: Existing climate conditions.

Month	Air Temperature (°C)	Relative humidity (%)	Daily solar radiation-horizontal (kWh/m²/d)	Atmospheric pressure (kPa)	Wind speed (m/s)	Earth temperature(°C)
January	22.2	62.8	6.20	89.3	3.7	24.6
February	22.7	59.4	6.55	89.3	3.6	25.3
March	22.3	67.2	6.02	89.3	3.4	25.0
April	21.3	73.6	5.24	89.4	3.7	23.8
May	21.0	67.3	4.56	89.5	3.9	23.8
June	20.4	60.1	4.26	89.7	4.1	23.8
July	19.9	58.6	4.44	89.7	4.3	23.7
August	20.2	58.5	4.89	89.7	4.6	24.7
September	21.2	57.3	5.79	89.6	4.6	26.6
October	21.6	61.9	5.98	89.5	4.5	26.8
November	21.4	70.2	5.58	89.4	3.9	25.2
December	21.5	70.2	5.74	89.4	3.5	24.1
Annual	21.3	63.9	5.43	89.5	4.0	24.8

3.3 METHODOLOGY

The Hybrid energy system integrates numbers of renewable resources components such as solar, wind, diesel generator, invertors, and batteries. The criteria of selecting the best hybrid energy component,combination for a proposed site (Bellaview Fresh Fruit Processing Industry Ltd in Rombo) is based on the trade-off between cost, sustainability, maturity of technology, efficiency and minimum use of diesel fuel. The methodology which will be applied in this study are listed below.

3.3.1 Literature review

This was conducted through reading different materials including books, papers, journals, internet and documents of relevant study. This will be useful methodology where by the information and data concerning about my study was obtained.

3.3.2 Site visit and physical Observation

The site visit and observation was focused on the existing practice based on energy use, electricity demand for each section of the industry. Also all sections have been visited to find out the effectiveness of the existing energy requirement. During site visit various photos were taken to show the existing situation and some necessary data that can be obtained just by observation were collected.

Figure 3.4: Site visit and observation ahead.

3.3.3 Checklist

Checklist was conducted as the third stage during the research methodology, the main purpose of this methodology is to know or to find out the energy demand for each point within the industry also by passing throughout the electricity bills from TANESCO for past months.

3.3.4 Sampling design

Depending on the area and different influencing factor, the study was conducted by selecting One of among of small industries which can be used as a case study area to present other small industries in Tanzania, although some of the influencing factors may vary from one industry to another like geographical conditions etc., but as a case study it's obvious that the results will be used as a reference point to other industries.

3.3.5 Interview and consultation

Interviews were conducted at various levels such as technical personnel at the study area, also consultation was done at different private sectors as well as Government sectors including Ministry of Industry, Trade, and Investment (MITI) and Ministry of Energy The purpose of this part was to obtain different views on how Hybrid Renewable energy can be achievable in context of industrialization especially in Tanzania.

3.4 HYBRID POWER SYSTEM AND HOMER TOOL

3.4.1 Introduction

Hybrid energy system is a configuration of two or more renewable and even non-renewable energy as main sources of energy generation so that the capacity shortage of power from one source will substitute by other available sources to cater sustainable power. It is appropriate means to provide electricity from locally available energy sources for areas where grid extension is capital intensive, geographically isolated places for which electricity transmission from centralized utility is difficult. Naturally gifted renewable sources can be harnessed to generate electricity in a sustainable way to provide power and make comfortable the living standard of people. There are different merits and drawbacks of using only renewable sources for electricity generation in rural villages, merits like fuel cost incline, fuel transport cost is high, issues of global warming and climate change in large. The drawbacks of using renewable sources as off-grid power systems, it has intermittence nature that makes difficult to regulate the power output to manage with the load sought. To make sure for the reliability and affordability of the supply, combining conventional diesel generator with nonconventional energy generators can solve the problem visible while operating individually. Some of the advantages combining the two sources of energy production are stated as follows **[23]**.

- Diesel generator fuel usage and greenhouse gas reduction
- Resourceful use of locally available resources
- Deducts/avoids power shortfalls, increase sustainability power supply
- It provides electricity access in short periods than waiting for grid extension and ease to scale-up at any time.

  Hybrid standalone systems have power control flexibility and merits of environmental protection than diesel generator alone. Hybrid systems can expand its capacity when load demand is getting higher in the future, from renewable systems, diesel generator rated power or both of them. Some of the components produce DC power and others AC power directly with no use of converter. Figure 3.1 describes the hybrid power system components considered in this thesis

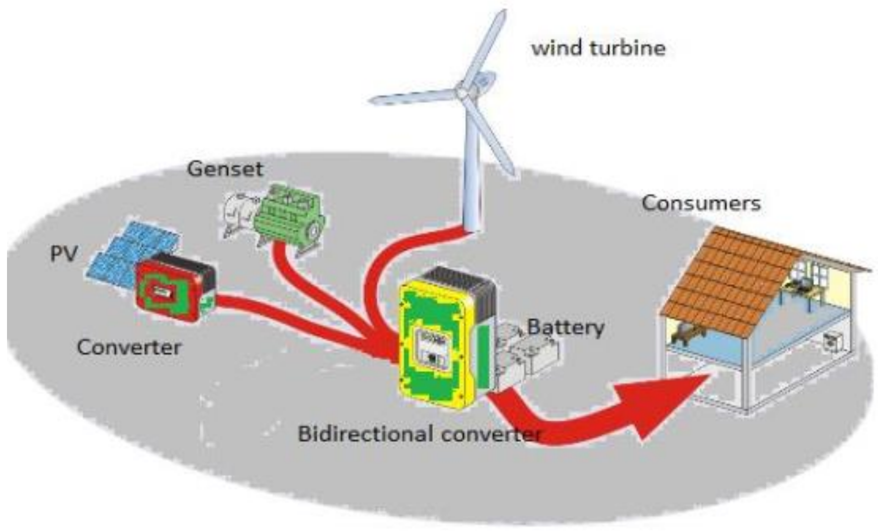


Figure 3.5: Hybrid system configuration **[30]**.

3.4.2 Classification of hybrid configuration

Hybrid power systems can be designed based on the following technical topologies to harness the available renewable sources and to meet the required load. This can be configured in different ways with the voltage and the load demand as the determinant factors. According to **[30, 31, 32, 33, 34]** any power system configurations are grouped in the following forms. Hybrid power systems can be categorized into four common configurations according to the voltage and the load demand they are coupled with.

3.4.2.1 AC-Coupled hybrid power Systems

In such topology all the energy generating components or units and the energy storage technologies are connected to the AC bus in line with the load or directly to the load (in the case of decentralized configuration). This type of power system setup could also subdivide into centralized and decentralized configuration systems.

Centralized AC-coupled hybrid system: All the components are connected to the AC line. AC Electricity generating components could connect directly to AC line or may require AC/AC converter to get stable component coupling topology. The master inverter helps to control the energy flow to the battery and out of the battery to the load. Furthermore DC electricity can be provided from battery if needed. Figure 3.6 depicts centralized AC coupled hybrid system configuration.

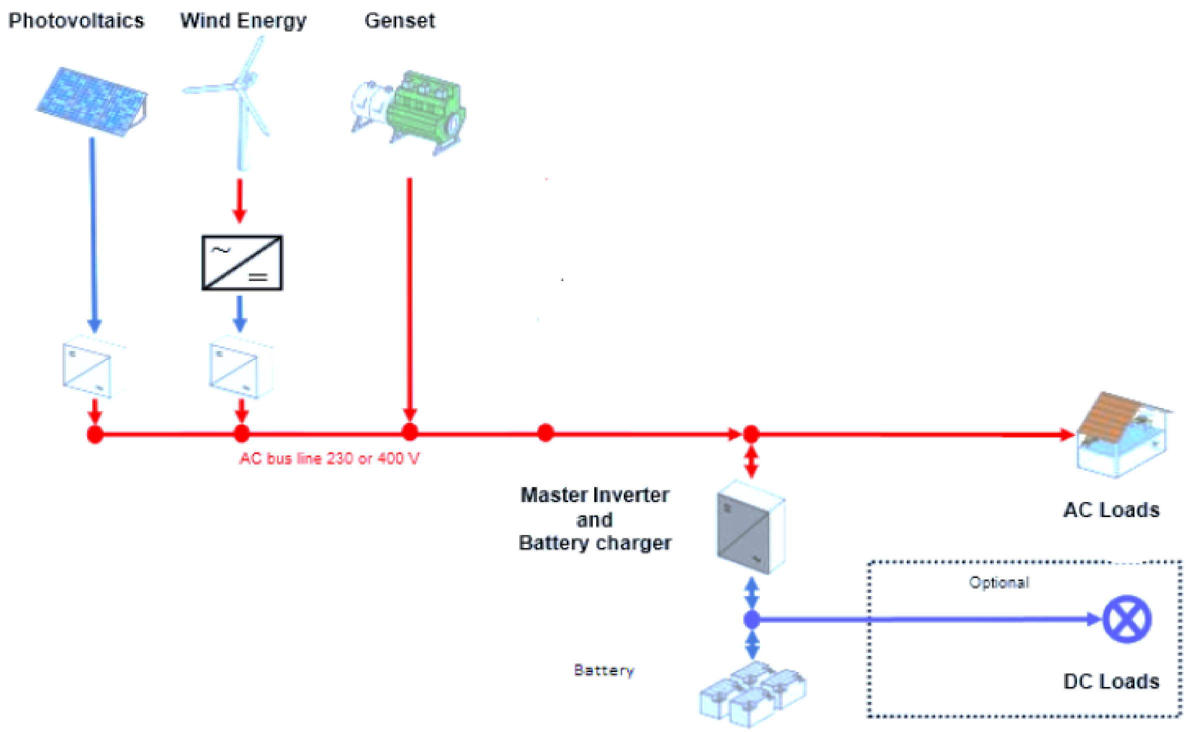


Figure 3.6: Centralized AC-coupled hybrid power system **[31, 33, 34]**.

Advantages in contrast with decentralized system.

The centralized system has capability of increasing battery life due to the presence of central control system for the overcharging and deep discharging. It is also compatible with utility grids and enables to export excess electricity during minimum load demand times; moreover battery bank could simply charge from wind and solar PV. Parallel operation of the components allows for further expansion of the system with safe reliability.

Decentralized AC-coupled hybrid system. In this type of architecture all the technologies are not connected to any of the bus, rather they individually connect to the load directly. Figure 3.3 exhibits the combination of the system topology, as it is visible from the figure energy sources may not be situated in one location or close to one another and they can connect to the load from anywhere the renewable resources is available. The merit of such configuration is that the power generating components can install from the location where renewable resource is available. But it has a disadvantage due to the difficulty of power control of the system. Thus, comparing the two configurations the centralized system is better due to its controllability than the distributed system **[30]**.

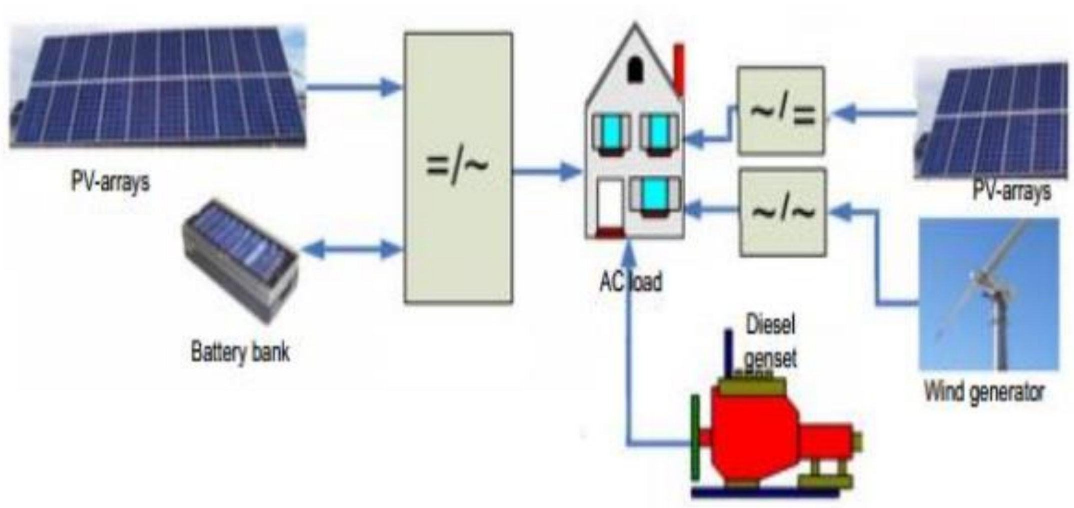


Figure 3.7: Distributed AC hybrid power system **[30, 35]**.

3.4.2.2 DC-Coupled configuration

In the direct current combination all the energy conversion systems are connected to the main DC bus before connected to the AC load side. All AC power sources are converted into DC power sources then connected to the AC load consumer using a relevant converter. Such combinations are used in solar PV home systems up to a certain size of kW **[31]**. Home system energy providers can be supported with inverters to provide AC load as needed. Single home system power suppliers are combined with other generating units/systems when large amount of energy is sought. The added energy generating unnits are normally wind energy and diesel generator as depicted below. Referring to Figure 3.8 all power sources are employed to the DC bus, then to the consumer. The merit of DC-coupled topology is that the demand is met with no cut offs. Despite the advantage of this, it has disadvantages of low conversion efficiency, no power control of diesel generator. Wind turbine and diesel generator produces AC voltage and needs AC/DC converter to supply appropriate load to the DC bus. Charge controller is also employed to protect the deep discharge and over charge of the battery. If required AC load can be supplied using inverter.

