Pan African University
Institute of Water
and Energy Sciences

PAN-AFRICAN UNIVERSITY
INSTITUTE FOR WATER AND ENERGY SCIENCES
(including CLIMATE CHANGE)

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in

[ENERGY ENGINEERING]

Presented by

Flavio ODOI-YORKE

DESIGN OF SOLAR PV-BIOGAS HYBRID POWER SYSTEM FOR RURAL ELECTRIFICATION IN GHANA

Defended on 04/09/2018 Before the Following Committee:

Chair	**Abdellah Benyoucef**	**Dr.**	**Tlemcen University**
Supervisor	**Francis Kemausuor**	**Dr.**	**KNUST**
External Examiner	**Amine Boudghene Stambouli**	**Prof.**	**Oran University**
Internal Examiner	**Eric Tambo**	**Dr.**	**United Nations University**

DECLARATION

I, Flavio Odoi-Yorke, hereby declare that this thesis represents my personal work, realized 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.

13/09/2018
Flavio Odoi-Yorke ……………………….... ……………………….
(Student) (Signature) (Date)

Certified by:
13/09/2018
Dr. Francis Kemausuor ………………………… ……..………………….
(Supervisor) (Signature) (Date)

ABSTRACT

Globally, reliable access to electricity improves the well-being of people, provides quality education, and ensures good health. In this study, a solar PV-biogas hybrid power system for electrification is designed for Mankramso community located in the Offinso-North district in Ghana. The technical potential of crop residues and livestock manure available in the community for anaerobic digestion is assessed. Thereafter, the Hybrid Optimization Model for Electric Renewable (HOMER) software was used to perform technical, economic and greenhouse gas emission analysis. The daily electric load demand in Mankramso community was estimated at 262.05 kWh/d, for 400 households, school, health clinic, commercial loads (flour mills, cold store, and small businesses), church buildings and streetlights. The findings show that the system configuration which comprises of 18.6 kW of PV panels, 45 kW of biogas generator, 62 kWh of battery storage and 15.7 kW of converter is the most optimal hybrid power system configuration compared to other power system configurations to meet the daily electric load. The solar PV-biogas hybrid power system will generate annual electricity of 105,479 kWh/yr and the community AC loads will consume 95,633 kWh/yr of electricity. This optimal hybrid power system has levilized cost of energy (LCOE) of US$ 0.188/kWh and a total net present cost (NPC) of US$ 219,442. The LCOE is only 10.6% higher than current LCOE (US$ 0.17/kWh) for residential tariffs in Ghana. Moreover, sensitivity analysis on the effect of changes in nominal discount rate, components (PV panel, biogas generator and battery) prices and price of biomass feedstock on the optimal hybrid system LCOE and NPC is also presented. It is recommended that rural electrification projects of such nature are combined with innovative energy efficiency practices to help rural communities have access to reliable and affordable electricity.

Keywords: Solar PV, Biogas, Hybrid system, Mankramso Community, Hybrid Optimization Model for Electric Renewable (HOMER)

RÉSUMÉ

À l'échelle mondiale, un accès fiable à l'électricité améliore le bien-être des personnes, fournit une éducation de qualité et assure une bonne santé. Dans cette étude, un système d'énergie hybride solaire PV-biogaz pour l'électrification est conçu pour la communauté de Mankramso située dans le district d'Offinso-Nord au Ghana. Le potentiel technique des résidus de culture et du fumier disponible dans la communauté pour la digestion anaérobie est évalué. Par la suite, le logiciel HOMER (Hybrid Optimization Model for Electric Renewable) a été utilisé pour effectuer des analyses techniques, économiques et des émissions de gaz à effet de serre. La demande de charge électrique quotidienne dans la communauté de Mankramso était estimée à 262,05 kWh / j, pour 400 ménages, école, centre de santé, charges commerciales (minoteries, chambres froides et petites entreprises), églises et lampadaires. Les résultats montrent que la configuration du système qui comprend 18,6 kW de panneaux PV, 45 kW de générateur de biogaz, 62 kWh de stockage de batterie et 15,7 kW de convertisseur est la configuration de système d'alimentation hybride la plus optimale par rapport aux autres configurations charge électrique. Le système d'énergie hybride solaire PV-biogaz produira de l'électricité annuelle de 105479 kWh/ an et les charges AC communautaires consommeront 95633 kWh/ an d'électricité. Ce système d'énergie hybride optimal a permis d'obtenir un coût de l'énergie levé (LCOE) de 0,188 $ US/kWh et un coût actuel net total (NPC) de 219442 $US. Le LCOE n'est que de 10,6% supérieur au LCOE actuel (0,17 USD / kWh) pour les tarifs résidentiels au Ghana. En outre, une analyse de sensibilité sur l'effet des variations du taux d'actualisation nominal, des prix des composants (panneau photovoltaïque, générateur de biogaz et batterie) et du prix de la biomasse sur le système hybride optimal LCOE et NPC est également présentée. Il est recommandé que les projets d'électrification rurale de cette nature soient associés à des pratiques innovantes d'efficacité énergétique pour aider les communautés rurales à avoir accès à une électricité fiable et abordable.

Mots-clés: PV solaire, biogaz, système hybride, communauté Mankramso, modèle d'optimisation hybride pour le renouvelable électrique (HOMER)

ACKNOWLEDGEMENT

I thank the Almighty God for strength, wisdom, understanding and good health during my study at the Pan African University Institute of Water and Energy Sciences (including Climate Change). My sincere gratitude goes to the African Union through the African Union Commission (AUC) and all the partners of the PAUWES project for granting me the opportunity to undertake this master at PAUWES. Also, my appreciation goes to the AUC who provided me with research grant to carry out this research work. Furthermore, my profound appreciation goes to my supervisor, Dr. Francis Kemausuor at the Department of Biosystems and Agricultural Engineering-Kwame Nkrumah University of Science and Technology who took time out of his busy schedules to read through my bulky literatures and provided the best information to reshape this thesis to the present admirable form. I also, thank Mr. Van Dycke Asare Sarpong at Department of Physics of the Kwame Nkrumah University of Science and Technology who granted me access to use his office for my master thesis write up. Lastly, I thank my Parents, siblings, colleagues and friends for their effective and consistent prayers, love and support during my study. I love you all.

LIST OF ABBREVIATION

AC	Alternating Current
ATK	Aviation Turbine Kerosene
CEL	Cenit Energy Limited
CHP	Combined Heat and Power
CRF	Capital Recovery Factor
COE	Cost of Energy
D/A	District Assembly
DC	Direct Current
DPK	Dual Purpose Kerosene
ECG	Electricity Company of Ghana
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiation
GWh	Gigawatt hour
HOMER	Hybrid Optimization of Multiple Electric Renewables
HRES	Hybrid Renewable Energy System
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
ISSER	Institute of Statistical, Social and Economic Research
Kpone	Thermal Power Plant KTPP
K-T-T	Kumasi-Techiman-Tamale
kW	Kilowatt

kWh	Kilowatt hour
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
Mt	Million Tonnes
Mm3	Million Cubic Metre
MRP	Mines Reserve Plant
MW	Megawatt
NASA	National Aeronautics and Space Administration
NEDCo	Northern Electricity Distribution Company
NES	National Electrification Scheme
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
PJ	Petajoules
PV	Photovoltaics
RE	Renewable Energy
REN21	Renewable Energy Policy Network for the 21st century
RF	Recoverability Fraction
ROI	Return of Investment
RPR	Residue to Product Ratio
SDG's	Sustainable Development Goals
SOC	State of Charge
TAPCO	Takoradi Power Company
TT1PP	Tema Thermal 1 Power Plant

TT2PP	Tema Thermal 2 Power Plant
UNFCCC	United Nations Framework Convention on Climate Change
VALCO	Volta Aluminium Company Limited
VRA	Volta River Authority
WT	Wind Turbine
$/USD	United States dollars

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CHAPTER 1

1 INTRODUCTION

1.1 Background of study

Globally, access to energy plays a very keen and relevant role in socio-economic and sustainable development of every country. It plays pivotal role in performing human daily activities such as cooking, lighting, heating and transportation. According to the United Nation (UN) Sustainable Development Goals (SDG's), universal access to affordable, reliable and clean energy will transform the energy system as well as assist and contribute tremendously in meeting other SDG's such as poverty alleviation, good health, water supply, sustainable cities and mitigating climate change (IEA, 2017; IRENA, 2015a)

An estimated 1.1 billion people in the world do not have access to electricity and roughly about 588 million people live without electricity access in sub-Sahara Africa as at the year 2014 (REN21, 2017). A few African countries, including Ghana, have relatively higher access to electricity. As at the end of the year 2016, the electrification access rate in urban and rural areas in Ghana were 89.8% and 66.6% respectively (World Bank, 2018a). Deploying renewable energy solutions can expand electricity access, alleviate poverty, increase productivity, create jobs and improve water security (IRENA, 2015a). Presently, decentralized renewable energy systems such as standalone and mini-grid systems are categorized within cost-effective alternative energy choices required to expand and accelerate electricity access to many rural communities (IRENA, 2014). The aforementioned reasons have recently accelerated the promotion of clean energy policies and projects in almost all part of the world.

Over the decades, the combustion of fossil fuels such as oil, natural gas and coal have contributed tremendously in the world energy sector. Many scientific studies and research conducted all over the world depicts fossil fuels as a major producer of Greenhouse Gases (GHG) which causes drastic changes to the climate thus creating havoc to the environment. Furthermore, studies assert that fossil fuels will deplete in due time. Even though these conventional energy sources have negative impact in the world, they are still today's major source of energy for power generation and transportation in most developed and developing countries including Ghana.

Recent efforts to protect and save the environment from GHG emissions have led to the drafting and implementation of national and international policies to curb the use of fossil fuels. For instance, the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement is aimed at strengthening the global response to the threat of climate change, by keeping a global temperature rise below 2 degrees Celsius and also GHG emissions mitigation and adaptation. Additionally, it strengthens the ability of countries to deal with the impact of climate change (UNFCCC, 2015). Moreover, many countries have considered and directed state policies toward the utilization of biomass for meeting future energy demands to meet carbon dioxide reduction targets as specified in the Kyoto Protocol as means to decrease reliance and dependence on the supply of fossil fuels (Sarkar et al., 2012). Recent increase in electricity demands, depletion and rising prices of fossil fuels, depleting crude oil reserves, limited fossil fuels such as coal and environmental issues have resulted in global worldwide interest in renewable energy resources for power production (Hailu & Mezgebu, 2017; Sarkar et al., 2012).

Renewable energy plays an intense role in mitigating global GHG's emissions by drastically lowering the emissions profile of the global energy system (IRENA, 2015a). Renewable energy is free, environmentally friendly and available everywhere. It can offer a unique opportunity to provide electricity to people living in decentralized remote areas lacking access to the national grid as well as help tackle the issue of un-electrified communities in most developing countries. Many peri-urban and rural areas in Ghana lack access to reliable electricity from the utility grid. There are two main reasons that undermine the supply of electricity in these areas: (1), electricity supplied from the national grid is less than current electricity demand from the people (Ansong et al., 2017). (2), topographical locations in some localities prevents the extension of utility grid to remote areas (Ansong et al., 2017). The provision of electricity for remote areas in developing countries through grid extension can be very expensive and normally requires long-term planning. However, using decentralized power generation systems to supply electricity from locally available renewables like solar energy, biomass and wind energy, might be a better solution for developing countries (Sigarchaian et al., 2015). A long-term promising renewable energy resource like biomass has the ability to tackle environmental impacts, rising fossil fuels prices and security concerns posed by current dependence on fossil fuels (Ayamba et al., 2015).

The Government of Ghana "Renewable Energy Act", Act 832 ratified in 2011, encourage the development, management, utilization of renewables for power and heat production. Also, it aims to diversify the energy supply mix in the national energy supply (Government of Ghana, 2011). Ghana has policies that drive the deployment of renewable energy technologies which makes the country one of the leading countries with significant renewable energy (RE) regulatory and fiscal policies in Africa (Sakah et al., 2017). Presently, the Government has a target to increase the nation's share of renewable resources for power generation in the national energy supply mix to 10% by 2020 (Energy Commission, 2006). These aforementioned reasons aim to promote and encourage the utilization of solar energy and bioenergy for energy related activities in Ghana.

The intermittency of some renewable energy resources such as solar and wind has resulted in the development of hybrid energy systems. Generally, a hybrid system consists of two or more power generation based on renewable energy or fossil fuel units, that works in a standalone or grid-connected mode

(Bajpai & Dash, 2012; Sinha & Chandel, 2014). Recent studies vindicate that hybrid systems are popular for decentralized power generation in off-grid locations due to recent advancement in RE technologies. Most studies on the feasibility, reliability and economic analyses on hybrid system conducted shows that hybrid power systems are cost-effective and more reliable than single source power system (Adaramola et al., 2014). Furthermore, the advantage of utilizing hybrid renewable energy systems (HRES) helps to explore the combination of two or more renewable power generation technologies by making use of their operating characteristics and obtain higher efficiencies than that of single power source. Above all, hybrid systems can address limitations in terms of fuel flexibility, efficiency, reliability, emissions and economics (Bajpai & Dash, 2012).

1.2 Problem statement

- Most rural areas in Ghana lack access to electricity due to unavailable of grid power system – need to develop off-grid or standalone power systems.
- Intermittency of some renewable resources (solar and wind for example) – require the development of hybrid systems.
- High emissions from the combustion of fossil fuels – need to switch to cleaner power systems.
- Depletion of fossil fuels – need to develop alternative and renewable energy systems and increase the penetration of renewable power systems in the energy mix.
- Population growth – The future energy demand will increase due to population growth thus increase the energy production and diversification of the energy systems.

1.3 State of the art

Globally, many researchers have used diverse appropriate methods such as artificial intelligence, mathematical modelling, stimulation and optimization software to design and optimize hybrid renewable energy systems (Kaur & Segal, 2017). In this study, the Hybrid Optimization of Multiple Electric Renewables (HOMER) software will be used to perform stimulation and optimization of the Solar PV-Biogas hybrid power system.

In fact, many notable scientific studies on solar photovoltaics and biogas hybrid renewable energy systems (HRES) using HOMER software have been conducted in different parts of the world and documented in literature. Nevertheless, studies on HRES for rural electrification in Ghana is limited. However, a limited number of studies have been conducted in Ghana on HRES and available in open literature. Some of these prominent studies are discussed as follows:

(Addo et al., 2014), used iterative algorithm to design and determine the optimal number of generating units of wind-turbine generator, PV array, battery and diesel generator for a standalone hybrid power system for a cluster of villages at Bonsaaso in Ghana. The optimal configuration was found to consist of 92 PV panels, 9 wind turbines, 32 batteries, and 1 diesel generator. The simulations result depicted that the best solution to reliable load supply without interruption under climatic changes is the combination of PV-Wind-diesel generator hybrid system. Additionally, the hybrid PV-wind-battery-diesel power system can be considered as the optimum combination system which is capable of supplying the load demand at any hour in every day in a year with a zero-load rejection and minimum dumped power. Nevertheless, the results show that the authors exempted the addition of converter input in their optimal design since the hybrid system contains both AC and DC bus. Also, they did not perform emission analysis on diesel fuel to estimate the renewable energy fraction of the hybrid power system. Moreover, the levelized cost of energy of the optimum hybrid system was not estimated to make deductions to determine if the cost of electricity from the hybrid power system can compete with the cost of electricity from the grid. Lastly, they did not consider variation in the electric load demand for the community.

Also, (Adaramola et al., 2014), used HOMER software to perform economic analysis on the feasibility of utilizing solar/wind/diesel generator hybrid power system in an isolated location in southern Ghana. The most economic feasibility solution of the proposed hybrid system was based on two parameters; (1) Levelized Cost of Electricity (LCOE) and (2) Net Present Cost (NPC). The results show that the optimal power system which can meet the daily load comprises: 80 kW of PV panels, 100 kW of wind turbine, 100 kW of diesel generator, 60 kW of converter and 60 units of battery. This power system will produce an annual electricity of 791.1 MWh. Optimum LCOE and NPC for this hybrid system was found to be US$ 0.281/kWh and US$ 3,840,500 respectively. However, studies depict that, Ghana’s wind speed is moderate and only available in certain locations along the coast of Ghana as compared to biomass, hence, the findings of this research can only be employed and applied to locations with such characteristics.

(Adaramola et al., 2017), in another study on hybrid system in Ghana, used HOMER software to perform the feasibility of utilizing solar PV and jatropha biodiesel generator hybrid power system to provide electricity and domestic water to a remote community in the Upper West region of Ghana. They considered five different initial investment support scenarios: 100%, 75%, 50%, 25% and 0%. The optimal system configuration comprised of 30 kW of Solar PV, 364.8 kWh of battery storage, 30 kW converter and 10 kW generator. The investment cost, the net present cost (NPC) and the levelized cost of electricity (LCOE) are estimated at US$243,000, US$412,104 and $0.76/kWh respectively at 100% cost without any aid from the government or donor agencies. However, with a capital investment of 100%, the LCOE reduces to US$0.20/kWh with a NPC of US$109,520 compared with US$169,046.94 for a grid-based option. Nevertheless, jatropha for biodiesel production has not been fully exploited for commercial basis as a fuel to run on a generator for electricity production in Ghana. This problem will be a hindrance to the feasibility and implementation of this project.

Correspondingly, (Ansong et al., 2017) performed a technical and economic assessment of hybrid system to supply power for an off-grid mine using HOMER Software. The optimum hybrid system was based on the following parameters: lowest LCOE, minimum total NPC cost, high renewable fraction and low fuel consumption. The HOMER optimization results revealed that, 50 MW PV array, 15 MW of fuel cell system (which consists of 30 MW electrolyser and 25,000 tonnes of hydrogen storage tank), 600 batteries, 20.5 MW converter and 20 MW of diesel generator sets configuration was the best option needed to power an off-grid mine in Ghana producing 152.99 GWh of electricity per year. The optimum LCOE and NPC of the system was US$0.242/kWh and US$345.10 million respectively with a renewable fraction of 85% and emission quantity of 21.56 ktCO2/yr. Moreover, the LCOE determined from the optimal hybrid power system is over 28% lower compared to tariffs allocated to mines in Ghana.

1.4 Knowledge gap

However, the aforementioned notable studies on hybrid power systems in Ghana concentrated on the utilization of solar PV, wind turbine, fuel cells, diesel and biodiesel generators for power generation in Ghana. Moreover, there are no studies on hybrid power systems for Ghana in the open literature that focuses on the utilization of solar PV and biomass-biogas for rural electrification. Off-grid areas need to be electrified through mini-grids since grid extension might take longer time and to some extent it is very expensive. Consequently, the government target of achieving 100 % access to electricity and 10% share of renewables in the national energy generation mix by 2020 calls for more research and scientific works to conducted in the energy sector by utilizing available renewable energy sources to develop more reliable and cost-effective energy systems.