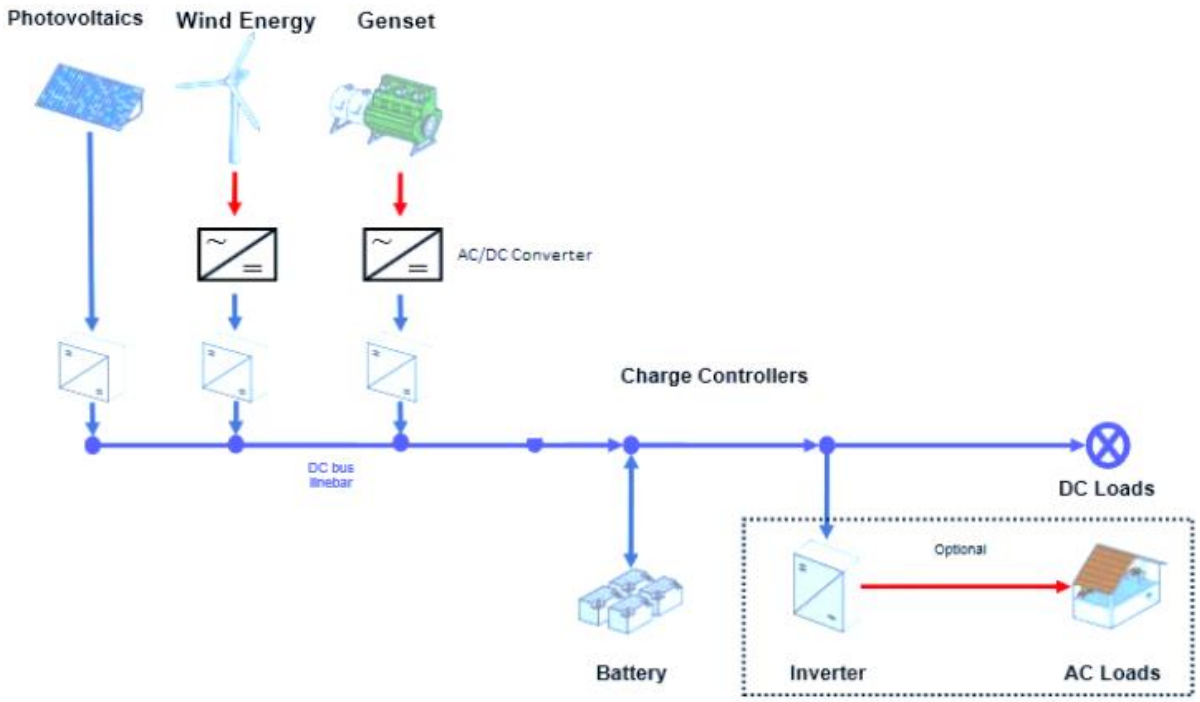


Figure 3.8: DC-coupled hybrid power system **[31, 33, 34]**.

3.4.3 Auxiliary components of the hybrid System

3.4.3.1 Backup diesel generator

Backup generator is part of the hybrid system contemplated in this thesis. A power generator is a machine used to generate electricity by changing/transforming the kinetic energy of motion of the combustion engines into electricity using different energy sources. Combustion engines are the simplest means of electricity generators with the use of oil due to their low initial capital investment. Backup generator is used to optimize renewable power output, to improve frequent shortfall of energy when power interruption is happened from renewable sources and the battery is unable to provide the required energy. The running cost of generators is high as compared to the running cost of renewable sources. When considered the incorporation of combustion engine into the hybrid system, the fuel availability and engine efficiency are the significant factors to consider. Backup generators allow designing power systems with minimum or without storage batteries. Based on the explanation given in **[36]** generator operates efficiently at full load, and thus it’s better to run only after the energy storage (batteries) have fallen 20% of their full charge. DC generators and AC generators are the two basic types of generators. Referring into **[37]** AC machines also categorized as asynchronous and synchronous generators/motors.

Synchronous generators: They are machines that convert mechanical power into AC electricity. They provide precise control of voltage, frequency. Runs at synchronous speed, moreover, provide the alternating current needed. They provide the electric energy required by the society. It can be used for both grid and off the grid power providing systems **[30].** Synchronous generator drives through a constant speed engine 40 that corresponds to the required generator output voltage frequency. Here below is described the mathematical expressions for the generator fuel curve and efficiency curves.

Fuel curve: It shows the fuel quantity the generator consumes to generate electricity. The mathematical expression below is to give the generators fuel consumption in units per hour **[7]**.

$$F = F_o . Y_{gen} + F_1 . P_{gen} \tag{33}$$

where F_o: the fuel curve intercept coefficient (units/hr/kW), Y_{gen}: fuel curve slope, (units/hr/kW), F_1: rated capacity in (kW), P_{gen}: electric output in (kW)

Efficiency curve: the efficiency is the ratio of the electrical energy generated to the chemical energy of the fuel consumed by the generator **[15]**

$$\eta_{gen} = \frac{3.6 * P_{gen}}{m_{fuel} * LHV_{fuel}} \tag{34}$$

where, η_{gen}: generator efficiency, m_{fuel}: the mass flow rate of fuel (kg/hr), LHV_{fuel}: the lower heating value (MJ/kg), P_{gen}: the electrical output (kW), 1 kWh = 3.6 MJ.

The fuel consumption and the mass flow rate relate as follows, however the relation depends on fuel units. When the fuel unit is in kg, then mass flow rate is equal to consumption

$$m_{fuel} = F = F_0 . F_{gen} + F_1 . P_{gen} \tag{35}$$

When liter is the unit of the fuel, the mass flow rate and fuel consumption relation depends on density. Thus the equation for mass flow is given as below

$$m_{fuel} = \rho_{fuel} \left(\frac{F}{1000} \right) = \rho_{fuel} \left(\frac{Fo . Y_{gen} + F_1 . P_{gen}}{1000} \right) \tag{36}$$

where ρ_{fuel}: fuel density (kg/m^3), when m^3 the unit of fuel flow, the factor 1000 is omitted from the above equation, so the nmass flow equation is now expressed as follows.

$$m_{fuel} = \rho_{fuel} * F = \rho_{fuel} \left(F_0 . Y_{gen} + F_1 . P_{gen} \right) \tag{37}$$

The efficiency equation when the unit of fuel flow is in liters is given in below

$$\eta_{gen} = \frac{(3600 . P_{gen})}{\rho_{fuel} (F_0 . Y_{gen} + F_1 . P_{gen}) . LHV_{fuel}} \tag{38}$$

3.4.3.2 Converters

The power conditioning units are electronic devices and grouped into DC-DC/AC, AC/DC. The DC/DC converters are electronic devices used to change DC voltage or current in to needed voltage and frequency outputs. This type of converter is required since DC voltage cannot easily be stepped-up or down with transformers. The DC/AC converter uses to switch the DC voltage or current produced by the hybrid system to the AC type voltage output. This type of power converter is called power inverter. The AC/DC power converter functions as an inverse of the inverter and it is called rectifier. It converts the AC input voltage to rectified direct current output voltage. In this paper bi-directional DC/AC or AC/DC converter type was considered as part of the hybrid system component. The incorporation of the bi-directional converter is used to switch the DC voltage that comes from battery and PV, moreover to change the AC voltage from the wind or diesel generator into direct current when it is needed to charge the battery. In order to determine the size of an inverter, the determination of all the demanding loads from all consumers which are likely to function at the same time is an important step, however in this paper case since power is provided from both diesel generator and wind turbine directly to the consumers so inverter size can be smaller than the load to be supplied at one time. The rectifier and the inverter are the two main power electronics components of the solar PV and wind power systems.

3.4.4 Energy storage types and selection criteria

To keep the demand and supply energy balance stable, as much as possible energy storage mechanism has to be introduced to the hybrid system. This method enables the excess produced energy from renewable sources to store for later uses. Most of the time such cases happened during the day time when solar radiation and wind flow is high and load is low; and also it provides excess energy to the demanding loads to cover for the deficit of supply, which is during the night times or cloudy sky and low wind flow times. Energy can be deposited using methods of chemicals (batteries or hydrogen), as potential energy (pumped hydro or compressed air), as electrical energy (capacitors) or as mechanical energy (flywheels). The fundamental characteristics applied to define a storage technology for most energy systems include the following **[21]**.

Energy storage capacity [kWh or Ah]: It is the amount of energy that can be stored. The useful energy capacity of a battery will often be smaller than the rated capacity due to different reasons. If power is pulled out quickly its capacity will be less however if power is drawn slowly its capacity will get greater.

Charge and discharge rates [kW or A]: It is a measures of power at which energy is added or removed to/from energy storage systems. For many technologies the rate of charging and discharging varies; in practice, they will change with how much energy is in storage and how long power has been continuously removed or added to storage system. The rate of charging is lower than the rate of discharging for most technologies.

Lifetime [cycles, years, kWh]: Energy storage technologies lifetime is measured according to how much they are charged and discharged in cycles, while others measured due to time passing in years, however others have lifetimes restricted by total energy throughput in kWh or Ah. *Round-trip efficiency*: Energy storage mechanisms require more energy to make full/charge than to be drawn energy/discharged, thus this loss of energy is called round-trip efficiency. It is expressed by the ratio of discharged energy to the charged /input energy into the storage. A less efficient storage system requires more electricity to store the same amount of electricity supplied than a more efficient storage system. It largely affects the cost of storage.

Energy density [Wh/kg and Wh/m^3]: It indicates how much amount of energy per unit weight or volume can be stored; whereas power density [W/kg] is the amount of energy released from the storage system per unit of kilogramm.

Table 3.2: Advantages and disadvantages of the different energy storage technologies **[21].**

Energy Storage Types	Advantages	Constraints
Lead-acid batteries	Market availability, moderate costs, high performance over cost ratio	Limited lifetime
Li-Ion batteries	Compacted size	Less experienced with use in electric grids
Na-S batteries	High round-trip efficiency	Only for larger electricity systems, corrosive
Flywheels	Modular, low maintenance	Expensive
Pumped Hydro	Technically proven, low costs	Very large scale
Hydrogen	Compatible with fuel cells	Low round-trip efficiency, expensive

3.4.4.1 Battery Bank

From the energy storage devices listed in Table 3.2, the selected and most common one is lead-acid battery which is applicable for standalone systems due to its moderate cost, maturity, high performance over cost ratio. It is available in different capacities like 6 V, 12 V and 24 V terminal voltages. A battery life is affected with how much of their energy storage capacity is consumed at a time known as depth of discharge. During unfavorable climatic conditions, the demand has to meet by the batteries; moreover, if the battery is discharging deeper, the diesel generator caters the energy demand, and at the same time charges the battery if the power controls mechanism could be cycle charging. Deep cycle batteries can discharge from15-20% of their capacity, which means that it shows a discharge of 85-80% **[15, 21, 30]**. Some of the Factors that affect the sizing of battery system are the following, daily energy demand, days of autonomy, maximum depth of discharge, temperature correction, rated battery capacity and battery life.

To use part of the total stored energy of the battery it should be sized large enough and this is determined using the DOD. Energy generated from renewable energy conversion technologies has energy outages when there is no sun or wind blow, to avoid such shortfalls a battery bank should maintain days or hours of autonomy. It is described mathematically by the following formulas **[22, 23]**. Total capacity of the battery capable to supply the full load demand can be determined using the following mathematical expression.

$$C_B = E_L . \frac{S_D}{V_B (DOD)_{max} T_{cf} . n_B} \tag{39}$$

where C_B: capacity of battery (Ah), E_L: the electrical load (Wh), S_D: battery autonomy (days), V_B: storage battery voltage (V), $(DOD)_{max}$: maximum depth of discharge of battery, T_{cf}: temperature correction factor, η_B: efficiency of battery (%).

The state of charge of the battery depends on energy production by the solar photovoltaic, wind speed, and the required load, thus the state of charge can be determined using the equation below.Battery charging state: During the charging, as the PV and wind generator output is larger than demand, the battery capacity at time t is given below in the equation

$$SOC_{(t)} = SOC_{(t-1)}(1-\sigma) + \left[E_{gen(t)} - \left(\frac{EL_{(t)}}{\eta_{inv}}\right)\right] H_b \tag{40}$$

Battery discharging state: As the power generated by the renewable resources is less than the load demand, thus the battery is discharging and it is determined using the following equation.

$$SOC_{(t)} = SOC_{(t-1)}(1-\sigma) + \left[\frac{EL}{\eta_{inv}} - E_{gen(t)}\right] \tag{41}$$

$$E_{gen(t)} = E_{pv(t)} + E_{wg(t)} \tag{42}$$

where, $SOC_{(t)}$: state of battery capacity at hour (t) (Wh), $SOC_{(t-1)}$: state of battery capacity at hour (t-1) (Wh), σ: battery hourly self-discharge rate. The manufacturer gives a self-discharge of 25% over six months for a storage temperature of 20°C **[22, 23]**, EL(t): load requirement at time (t), η_{inv}: inverter efficiency (in this paper assumed as constant, 90%), η_B: battery charging efficiency (during discharging the efficiency is equal to 100% and during charging is set from 65 to 85% depending on the charging current), $E_{gen(t)}$: total energy from wind and PV generated (kWh), $E_{pv(t)}$: energy generated from PV (kWh), $E_{wg(t)}$: energy generated from wind (kWh).

The autonomy period of a battery bank can be expressed by the following mathematical expression. It is the ratio of battery bank size to the load demand **[15]**.

$$A_{batt} = \frac{\left((N_{batt}V_{nom}Q_{nom})\left(1-\frac{q_{min}}{100}\right)\left(\frac{24hr}{day}\right)\right)}{\left((I_{prim,ave})\left(\frac{1000Wh}{kWh}\right)\right)} \tag{43}$$

where A_{batt}: battery autonomy (hr), N_{batt}: number of batteries, N_{nom}: single battery nominal voltage (V), Q_{nom}: single battery nominal capacity (Ah), q_{min}: battery bank minimum state of charge (%), $I_{prim,ave}$: average primary electrical load (kWh/day).

3.4.5 Overview of Homer software

In designing power systems different decisions can be made about the configuration of the system, such as; what components to include in the system, the size and the quantity of the components and the cost of each components. Incorrect power system design can lead to shorter life of battery, increase cost of energy production, insufficient supply of electricity demand. Hybrid Optimization Model for Electric Renewable (HOMER) is a computer model developed originally by the National Renewable Energy Laboratory (NREL). It has different energy generating components in its library. The user must select the components from the library to represent the architecture considered. This modeling tool uses time step from 1 minute to several hours. HOMER simplifies or helps the designer to compare various power systems options based on technical and economic aspects. The software answers questions like:

- What type of component to buy (solar PV, wind turbine, either both with battery or only wind and PV)?
- Does the designed system would meet future growing demand?
- What quantity of battery to buy?
- What if the cost of fuel and other prices changes?
- How to control the power system?

The software also chooses between the dispatch strategies (cycle charging and load following) by making comparisons. Design and analysis of systems can be challenging task because the large combination of design options and the inclusion of uncertainties. The design complexity and uncertainty increase when renewable sources are included in the system, because they are non-dispatch able and intermittent nature. HOMER developed to overcome these challenges. It does three main tasks as indicated in Figure 3.9.

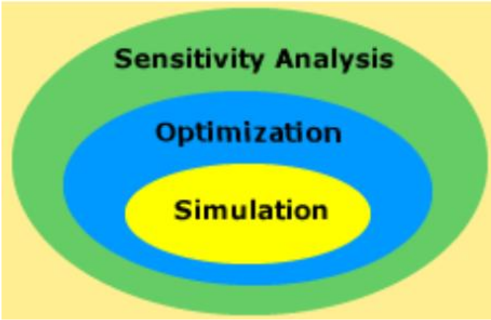


Figure 3.9: Interactions between simulation, optimization and sensitivity analysis **[15]**.

Simulation: At its core, HOMER is a simulation model. It will attempt to simulate a viable system for all possible combinations of the equipment that you wish to consider. Depending on how you set up your problem, HOMER may simulate hundreds or even thousands of systems.

Optimization: The optimization step follows all simulations. The simulated systems are sorted and filtered according to criteria that you define, so that you can see the best possible fits. Although HOMER fundamentally is an economic optimization model, you may also choose to minimize fuel usage.

Sensitivity analysis: This is an optional step that allows you to model the impact of variables that are beyond your control, such as wind speed, fuel costs, etc, and see how the optimal system changes with these variations.

CHAPTER FOUIR

4.0 ANALYSIS OF THE DATA COLLECTED AND DISCUSSION OF THE RESULTS

4.1 ELECTRICITY LOAD ESTIMATION OF THE INDUSTRY

Tanzania, especially the area under this study does not experience summer and winter seasons as extreme cases, the electricity consumption does not vary almost the whole year. In this paper the electricity load demand of the Industry is divided in to the following two major categories like; primary load (lighting, TV, running all machines, printer, laptops etc); and deferrable load (water supply). The total electric load estimated for the listed appliances above were summed up to get the required load to be supplied by the system. To design an off grid hybrid power system for a specific Industry the establishment of information like the load profile of the industry, climatic data of the area, initial cost of the components, cost of diesel fuel and project lifetime etc., are the important parameters to be accounted.

It is obvious that the load factor in small industry is lower than big industries; therefore, it is necessary to keep the load factor from being poor when designing an energy system with balancing the cost of energy per kilowatt hour. Load estimation was approached based on the electric appliances to be used by each sector, with no attention given for their efficiency. Renewable sources power production systems cannot generate the exact amount sought to meet the load demand, either they produce excess electricity or below the demand. Thus instead of calculating the estimated load of the industry by the efficiency factor of each appliances it is better to allow excess electricity production from the system. The initial point to know in calculating the load is deciding which appliance has to be used by the Industry accounting the current and future situation of the Industry as well as the countries energy system framework.

4.1.1 Estimation of electric load

Primary load is the load that should meet by the energy providing system as it requires immediately; which includes lighting, running machines, TV, radio, computer, printer, and others. Here the electricity load consumption in the industry is considered to be the same and constant throughout the year. Although there is a bit variation from one month to another as indicated in the Table 4.1 as have been obtained from the Energy Department at Bellaview Industry with respect to each month electricity bills from TANESCO.

Table 4.1:Electricity load consumption .

Month	Amount (kWh)
January	41617
Febebruary	46924
March	49638
April	46912
May	57245
June	58185
July	59670
August	54619
September	45331
October	43701
November	45694
December	42259

4.2 LOAD INPUTS AND OPTIMIZATION OF HYBRID SYSTEM

The energy system should meet the load demand of the proposed industry as a case study area. The main renewable sources of energy considered in this thesis are solar and wind. Diesel generator as backup and battery bank as energy storage system are employed due to the intermittent nature of the renewable sources. The wind turbine and diesel generator produces AC type voltage as they are alternating in nature, whereas the PV panels output is DC type. Bidirectional converter is fitted in this configuration which is basically used to charge the battery by changing the alternating current type load into DC, moreover supplies alternating current type electricity back from battery to AC load consumers.

All loads required by Industry are AC type. Some of the input values into the software are expressed in size and in quantity. Wind turbines, batteries are the power system components which vary in quantity, and solar PV, diesel generator and converter are other components that vary in size. This chapter is to illustrate the input variables that will help for optimization and modeling of the system and to brief some resulted value related to the inputs. Detail of the components of the power system and the electricity load of the selected Industry has already explained in previous paragraphs. Figure 4.1 is the schematic representation of HOMER simulation model of the hybrid system architecture considered in this paper.

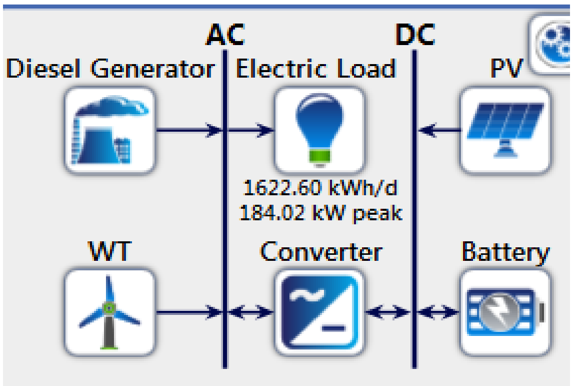


Figure 4.1: Architecture of the selected technologies of the hybrid system produced by HOMER.

4.2.1 Electricity load input

Next to the selection of the components technology from the library of HOMER software, the electricity load is the first to be entered in to the modeling tool. The primary load input, which was determined in Table 4.1 above has entered on monthly basis and thereafter the software modeled the peak load.Moreover it also synthesized the monthly load from the 24 hour input data. The diurnal variation of the primary load profile of the selected industry is depicted in Figure 5.2 generated by HOMER after inserting the monthly load data. Most of the appliances employed in the industry and service areas operate with alternating current voltages and hence AC loads were proposed,load profiles have almost the same daily demands, peak demands, average demands, base demands.

Figure 4.2: Diurnal variation of primary load profile produced by HOMER.

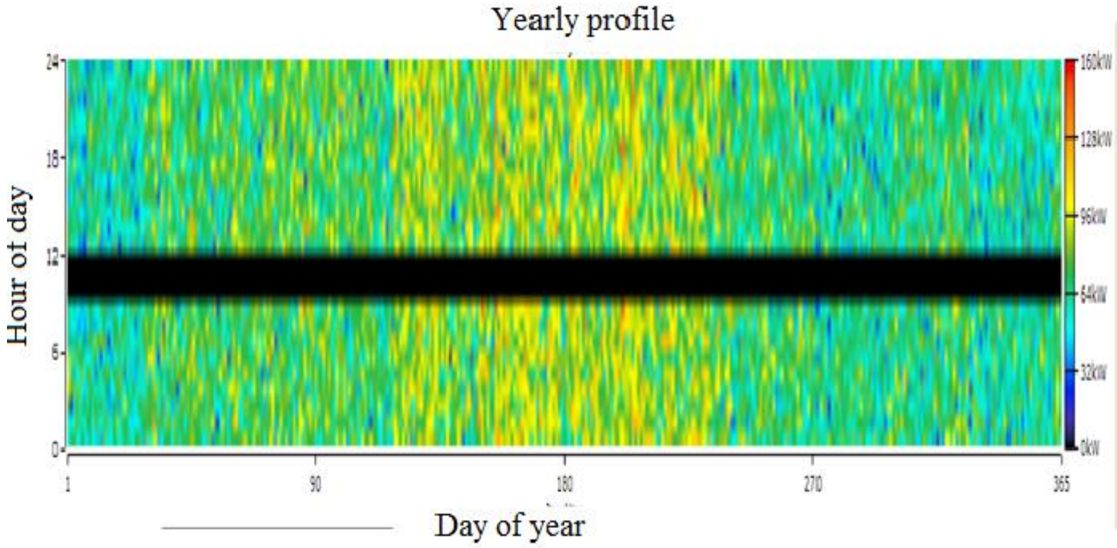


Figure 4.3: Data-map of the yearly primary load profile system produced by HOMER.

4.3 SOLAR AND WIND ENERGY SOURCES

The solar resource raw data inputting to the software is the average global horizontal radiation was adapted from NASA. On top of the solar resources data the latitude and longitude of this area would also be used as an input. The time zone is another parameter to be set. The industry is located at latitude: 3°S, longitude: 37°E, and with time zone of GMT +3:00. In order to get how much power is generated by the solar PV it requires inputting measured solar resources data in units of kW/m^2 into HOMER software. Similar to the solar sources data the wind speed was adapted from NASA.

4.4 COST DATA AND SIZE SPECIFICATIONS OF EACH COMPONENT

The basic criterion related to the selection of the power system components in this thesis work is the cost of components, as the main purpose of the work is searching the optimum power system configuration that would meet the demand with minimum NPC and COE. The estimation of the components cost was made based on the current cost available on market. **Initial capital cost of components:** It is the total installed cost deployed to purchase and install the component at the commencement of the project.

O&M cost: It is the cost accounted for maintenance and operation of the system. The entire scheme components considered in this paper has different operation and maintenance costs. Miscellaneous O&M costs considered by HOMER are like emission penalties, capacity shortage penalty and fixed operation and maintenance costs.

Replacement cost: This is the cost required to replace wear out components at the end of its life cycle. This cost is different from initial cost of the component, due to the following reasons. At the end of its lifecycle not all of the spares of the component need to replace, Costs from donors may eliminate or can reduce initial cost, however replacement cost may not account travel costs but initial costs do.

4.4.1 Solar PV size and cost

After surveying different products focusing on the cost provided the following panel was chosen. The reason for choosing the product from the stated company is due to its low cost delivered as long as efficiency is not a big concern here. The solar panel considered was 1 kW, which is with 4 number of solar module having 250 W capacities from Trina-solar Company. The selected panel was poly-crystalline silicon made which is known as TSM 250-PA05 model with an efficiency of 14 to 15 %, the price varied from $1.16 to $1.31/watt **[38]**. In this paper the installation cost is taken as 60% of the PV price and the operation and maintenance cost would be 1% per year **[22, 39, 40]**. The author considered the current installation cost of PV the average value ($2784/kw) of the upper and lower limit values indicated in Table 4.2. The other input costs, sizes and lifespan of the PV are displayed in Table 4.2.

Table 4.2: Size and cost of PV panel.

PV Size (kW)	Capital cost ($)	O & M cost ($/year)	PV Life (year)	Sizes considered (kW)
1	1856 to 3712	28	25	0, 1, 100, 200, 300, 400, 450, 500, 550, 600

There is no any tracking system considered in this paper, thus the system is modeled as fixed tracking mount at ground. Derating factor is a term accounted for both PV systems efficiency and charge controller efficiency since charge controller is not being designed by HOMER. This factor is to be subsidized for dust, high temperature, shading, wiring losses, and so on. The size of the PV panels input in to HOMER is in kW, not in m^2, thus its efficiency is not taken into account as an input also. The azimuth angle or orientation and angle of inclination of the PV panel are the two important factors that should be considered during solar system design.

4.4.2 Wind turbine size and cost

Depending on the wind speed sources the turbine has to generate large amount of energy to contribute significant renewable fraction and this can be performed using single large wind turbine or number of smaller turbines. Quantities of turbines, service time, hub height, cost of the component, type of electricity generated, cut-in wind speed are the restrictive values to select wind turbine. The selected turbines can generate AC type electricity to satisfy the need of AC load consumer appliances. The wind turbine taken for this thesis work is 50 kW power rating. The wind turbine was manufactured by the Viktor Krogmann GmbH & Co.KG, Germany **[41]**. O&M cost of wind turbine was proposed about 2% of its initial capital cost as given in **[22]**. The total installation cost of wind turbines was estimated based on the installed wind turbines in Europe and China since 2011. The total installed capital cost was averaged from $1050/kW to $1350/kW in China and in Europe it was $1800/kW to $2050/kW **[42, 43]**. In this thesis installed cost was taken about $1800/kW. Replacement cost of the wind turbine considered in this case is about 70% of capital cost after 20 year service life. In Table 5.3 wind turbine parametric inputs into HOMER are given.