1.5 Research questions

- What are the biomass resources available and quantity that will be will be converted to biogas?
- What is the efficiency of converting raw biomass into electrical power?
- Can the Solar PV-Biogas hybrid power system meet the energy demand of the community?
- What is the capital cost of the Solar PV-biogas hybrid power system and what is the return of investment?
- What is the cost of energy from the HRES?

1.6 Research hypothesis

- Daily solar global horizontal irradiation (GHI) in Mankramso community is sufficient to be converted into sustainable electricity.
- Biomass feedstock available in Mankramso community can be sustainably converted into biogas to produce electricity to meet the community energy demand.
- Solar PV-biogas hybrid power system can supply sustainable electricity to meet the community energy demand.
- The cost of energy from the HRES will be competitive compared to the cost of energy from the national grid.

1.7 Research objectives

1.7.1 Main objective

- To design and optimize an off-grid solar PV-biogas hybrid power system for rural electrification in Mankramso community in Ghana.

1.7.2 Specific objectives

- To estimate daily electrical load demand for Mankramso community.
- To assess the technical potential of crops residues and livestock manure available for anaerobic digestion.
- To model, stimulate and optimize the Solar PV-biogas hybrid power system using HOMER Pro software.
- To perform technical, economic and greenhouse gas (GHG) emission analysis of the hybrid System using HOMER Pro software.

1.8 Significance of this study

- Provide clean and sustainable electrification options via hybrid renewable energy system (HRES) to improve electricity access in remote areas and contribute tremendously in abating climate change in Ghana.
- Contribute and consolidate to increase in the share of renewables in the national energy mix.
- Enhance food security via the use of crop and livestock residues instead of utilizing edible food crops for electricity generation.
- Alert and inform policy makers to facilitate investment into renewable and clean energy technologies using crops and livestock’s residues as feedstock.

- Raise awareness to policy makers on off-grid HRES as a viable key to the current electricity deficit and un-electrified areas in the country, whereas providing some key recommendations to better renewable energy policy.
- It will add and increase recent knowledge on renewable energy, hence, researchers and students can make inference for their scientific research.

1.9 Delimitation and limitation of research

- One of the major challenges to be faced is the seldom insufficient solar energy and biomass resources.
- Another challenge is seeing through the full implementation of the research idea on a large scale and its widespread locally, internationally and globally.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Overview of Ghana energy sector

2.1.1 Brief description of Ghana

The Republic of Ghana is located in the western part of Africa. It lies in the geographic location of latitude: 4° 30′ and 11° North; and longitude 1° 11′ East and 3° 11′ West respectively. It shares boundaries with Burkina Faso to the North, Togo to the East, and Cote d'Ivoire to the West and the Gulf of Guinea and the Atlantic Ocean to the South respectively (see Figure 2.1).

Figure 2.1: Political map of Ghana

Source: (Nationsonline, 2002)

The country's total land area is about 238,842.45 square kilometers and is divided into 10 administrative regions and 216 administrative districts (Ghana Statistical Service, 2017; Ministry of Food and Agriculture, 2015). However, agricultural land area covers about 136,000 square kilometers representing 56.94% of the total land area of which total cultivated land is 64,214.5 square kilometers, which represent 47.22%. The area under inland waters, forest reserves, savanna and woodland cover an area of 88,560.21 square kilometers representing 41.2% (Ministry of Food and Agriculture, 2015).

The country's Gross Domestic Product (GDP) growth was around 5.5% from the year 2001-2009. Moreover, the GDP grew to 7.8% and 14.0% in the year 2010 and 2011 respectively (Ghana Statistical Service, 2017). This fast growth was due to the production of crude oil which commenced in the year 2010 (IRENA, 2015b). At the end of the year 2017, Ghana population was estimated at 28.96 million with a population growth rate of 2.3% per annum and the GDP was estimated at US$47.3 billion. The GDP showed a growth rate of 8.5% compared to 3.7% in 2016 as summarized in Table 2.1.

Table 2.1: Ghana Gross Domestic Product growth rates from 2009 – 2017

Economic parameter	2009	2010	2011	2012	2013	2014	2015	2016	2017
GDP current (billion US$)	25.8	32.2	39.5	41.7	48.7	38.6	36.3	42.7	47.3
Per capita GDP (US$)	1100	1305	1566	1613	1841	1428	1311	1508	1632
Growth Rate (%)				%					
GDP at current market prices	21.3	25.8	29.9	25.9	24	21.3	20.8	22.2	23
GDP at constant 2006 prices	4	7.9	14	9.3	7.3	4	3.8	3.7	8.5

Source: Data from (Ghana Statistical Service, 2017)

The service sector is the main the pillar of the economy because it contributes higher to Ghana's GDP. The service, industry and agriculture sectors accounted for about 56.2%, 25.5% and 18.3% respectively of the country's GDP in 2017 (Ghana Statistical Service, 2017). Figure 2.2 shows the GDP growth share for each economic sector from 2006-2017.

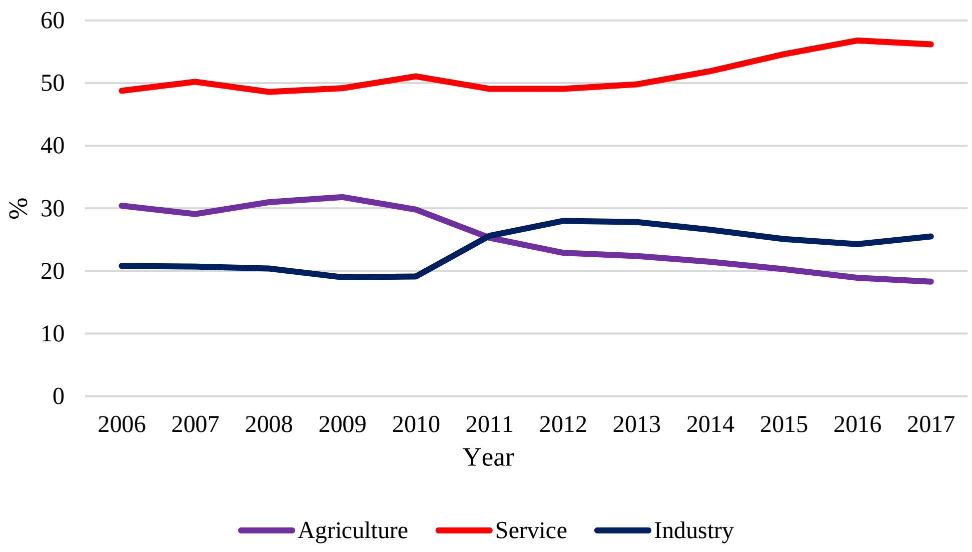

Figure 2.2: Sector growth rates in Ghana, 2006 – 2017

Source: Data from (Ghana Statistical Service, 2017)

2.1.2 Electricity situation in Ghana

Over the years, Ghana's electricity generation sector has shown a transition from one phase to another phase: Firstly, industrial mines and factories which had their own diesel generators and standalone power systems, then to the building of the Akosombo dam and lastly to the phase where most thermal plants are powered with gas and light crude oil (Eshun & Amoako-Tuffour, 2016). The Ghana power sector has suffered severely from intermittency of power supply resulting in negative impact on the socio-economic development of the country. For instance, Ghana suffered severe power rationing in the following periods: 1983-1984, 1997-1998, 2003, 2006-2007, 2011-present due to low levels of water in the Akosombo dam and fuel supply challenges and natural gas shortage (Kemausuor & Ackom, 2017; Kumi, 2017).

Almost 1.8% of Ghana's GDP was lost during the 2007 power crises (Kumi, 2017). In addition, the power crises affected Ghana's productivity and economic growth which caused the country to lose between U$320 million and U$924 million per year at the end of the year 2014 (Eshun & Amoako-Tuffour, 2016).

Over the years, Ghana's electricity generation was chiefly derived from hydropower with a little portion derived from thermal plants (see Figure 2.3). Until recently, hydropower was the major source of power supply. Nevertheless, recent low flow of water into the dams during the dry seasons as impelled the government to explore alternative energy sources such as thermal and renewables (see Figure 2.3).

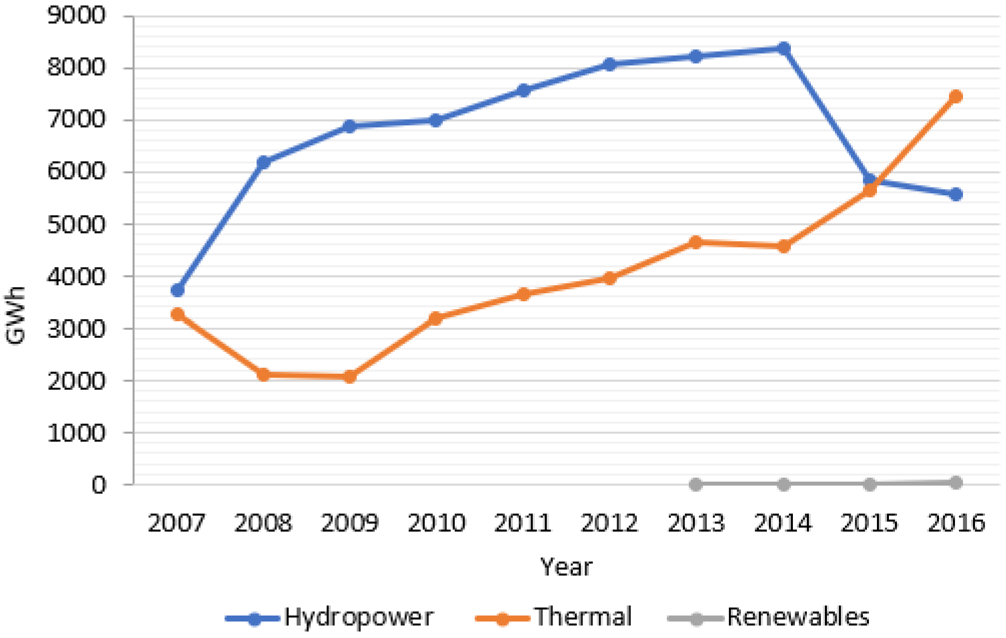

Figure 2.3: Trend in electricity generation by plant (GWh) per installed capacity (MW) from 2007-2016
Source: Data from (Energy Commission, 2017b)

Moreover, in recent years, the country has been able to introduce some amount of renewable energy into the electricity generation mix. As at the end of year 2016, the country's total electricity generation was estimated at 12978 GWh, about 13% more than in 2015, with 56.2% being generation from thermal power plants, 42.9% from hydropower and the remaining 0.20% from renewables (see Figure 2.4) (Energy Commission, 2017a). Additionally, the grid electricity made available for gross transmission was estimated at 13533 GWh, with 55% being generation from thermal plants, 41% from hydropower, and about 3.8% from imports (see Figure 2.5). Furthermore, about 410.46 GWh of electricity was transmitted to Togo and Benin comprising of 186.52 GWh power exported from Volta River Authority (VRA) and 223.94 GWh wheeled from Cote d'Ivoire (Energy Commission, 2017a).

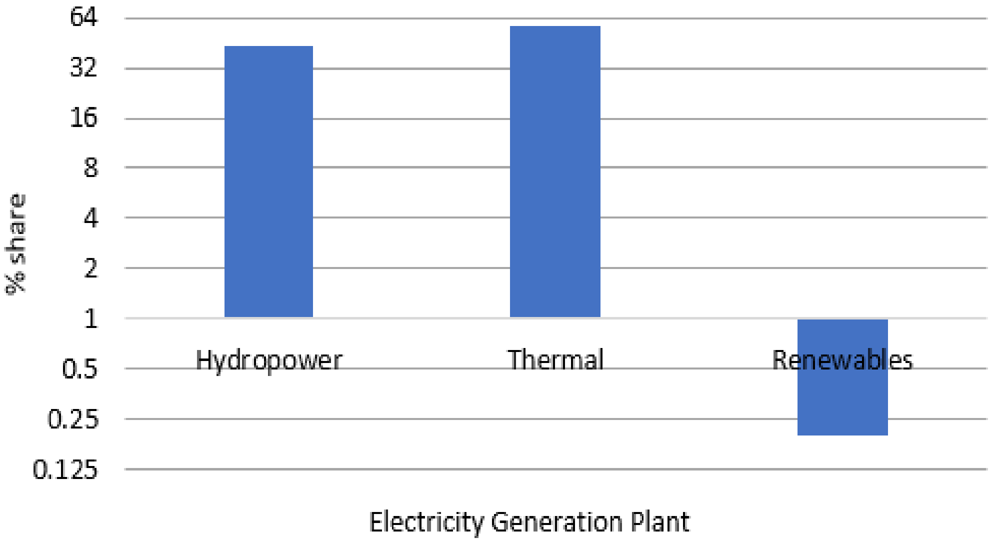

Figure 2.4: Electricity generation mix in 2016

Source: Data from (Energy Commission, 2017b)

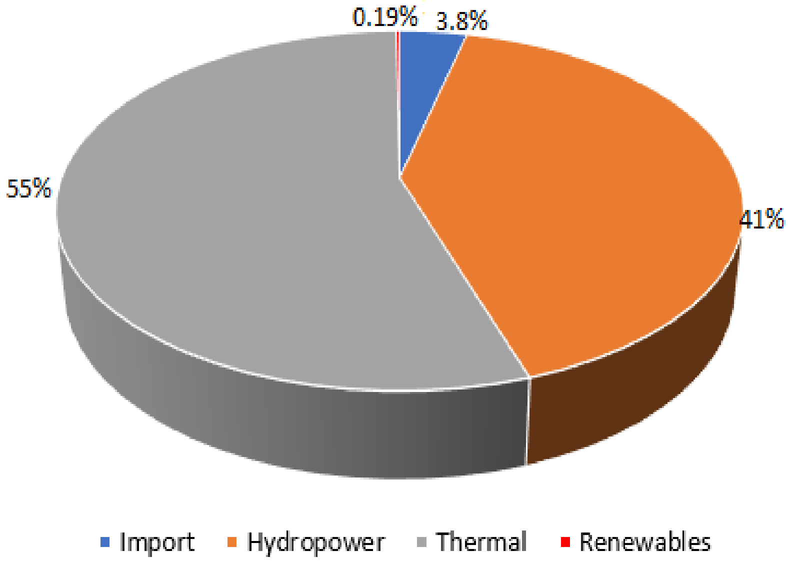

Figure 2.5: Electricity generation mix including imports in 2016

Source: Data from (Energy Commission, 2017b)

Furthermore, as at the end of the year 2016, the overall electricity generation capacity installed and dependable capacity available for grid power supply was 3794.6 MW and 3481.1 MW respectively. Also, grid installed capacity of all the thermal plants was estimated at 2172 MW representing 57.8%, whiles hydropower plants was estimated at 1580 MW representing 41.9% and renewables was estimated at 22.6 MW representing 0.6% respectively of the total installed capacity. The installed grid renewable plants consist of 100 kW plant from Safisana biogas, 2.5 MW from VRA Solar and 20 MW from BXC Solar (see Table 2.2) (Energy Commission, 2017a). From these figures, it can be concluded that renewables for electricity generation still lag behind in the electricity generation mix. This share of renewables is significantly small in regard to the government agenda to increase renewables to 10% in the national energy supply mix by the end of the year 2020.

Table 2.2: Installed generation facilities in Ghana as of 2016

Plant	Fuel Type	Installed Capacity (MW)	Average Dependable Capacity (MW)	% of Installed Capacity
Hydro				
Akosombo	Hydro	1020	1000	41.9
Bui	Hydro	400	360	
Kpong	Hydro	160	148	
Thermal				
Takoradi Power Company	Oil/Natural gas	330	300	57.8
Takoradi International Company	Oil/Natural gas	340	320	
Sunon Asogli Power (Ghana)	Natural gas	200	180	
Sunon Asogli Power (Ghana)	Natural gas	180	170	
Cenit Energy Ltd (CEL) - IPP	Natural gas/Oil	126	100	
Tema Thermal 1 Power Plant	Natural gas/Oil	126	100	
Tema Thermal 2 Power Plant	Natural gas/Oil	50	45	
Mines Reserve Plant (MRP)	Natural gas/Oil	80	70	
Kpone Thermal Power Plant	Oil/DFO	220	200	
Karpowership	HFO	225	220	
Ameri Plant	Natural gas	250	240	
Trojan	Diesel/Natural gas	25	22	
Genser	Coal/LPG	20	18	
Renewables				
Safisana Biogas	Biogas	0.1	0.1	0.6
VRA Solar	Solar	2.5	1.5	
BXC Solar	Solar	20	10	
Total		**3774.6**	**3504.6**	

Source: Data from (Energy Commission, 2017b)

2.1.3 Electricity access situation

Approximately 632 million people in sub-Sahara Africa live without access to electricity as at 2014. In addition, about 35% of the total population living in sub-Saharan region have access to electricity in 2014 (REN21, 2017). Table 2.3 shows regional electricity access rate in 2014.

Table 2.3: Electricity access by region

Region	Electrification Rate in 2014	Population lacking electricity access in 2014
	Share of population with access	*Millions*
Africa	45%	634
Northern Africa	99%	1.3
Sub-Sahara Africa	35%	632
Developing Asia	86%	512
Latin America	95%	22
Middle East	92%	18
Transition Economies & OECD	100	1
World	84	1186

Source: Data from (REN21, 2017)

Over the years, even though the country finds itself saddled with unreliable power supply challenges, electrification access rate has shown drastic increment (see Figure 2.6).

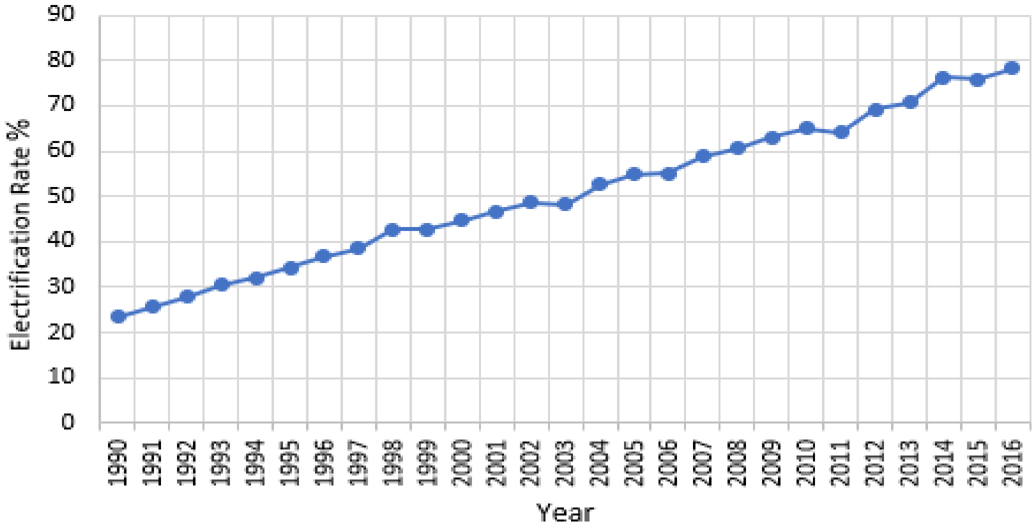

Figure 2.6: Trend in electricity access rate in Ghana, 1990-2016

Source: Data from (World Bank, 2018a)

As at 2013, electricity from the utility grid covered more that 70% of country, which makes Ghana's electrification access rate to outshine other West African neighbours (Kemausuor & Ackom, 2017). The country recorded approximately 78.3% as electricity access rate in 2016, which makes it the second highest electrification access rate country in West Africa, aside Cape Verde (See Figure 2.7). Presently, the government has set a target to achieve 100% electrification rate in the country by 2030 (Government of Ghana, 2011). Meanwhile, since electricity consumption has a direct link with human development, hence, Ghana and other sub-Saharan countries still need to work harder to achieve 100% universal electricity access in respective countries.