Table 4.3: The wind turbine parametric inputs into HOMER.

Capacity (kW)	Capital cost ($)	Replacement cost ($)	O & M cost ($/year)	Life (years)	Tower height (m)	Quantity
50	90000	63000	1800	20	32	1 to 8

4.4.3 Cost and size of batteries

Like the other components of the power system, input parameters inserting into the software are cost and number of batteries. Note the following definitions; the battery rated/nominal capacity is the quantity of energy discharged from battery. Minimum state of charge of batteries is the state of charge below which the battery is never discharged to prevent from damage. From 30-50 percent is the recommended minimum state of charge. Round-trip battery efficiency is the energy flow into the battery that can be extracted for later use. Lifetime throughput is the energy quantity that circulated in the battery through its lifelong. The storage battery chosen is CL E-KwBe from the manufacturer GCL system Integration Co.Ltd which is given in HOMER tool library. Thus, the selected battery has the following characteristics obtained from the modeling tool. The nominal capacity of the selected battery is 5.77 kWh with nominal voltage of 55.5 V for single battery and the amount of energy stored in a single battery is 6.94 kWh, maximum charge current is 52 A, lifetime throughput of 5,342 kWh was considered, minimum state of charge is accounted for 15%, round-trip battery efficiency is taken as 80%. Replacement cost for battery is assumed about 70% of its capital cost.

- Quantity of Batteries considered are: 1, 50, 150, 200, 300, 400
- Capital cost of batteries: $1200/battery
- Replacement cost: $1000/battery
- Operation and maintenance cost: $12/year.

5.4.4 Diesel generator size and cost

Diesel generators are available in a wide range, however different suppliers cater different cost evidences and this makes challenging to compare. Diesel generators do not allow running at less than the minimum load ratio of 30%. Generators operations lifetime is measured in hours. Since generators lifetime depend on fuel quality and operating conditions this makes difficult to get lifetime data. The well-known engines used to produce electricity are internal combustion engines of which diesel engines last long than gasoline powered engines **[15]**. Frequent load variation results in the poor performance of generator and larger fuel consumption and higher O&M cost accordingly higher cost of energy would be obtained. In this paper, after surveying of various diesel generator suppliers, the selected one is from Cummins, supplied by Guangzhou Kanghai M&E Equipment Co.Ltd **[44]**. Generator size is among the input sizes to consider working with wind and solar PV to meet the load requirement in the case of no wind flows and no sunshine times. Thus range of size of the generator could be less than the peak load demand as it would function in collaboration with the renewable sources and battery bank. The choice of diesel generator accounts the constraints of power delivering capacity, the load type, cost efficiency and fuel consumption. The cost of diesel generators available in the market varies from \$250 to \$450/kW **[45]**. The selection of a particular generator size deliberates the constraint of both cost effectiveness and capacity of delivering the required power. The optimal and appropriate capacity of generator could be picked after simulation. In this paper the cost of generator was suggested as \$450/kW, thus the related costs are listed as follows

- Capital cost was taken as \$18000
- Replacement cost: \$18000
- Sizes of Gen set considered are: 0, 40, 80, 100, 200, 300kW
- The minimum load ratio of 30% of rated load was accounted
- Operation and maintenance cost was around \$0.103/hr.

4.4.5 Power converter size and cost

A converter needs to maintain flow of energy between AC and DC power system components. The rated power of the inverter should be equal to or larger than the peak load but since the load will supply both from the renewable and non-renewable, even below the peak would be installed. There is no estimated operating and maintenance cost for this case. converter sizes considered are: 1, 100, 150, 200, 300 kW; capital cost of converter is taken as \$800, replacement cost is about \$560 which is 70% of the capital cost, efficiency of converter is around 90% and the lifetime of the converter will end for 15 years.

4.5 OTHER INPUTS THAT AFFECT POWER SYSTEM OPTIMIZATION

4.5.1 Economic inputs

HOMER is provided also with economic inputs window, thus to get the NPC of the system. Economic input parameters include like project lifetime, annual real interest rate, capacity shortage penalty, fixed capital cost, and system fixed O&M cost. System fixed capital cost is the cost that engaged at the beginning of the project implementation. Despite of the size and scheme architecture, the system fixed capital cost and O&M cost are considered as fixed values. Though these values have an effect on the NPC of each system however it affects them all at the same rate, thus they have no effect on the power system ranking. In this paper; fixed capital cost, fixed O&M cost and capacity shortage penalty was taken as zero. Real interest rate is the difference between inflation rate and nominal interest rate. HOMER discounted the capital cost of each components of the power system in to annual cost by amortizing the lifelong time of the components using real interest rate. It does not consider inflation; rather it assumes prices will rise at the same rate during the life long period of the power system. To compare the economics of the power system configuration with renewable and non-renewable sources of energy, the modeling tool would consider the following additional inputs. The lifetime of the off-grid power system is designed to end for 25 years long with generating capacity to meet the demand and the annual real interest rate is taken as 7% that is used to calculate the NPC of the project.

4.5.2 Constraint inputs

Constraint is a condition set by the power system designer in which the power providing scheme should satisfy to be feasible. An infeasible power system is a system that does not meet the constraints set by the modeler. It should be noted that capacity shortage is a power shortfall made between the needed operating capacity and system actual operating capacity of the scheme at certain time period. The needed operating capacity includes the surplus demand and operating reserve loads. The operating reserve is safety margin for excess electrical energy generating capability that ensures reliable provision of electricity, despite of the load, solar and wind fluctuations. HOMER is smart enough to calculate the capacity shortage of any power system architecture per annum. Excess electricity is produced due to either excess generation of power from renewable sources above load demand beside to this when battery bank is fully charged so unable to store the produced energy. For this paper case the following constraint inputs are considered and no thermal load is accounted for this site of interest. Maximum annual capacity shortagen of 10%, minimum renewable fraction 40%, operating reserve, as percentage of hourly load 10% and annual peak load of 0%, operating reserve, as percent of renewable output, solar power output: 25% and wind power output of 50%.

4.5.3 Emission and system control parameters

In Tanzania, there is no framework that leads to penalizing rules for emission. Although emission penalty is already applied in the developed world, however as the African continent is considered as unindustrialized continent emission penalty is not adopted yet. In this paper no emission penalty is considered at all for the system. The power flow control mechanism is an important input parameter for the power system. The control strategy is simple when the hybrid system includes PV, wind and battery components, however it becomes complex when generator is included in the hybrid system, as it is important to know how to charge batteries and how to supply the power either from the batteries or from generator.

Cycle charging: batteries are to be charged to the set point state of charge when the system starts to charge with no interruption until it will reach the set point state of charge. It helps to reduce the generator number of start cycles, charge and discharge cycles of the battery bank and also the time the battery waste at minimum state of charge.

Load following (zero charging strategy): this means batteries do not get charged by the diesel generator, it gets maximum charging time when renewable sources gets higher, meaning when generated power is greater than the load demand.

Set-point state of charge (SOC) 80%: This would help to minimize the operation cost of the power system however during the load following strategy this percentage would be zero.

4.6 SENSITIVITY VARIABLES

The modeling tool permits to take an account for future dynamic changes, meaning increasing or decreasing demands, renewable and non-renewable resources fluctuations. Sensitivity parameters chosen by the modeler would tell how sensitive the power system is for each change of the input variables. The benefit of putting sensitivity analysis is to define the uncertainty pertaining with the power system, when the modeler is not quite sure about the values of the components considered choosing several parameters to ensure the likely range and see how the system changes. When considering large number of sensitivity variables, it should be noted that the computational time of HOMER takes too much to complete the simulation which is very challenging to the software. The computational time depends on the quantity and sizes of the power system components and the sensitivity number of variables. Thus, this all combinations prolongs the running time, which is the limitation of the software. Although the accuracy of simulation result increase with the increase of the number of sensitivity variables, computational time is long and it requires larger memory computer.

4.7 RESULTS AND DISCUSSIONS

This section would give the details of the optimization results for the selected hybrid power system of a typical selected Industry. The system was designed with the help of HOMER with no given much concern to the efficiency of the components. After introducing all of the input variables in to the modeling tool, the software is run repeatedly to get the feasible results. Optimization results are displayed in the form of overall and categorized showing the most feasible power systems architecture which meets the load and the inputs constraints made by the modeler. The feasible solutions are presented in an increasing order of the net present cost from top to down. The categorized table presented the least cost effective combinations from among all components setup, whereas, the overall optimization results displayed all of the affordable system combinations based on their NPC. Power systems are selected after simulation based on primarily minimum net present cost. On top of these parameters less cost of energy, high renewable fraction, low capacity shortage, low excess electricity generation, and less diesel fuel consumption could be used for comparison of power generating schemes in order to check their technical feasibility.

4.7.1 Systems optimization and selection scenarios

HOMER simulated different configurations of energy system components,although it only displays the feasible power schemes scenarios for extra detailed analysis. The complexity and computation time are affected by the number of parameters and total number of potential values involved in the design. Four different scenarios are proposed for further analysis and to increase the chance of finding most optimized system. Power schemes (scenarios) with less NPC, less COE, higher renewable fraction, less capacity shortage, smaller excess electricity and minimum fuel consumption would be suggested as optimum system. From Table 4.4 truncated from the overall optimization results, the suggested scenarios based on the same datum values are to compare using the same variable cases in terms of techno-economic aspects from among the least cost results.

- PV-wind turbine-battery bank (scenario A)
- Solar PV-wind turbine-generator-battery bank (scenario B)
- Wind-battery bank (scenario C)
- Wind turbine-generator-battery bank (scenario D).

In the optimization section, the different configurations of power schemes with less NPC and minimum cost of energy was supposed to be selected with the idea of cost effective system. However, HOMER computes the efficient system in such a way that, the one with low NPC as listed in row one of truncated results Table 4.4 from overall optimization results which can be found through https://www.academia.edu/s/432ca4ff08/final-thesis-results-by-kaare-manyama?source=link

The comparison of the scenarios was performed based on the above stated technical measuring parameters. As a datum value to develop (structure) the scenarios the following constraints like; the current diesel price of $0.9/liter, renewable fraction of 40% and primary load of 1622.6 kWh/day were inserted into the software.

Table 4.4 Truncated from the overall optimization results.

PV (kW)	WT	Diesel Generator (kW)	Battery	Converter (kW)	Cost of Energy (COE) ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Fuel cost ($/yr)	O&M ($/yr)	Elec Prod (kWh/yr)	Total Fuel (L/yr)	CO2 (kg/yr)
189	8		487	142	0.245	1700920	39552	1237103	0	13679	1420843	0	0
184	8		493	146	0.245	1702628	39908	1234638	0	13685	1414428	0	0
181	8		501	141	0.245	1702642	40158	1231718	0	13616	1410119	0	0
188	8		489	142	0.245	1703474	39675	1238223	0	13695	1419959	0	0
191	8		484	142	0.245	1703478	39455	1240805	0	13720	1424298	0	0
167	8		550	150	0.255	1767569	43296	1259852	0	14228	1390920	0	0
260	8	10	392	150	0.255	1769574	36002	1347384	36	14873	1520651	40	105
642	7	10	308	221	0.475	3302324	80036	2363766	3	48079	1906816	3	7
642	6		333	212	0.476	3304362	80013	2366078	0	51024	1762013	0	0
514	2	10	782	152	0.476	3305065	67520	2513274	23	27468	1005510	26	67
762	6	10	385	139	0.476	3306035	49723	2722950	34	28395	1929584	38	99
693	4	10	385	170	0.477	3311460	64697	2552781	17	38364	1544104	18	48
642	6	10	333	212	0.478	3319075	79732	2384078	0	51024	1762013	0	0
447	4		690	213	0.478	3319187	91173	2250024	0	49497	1201555	0	0
579	2		707	141	0.478	3321100	63512	2576319	0	27018	1095503	0	0
	8	10	1154	417	0.479	3322908	134052	1750919	31	12925	1158463	35	91
140	8		1120	267	0.479	3324461	116125	1962696	0	31461	1353757	0	0
551	2		751	150	0.479	3327194	65660	2557218	0	26894	1055968	0	0
762	5	10	385	139	0.479	3327411	51699	2721150	38	28360	1784798	42	109
642	5		333	212	0.479	3328346	82211	2364278	0	50988	1617218	0	0
585	2		699	145	0.479	3328784	63322	2586226	0	27153	1103479	0	0
590	1	10	914	139	0.542	3762380	76109	2869877	76	29759	966105.4	84	219
	8		2240	416	0.775	5380090	199996	3034800	0	552	1158360	0	0
1283	6		262	277	0.775	5381635	107621	4119600	0	50349	2655255	0	0
1404	2	10	339	140	0.776	5389451	80289	4447931	60	45691	2243679	66	174
	8	10	2240	416	0.777	5394803	199715	3052800	0	552	1158360	0	0
579	1	10	933	147	0.544	3774085	77136	2869533	34	29806	951352	38	100

4.7.2 Comparison of scenarios for economic power systems

The cost effective system in the form of categorized simulation result is displayed in Table 4.5, scenario comparison was performed keeping the constraint values constant to all system configurations. The best energy system were selected with less net present cost (NPC), less cost of energy (COE), high renewable fraction, less capacity shortage, less excess electricity and less fuel consumption. The maximum annual capacity shortage and minimum renewable fraction are the worst constraints case.

Table 4.5:Categorized simulation result system produced by HOMER.

Architecture					Cost			
PV (kW)	WT	Diesel Generator (kW)	Battery	Converter (kW)	NPC ($)	Initial capital ($)	Fuel cost ($/yr)	O&M ($/yr)
189	8		487	142	$1.70M	$1.24M	$0.00	$13,679
258	8	10.0	393	150	$1.76M	$1.34M	$36.09	$14,642
	8		1,186	232	$2.93M	$1.62M	$0.00	$37,860
	8	10.0	1,166	246	$2.94M	$1.63M	$31.26	$33,882

47.2.1 Based on total net present cost

For the parameters specified as primary load of 1622.6 kWh/day, diesel price of $0.9/liter, maximum capacity shortage of 10% and minimum renewable fraction of 40%, the considered comparison parameters are discussed as follows in order to select techno-economic feasible power system. Referring Table 4.4 and Table 4.5 the architecture of the systems (scenario A) net present cost is less than all other scenarios which is about $1700920, scenario B is the next system with less NPC $1702628 followed by scenarios (C and D) are ranked in the order of increasing net present cost next to scenario A, respectively.

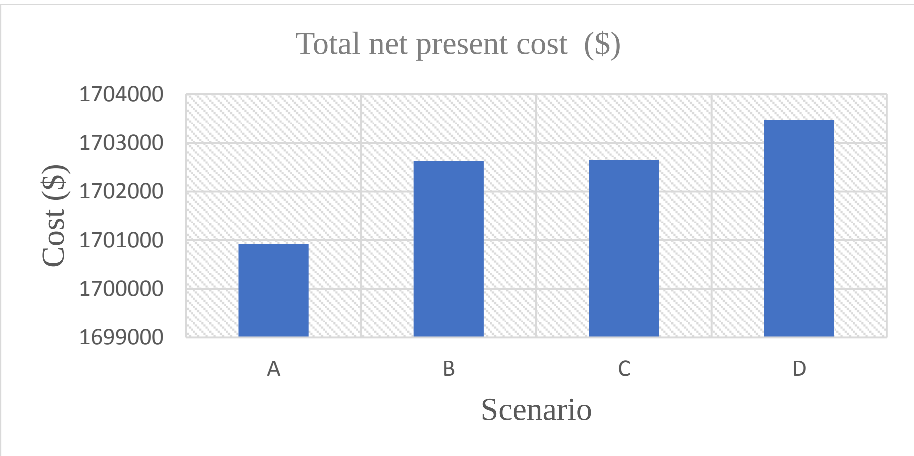


Figure 4.4: Comparison of selected scenarios based on NPC.

4.7.2.2 Based on excess electricity production

The other comparison parameter considered is the excess electricity production. The lowest excess electricity production is the optimal system which is first option to implement. Scenarios (C& D) have produced the lowest excess electricity of 46.2 both of it and chosen as winners of this competition; following these two scenarios, scenario B, has produced 59.4%. Excess electricity production should be accounted for all the constraints set by the designer. Although excess electricity production can be used for further expansion of load demand but it incurs extra cost. Looking into the magnitude of excess electricity only, scenario D and C is good option but as explained above considering all the constraints like 10% hourly operating reserve, solar and wind variations and capacity shortages set by the designer (option A) is selected for this case.

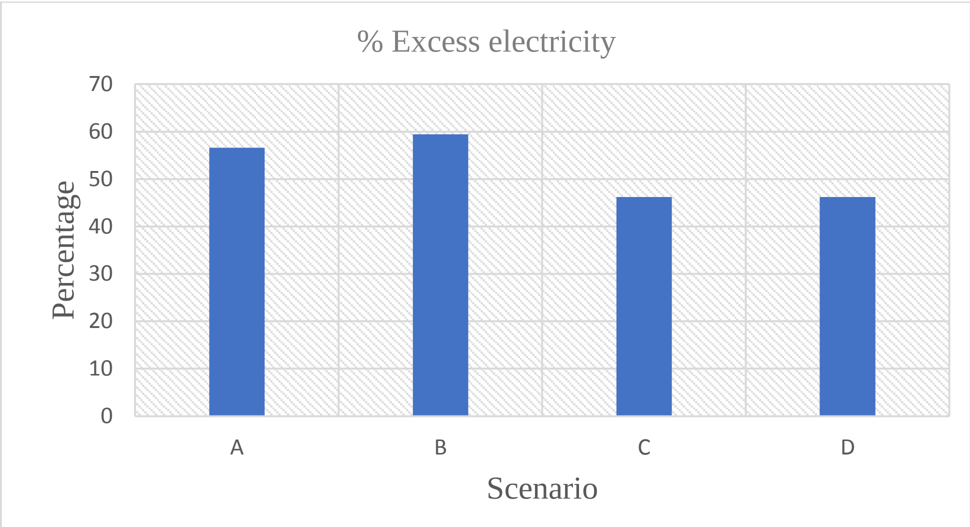


Figure 4.5: Comparison of scenarios based on excess electricity.

From all scenarios one system architecture with low cost of energy, less NPC, less minimum capacity shortage, high renewable fraction and less diesel fuel consumption, is the winner in terms of technical and from economics point of view. Based on the discussions made above the supper architecture, (scenario A) has taken almost all the priority to be nominated as sound power scheme among the proposed scenarios. The optimization analysis of the selected (scenario A) which encompasses wind turbine-solar PV -battery and converter is discussed in the proceeding sections.

4.7.2.3 Based on diesel fuel consumption

The third comparison criterion is the lower diesel fuel consumption. The lower the consumption of diesel and the higher energy generation from renewable sources is recommended as good choice, because the burning of diesel oil is the main source of environmental polluting elements and its availability in far rural areas is restricted due to different reasons. From the listed situations, scenario A and C has consumed the lowest diesel fuel which is about zero (0) liters/year this is just due to the absence of diesel generator in the two schemes, whereas scenario B and D has consumed about 40.1 and 34.7 liters/year respectively. The variations of the fuel consumption by the four scenarios are depicted in Figure 4.6. Thus, based on this measuring parameter and given due merit for environmental protection scenarios (A and C) are the best choices from the competent scenarios.

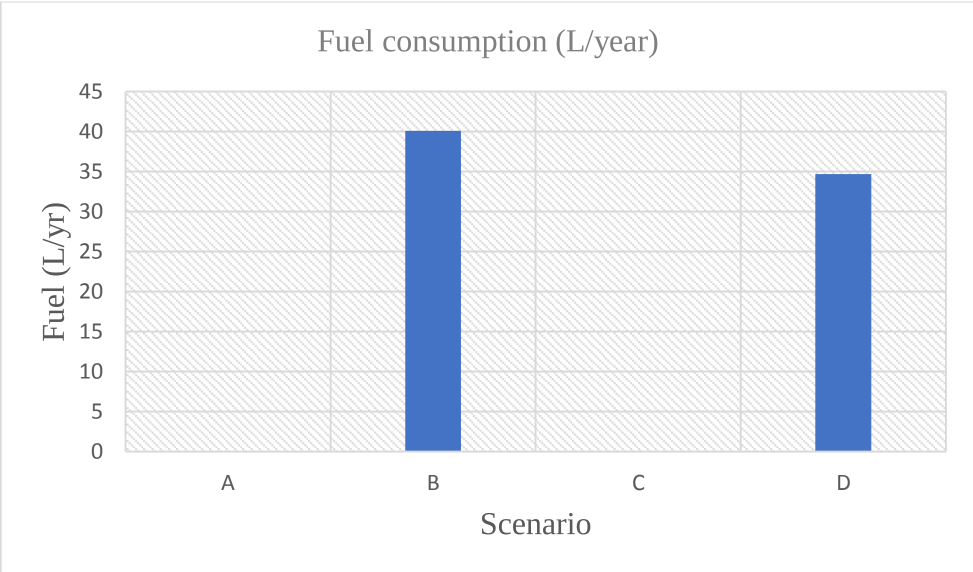


Figure 4.6: Comparison of scenarios based on diesel fuel consumption.

4.7.2.4 Based on cost of energy

To get detail information of the COE for each power system configurations (scenarios) refer into Figure 4.7. For scenario A the COE is around $0.245, for scenario B which is about $0.254, for scenario C it is $0.422 for scenario D it costs $0.424. Taking into account this parameter as comparison benchmark, thus scenario A is the winner from all eight set-ups. On top of the net present cost and cost of energy, other secondary comparison criteria's has set and are described below.

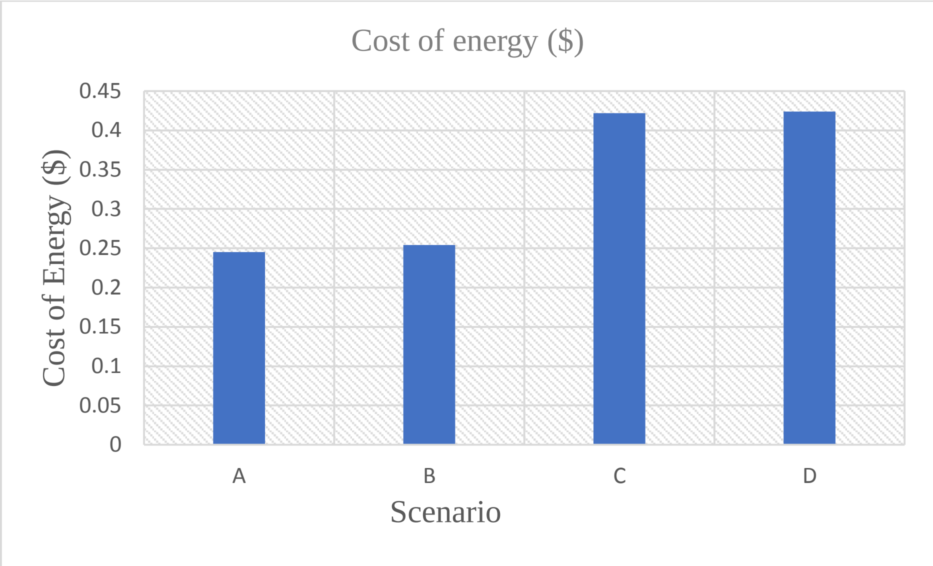


Figure 4.7: Comparison of scenarios based on COE.

4.7.3 Optimization analysis of the selected scenario

Based on the inputs made available in this chapter, different data simulation were performed which includes sensitivity cases using 64-bit operating system, 2.2 GHz processor and 8GB RAM, HP eliteBook 840G2 Laptop Core i5. The power system were designed taking an account for an operating reserve as a safety margin in order to permit the power system to cater reliable electricity, moreover, makes easy for further load expansion in the future to come since the industry now is operating under one section only (water production section) in future they will be produsing juice as well which they will require more energy, thats why now it looks that the excess of electyricity is about 50%. After simulation the following characters would be resulted such as; annual electrical energy production, initial capital cost, excess electricity, renewable fraction, unmet electric load, capacity shortage, annual fuel consumption, and operation hours of generator, etc. In Table 4.4 is the truncated overall optimization result of all the promising configurations of feasible power scheme based on total NPC of the system. There was no any requirement for pre-selection of the truncated power systems listed in the Table but only the ones from top ranked cost effective scheme architectures are displayed here. The result is for the selected scenario A based on current diesel price of \$0.8/liter, primary load demand of 1622.6 kWh/year, maximum annual capacity shortage of 10%, and minimum renewable fraction of 40%.

The system set-up in the first row of Table 4.4 is the cost efficient system composed of 8 unit wind turbines with 100 kW each rating power, 189 kW photovoltaic panel, 487 unit batteries, and 142 kW converter. The trend of monthly power generation in kW obtained after simulation is shown in Figure 4.8. Wind speed potential is high in five months June, July, August, September and October. The electricity generation by the wind turbines is minimum in two months in March and December. All of the power schemes remain producing electricity throughout the year, no power unit is producing peak load.

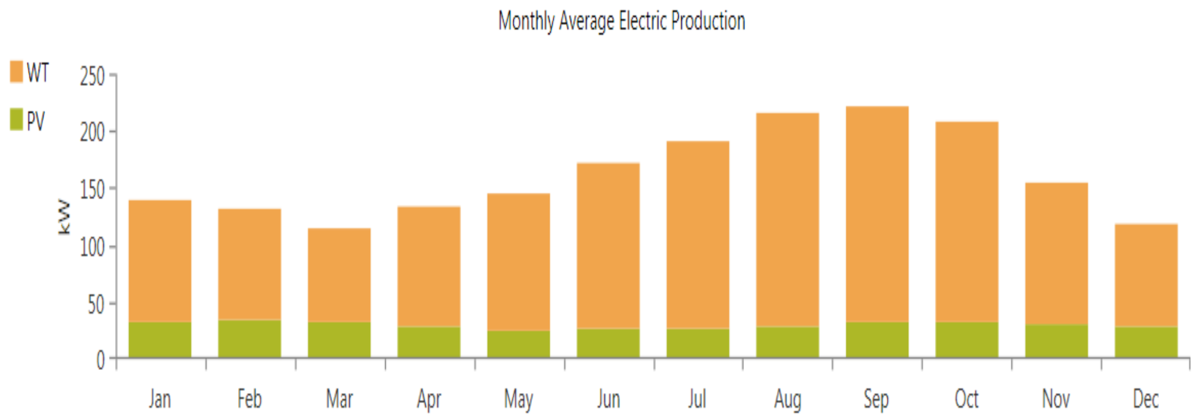


Figure 4.8: Share of electricity generation from the optimum system.

The electricity generation by individual power units of the hybrid system and consumptions by load are given in Figure 4.9, PV array power production accounts for 18.5% (262483 kWh/year) whereas wind turbine accounts for only 81.5% (1158360 kWh/year) of total electricity produced by the hybrid scheme. As generation of electricity from wind sources is higher than any other scheme incorporating in the hybrid structure, hence it is considered as the base load of the hybrid assembly The magnitudes of the power generated from PV has small magnitute.