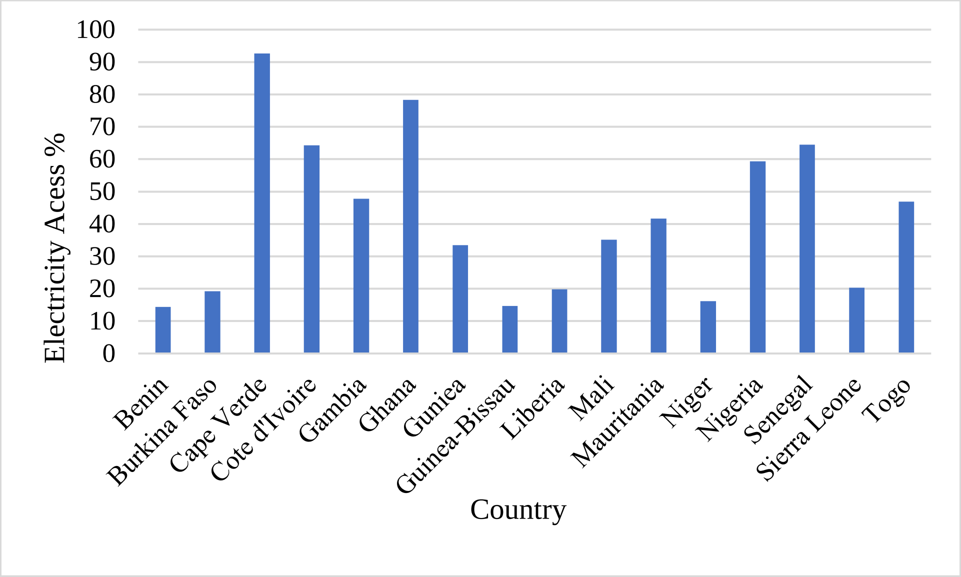

Figure 2.7: Electrification access rate in ECOWAS region
Source: Data from (World Bank, 2018b)

Energy consumption has effect on the development of a country. Ghana’s electricity consumption per capita has shown a drastic increment with a little fluctuation over the years (see Figure 2.8). As at the end of the year 2016, electricity consumption per capita was estimated at 403.5 kWh/capita.

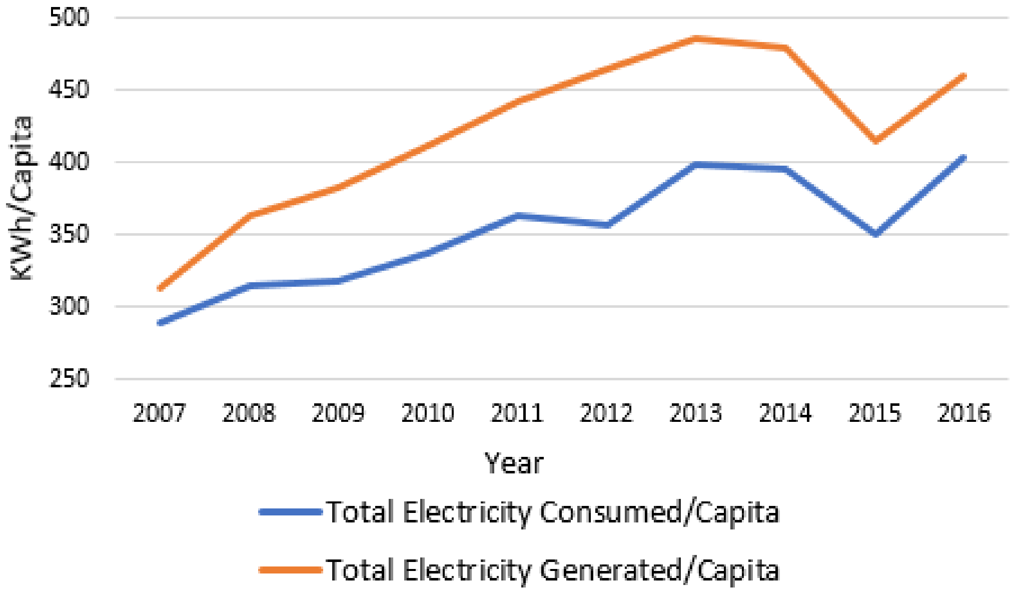

Figure 2.8: Trend in electricity generated per capita and electricity consumed per capita from 2007 – 2016

Source: Data from (Energy Commission, 2017b)

2.1.4 Energy demand and supply in Ghana

2.1.5 Primary energy supply

Over the decades, biomass has been a major primary energy supply in Ghana. Biomass dominated over oil, natural gas and hydro and accounted for almost 50% of the total primary energy supply from the period of 2007 – 2012. Oil started to dominate over other primary energy supply from the year 2013 – 2016 (see Figure 2.9). As at the end of the year 2016, oil accounted for 50.61% of the total primary energy supply, which makes it the commonly used energy in the country whiles biomass, natural gas, hydro and solar accounted for 37.29%, 7.12%, 4.59% and 0.02% respectively. See Figure 2.9 for the trend in primary energy supply, 2007 – 2016.

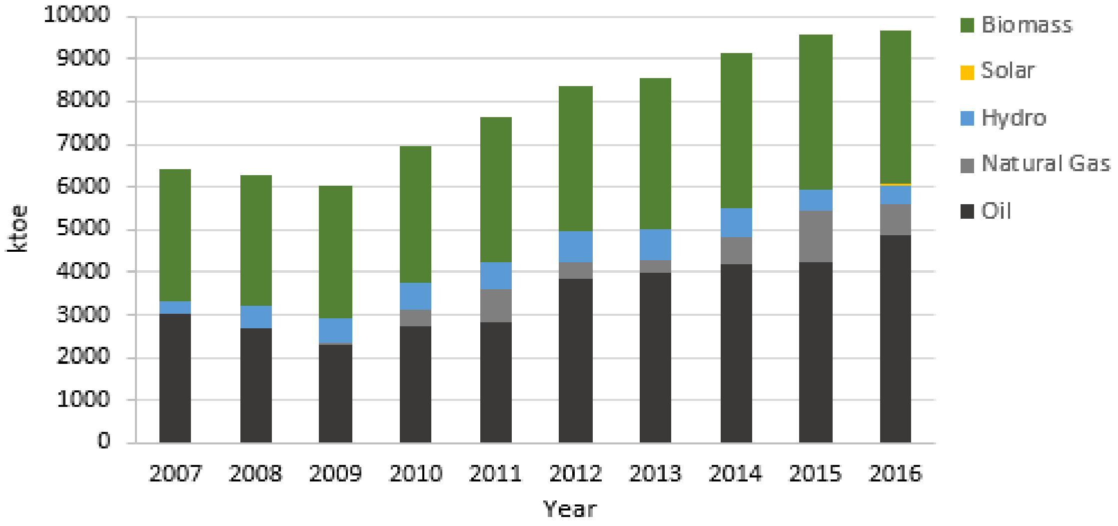

Figure 2.9: Trend in primary energy supply, 2007-2016
Source: Data from (Energy Commission, 2017b)

2.1.6 Final energy consumed

The Ghana Energy Commission categorized final energy consumption into three groups, namely, electricity, petroleum products and biomass. Petroleum products which consists of liquefied petroleum gas (LPG), kerosene, gasoline, gas oil, aviation turbine kerosene (ATK), fuel oil, dual purpose kerosene (DPK) dominates as the most widely consumed final energy in Ghana (see Figure 2.10) (Energy Commission, 2017b). As at the end of the year 2016, petroleum products accounted for 47% of the total final energy consumed followed by biomass which accounted for 39% and electricity which accounted for 14% respectively (see Figure 2.11). Figures from 2010 population and housing census revealed that about 17.8% of the population in Ghana depend on kerosene as a source of energy for lighting. In addition, more than 18% of households use LPG as a cooking fuel and less than 1% of households use kerosene and electricity for cooking (IRENA, 2015b). A report from (REN21, 2017) revealed that roughly 82% of the Ghanaian population relied on traditional biomass for cooking in the year 2014. Figure 2.10 shows the trend in final energy consumed (ktoe) from the year 2007 – 2016.

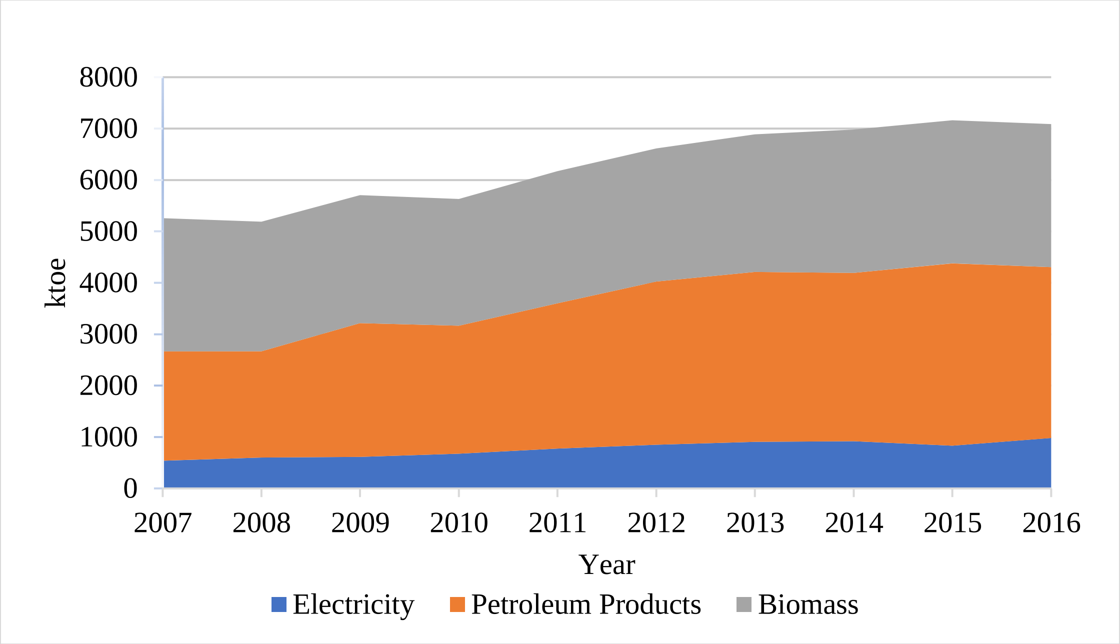

Figure 2.10: Trend in final energy consumed (ktoe), 2007 – 2016

Source: Data from (Energy Commission, 2017b)

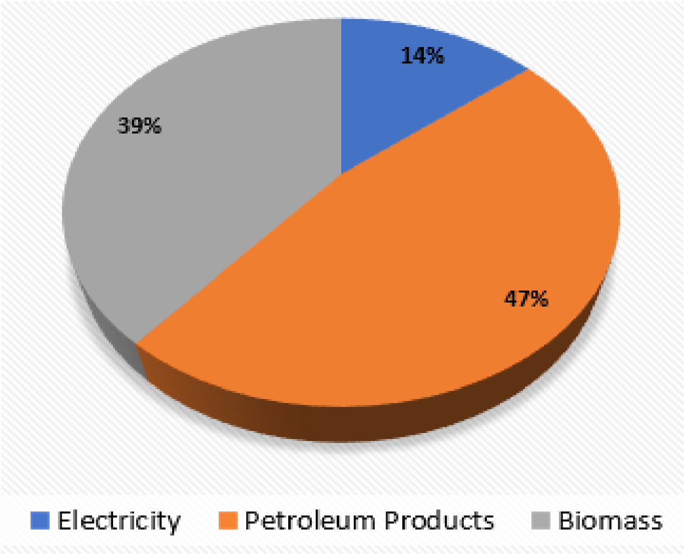

Figure 2.11: Percentage share of final energy consumed in 2016

Source: Data from (Energy Commission, 2017b)

Biomass consumed in Ghana consists of firewood, charcoal, sawdust, sawmill residues, crop and animal residues, etc. About 90% of wood fuel consumed in Ghana mostly emanates from the natural forest. However, the 10 % remaining originates from wood waste like sawmill residues and plantations (IRENA, 2015b). Firewood is the most consumed wood fuel in the country. As at the end of 2016, firewood, charcoal and other (sawdust, sawmill residues etc.) consumed was estimated at 1540 ktoe, 1214 ktoe and 29.4 ktoe which represents 55%, 44% and 1% respectively of the total woodfuel consumed in 2016 (see Figure 2.12).

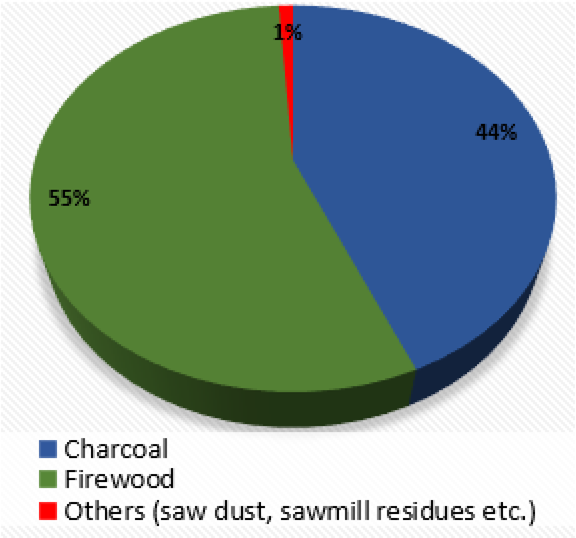

Figure 2.12: Percentage of Woodfuel consumption in 2016

Source: Data from (Energy Commission, 2017b)

The Energy Commission of Ghana classify electricity consumers into categories, namely, residential, non-residential, special load tariff and street lighting. Special load tariff refers to customers of Electricity Company of Ghana (ECG) and Northern Electricity Distribution Company (NEDCo) as well as bulk customers of Volta River Authority (VRA) including Volta Aluminium Company Limited (VALCO), the mining companies and other production and manufacturing facilities (IRENA, 2015b). Special load tariff is regarded as the major consumer of electricity in the country (see Figure 2.13). As at the end of the year 2016, special load tariff customers consumed approximately 4528 GWh of electricity as compared to residential, non-residential and street lightning which consumed 3932 GWh, 1066 GWh and 603 GWh of electricity respectively. Electricity transmission losses and electricity exported to other countries was estimated at 607 GWh and 187 GWh respectively in the same year (Energy Commission, 2017b). Figure 2.13 shows the trend in electricity consumption pattern by customer class in Ghana from 2007 – 2016.

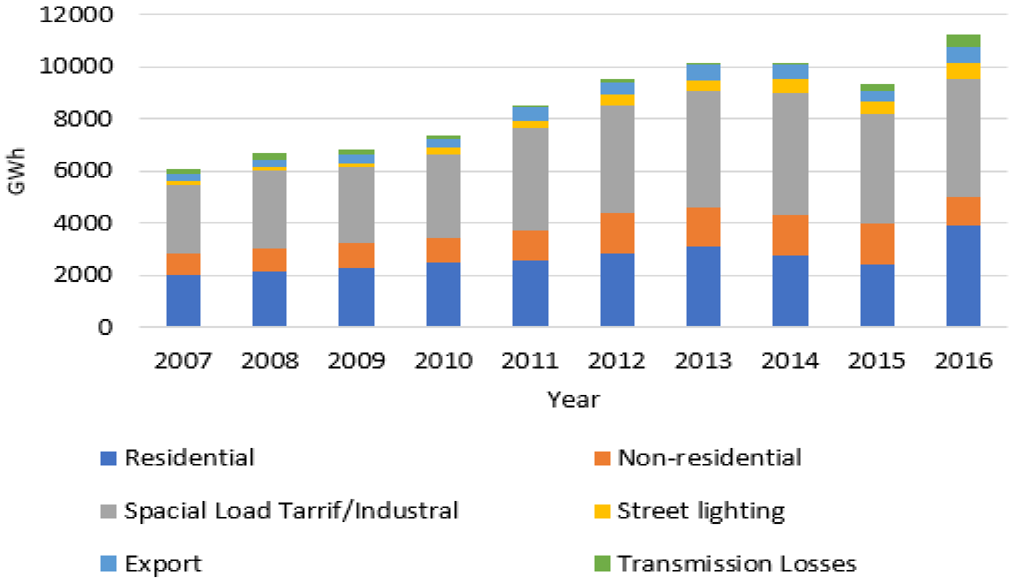

Figure 2.13: Trend in electricity consumption pattern for Ghana, 2007 – 2016

Source: (Energy Commission, 2017b)

2.2 Renewable energy potential and development status in Ghana

Ghana is well gifted with abundant renewable resources, namely, solar energy, modern biomass, wind energy, tidal wave and small, mini and large hydro. These resources can be harnessed efficiently to boost and accelerate electricity access, contribute in combating climate change, abate environmental issues and create sustainable jobs in the country. However, most notable recent studies conducted depicts that only a little portion of these renewables have been exploited in the country.

2.2.1 Solar energy

Ghana's monthly average solar irradiation ranges from 4.5-6.0 kWh/m^2/day. The country enjoys abundant sunshine hours which include 5.3 hours at Kumasi in the cloudy semi-deciduous forest region to 7.7 hours at Wa in the dry savannah region (IRENA, 2015b). Moreover, the northern part of the country which includes the Brong-Ahafo region experience a monthly average solar irradiation between 4 - 6.5 kWh/m^2/d. In addition, certain areas in Brong-Ahafo region, Ashanti region, Western region, Eastern region and some portions of Central region and Volta region have monthly average solar irradiation level range of 3.1-5.8 kWh/m^2/day. Lastly, the Greater Accra and the Central and Volta coastal regions have monthly average radiation levels between 4.0-6.0 kWh/m^2/day (see Figure 2.14) (Bensah et al., 2014). Moreover, these high solar irradiation level makes many parts of the country potential for installation of solar energy systems, particularly communities located in northern regions where electrification access rate is very poor.

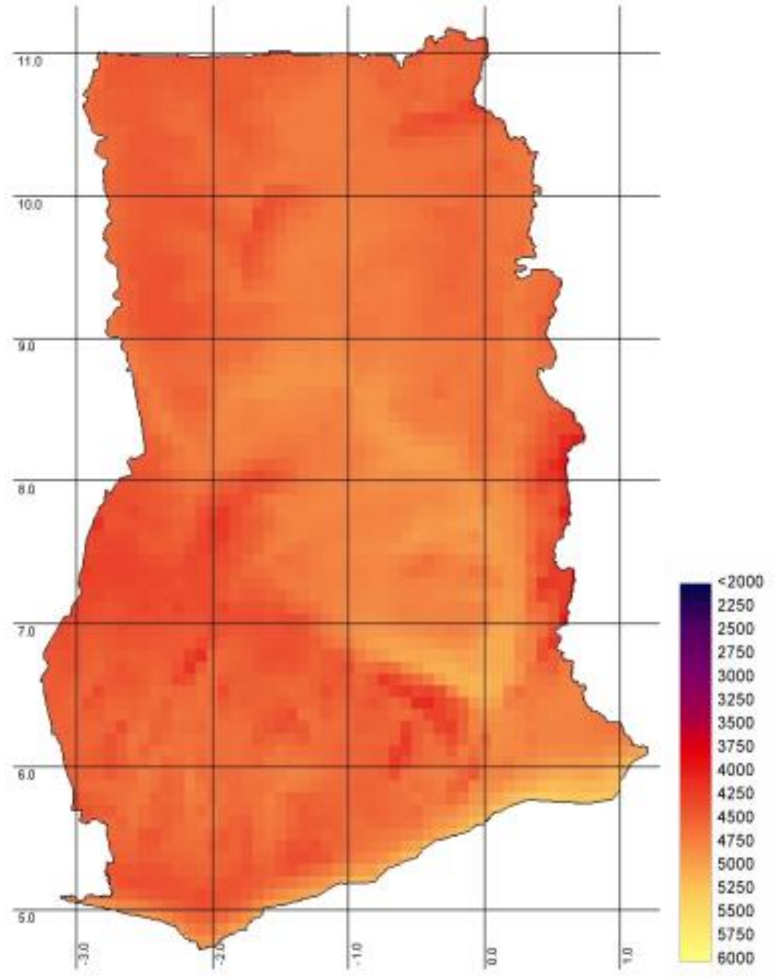

Figure 2.14: Annual Global Horizontal Irradiance in Ghana in Wh/m^2/day

Source: (Schillings et al., 2004)

As at the end of 2014, approximately 38,200 solar systems and lanterns were deployed successfully to more than 120 communities throughout the country for off-grid applications (Government of Ghana, 2015). In addition, the country has been able to introduce solar energy into the grid power supply electricity generation mix. These include the VRA and BXC solar power plants with total installed capacity of 2.5 MW and 20 MW respectively (Energy Commission, 2017b). Table 2.4 shows the main solar grid-connected systems in Ghana.

In February 2016, the Energy Commission initiated the implementation of a rooftop solar PV programme which aimed to add approximately 200 MW of electricity to the national grid via solar photovoltaic technology (Energy Commission, 2017).

Table 2.4: Main solar grid-connected systems in Ghana

Name of Institution	Location	Region	Installed Capacity kW
BXC Company Ghana Limited	Gomoa Onyadze	Central	20,000
Volta River Authority (VRA)	Navrongo	Upper East	2,500
Ministry of Energy	Accra	Greater Accra	50
Noguchi Memorial Institute. UG	Legon, Accra	Greater Accra	315
KNUST	Kumasi	Ashanti	44
Wienco Gh Ltd	Atimpoku	Eastern	42.77
Trade Works Company Ltd (Office)	South Dome	Greater Accra	10.58
Valley View University	Oyibi	Greater Accra	8.36
R. Tuffour – Residence	Sakumono	Greater Accra	7.6
Residence installed by TW	West Legon	Greater Accra	5.17
Energy Commission	Accra	Greater Accra	4.25

Source: (Bensah et al., 2014)

2.2.2 Wind energy

Most notable studies have revealed Ghana's wind energy potential as moderate which has an average annual wind speeds varying from 6.4 m/s – 7.5 m/s at 50 metres hub height located in the coast and some islands with technical wind power potential estimated at approximately 5.64 GW (IRENA, 2015b).

Ghana's total wind resource covers a land area of about 1125 km^2 which is divided into 4 wind resource utility, namely, moderate, good, very good and excellent. The highest technical wind capacity is 3575 MW with moderate wind resource utility and covers 0.3% windy land (designated as class 3). Also, 0.1% of wind land belongs to wind class 3 with a technical potential of 1340 MW (see Table 2.5) (Agbeve et al., 2011).

Table 2.5: Wind resource potential in Ghana

Wind resource utility	Wind class	Wind Speed at 50 metres m/s	Wind Power at 50 metres W/m^2	Total Area km^2	Windy Land %	Total Technical Capacity MW
Moderate	3	6.4-7.2	300-400	715	0.3	3575
Good	4	7.0-7.5	400-500	268	0.1	1340
Very Good	5	7.5-8.0	500-600	82	0.1	410
Excellent	6	8.0-8.8	600-700	63	0.1	315
Total				1128	0.5	5640

Source: (Agbeve et al., 2011)

The findings from Solar Wind Energy Resource Assessment (SWERA) project revealed that most wind resources of the country are class 3 wind resources and are available at some limited locations like Greater Accra region, Ashanti region, Brong Ahafo region, Central region, Eastern region, Western region, Northern region and Volta region. However, good to excellent wind resource can be found in few locations in the Volta region especially the area close to the Ghana-Togo border. Figure 2.15 depicts the wind resource map of Ghana at 50 metres height developed by the National Renewable Energy Laboratory (NREL) (Essendon et al., 2013)

Currently, Ghana has no utility-scale installed wind power plant for electricity generation. Nevertheless, the Government has made effort to develop initiatives for commercial wind power projects. For instance, the Volta River Authority has deliberated to install approximately 150 MW of wind farm by 2020. Moreover, companies such as NEK/Upwind Limited has been provided with construction license to commence a 250 MW wind farm. A company called EleQtra/InfraCo has also acquired a site to develop 30-50 MW wind farm by 2020 (Bensah et al., 2014).

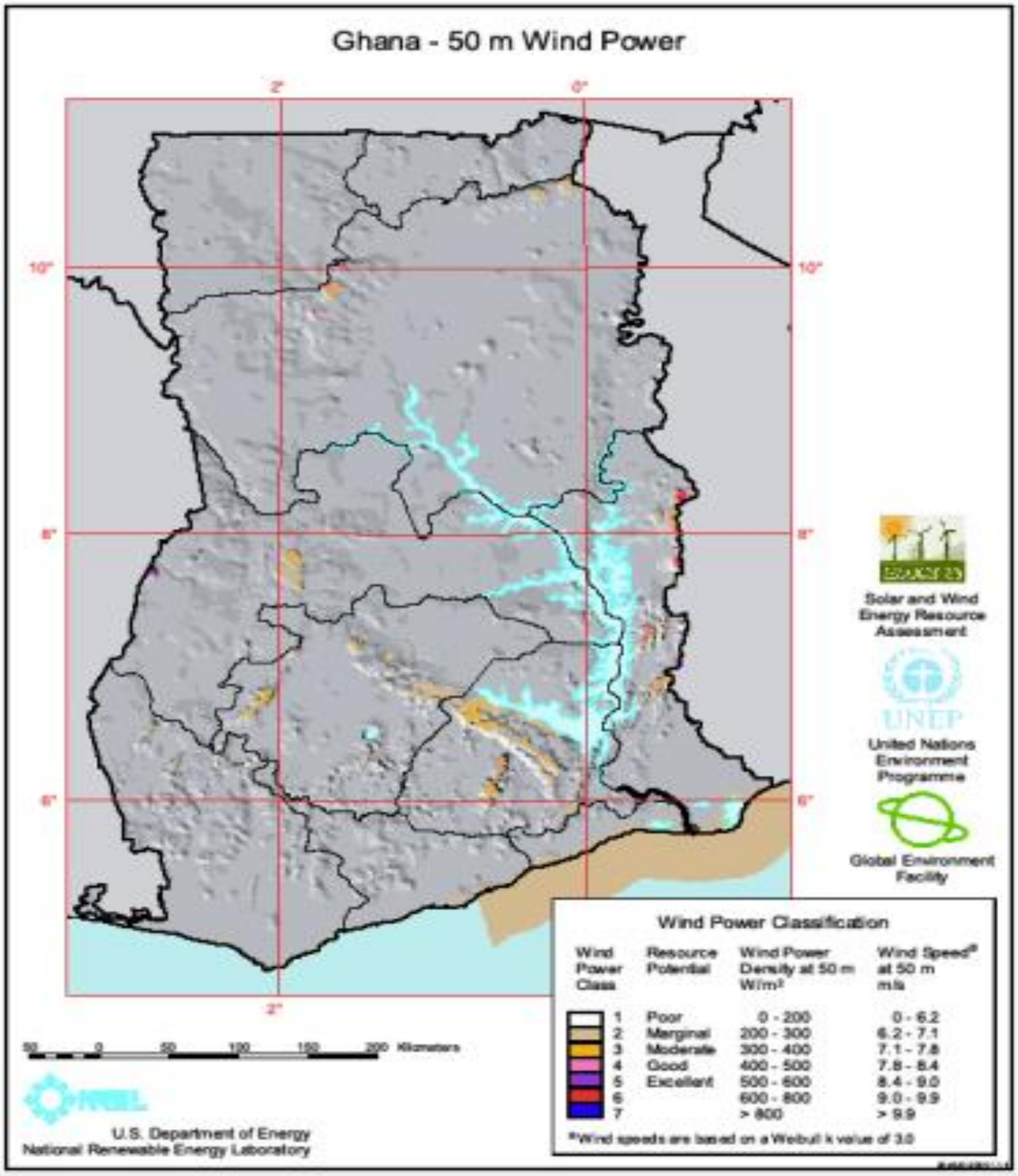

Figure 2.15: Wind map of Ghana at 50 m height

Source: (Hossain, 2014)

2.2.3 Hydropower

In Ghana, hydropower resources range from large, medium and mini/small. Over the decades, the Akosombo hydropower plant has been the backbone of the Ghana electricity sector until thermal plants took over. Currently, the three large grid-connected hydropower plants, namely, Akosombo, Kpong and Bui hydro power plants have an overall installed capacity of 1580 MW, and generated approximately 5560 GWh of electricity for Ghana in the year 2016 (Energy Commission, 2017b). The country also has potential for mini, small and medium hydro plants. Table 2.6 shows mini hydropower sites in different regions with their exploitable capacities in Ghana. Presently, the country has about 800 MW potential from about 22 mini/small and 17 medium hydropower locations with exploitable capacities ranging from 15-100 kW (Figure 2.16).

Table 2.6: Potential locations for mini hydropower in Ghana

Region	Site quantity	Power Minimum kW	Power Maximum kW
Ashanti	4	140	720
Brong-Ahafo	-	364	1900
Eastern	9	569	1150
Central and Western	9	332	2150
Northern	16	913	4420
Upper East and Upper West	8	499	2100
Volta	17	4919	12065

- means no available data
Source:(IRENA, 2015b)

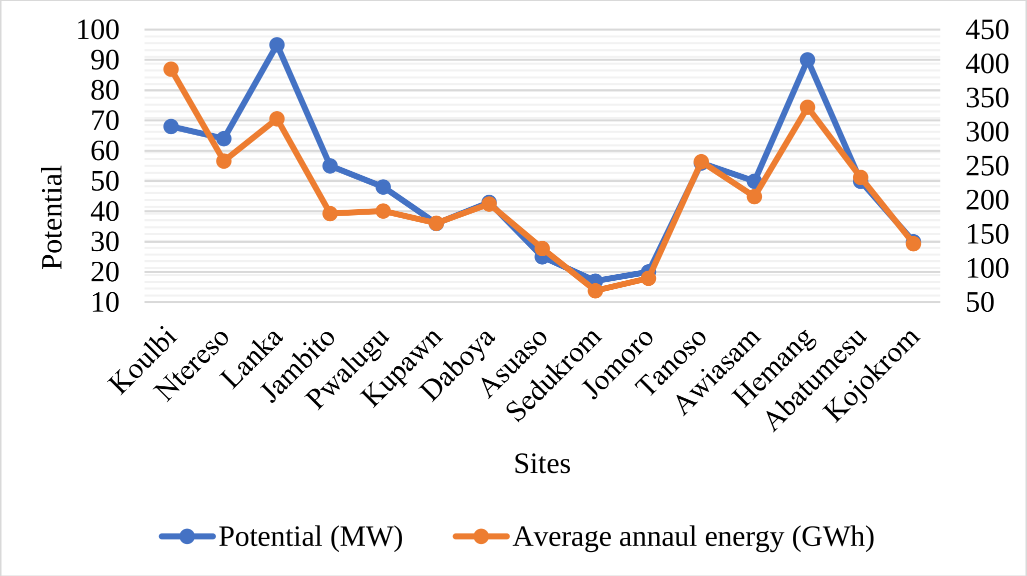

Figure 2.16: Locations for small and medium hydropower potential in Ghana

Source: Data from (IRENA, 2015b)

2.2.4 Biomass resources

Biomass refers to all organic matter that is derived from plants and animals. Biomass resources includes of agricultural crops and their residues, wood and wood wastes, municipal solid waste, animal residues, food processing residues, aquatic plants and algae (Duke et al., 2011). Biomass is regarded as a versatile energy source because it can be converted into solid, liquid and gaseous fuels compared to other sources of energy. Moreover, these fuels can be used globally for the production of electricity, transportation, heating and cooling and industrial applications (World Energy Council, 2016).

2.2.5 Bioenergy in Ghana

Ghana has a suitable potential of bioenergy resources and this holds a significant promise for future energy delivery in the country (Mohammed et al., 2013). Biomass accounted for 37.29% of total primary energy supply and 39% of the final energy consumed for the year 2016 (see Figure 2.9 and Figure 2.10 above). Out of the 23,800,000-hectare land mass in the country, biomass resources cover approximately 20,000,000 hectares. Biomass is primarily used for cooking and heating in urban and rural areas in Ghana. The country's enormous arable and degraded land mass has the potential for the cultivation of crops and plants that can be converted into diverse range of bioenergy such as solid and liquid biofuels (Gyamfi et al., 2015).

2.2.6 Bioenergy potential from crop production

Ghana's agricultural sector is a major industry in Ghana which contributes to the economic development of the country. The farming communities in Ghana cultivate crops and keep livestock that generate residues that are important for power generation using appropriate technologies. The main crops cultivated in Ghana comprises of maize, cassava, rice, yam, sorghum, plantain, cocoyam, groundnuts, cowpea, cocoa and oil palm. Approximately 90% of farms in Ghana are less than 2 ha with the exception of commercial plantations such as cocoa, rubber, palm oil and coconut and to a lesser extent, rice, maize and pineapple (Duku et al., 2011). As at the end of 2015, the total annual major crop production was estimated at 33,720,000 tonnes (see Table 2.7).

Table 2.7: Trend in Annual Production of Major Food Crops (‘000 Mt) from 2010-2015

Crop	2010	2011	2012	2013	2014	2015
Maize	1872	1683	1950	1764	1769	1692
Millet	219	183	180	155	155	157
Rice(paddy)	492	463	481	570	604	641
Rice(milled)	295	278	332	393	417	443
Sorghum	324	287	280	257	259	263
Cassava	13504	14240	14547	15990	16524	17213
Cocoyam	1355	1299	1270	1261	1299	1301
Plantain	3538	3619	3556	3675	3828	3952
Yam	5960	5855	6639	7075	7119	7296
Groundnut	531	465	475	409	427	417
Cowpea	219	237	223	200	201	203
Soya bean	145	165	152	139	141	142
Total	28454	28774	30085	31888	32743	33720

Source:(Ministry of Food and Agriculture, 2015)

2.2.7 Bioenergy potential from livestock population

Livestock manure refers to animal refuse. The amount of manure generated mostly rely on the amount of fodder eaten, the quality of fodder, and the live weight of the animal (Duku et al., 2011). According to (Ministry of Food and Agriculture, 2015), cattle, sheep, goat and poultry population dominates over other domestic livestock’s in Ghana. Table 2.8 provides figures for trend in livestock population from 2010 – 2015.

Table 2.8: Trend in Livestock Population (‘000) Heads from 2010-2015

Type of livestock	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Cattle	1454	1498	1543	1590	1657	1734
Goats	4855	5137	5435	5751	6044	6352
Sheep	3759	3557	4019	4156	4335	4522
Pigs	536	568	602	638	682	730
Poultry	47752	52575	57885	63732	68511	71594

Source: (Ministry of Food and Agriculture, 2015)

2.2.8 Bioenergy potential from municipal solid and liquid waste

Currently, solid and liquid management in Ghana is very poor in both urban and rural locations which creates havoc in most communities in the country (Ahiataku-Togobo, 2015a). It is estimated that only 1,200-1300 Mt of solid wastes are collected for disposal in landfills out of the 2000 Mt of solid waste generated each day. The calorific value of solid waste in Ghana range from 14-20 MJ/kg with a moisture content of 39-62%. Moreover, it is estimated that 60% of solid waste in Ghana is organic (Ahiataku-Togobo, 2015a). Most landfill sites have become a dumping site for raw faecal and sewage sludge which can be treated at sewage treatment facilities in the near future for bioenergy (GIZ, 2014).

2.2.9 Available scientific studies on bioenergy potential in Ghana

Several notable scientific studies have been conducted to estimate the potential of modern biomass available for bioenergy in Ghana. For instance, (Arranz-Piera et al., 2016), in their study assessed the levels of agriculture residues produced in small-holder farms in 11 districts in Ghana and the possible clustering and supplying of these residues to a centralized combined heat and power (CHP) plant. The findings of the study depicted that, clustered agriculture waste from small-holder farms has a high potential for cogeneration and possibly trigeneration. Moreover, plants with 600 kW and 1 MW capacity which run on agro-waste are feasible in certain rural districts with a minimum 20% yearly profit for investors. In addition, farmers will gain additional income from crop residues in the range of 29-64 US $/tonnes.

Also, (Kemausuor et al., 2014), assessed the potentials for bioenergy (biogas and cellulosic ethanol) using available residues and waste-based biofuels to meet energy requirement in Ghana. The study shows that crop residues stood up to be the important feedstock in terms of energy potential as compared to forestry residues, animal manure and municipal waste. Moreover, the technical potential of bioenergy from these feedstock's is 96 PJ in 2700 Mm^3 of biogas and 52 PJ in 2300 ML of cellulosic ethanol. These findings show that biogas potential is sufficient to replace more than a quarter of Ghana's present woodfuel use.

Additionally, (Duku et al., 2011), found the total theoretical energy potential of crop residues (sorghum, rice, millet, sugarcane, coconut, oil palm fruits, coffee, cocoa and maize) to be approximately 75.20 TJ base on 2008 crop production data in Ghana.

Moreover, (Mohammed et al., 2013), conducted a study on overview of the potential of agricultural biomass resources for decentralized energy in rural areas in Ghana. They assessed the same 8 crop residues employed by (Duku et al., 2011) in their study with the exception of coconut oil but used crop production data for the year 2010 as their reference base year. The findings revealed that, the theoretical energy potential from available crop residues and livestock manure are 86.60 TJ and 47.6 TJ respectively.