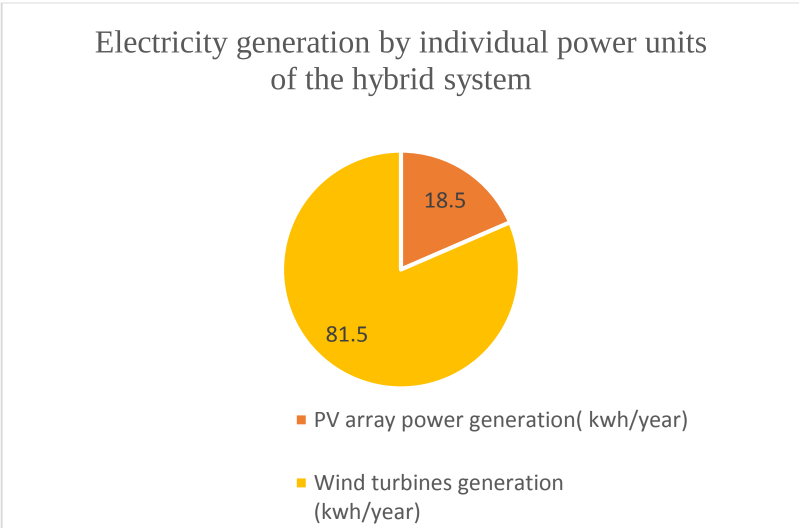


Figure 4.9: Power generation percentage share from each system components.

The total power production of this power system setup is 1420843 kWh/year, whereas the total electric power consumption of the AC load is about 591909 kWh/year, looking into the magnitudes of the power production and consumption of Figure 4.9, there is surplus of electricity. Although an excess electricity of 803876 kWh/year was produced, which is 56.6 % of the total energy generated but a capacity shortage of 551 kWh (0.09%) was experienced during the year. Actually this power system architecture indicates that it would enable to cater the demand growth of the industry in the future since the industry for the time being it operating under one section only (water production) but in future they will be operating under two section including Juice production, so the excess electricity which is about 56.6% have been reserved for that, also this excess electricity can provide to neighboring villages or introduce small businesses to increase the load factor of the power system; consequently the cost of electricity will decrease also. The quantities for the capacity shortage, unmet load and excess electricity generation are depicted in Figure 4.10.

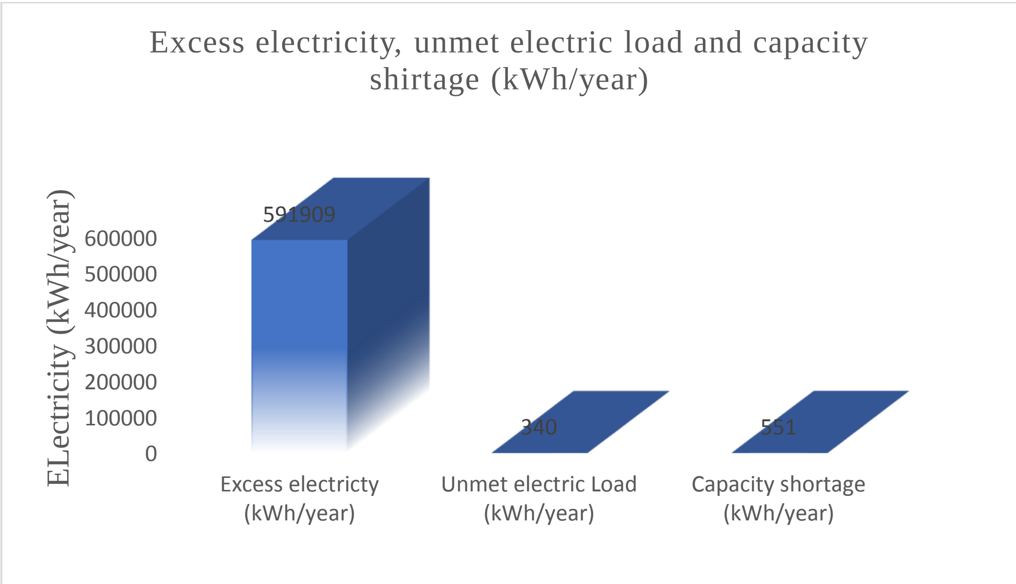


Figure 4.10: Capacity shortage, unmet load, and share of excess electricity.

The distribution of electricity production by the wind turbines is depicted in Figure 4.10 and Table 4.6 as well as Figure 4.11 which show Wind Turbine Power output throughout a year . As noticed the energy production by wind turbines is relatively higher in summer season (June, July, August, September and October) this is normally due to the higher wind flow as solar radiation gets lower. Maximum wind power output above 400 kW is registered during seven months from May till November. The levelized cost of electricity for wind turbine only is being 0.0014 $/kWh.

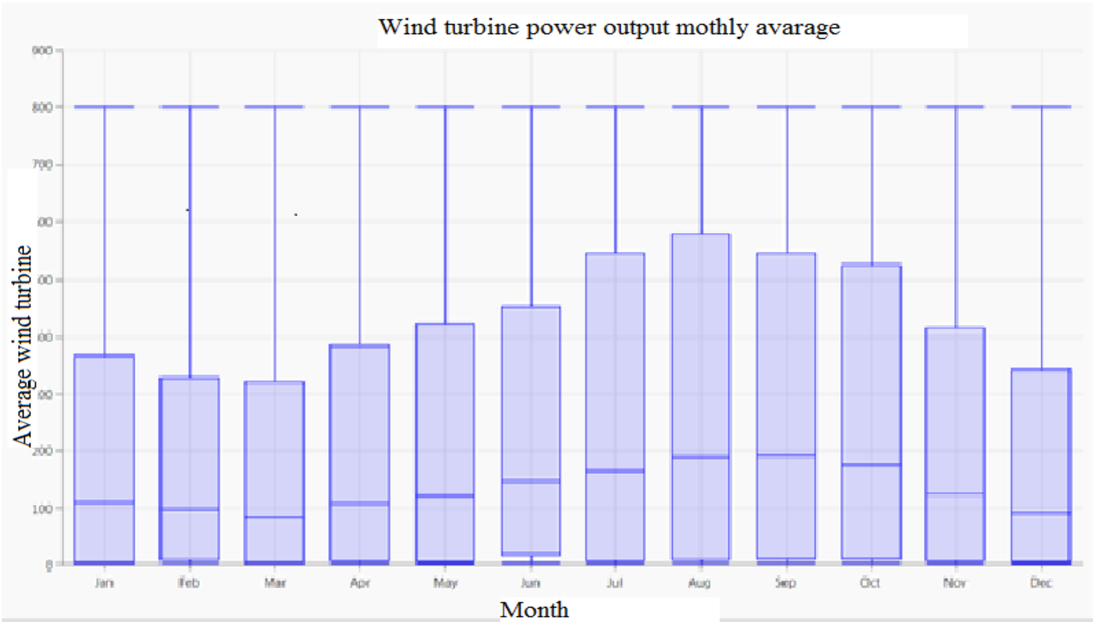


Figure 4.11: Wind turbine power output.

Table 4.6: Wind turbine scheme result.

Quantity	Value	Units
Total rated capacity	800	kW
Mean output	132	kW
Maximum output	800	kW
Wind penetration	196	%
Hours of operation	6482	Hrs/yr
Levelized cost of energy	0.0014	$/kWh

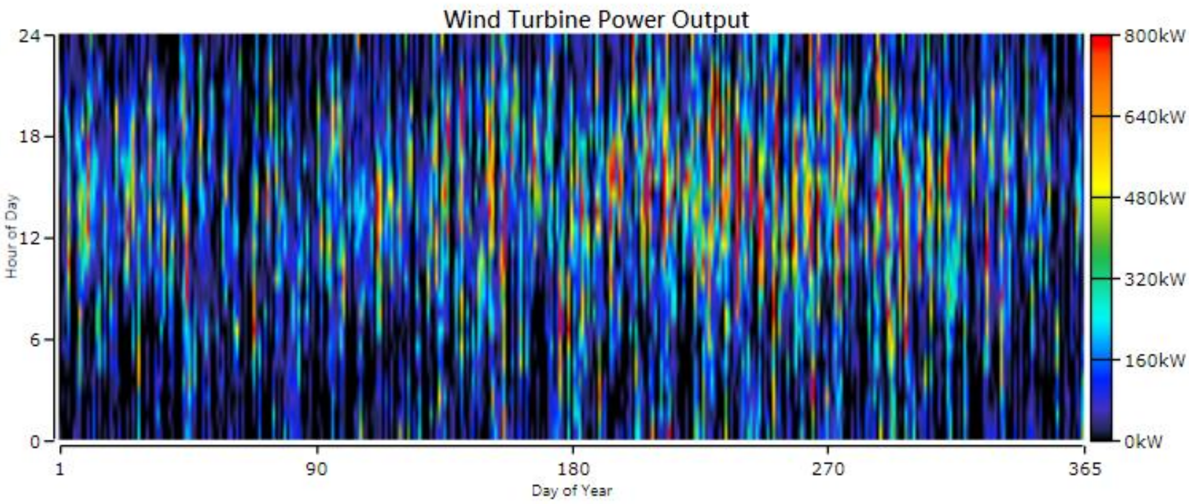


Figure 4.12: Wind turbine power output throughout a year.

Figure 4.13 and Table 4.7 as well as Figure 4.14 depicted the share of electricity generation via solar PV. As noticed from the figure, electricity generation is higher at the times of high solar radiation striking the earth's surface, of which February is the month that gets the largest amount of irradiation. Starting from May and June PV power generation is lower than the other months which is below 100 kW due to cloud coverage of the sky. Mean power output is about 30kW. The rated power output is 100 kW when sky is clear enough, and during no sun time the minimum power output is 0 kW. Daily high power output above 100 kW is registered in ten months such as; January, February, March, April, July, August, September, October, November and December. Solar PV total hours of operation is 4,303 hours per annum. Levelized cost of electricity only for this system case is about 0.191$/kWh.

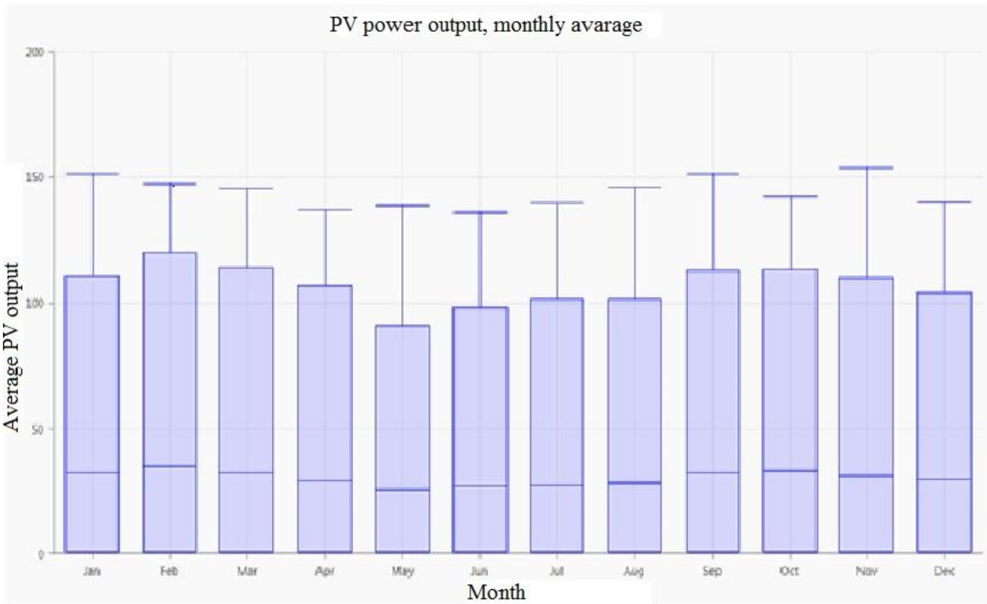


Figure 4.13: PV power production.

Table 4.7: PV Scheme simulation result.