According to (Arthur et al., 2011), Ghana has been able to establish only a little over 100 biogas plants out of the total the technical potential of 278,000 biogas plants. This technical potential calls for the construction of more biogas digesters in Ghana.

The above studies justify the fact that Ghana has vast potential for bioenergy which can be harnessed using appropriate technology to provide electricity to decentralized communities, hence, boost and accelerate electrification access rate in the country. Currently, the country has 100 kW installed capacity of biogas plant connected to the national grid. Furthermore, there are several other CHP biomass plants installed in industries/companies to supply reliable electricity and to generate steam for their industrial applications (see Figure 2.17).

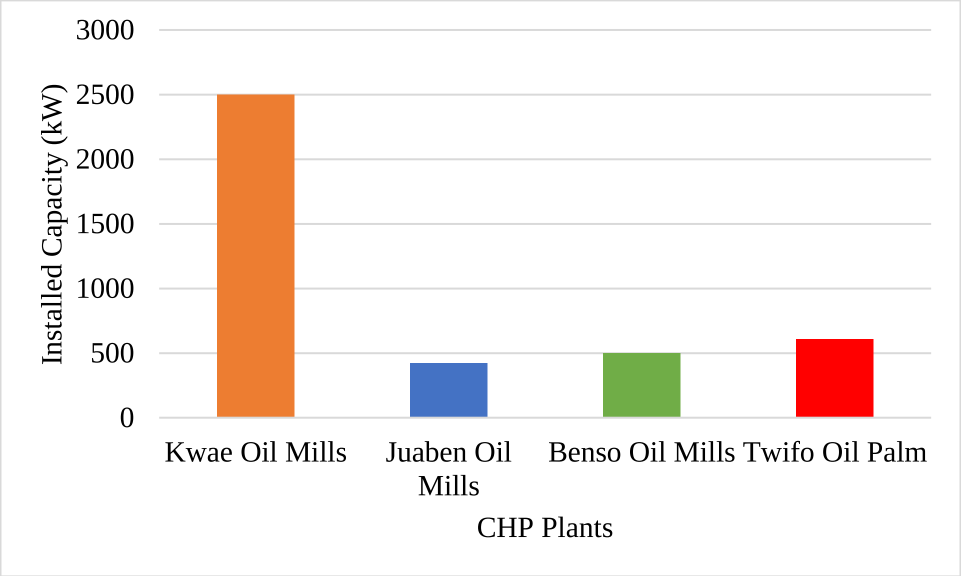

Figure 2.17: Biomass-fired co-generation plants in Ghana

Source: Data from (Energy Commission, 2012)

CHAPTER 3

3 RESEARCH METHODOLOGY AND DATA COLLECTION

3.1 Study area

3.1.1 Location and size

Mankramso community is the location for this study (see Figure 3.1). The community is located in the Offinso - North District of the Ashanti Region of Ghana. It lies within latitude 7^0 24.8 N and longitude 2^0 0.8 W. The community has an average household size of 5 persons with a total population of 1,892 people. This shows that there are approximately 380 households in Mankramso (Ghana Statistical Service, 2014) but 400 households will be considered in this study. Figure 3.0 shows the various communities located in the Offinso North District

Figure 3.1: A map showing various communities in the Offinso - North District

Source: (Ghana Statistical Service, 2014)

3.1.2 Climate

Mankramso experiences a double maxima regime because it lies in the semi-equatorial climatic zone. In addition, the community experiences two rainfall seasons: the major rainfall season which commence in April and ends in July and the minor rainfall season which usually commence in September and ends in October. The dry harmattan season normally occurs between November – March. Furthermore, the community experience high relative humidity ranging between 75-80 % in the rainy season and 70-72 % in the dry season respectively (Ghana Statistical Service, 2014).

3.1.3 Agriculture

Mankramso is a typical remote community and most households are agricultural households which makes farming the dominant occupation in the community. Children help parents in the farm after closing from school. Approximate 89.8% of households in the community are engaged in agriculture activities such as crop farming (maize, cassava, tomatoes etc.), livestock rearing (cattle, sheep, goat, pig, chicken) and tree planting (Ghana Statistical Service, 2014).

3.1.4 Electricity Access

Electricity access is a major problem in the community. The Kumasi-Techiman-Tamale (K-T-T) road connects the three cities for business activities. However, in the Offinso North District, only communities along (K-T-T) trunk road are connected to the national grid and therefore have access to electricity supply from the Government (see Figure 3.1) (Ghana Statistical Service, 2014). Mankramso is a remote community, about 7.0 km away from the national grid (see Figure 3.2). The community is not electrified and deprived of electricity supply from the national grid. The people have to travel for about 7 km to the nearest community (Afrancho) to have access to electricity for their daily activities. Students at Mankramso DA Primary/JHS school do not have computers for learning as a result of unavailable electricity to power the computers. The community mainly rely on firewood, charcoal, kerosene lamps, candles, torches and to a lesser extent solar lanterns for lighting and other energy activities. This electricity situation is a major hindrance to quality education, human well-being and business activities in the community.

Figure 3.2: Map showing isolated Mankramso community away from other communities and the national grid

3.2 Data acquisition

3.2.1 Questionnaires and literature

Primary data collection on crop production and livestock population was obtained from the following sources: (1) a detailed questionnaire survey of 300 household heads in the Mankramso Community; (2) a comprehensive questionnaire survey to 400 crop farmers and 400 livestock farmers in the Mankramso community; (3) personal interview with the community chief and headmaster of Mankramso D/A Primary/JHS school. In addition, other relevant data was obtained from National Statistical Agencies in Ghana such as the Ghana Energy Commission (National Energy Statistics), Ghana Statistical Service (2010 Housing and Population Census-Offinso North District) and Ministry of Food and Agriculture.

3.3 HOMER Pro Microgrid Analysis Tool

3.3.1 HOMER software input data

HOMER software performs three main tasks: simulation, optimization, and sensitivity analysis. HOMER software requires input data such as electric load, renewable resource (monthly solar radiation and temperature and monthly available biomass feedstock's), component types (PV module, biogas generator, battery, converter), component cost details (capital, replacement operation and maintenance) costs, lifetime of components, economic parameters (nominal discount rate, expected inflation rate, project lifespan, system fixed capital cost and capacity shortage penalty), system constraints (maximum annual capacity shortage, minimum renewable energy fraction, operating reserve) and emission penalties to perform simulation and optimization of the proposed hybrid power system. Figure 3.3 displays the schematic layout and the working principle of the HOMER software for this study.

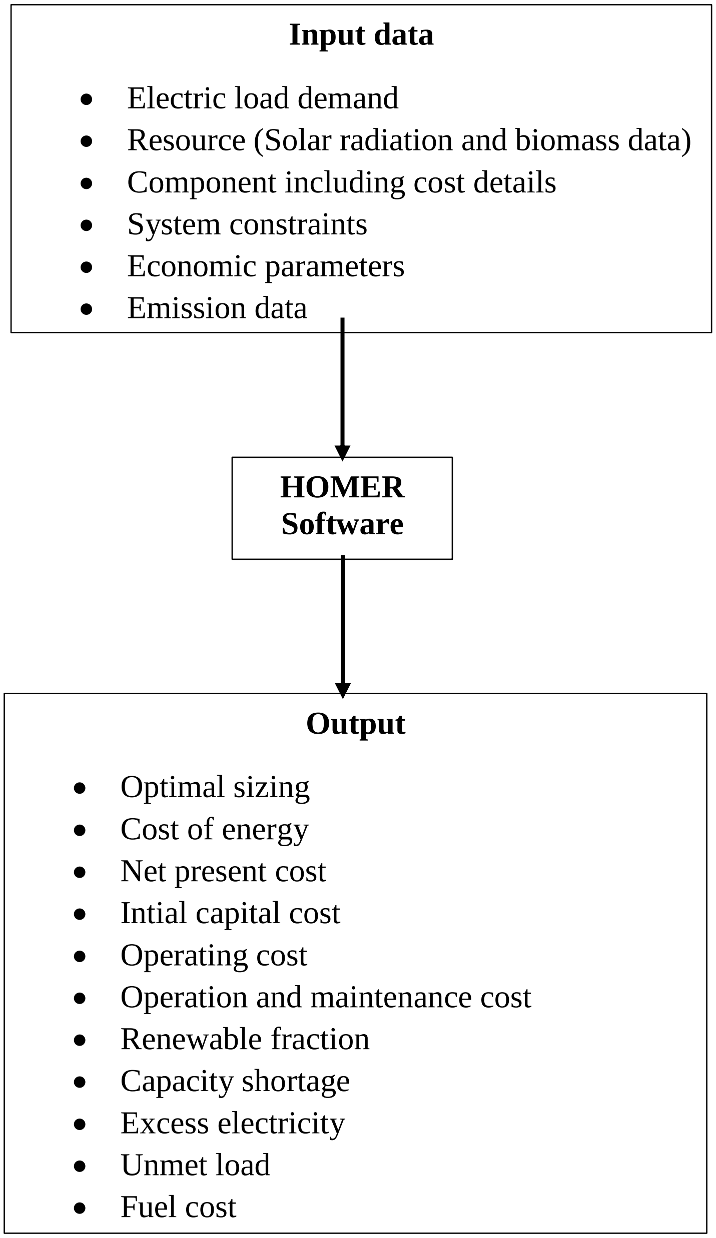

Figure 3.3: Schematic layout of HOMER software

3.4 Community electrical load estimation

The electrical load requirement for Mankramso was estimated through a field survey by virtue of structured interview to investigate the various electrical appliances owned by the households and appliances that they will be eager to own in the future when the community is electrified. Also, a typical remote village energy usage duration in Ghana and the average household size for the community was taken into consideration in doing the estimation. Field survey via interview revealed that household size varies from 4 family members to 7 family members and house sizes range from 1 bedroom to 3 bedrooms. In this study, an average of 3 rooms per household, household size of 5 persons and a total of 400 households instead of the exact 380 households is considered for analysis.

3.4.1 Community load description

The community electrical load is grouped into 3 categories, namely, household (home) load, commercial load and community load. Table 3.1 shows detailed description of all appliances and their operation time considered in this study.

3.4.2 Community load calculation

The total Mankramso daily primary load is estimated at 262.05 kWh/d with a peak load demand of 65.40 kW. The load was calculated using the following:

$$P_L = (P_r) x\ (N_a)\ x\ (t) \qquad Equation\ 1$$

where P_L is the primary load (kWh/d), P_r is the power rating (W) of the appliance, N_a is the total number of appliances, t is the time of use (hr/d).

Table 3.1: Summary of all electrical appliances used to estimate Mankramso daily electric load

Load Category	Appliances	Quantity	Power W	Time of use hr/d	Usage hr/d	AC loads (KWh/d)
Household						
	Television	200	80	19:00-22:00	3	48
	Radio	400	15	6:00-8:00	2	12
				16:00-22:00	4	24
	Mobile Phones	600	6	18:00-21:00	3	10.8
	Bulbs	1200	10	18:00-22:00	4	48
	Fan	200	30	19:00-22:00	3	18
School						
Nursery school						
3 classrooms	2 bulbs each	6	10	6:00-8:00	2	0.12
1 office	Bulb	1	10	6:00-8:00	2	0.02
	External bulb	1	15	18:00-6:00	12	0.18
Primary School						
6 classrooms	2 Bulbs each	12	10	6:00-8:00	2	0.24
1 office	Bulb	1	10	6:00-8:00	2	0.02
	External bulb	1	15	18:00-6:00	12	0.18
	Desktop Computer	1	100	9:00-12:00	3	0.3
	Printer	1	100	10:00-12:00	2	0.2
Junior High School						
3 classrooms	2 Bulbs each	6	10	6:00-8:00	2	0.12
1 office	Bulb	1	10	6:00-8:00	2	0.02
	External bulb	1	15	18:00-6:00	12	0.18
	Desktop Computers	3	100	9:00-12:00	3	0.9
	Printers	1	100	10:00-12:00	2	0.2
	Photocopier	1	200	8:00-10:00	2	0.4
Health Clinic						
2 wards	Bulbs (3)	6	10	00:00-23:00	24	1.44
1 office	Bulbs (2)	2	10	19:00-7:00	12	0.24
	Vaccine refrigerator	1	100	00:00-23:00	24	2.4
	Microscope	1	30	9:00-11:00	2	0.06
	Small radio	1	15	12:00-18:00	6	0.09
	TV	1	80	8:00-20:00	12	0.96
Commercial						
	Street Lights	20	100	18:00-6:00	12	24
	Flour Mill	2	1000	9:00-12:00	3	60
				14:00-18:00	4	8
	Cold Store	2	400	0:00-23:00	24	19.2
	Small Business	40	80	8:00-18:00	10	32
	Church Building	4	150	8:00-10:00	2	1.2
				19:00-21:00	2	1.2

3.5 Resource assessment

HOMER software requires Solar Global Horizontal Irradiance (GHI) and biomass feedstock data for simulation and optimization of the hybrid power system. Mankramso community has significant solar and biomass potential to meet the community electricity requirement.

3.5.1 Solar resource assessment

The monthly average solar GHI data was obtained from NASA Surface Meteorology and Solar Energy database via HOMER software based on the latitude 7^0 24.8 N and longitude 2^0 0.8 W values of the study area. The NASA database provides monthly average solar global horizontal radiation values over 22-year period (July, 1983- June, 2005). HOMER uses the solar radiation data to calculate the photovoltaic (PV) array power for each hour of the year. HOMER displays the monthly average radiation and clearness index of the baseline data in the solar resource table and graph. Table 3.2 show monthly solar GHI and clearness index data for Mankramso community.

Table 3.2: Monthly average solar global horizontal irradiation data for Mankramso community located within latitude 7^0 24.8 N and longitude 2^0 0.8 W

Month	Clearness Index %	Daily radiation (kWh/m^2/day)
January	0.596	5.49
February	0.578	5.67
March	0.545	5.63
April	0.521	5.45
May	0.501	5.14
June	0.447	4.49
July	0.393	3.97
August	0.358	3.69
September	0.371	3.83
October	0.444	4.40
November	0.518	4.82
December	0.565	5.08

Source: (NASA Surface Meteorology and Solar Energy, 2018)

3.5.2 Biomass resource assessment

Mankramso farmers were interviewed using a comprehensive questionnaire to evaluate the total crop and livestock production in the community. The field survey and interview revealed that, major agriculture crops cultivated by the farmers are maize and cassava and also major livestock reared by farmers are cattle, sheep, goat, pig and chicken.

3.5.3 Biomass potential assessment

Globally, estimation of biomass potential can be categorized into theoretical potential, technical potential, economic potential, implementation potential and sustainable potential (see Figure 3.4). The theoretical potential refers to the overall maximum amount of terrestrial biomass available for bioenergy production within fundamental bio-physical limits. The theoretical potentials equal the total amount of residues and waste that is produced when considering residues and waste for bioenergy production. The technical potential is the fraction of the theoretical potential that is available under the regarded techno-structural framework conditions with the current technological possibilities (such as harvesting techniques, infrastructure and accessibility, processing techniques) (Bioenergy Energy Group, 2010).

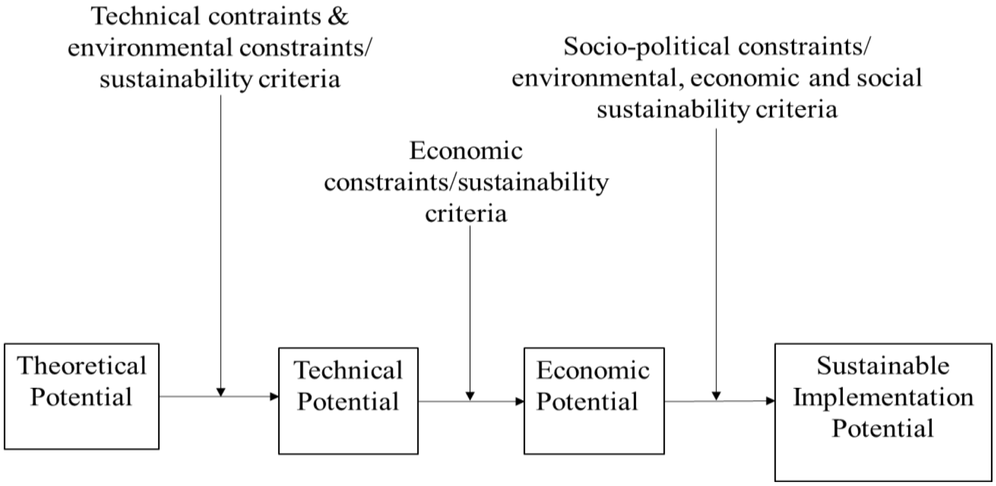

Figure 3.4: Classification of biomass potential assessment
Source: (Bioenergy Energy Group, 2010)

Due to unavailability of relevant data, this study focused on estimation of technical potential which is required to be lower than technical potential. Based on recent technology, the estimated technical residues potential should be considered as the optimum that could be achieved for analysis in this study.

3.5.4 Estimation of technical potential of crop residues

The main agricultural crops cultivated in Mankramso are maize and cassava. The maize residues are stalk, husk and cob and cassava residues are stalks/trunks and peelings. The theoretical and technical potential of crop residues is estimated using equation 2 and equation 3 respectively adopted in (Kemausuor et al., 2014).

$$P_{AR} = \sum_{i=1}^{n} (C_i \times RPR_i) \qquad Equation\ 2$$

where, P_{AR} is the annual crop residue potential, C_i represents the annual production of crop *i* and RPR_i is the residue to product ratio of crop *i*. Factor n is the total number of residue categories.

$$(T_{BP}) = (P_{AR} \times RF_i) \qquad \text{Equation 3}$$

where T_{BP} represents the annual technical biomass potential, RF_i is the recoverability fractions for individual residue types to estimate the technical biomass potential. Table 3.10 shows crop residues to product ratio (RPR) and recoverability fraction used for the estimation of technical biomass potential in this study.

Table 3.3: Crop residues and their respective RPR and RF values

Crop Type	Production tonnes/yr	Residues	(Y_{RPR})* g/g	(Y_{RF}) g/g
Maize	1680[#]	Husks[P]	0.23[a,c]	1.00[a]
		Cobs[P]	0.28[a,c,d]	1.00[a]
		Stalk[F]	1.55[a,b,c,d]	0.8[a]
Cassava	6434[#]	Stalk[F]	0.65[a,c]	0.8[a]
		Peelings[P]	0.30[a,b,c,d]	0.2[a]

[F] represents field base residues and [P] represents processing residue

*Average RF values based on literature sources

[#] Primary data collected on the field

[a] (Kemausuor, 2015)

[b] (Duku et al., 2011)

[c] (Jekayinfa & Scholz, 2009)

[d] (Kartha & Larson, 2000; Koopmans & Koppejan, 1997)

3.5.5 Estimation of technical potential of livestock manure

Estimation of available manure potential depends on factors such as number of livestock, average manure production per animal, coefficient of manure collection and dry matter fraction (Cai et al., 2008; Kemausuor et al., 2014). According to (Junfeng et al., 2005), amount of manure per head per day depend on factors such as body size, type of feed, physiological state (lactating, growing, etc.), and level of nutrition. Technically available livestock manure was estimated using the following equation adopted in (Kemausuor et al., 2014);

$$P_{manure} = \sum_{i=1}^{n} (P_{live} \times y_{man} \times \eta_{rec})_i \qquad \text{Equation 4}$$

where P_{live} is the number of specific livestock population, y_{man} is manure produced by one specific livestock per day, η_{rec} is the recoverability fraction of manure for specific livestock. Table 3.4 shows livestock population, manure produced per day by the livestock and recoverability fraction used for the estimation of technical livestock manure in this study.

Table 3.4: Parameters used to estimate technical available livestock manure

Type of livestock	Population P_{live}[a] (heads)	Estimated amount of manure y_{man}[b*] (kg/head/day)	Recoverability Fraction η_{rec}[c] (kg/kg)
Cattle	150	12	0.2
Goat	1568	2	0.2
Sheep	980	1.2	0.2
Pigs	190	2.5	0.5
Poultry (chicken)	5251	0.07	0.3

[*] Average RF values based on literature sources

[a] Primary data collected on the field

[b] (Junfeng et al., 2005; Kartha & Larson, 2000; Milbrandt, 2009)

[c] (KITE, 2008)

3.6 Hybrid power system components specification and cost data

In this study the hybrid system comprises of the following components: PV system (PV module, battery, charge controllers, converters), biogas system (digester and biogas generator) and a mini-grid transmission and distribution system. HOMER requires capital cost, replacement cost and operation and maintenance cost for stimulation and optimization analysis. The capital cost is the initial purchase price, the replacement cost is the cost of replacing the component at the end of their lifetime, and the operating and maintenance cost is the annual cost of operating and maintaining the component. In this study, all the cost information for the selected components are obtained from notable local suppliers and manufacturers, international retailer prices and through literature search.

3.6.1 Description of the solar PV system

Generally, a typical solar PV system consists of the following components: PV module, battery, charge controller and an inverter (see Figure 3.6)

3.6.2 Solar PV modules design

The solar cells inside the PV panels convert the sunlight into direct current (DC) through a process called photoelectric effect. The PV module will be installed on the ground on a fixed axis. The PV panels will be mounted at a slope equal to the latitude value of the chosen location to capture maximum solar radiation. The PV panel azimuth angle is zero and the PV panels will be oriented towards the south. The lifetime of the PV panels is considered as 25 years. There will be no tracking of the PV panels. The derating factor which accounts for losses due to temperature effect, dirt, wire losses, shading, aging etc. is taken as 80%, which means that the panel will produce 20% less power than the nominal. In addition, ground reflectance of 20% is considered for analysis. In this study, different PV array sizes ranging from 0 – 60 kW is considered for the stimulation and optimization analysis. HOMER calculate the power output (PV_{output}) of the PV array using the following equation (Adaramola et al., 2017; Lambert et al., 2006):

$$PV_{output} = C_{PV} D_{PV} \left(\frac{\overline{I_T}}{I_{T,STC}} \right) \left[1 + \alpha_p (T_c - T_{c,STC}) \right] \qquad Equation\ 5$$

Where C_{pv} = is the rate capacity of the PV module in (kW) under standard test conditions, D_{pv} = PV derating factor (%), $\overline{I_T}$ = solar radiation incident on the module surface (kW/m^2), $I_{T,\ STC}$ = incident solar radiation at standard test conditions (1000 W/m^2), α_p = temperature coefficient of power (%/^{o}C), T_c = PV cell temperature in ^{o}C and $T_{c,\ STC}$ = PV cell temperature under standard test conditions (25 ^{o}C). If the temperature effect on the PV module is neglected in some circumstances, it causes α_p to be taken as zero which reduces equation 5 to equation 6 as shown.

$$PV_{output} = C_{PV} D_{PV} \left(\frac{\overline{I_T}}{I_{T,STC}} \right) \qquad Equation\ 6$$

3.6.3 Solar PV module specification and cost data

Capital and replacement costs accounts for all costs associated with the PV subsystem, which may include PV panels, mounting hardware, tracking system, control system (maximum power point tracker), wiring and cables and installation cost. Currently, solar panels are free from import duties in Ghana which makes it very cheap and affordable. In the Ghanaian market, the cost of PV modules from qualified retailers such Solar-light, Suka Energy, Greener Systems, AIMS Power, Sollatek Ghana and Franerix ranges from US$ 0.40 – 0.90/watt. According to (Ahiataku-Togobo, 2015b), the initial capital cost for installation of a 100 Wp solar home system to provide three lighting points and a socket for radio/TV in Ghana is about US$ 1,100. Figure 3.5 shows the percentage component cost associated with this 100 Wp PV system.

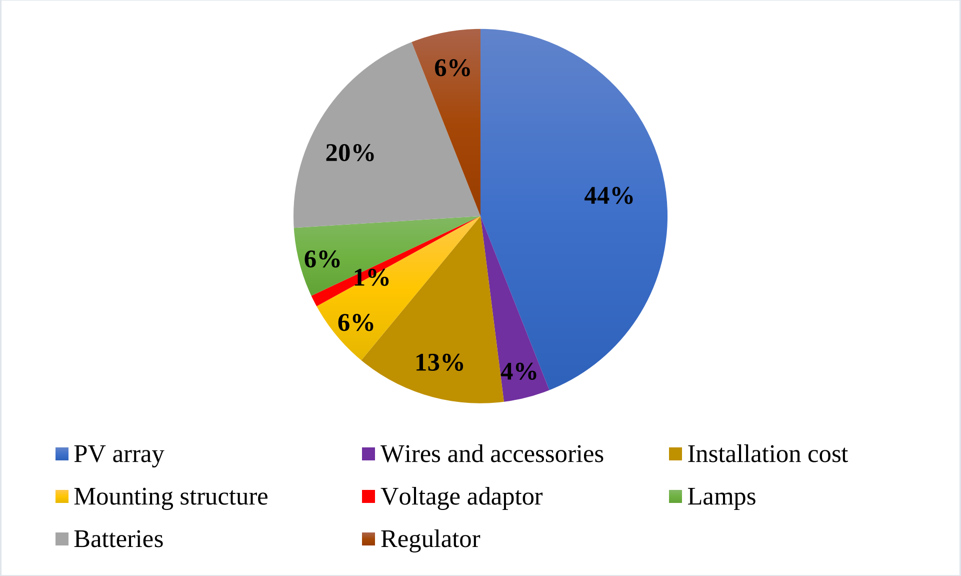

Figure 3.5: Percentage component cost of installed 100 Wp PV system in Ghana

Source:(Ahiataku-Togobo, 2015b)

In addition, the cost of installation, wires and accessories and mounting structure of the PV systems is taken to be 23% of the total capital cost of the PV system (Ahiataku-Togobo, 2015b). In this study, the capital cost of the PV system is taken to be US$ 1,000/kW. Replacement cost is taken to be US$ 0/kW because the PV panels lifetime equals the project lifetime (25 years) and also, operation and maintenance cost is taken to be US$10/kW/yr.

3.6.4 Battery

The battery will be used to store excess energy generated from the power system to meet the electric load of the community whenever there is an intermittency and non-availability of power supply from the PV panels and biogas generator. The cost of 1.2 kWh battery from (AIMS Power, 2018a; Solar-Light, 2018a) in the Ghanaian market ranges from US$ 215 – 240. The capital cost of battery is taken to be US$ 220/kWh with a replacement of US$ 220/kWh. This battery is maintenance free, therefore, it is assumed that the operation and maintenance cost is US$ 10.0/yr. HOMER software calculates the storage bank autonomy and the battery lifetime using equation 7 and equation 8 respectively (HOMER Energy, 2016; Lambert et al., 2006).

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} \left(1 - \frac{q_{min}}{100}\right) \left(24 \frac{h}{d}\right)}{L_{prim,ave} (kWh/d)} \qquad Equation\ 7$$

Where: N_{batt} = number of batteries in the storage bank; V_{nom}= nominal voltage of a single storage (V); Q_{nom}= nominal capacity of a single storage (Ah); q_{min}= minimum state of charge of the storage bank (%); $L_{prim,\ ave}$= average primary load (kWh/d)

$$R_{batt} = \min\left(\frac{N_{batt}Q_{lifestime}}{Q_{thrpt}}, R_{batt,f}\right) \qquad Equation\ 8$$

Where N_{batt} represents number of batteries in the battery bank, $Q_{lifetime}$ the lifetime throughput of a single battery, Q_{thrpt} the annual throughput (the total amount of energy that cycles through the battery bank in one year), and $R_{batt,f}$ the float life of the battery (the maximum life regardless of throughput).

3.6.5 Converter/Inverter

A converter is a device that converts electric power from direct current (DC) to alternating current (AC) in a process called inversion, and/or from AC to DC in a process called rectification (Lambert et al., 2006). The Solar PV-biogas hybrid system components consist of both DC and AC bus. The PV panel power output is DC and biogas generator power output is AC (see Figure 3.7). In Ghana, almost all electrical appliances operate with AC electricity. The converter/inverter will transform DC power stored by the batteries into AC electricity and also convert excess AC power generated from the biogas generator to DC before storing the electricity into the battery to power tools and appliances of all varieties. In this study, the converter is required to meet a daily peak load of 65.40 kWp (262.04 kWh/d). Moreover, a pure sine inverter charger of capacity in the range of 0 - 100 kW with an efficiency of 90% will be an ideal choice for stimulation and optimization.

3.6.6 Converter/Inverter specification and cost data

The cost of a pure sine converter from notable retailers in Ghana such as AIMS Power (AIMS Power, 2018b) range from US$ 719 for 2 kW and US$ 1019 for 3 kW. In this study, capital cost and replacement cost of the converter is taken to be US$ 500/kW each and operation and maintenance cost of US$10.0/yr are considered for stimulation and optimization analysis.

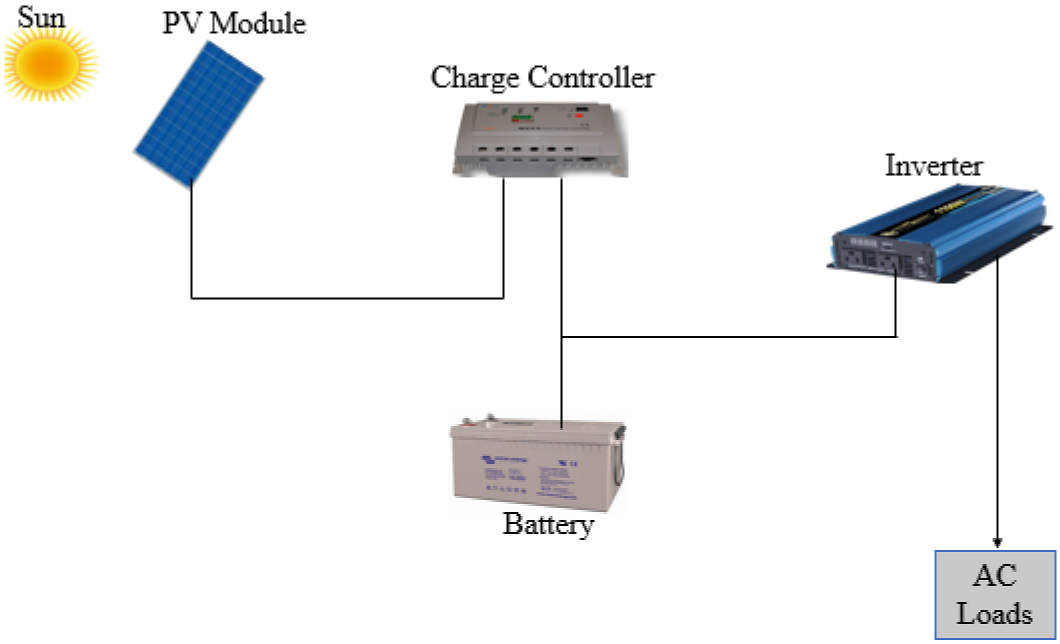

Figure 3.6: Layout and working principle of the Solar PV system

3.6.7 Biogas system design

A typical community fixed dome digester will be considered for the conversion of raw biomass feedstock into biogas for electricity generation since the raw biomass cannot be fed directly into a biogas generator. HOMER refers to biogas as gasified biomass, and estimation of biogas from the gasifier (anaerobic digester) depend strictly on parameters such as daily available biomass feedstock (t/d), average price of feedstock (US$/t), carbon content of biomass feedstock (%), gasification ratio (kg/kg) and lower heating value (LHV) of biogas (MJ/kg) (HOMER Energy, 2016; Lambert et al., 2006). In this study, the main biomass feedstock available for anaerobic digestion are livestock manure from cattle, goat, sheep, pig and chicken. However, crop residues from maize husk, maize cob, maize stalk and cassava peelings containing high amount of lignin, cellulose and hemicelluloses will co-digest with the manure to enhance the biogas yield from the digester. The average price of these feedstock which comprises of collection of feedstock, transportation and seasonality is assumed to be US$ 1.50/tonne since this feedstock will be collected within the community. The carbon content in the biomass feedstock is taken to be 20% - 50%. The gasification ratio which is the ratio of biogas produced to biomass feedstock consumed in the digester is estimated to be 1.89 and lower heating value of biogas is taken to be 5.5 MJ/kg.

Stimulation and optimization for reliable operation and function of the generator will depend on the following parameters; minimum load ratio (25%) of the generator, heat recovery of 0% since there is no thermal load, minimum runtime (0 minutes/day) and lifetime (20,000) hours of the generator. The biogas fuel produced from the digester will be fed into the biogas generator to generate electricity. In this study, biogas generator sizes in the range of 0 – 50 kW are considered for the stimulation and optimization analysis. The generator consumes fuel (biogas) to generate electricity, therefore, HOMER's generator module can model diverse generators such as microturbines, Stirling engines, internal combustion engine generators, thermophotovoltaic generators, fuel cells and thermoelectric generators (Lambert et al., 2006). HOMER software determine the fuel consumption based on the assumption that the fuel curve is a straight line with a y-intercept using the following equation:

$$F_c = aY_{gen} + bP_{gen} \qquad Equation\ 9$$

Where F_c is the generator fuel consumption (L), a is generator fuel curve coefficient (L/h/kW), Y_{gen} is the generator rated capacity (kW), b is the generator fuel curve slope (L/h/kW), (L/h/kW) and P_{gen} is the generator output power (kW).

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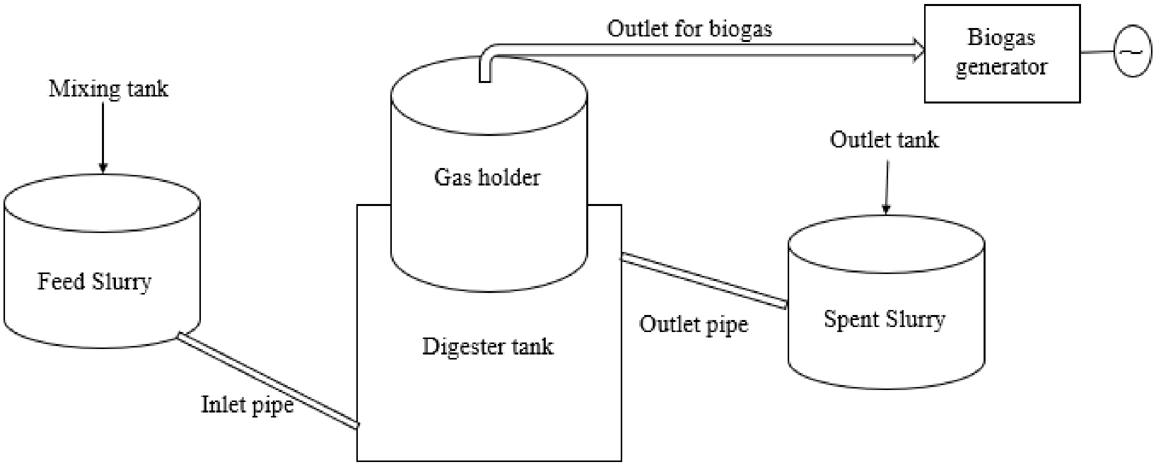


Figure 3.7: Layout and working principle of a biogas system

3.6.8 Biogas system specification and cost data

Capital cost of the biogas system is the sum of the capital cost of the digester and the capital cost of the biogas generator. Generally, the cost of a digester depends on the volume or size of the digester. The following equation adopted in (German Solar Energy Society (DGS) & Ecofys, 2005) is used to estimate the volume of the digester:

$$Digester\ volume\ (m^3) = \left(L_m\left(\frac{m^3}{yr}\right) + c_s\left(\frac{m^3}{yr}\right)\right)\ x\ \left(\frac{R_T\ (days)}{365}\right) \qquad Equation\ 10$$

Where: L_m is the technical livestock manure; C_s is the co-substrate from technical crop residues; R_t is the retention time which is normally around 30-40 days for mesophilic digestion. The volume of the digester is estimated at 12 m^3 using the technical potential of livestock manure and crop residues available biogas production. Furthermore, the cost of constructing biogas plants in Ghana, ranges from US$ 1,549 – 2,817 for a 6 m^3 plant, and from US$ 3000 - 6000 for 10 m^3 plant with a unit cost of US$ 235 – 446 per m^3 (Bensah et al., 2011). The cost of biogas generator in the international market from notable retailers such as (Shandong Haunyue International Trade Co., 2018) ranges from US$500 – 1300/kW. In this study, the capital cost of the biogas system is taken to be US 4,500/kW. However, in HOMER stimulation the capital cost of the digester will be added to system fixed capital cost. Hence, the capital cost of the biogas generator is taken to be US$ 500/kW with a replacement cost US$ 500/kW and operation and maintenance cost of US$ 0.50/hr.