Quantity	Value	Units
Total rated capacity	189	kW
Mean output	30	kW
Maximum output	154	kW
PV penetration	44.3	%
Hours of operation	4303	Hrs/yr
Levelized cost of energy	0.191	$/kWh
Mean Output	719	Kw/Day

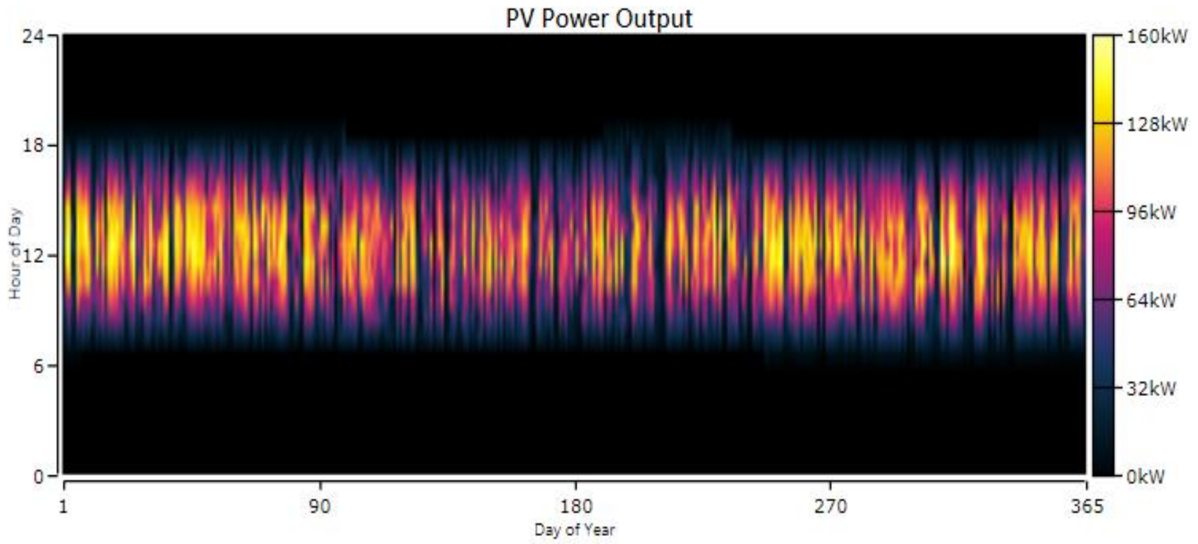
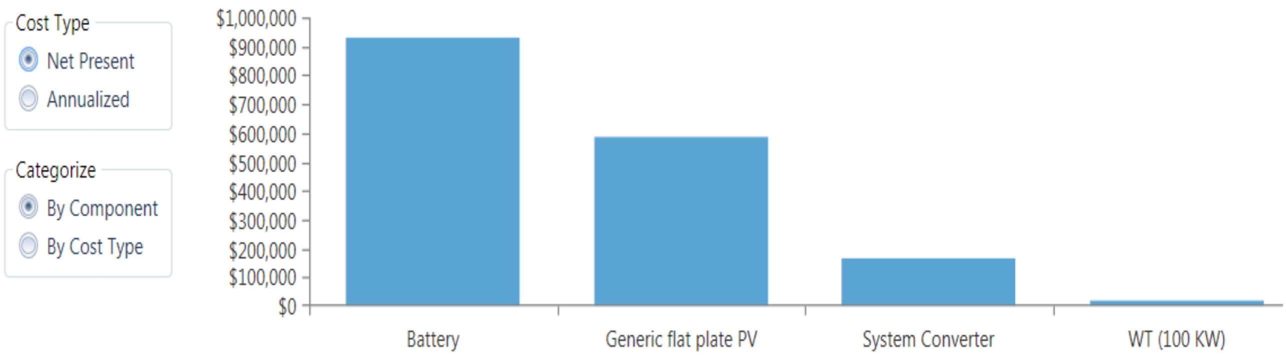


Figure 4.14: PV Power output throughout a year.

4.7.3.1 Cost summary of the system

It is clearly marked in Figures (4.15 & 4.16), although the initial Wind turbine has incurred low cost to purchase which is about 1.12% of the total capital cost, where the largest contributor is Battery, which costs a total NPC of 54.74% , followed with solar PV cost of 34.50% and converter with 9.64%.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery	$584,400.00	$316,400.21	$68,530.87	$0.00	($38,301.76)	$931,029.32
Generic flat plate PV	$524,941.54	$0.00	$61,912.13	$0.00	$0.00	$586,853.67
System Converter	$113,360.94	$29,041.95	$26,587.01	$0.00	($4,953.14)	$164,036.76
WT (100 KW)	$14,400.00	$2,638.84	$3,377.29	$0.00	($1,415.67)	$19,000.46
System	$1,237,102.48	$348,081.00	$160,407.30	$0.00	($44,670.57)	$1,700,920.21

Figure 4.15: Cash flow summary in terms of NPC by component type.

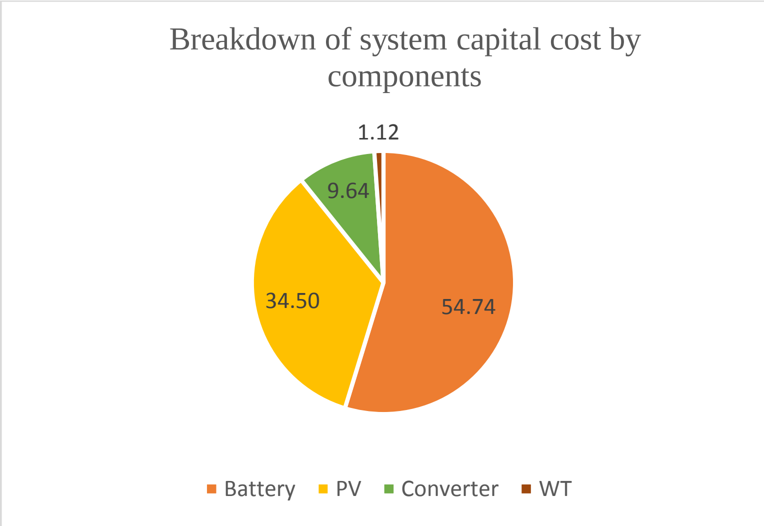
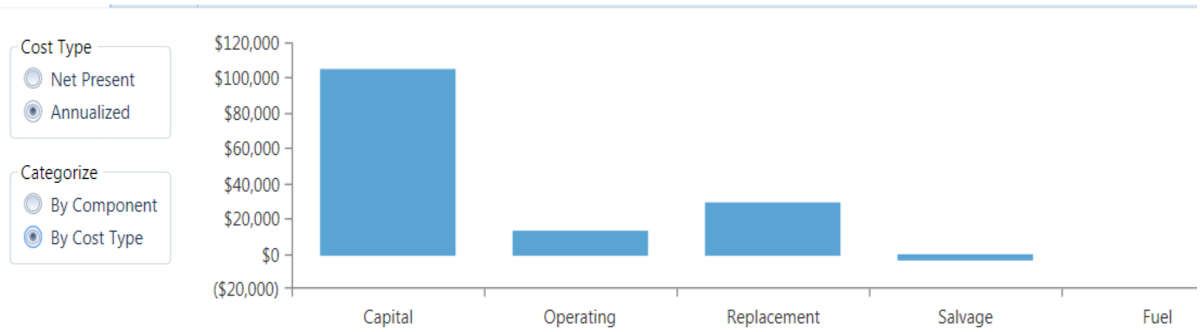


Figure 4.16: Capital cost percentage by components.

In Figure 4.16 displays the components cost flow summary for hybrid power scheme. It is easily noticed from the graph that total capital cost, total NPC of this optimal configuration is calculated to be $1237102.48, $1700920.21 respectively and COE is about 0.245$/kWh. Wind turbine contributed the lowest NPC with $1900.46, followed by the system converter that costs of $164036.76, PV had contributed the second highest cost and Battery the first for this system with cost shares of $586853.67 and $931029.32 respectively. The difference in COE of this system is not too much from the other one listed above. The highest share of the components was covered by capital cost and the second is from fuel followed by replacement cost, refer to Figure 4.17.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery	$49,834.97	$26,981.17	$5,844.00	$0.00	($3,266.20)	$79,393.94
Generic flat plate PV	$44,764.62	$0.00	$5,279.58	$0.00	$0.00	$50,044.21
System Converter	$9,666.90	$2,476.57	$2,267.22	$0.00	($422.38)	$13,988.31
WT (100 KW)	$1,227.97	$225.03	$288.00	$0.00	($120.72)	$1,620.27
System	$105,494.46	$29,682.76	$13,678.80	$0.00	($3,809.30)	$145,046.72

Figure 4.17: Cost breakdown of components by cost type.

4.8 SENSITIVITY ANALYSIS

Sensitivity is a measure of how the optimal mix of components changes for any parametric variations in the lifelong of the system. Optimal system design depends on interplay with various necessary input variables. When these input cases change, it is good to know how the optimum system changes with variation of the variables. Different sensitivity cases were carried out using variables of sensitivities like, design dependence on primary load, design dependence on diesel fuel, design dependence on maximum annual capacity shortage and minimum renewable fraction. The optimal system type, line graph and surface plot were used to make notes of the optimization results. In Figure 4.18 surface plot graph showing PV array capacity and wind turbine quantity variations with primary load and diesel fuel price is displayed. Considering only two of the sensitivity cases (electric load and diesel price) by keeping the other two variables as fixed (maximum capacity shortage at 10% and minimum renewable fraction at 40%), despite of the diesel price increment, PV size remained same as of the initial design (189 kW) and the quantity of wind turbines also left unchanged at 8 units. However with the rise of diesel price from \$0.9 to \$1.12/liter and primary load from 1622.6 kWh/day to 1925 kWh/day and, PV capacity changed from 189 kW to 251 kW but wind turbine quantities remains 8 units that is why its green colour throughout.

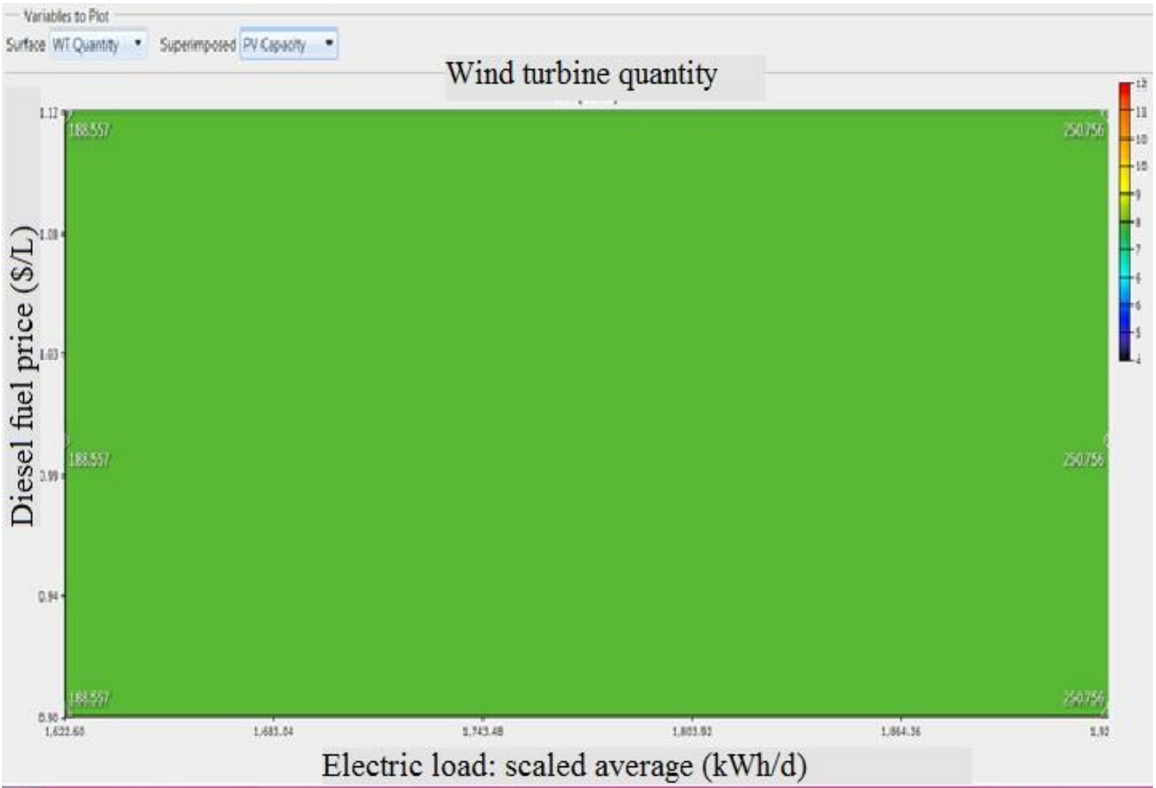


Figure 4.18: PV capacity and wind turbine quantity.

Again PV size and wind turbine quantity variations are seen in Figure 4.18, however the sensitive parameters are different from Figure 4.19, here maximum annual capacity shortage at 0% and minimum renewable fraction of the system at 60% are remained fixed, thus the only parameter that varies is the Industry primary load. With the increase of primary load, wind turbine quantities raise remains 08 units whereas PV size keep changing with the change of electric load as shown in figure below which means that solar panel capacity is affecting with load variation in this case. But with the increase of diesel price from $0.9 to $1.12/liter, solar panels size shift from 189 kW to 251 kW while wind turbines remains the same as 08 units.

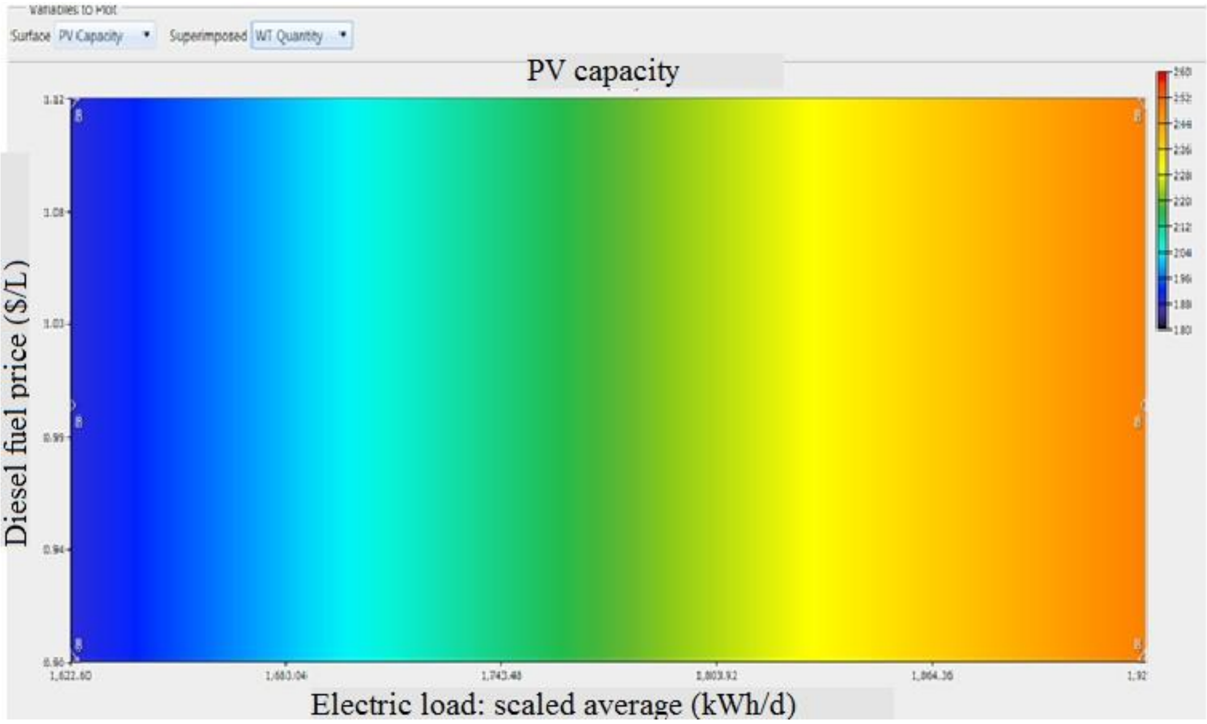


Figure 4.19: PV Capacity, wind turbine and electric load variations.