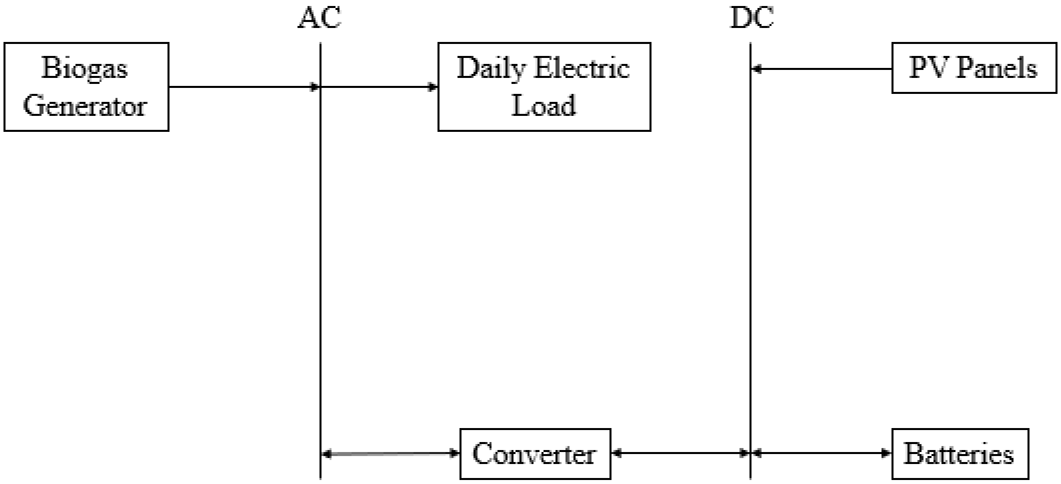


Figure 3.8: Schematic layout of the Solar PV-biogas hybrid power system

3.7 System constraints

The maximum annual capacity shortage is taken to 0 % since the power system is required to meet the daily electric load demand throughout the year without shortage. In addition, since this study combines solar radiation and biomass, thus, minimum renewable fraction is taken to be 100%. Operation reserve refers to surplus operating capacity which immediately react to unexpected increase in the electric load or a rapid reduction in the renewable power output. Operating reserve will ensure consistent power supply despite random variability in the electrical load and the renewable power supply (Lambert et al., 2006). Operating reserve consider a percentage of the electric hourly load and renewable output. To ensure reliable electricity supply, 10% of the hourly electric load and 25% of solar power output are considered for the operating reserve (Cotrell & Pratt, 2003).

3.8 Economic input and output parameters

Discount rate and inflation rate in Ghana as at May, 2018 was 16.80% and 9.60% respectively ("Bank of Ghana," 2018). The project lifetime is taken to be 25 years. Moreover, the system fixed capital cost for construction of biogas digester, mini-grid installation, transmission and distribution system and other initial fixed capital cost is taken to $ 45,000 with an operating and maintenance cost $ 1000/year. In this study, the major economic output metrics to be regarded for analysis, discussion, feasibility and implementation of the project are Net Present Cost (NPC) and Levelized Cost of Energy (LCOE). NPC of the system takes into account all costs that the system incurs overs its lifetime, minus the present value of all the revenue that the system earns over its lifetime. HOMER software calculates the total NPC of the project using equation 11 (Lambert et al., 2006)

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\ (i, R_{proj})} \qquad Equation\ 11$$

where $C_{ann,tot}$ is the total annualized cost, i the annual real interest rate (the discount rate), R_{proj} the project lifetime, and CRF(i,N) is the capital recovery factor which is given by equation 12 (Lambert et al., 2006)

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad Equation\ 12$$

where i represents the annual real interest rate and N represents the number of years.

HOMER software uses equation 13 to calculate the levelized cost of energy (LCOE) (Lambert et al., 2006):

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \qquad Equation\ 13$$

Where: $C_{ann,\ tot}$ is the total annualized cost, E_{prim} and E_{def} are the total amounts of primary and deferrable load, respectively and $E_{grid,\ sales}$ is the amount of energy sold to the grid per year.

3.8.1 Sensitivity analysis input variables

HOMER sensitivity analysis helps the modeller to know how the system optimal output changes within input variables. Input variables such as nominal discount rate, PV capital cost, biogas generator capital cost, battery storage capital cost and price of biomass feedstock will be varied to see the effect on NPC and LCOE of optimal system.

Table 3.5: Summary of technical and financial input data required for designing, stimulation and optimization

Parameters	Values	Comments/Reference
Community	Mankramso	Remote and un-electrified area
Number of households	400	Approximation from 380 household
Household size	5	Rural household size in Offinso-North [a]
Community Electric load	262.05 kWh/d	From electrical load estimation
Daily solar radiation	4.81 kWh/m2/day	Latitude 7.41°N, Longitude 2.08°S
PV capacity	0 – 60 kW	Sizes considered for analysis
PV capital cost	US$ 1000/kW	Average market price in Ghana[b]
PV O&M	US$ 10/kW-yr	From authors' assumption
PV lifetime	25 years	Typical PV warranty periods
Battery capacity	1 – 100 kWh	Sizes considered for analysis
Battery capital cost	US$ 220/kWh	Average market price in Ghana[c]
Battery O&M	US$ 10/year	Authors' assumption
Battery lifetime	5 – 15 yrs.	Typical manufacturer specification
Converter capacity	0 – 100 kW	Sizes considered for analysis
Converter cost	US$ 500/kW	Average market price in Ghana[d]
Converter O&M cost	US$10/year	Authors' assumption
Converter lifetime	15 yrs.	Typical manufacturer specification
Biogas generator capacity	0 – 50 kW	Sizes considered for analysis
Biogas generator capital cost	US$ 500/kW	Average price in international market[e]
Generator O&M cost	$0.10/hr	Authors' assumption
Generator operating hours	20,000 hrs	Typical operating hours
Minimum load ratio	25%	Authors' assumption
Inflation rate	9.80%	Market rate in Ghana[f]
Nominal discount rate	16.90%	Market rate in Ghana[f]
System fixed capital cost	US$ 45,0000	Author's assumption*
System fixed O&M cost	US$1000/yr	Author's assumption#
Project lifetime	25 years	Authors' assumption

[a] (Ghana Statistical Service, 2014)
[b] (AIMS Power, 2018a; Solar-Light, 2018a)
[c] (AIMS Power, 2018b; Solar-Light, 2018b)
[d] (AIMS Power, 2018c)
[e] (Shandong Haunyue International Trade Co., 2018)
[f] (Bank of Ghana, 2018)

* Cost needed for the development of (biogas digester, a mini-grid transmission and distribution system, etc.)

\# Labour and other related cost

CHAPTER 4

4 RESULTS AND DISCUSSION

4.1 Presentation of Mankramso daily hourly load profile

The daily electric load demand in Mankramso was estimated at 262.05 kWh/d. The lowest and highest (peak) daily electric load demand was estimated at 2.98 kW and 47.26 kW respectively. The hours of 22:00-06:00 shows a constant electric load consumption because at these hours almost 90% of the population will be sleeping and only appliances such as street lights and cold store refrigerators will be working. Additionally, the peak load was recorded at the hour of 19:00 – 20:00. In this period, almost all the people are back to their respective homes as well as using almost all appliances. In this study, weekdays loads are assumed to be the same as weekends electric loads. Figure 4.1 shows the trend in Mankramso hourly load profile.

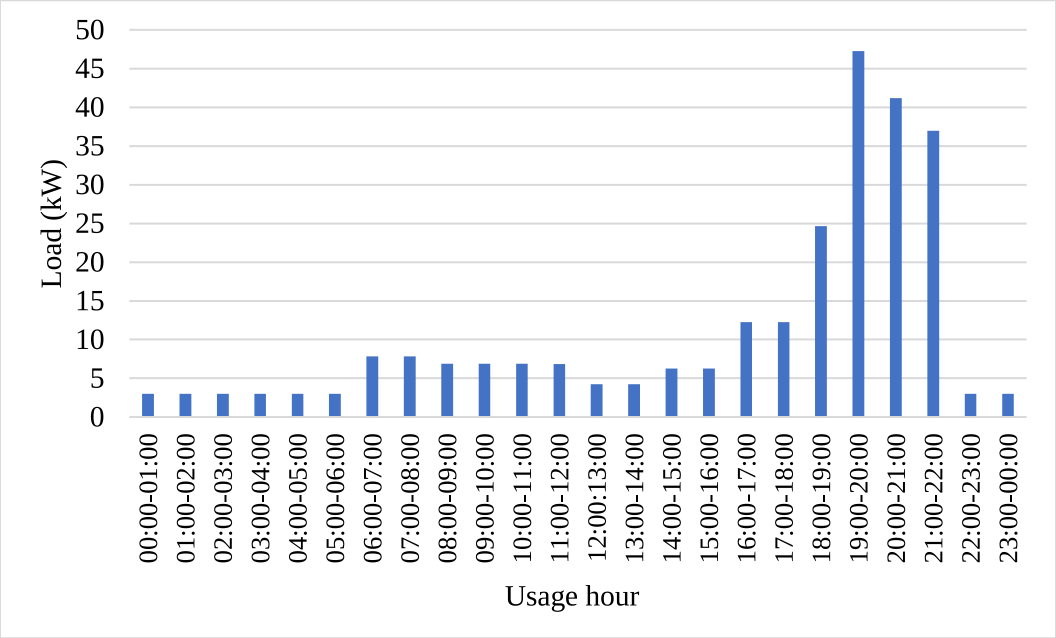


Figure 4.1: Trend in Mankramso community hourly load profile

To meet the operating reserve of the optimal power system, 10% of random variability was introduced into the electric load demand during HOMER stimulation and optimization. The random variability accounts for sudden increases in energy consumption to make the electric load more realistic. The 10% of random variability increased the community daily electric load peak load to from 47kW to 65.04 kW. Figure 4.3 shows the yearly electric load profile for Mankramso community after addition of 10% of random variability into the electric load profile.

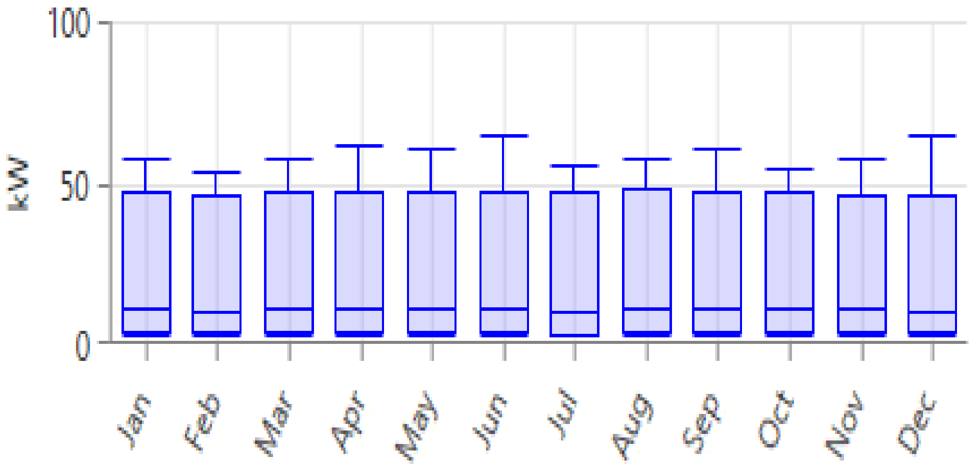


Figure 4.2: Monthly electric load profile for Mankramso community

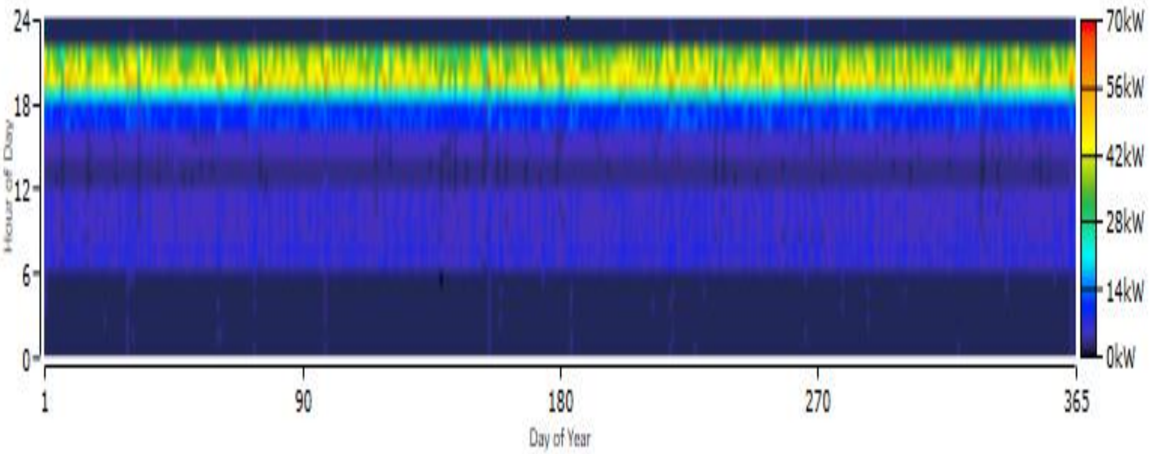


Figure 4.3: Yearly load profile for Mankramso community

4.2 Technical potential of crop and livestock residues available for bioenergy

4.2.1 Technical potential of livestock manure

The total amount of livestock manure generated on the field was estimated at 6.95 tonnes/day. Out of this amount, the technical potential of livestock manure available for bioenergy was estimated at 1.57 tonnes/day. Goat manure recorded the highest technical manure potential of 0.63 tonnes/day followed by cattle manure (0.36 tonnes/day), sheep manure (0.24 tonnes/day), and pig manure (0.24 tonnes/day) respectively. Poultry (chicken), recorded the lowest technical manure potential of 0.11 tonnes/day because it has a very low recoverability fraction. Figure 4.4 shows all the livestock manure with their technical potential available for bioenergy.

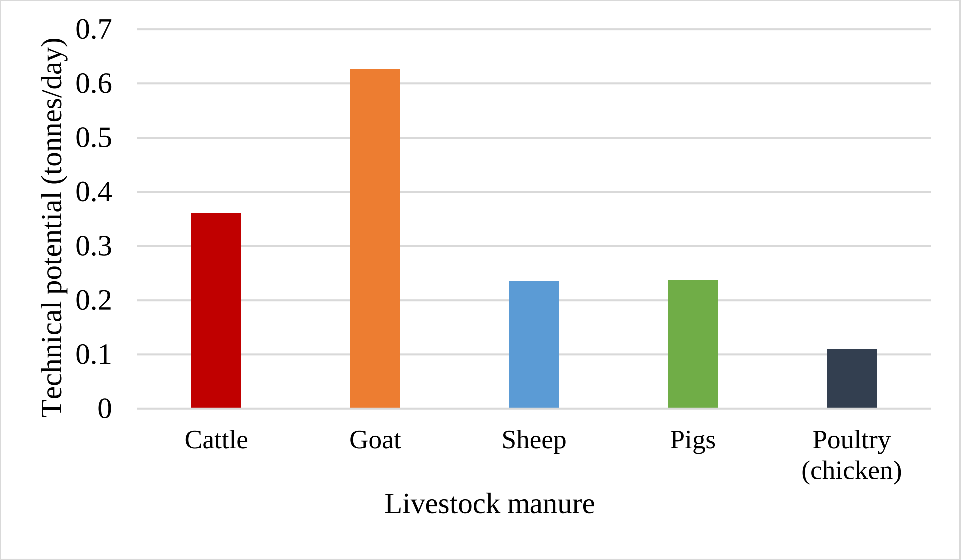


Figure 4.4: Technical livestock manure potential available for anaerobic digestion

4.2.2 Technical potential of crop residues

The total amount of maize and cassava residues generated on the field was estimated at 9.48 tonnes/day and 16.74 tonnes/day. However, the technical potential of maize residues and cassava residues was estimated at 7.92 tonnes/day and 10.22 tonnes/day. Cassava stalks recorded the highest residue technical potential of 9.17 tonnes/day, followed by maize stalk with a residue potential of 5.71 tonnes/day, maize cob recorded 1.16 tonnes/day and cassava peelings recorded 1.06 tonnes/day. Maize husk has the lowest residue technical potential of 0.96 tonnes/day. Figure 4.5 shows the various crop residues with their respective estimated technical potential available for bioenergy.

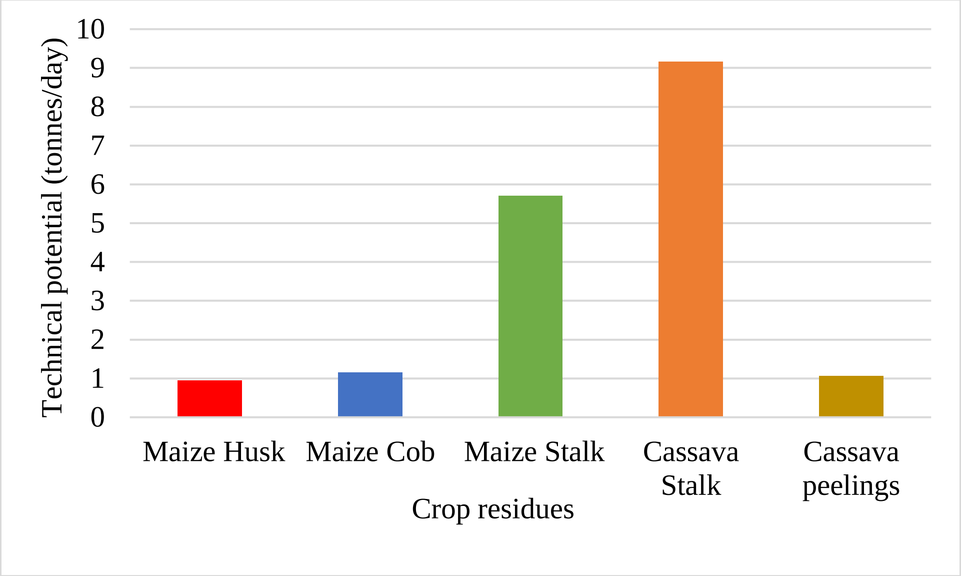


Figure 4.5: Technical crop residues potential available for co-digestion during anaerobic digestion

In this study, livestock manure from cattle, goats, sheep, pigs and chicken is the primary feedstock for anaerobic digestion needed to produce biogas to generate electricity. However, crop residues such as maize (husk, cob and stalk) and cassava peelings will act as co-substrate during anaerobic digestion in order to increase biogas production yield.

4.3 Presentation of HOMER Pro software optimization results

HOMER Pro 3.11.6 (64-bits) software installed on 4 GB RAM, 2.00 GHz processor and 64-bits laptop was used to perform the stimulation and optimization analysis of the hybrid power system. HOMER optimization results shows that, out of 739,081 solutions which were stimulated, only 332,354 solutions were feasible and 406,727 solutions were infeasible due to capacity shortage constraints. The most economically feasible system depends on parameters such as NPC, LCOE, operating cost, initial cost, fuel cost, renewable fraction, capacity shortage, unmet load, CO_2 emissions, excess electricity, annual electricity production and annual fuel consumption. HOMER ranks the optimal systems based on lower NPC, low cost of energy, low initial and operating cost. Figure 4.6 shows the HOMER architecture of all components employed in this study to perform optimization analysis of the most optimal solution.