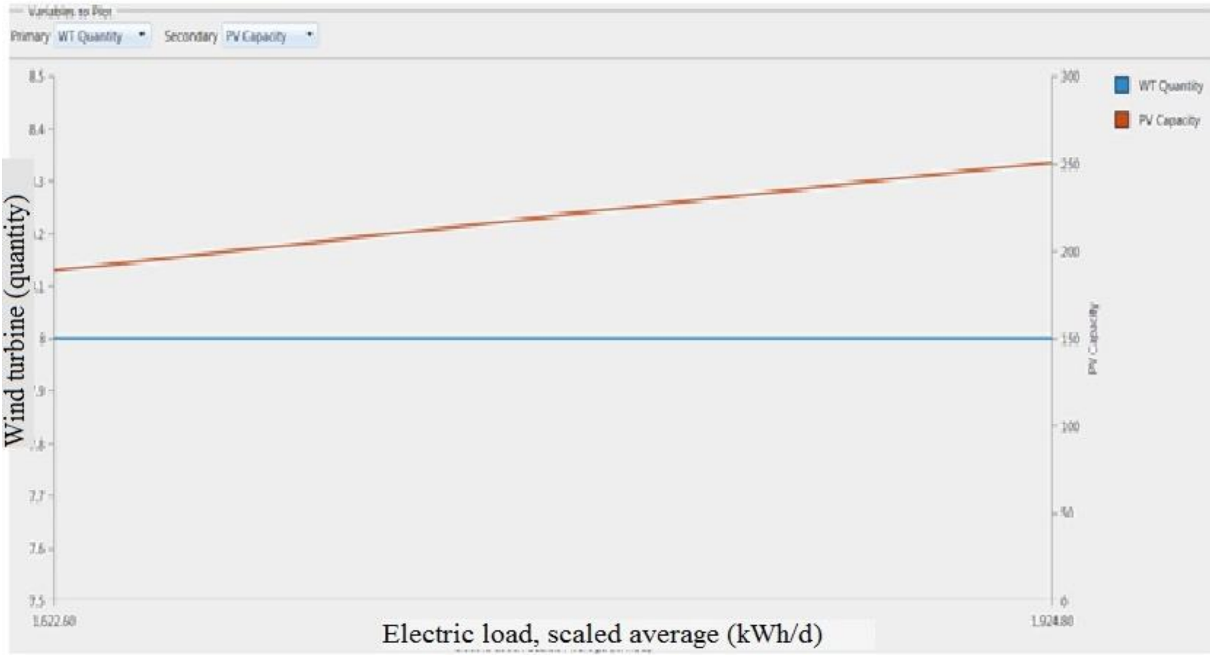


Figure 4.20: PV Capacity, wind turbine and electric load variations.

Another sensitivity analysis conducted in this section examines how PV size and Battery will change with the deviation of the sensitive parameters of NPC and COE. In Figure 4.20 the deviation of NPC and COE irelation to PV and number of battery is not constant. Some sensitivity cases are used as fixed values (diesel price at $1.12/liter, minimum renewable fraction at 60% and electric load fixed as 1622.6 kWh/d). What does indicated in the graph is, at small PV size the COE is also small and it increase with the increase of PV size as well as the NPC also increase. It is realized that the minimum cost of energy in this case is about $0.318/kWh.

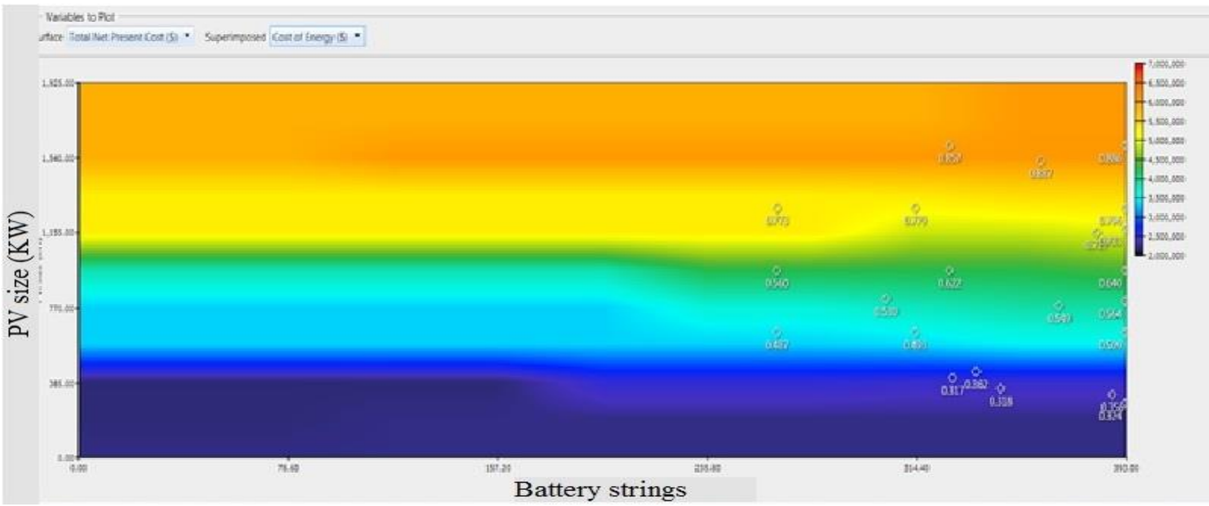


Figure 4.21: PV capacity, battery, COE and NPC variations.

Variation of PV size capacity and quantity of batteries with WT quantity and total fuel used per year is shown in Figure 4.22, quantity of wind turbine changes with the PV size changes, and again the number of batteries is increased as PV size is increased, although the amount of fuel seems to be so minimum especially when the number of wind turbine units increases.

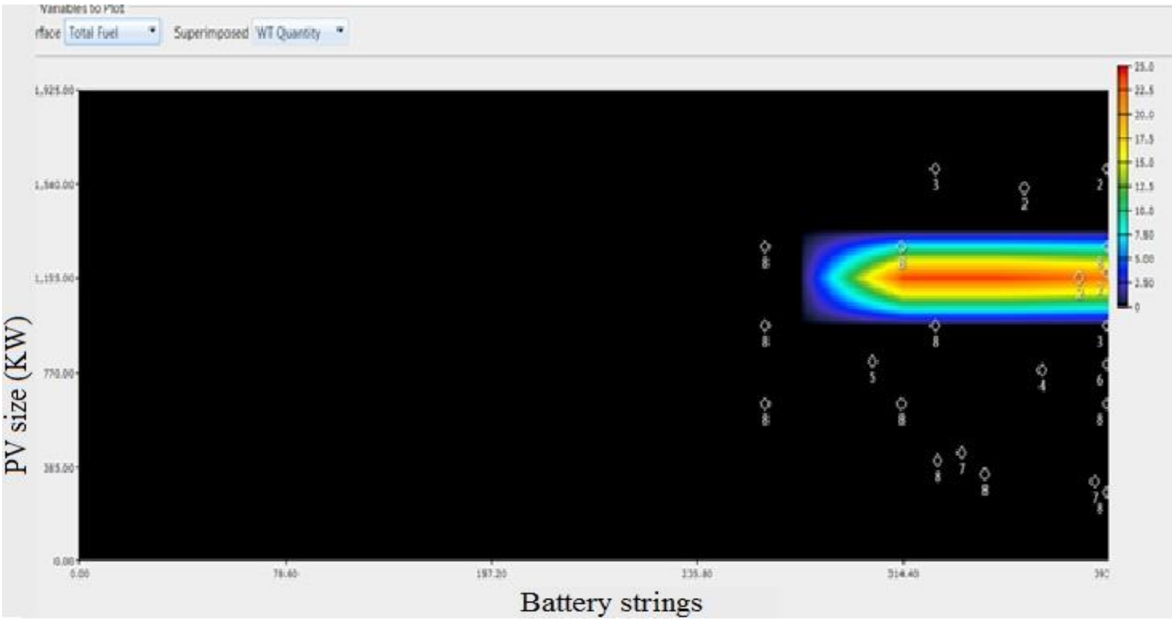


Figure 4.22: PV Capacity, battery, total fuel variations.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

This thesis work has been devoted to the design of an off-grid renewable hybrid power system for a selected industry which is Bellaview Fresh Fruit Processing Industry Ltd at Rombo in Kirimanjaro region in Tanzania, wind speed and horizontal global radiation for the selected industry have been obtained from Meteorological Department in Tanzania with respect to NASA. The average monthly profiles and hourly data for both sources were analyzed using HOMER, and the result displays wind and solar energy potentials are undisputable to exploit for the provision of electricity.

Electrifying small industry like Bellaview is now and will remain as challenging assignment for developing countries like Tanzania. To meet the energy requirement of the nation hybridizing renewable energy technologies can cater sustainable solutions. Currently, comparing renewable energy systems with conventional fuel powered plants and grid connected power systems, renewable hybrid schemes are not cost effective. Nonetheless, the necessity of environmental protection, farseeing the current living standard of rural communities and the incline of oil in global market forced to bring wise solutions that are environmental friendly technologies, hence renewable energy technologies are in the frontier.

During the design of the off-grid system set-up it was done an optimization process based on the electricity load, climatic data sources, and economics of the power components in which the NPC has to be minimized to select an economic feasible power system. HOMER simulation result displayed the most economical feasible system sorted by NPC from top to down, the prime system ranked first has renewable fraction of 100% containing of 8 unit wind turbines with 100 kW each rating power, 189 kW photovoltaic panel 487 unit batteries, and 142 kW converter. Sensitivity analysis was also performed for the system, different sensitivity cases were used such as; 2 values of primary loads, 3 cases of diesel prices and 2 cases of minimum renewable fractions. The sensitivity analysis showed that almost the same configuration was obtained except in some case there are quantity and size change of the components. The different setups resulted in this paper could be appropriate in areas that have the same climatic resources.

5.2 RECOMMENDATION

Across different corners of the country (Tanzania) there are renewable energy resources which varies from site to site, thus can be used for electricity generation either in grid or off-grid system. Electricity generation using off-grid systems form local renewables alleviates the country's electricity shortage. However, there are and will continue to face different challenges to implement such systems like; finance, infrastructures, absence of awareness how to use renewable resources and risk of taking decisions by investors and other related issues. To improve the energy deficiency at national and state level, grid and off-grid renewable energy technology systems should be promoted using different mechanisms including subsidy.

Empowering the rural communities' income to grow renewable generated electricity purchasing power is also fundamental. If due attention is given for land degradation, environmental pollution and development of small and medium industries renewable sources hybrid system should be implemented, however the current electrification of Tanzania government is based on constructing large hydropower dams and natural gases, but in order for Tanzania to become industrial country should now collaborate with private sectors to enable renewable energies which include wind power farms, furthermore PV system for individual industries where the system sound to be reliable and sustainable apart from high initial investment cost. Thus hybridizing of wind and solar should be given due merit which could be cost effective as it can provide a 24 hour quality electricity.

5.3 SUGGESTIONS FOR FUTURE WORK

- Considering current study with grid extension and solar thermal system instead of PV.
- The accurate electricity load consumption by the industry exposed to the study has to be calculated based on the availability of appliances in each sections.
- Renewable energy technology components accurate cost data has to be developed.
- High capacity computer should be ready for optimization, especially when considering various sensitivity cases analysis.
- In this study efficiency of components and temperature effects are not considered, thus studying with the inclusion of these two parameters could be done in future.

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ANNEX 1

Budget and Master thesis schedule

Item	Cost per Unit (USD $)	Qty	Total Cost
Research Material-Software			
Designing & Modelling Software Tools	720	1	720
Software Model Tools Training	250	1	250
Research Equipment/Material & Transport			
Internet bundle	150	1	150
Printing Services	120	1	120
Travelling Expenses			
Flight ticket for Internship & Data collection (Round Way)	1050	1	1050
Research Equipment setup tools			
Small Solar Panel	150	1	150
Sensor for solar irradiance	85	1	85
Datalogger	100	1	100
DC-AC converters	50	1	50
Fuel flow meter	135	1	135
Battery bank	140	1	140
GPS (hiring)	25	1	25
Cables	25	1	25
Total Expenses			**3000**

Work discripttion	**Time**						
	March	April	May	June	July	August	Sept
Internship							
Literature Review writting							
Site Vist and Data collection							
Data discussion and Report writting as well as consultation to the suppervisor							
Data discussion and Report writting as well as consultation to the suppervisor							
Internship report writting							
Thesis Defending & Graduation							