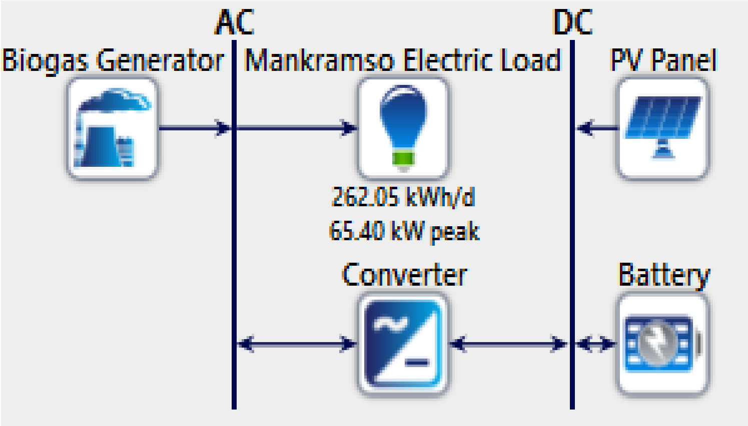
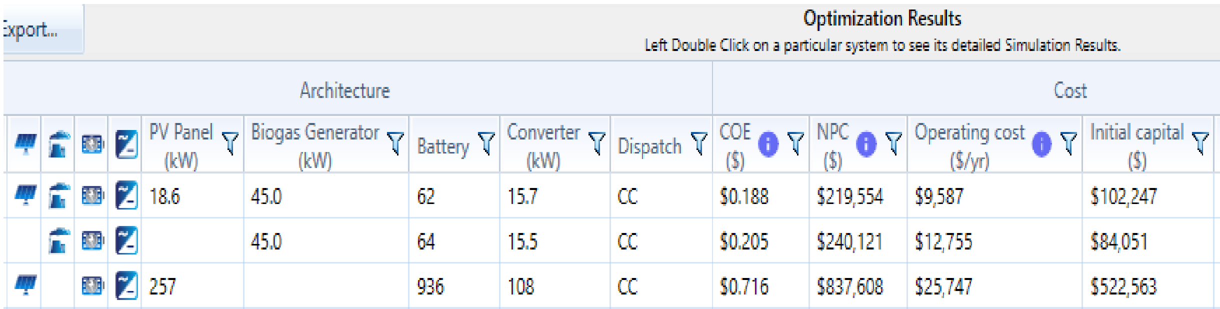


Figure 4.6: Schematic design of the hybrid power system

4.3.1 Optimization results of most optimal and feasible power system configuration for Mankramso community

The HOMER software procedure searched for the optimum solutions between the numerous sizes considered for the estimated electric load demand. Moreover, the most feasible solutions were ranked according to LCOE and NPC (see Figure 4.7). Optimization results show that, the system configuration that comprises of 18.6 kW of PV panels, 45 kW of biogas generator, 62 kWh of battery storage and 15.7 kW of converter is the optimal solution as compared to other system configurations. Figure 4.7 depicts the best categorized optimum system configurations.



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

Architecture									Cost			
				PV Panel (kW)	Biogas Generator (kW)	Battery	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)
●	●	●	●	18.6	45.0	62	15.7	CC	$0.188	$219,554	$9,587	$102,247
	●	●	●		45.0	64	15.5	CC	$0.205	$240,121	$12,755	$84,051
●		●	●	257		936	108	CC	$0.716	$837,608	$25,747	$522,563

Figure 4.7: Categorized optimum system configurations

Scenario A consists of solar PV/biogas generator/batteries/converters; scenario B consists of biogas generator/batteries/converters whiles that of scenario C comprises of solar PV/batteries/converters (see Table 4.1). The initial capital cost, net present cost (NPC), levelized cost of energy (LCOE) of the optimal power system (scenario A) is found to be US$ 102,247, US$ 219,554 and US$ 0.188/kWh respectively. This LCOE of US$ 0.188/kWh is approximately 10.6% higher than the LCOE (US$ 0.17/kWh) for household residents in Ghana. Furthermore, scenario B has a lower initial capital of US$ 84,051 as compared to US$ 102,247 for scenario A and US$ 522,563 for scenario C. In addition, scenario C has the highest LCOE and NPC values. Results from LCOE and NPC of the three scenarios depicts that the solar PV-biogas hybrid system is cost-effective and cheaper than the standalone biogas power system and standalone solar PV system in the long run.

Table 4.1: Optimization scenarios of optimal power system for Mankramso community

Proposed system	Scenario	COE (US$)	NPC 1000 (US$)
PV-biogas-battery-converter	A	0.188	220
Biogas-battery-converter	B	0.205	241
PV-battery-converter	C	0.716	838

In this study, the findings of the optimal power system (scenario A) is analysed and will be considered for implementation.

4.3.2 Electricity production from optimal PV Panels and biogas generator

The total annual electricity production from the optimal power system is estimated at 105,481 kWh/yr, where solar PV panels and biogas generator contributes to 23,966 kWh/yr (23%) and 81,515 kWh/yr (77%) respectively (see Figure 4.8).

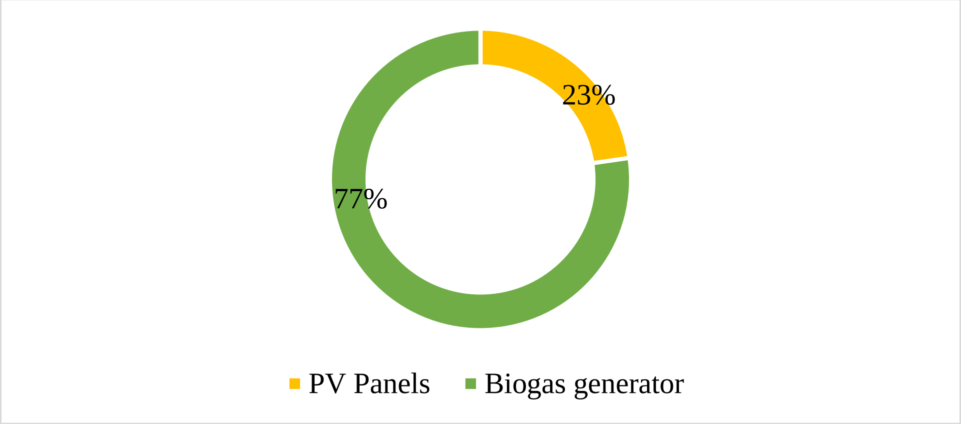


Figure 4.8: Share of electricity production by component

Out of this total annual electricity production, only 95,633 kWh/yr will be consumed by AC loads in the community since there are no deferrable and thermal loads. Biogas generator annual electricity production dominates over solar PV due to high amount of biomass feedstock and low solar irradiation in the study area. In addition, electricity generation from the biogas generator increases from the month of June –

September due to very low solar irradiation during these periods (see Figure 4.9 for monthly average electricity production from solar PV and biogas generator). This optimal power system generates excess electricity which is estimated at 4,676 kWh/yr. Additionally, the unmet load that the power system is unable to serve which occurs when the electrical demand exceeds the supply is estimated at 95.3 kWh/yr. Moreover, annual capacity shortage which accounts for feasibility of the power system is estimated at 86 kWh/yr representing 0.09%. Nevertheless, according to (Adaramola et al., 2014), feasible power systems annual capacity shortage must fall in the range of 0.5 – 5%. However, this solar PV-biogas hybrid power system is feasible because it has a very low annual capacity shortage of 0.09% which below the value estimated by (Adaramola et al., 2014) in their study.

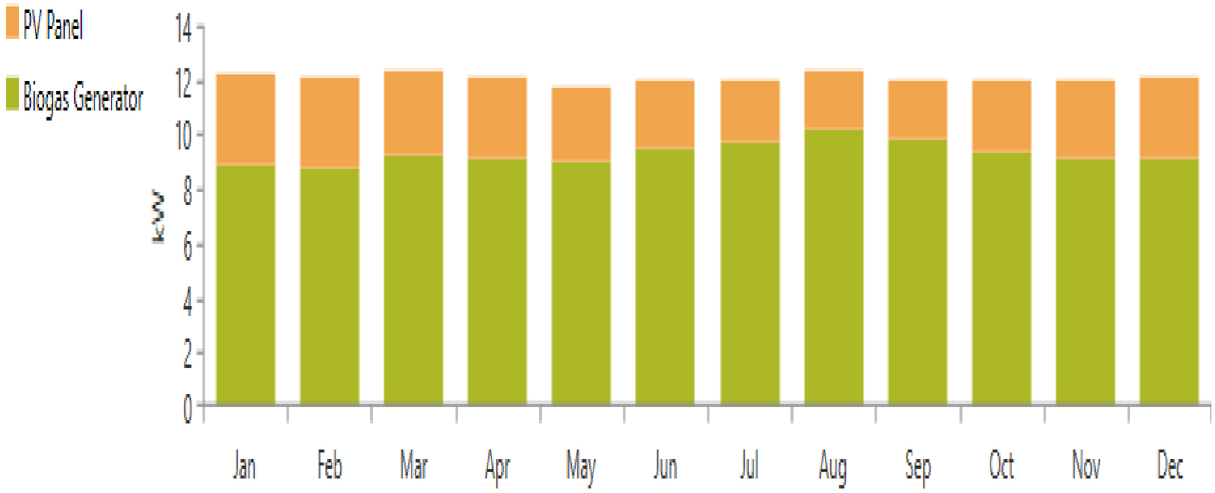


Figure 4.9: Monthly average electricity production

4.3.3 Optimal performance of solar PV array

The rated capacity of the PV array is 18.6 kWp with a mean output of 65.7 kWh/d and capacity factor of 14.7%. PV penetration which accounts for PV array output divided by the average primary electric load is found to be 25.1%. This PV array is expected to operate for 4,361 hrs/yr. Moreover, the LCOE from this solar PV array is estimated at US$ 0.0712/kWh. Furthermore, PV power production starts around 6.00 am in the morning and ends at 18:00 in the evening with a peak electricity production during noon (see Figure 4.10). The performance of PV array production is expected to be the same throughout the day, week, month and year. The electricity generated from the PV output decreases from the month of June – September due to low solar irradiation which results from frequent rainfall and cloudy atmosphere during this season in the country (see Figure 4.11)

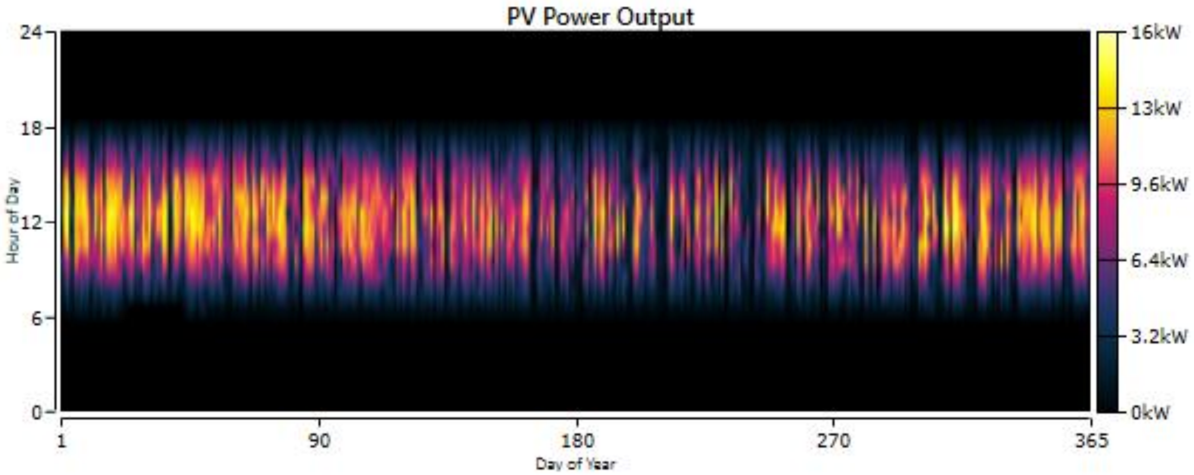


Figure 4.10: Daily operation and performance of electricity generated from PV power output

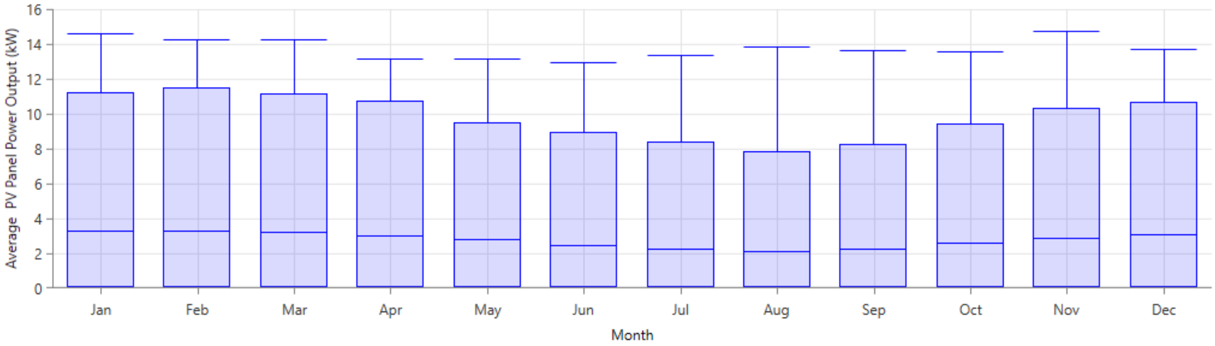


Figure 4.11: Monthly performance of optimal PV array

4.3.4 Optimal performance of biogas generator

The overall maximum, minimum and mean electrical output of the biogas generator are estimated at 45 kW, 11.3 kW and 25.2 kW respectively, thus, the biogas generator can produce approximately 81,515 kWh/yr of electricity. The annual operation of the biogas generator is 3,237 hrs/yr with 759 starts/yr. Also, it will work and operate for 6.18 years before replacement. In addition, it has an efficiency and capacity factor of 36.3% and 20.7% respectively. The biogas generator will consume 18.4 tonnes/yr of biogas with a specific biogas consumption of 1.80 kg/kWh. Moreover, in every hour the biogas generator will have a fixed generation cost of US$ 1.58 which will generate a marginal generation cost of US$ 0.000375/kWh. Furthermore, the biogas generator works maximum from the hours of 18:00 – 22:00 and 6:00 – 8:00 throughout the year (see Figure 4.12). During these hours, it will produce power in the range of 8 – 40 kW to meet the community peak load. Figure 4.12 shows the average monthly biogas generator power output.

Figure 4.12: Daily operation and performance of biogas generator

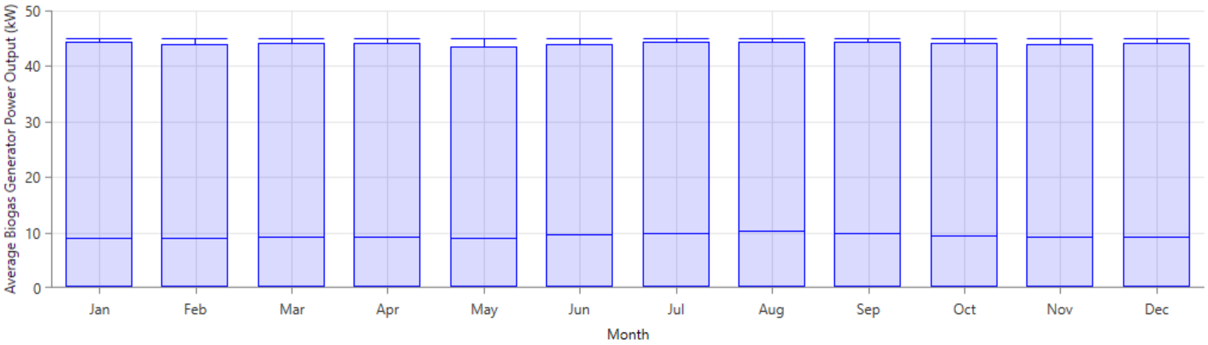


Figure 4.13: Average monthly biogas generator power output

4.3.5 Optimal operation and performance of battery storage

The battery storage capacity is estimated at 62 kWh with string size of 1 battery. The connection of these batteries will be in strings in parallel with a bus voltage of 12.0 V. The total battery storage energy in (charge) and energy out (discharge) are 16,201 kWh/yr and 12,970 kWh/yr respectively. In addition, it has losses of 3,241 kWh/yr and annual throughput of 14,501 kWh/yr. The battery storage has an autonomy of 3.41 hours to meet the electric load when both PV panels and biogas generators generates no power. It has a nominal capacity and usable nominal capacity of 62 kWh and 37.2 kWh respectively. The storage wear cost and average energy cost from the battery storage is estimated at US$ 0.307/kWh and US$ 0.000222/kWh respectively. The expected lifetime of the battery is 4.00 years with lifetime throughput of 49,600 kWh.

State of charge (SOC) describes how fully a battery is charged, thus, it is the inverse of depth of discharge. SOC of 100% means the battery is fully charged and 0% means the battery is empty. During the hours of

00:00 – 6:00 am, the battery storage SOC lies between 40% - 80%. Also, from the hours 7:00 – 12:00 pm, the battery storage has moderate SOC which lies in the range of 60% - 90%. In addition, the SOC is almost 80% - 99% during the hours of 13:00 – 23:00 of the day (see Figure 4.14). High percentage of SOC is as result of biogas generator which operates maximum in these hours, thus, the system charges the batteries by storing excess energy into the batteries.

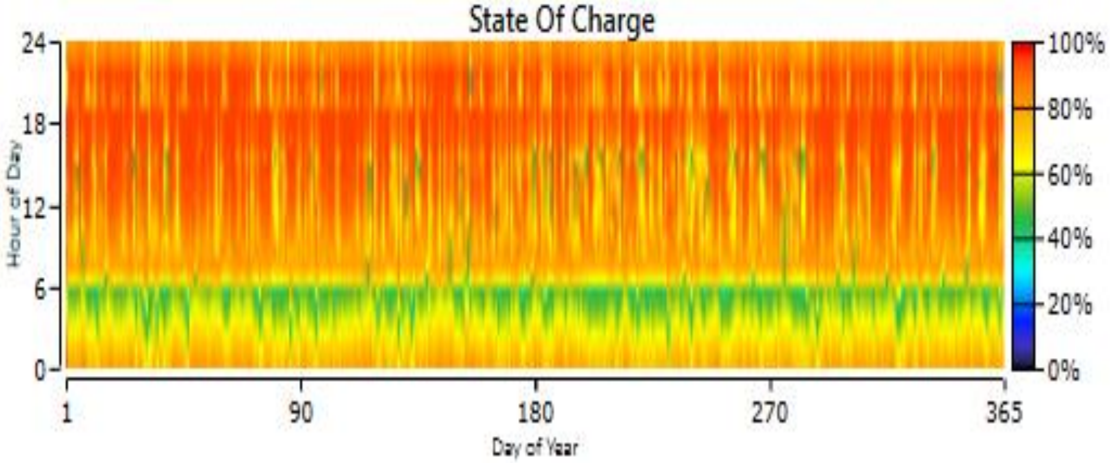


Figure 4.14: Battery storage yearly state of charge

4.3.6 Optimal operation and performance of converter

The optimal converter will convert the DC loads to AC using an inverter as well as convert AC loads to DC using a rectifier. The inverter and rectifier has a capacity of 15.7 kW each with a capacity factor of 19.1 kW and 7.77 kW respectively. Also, the inverter and rectifier annual operation times are 6,134 kWh/yr and 2,447 kWh/yr. The inverter energy in and energy out are 27,584 kWh/yr and 26,205 kWh/yr and the rectifier energy in and energy out are 11,231 kWh/yr and 10,669 kWh/yr respectively. Inverter has losses of 1,379 kWh/yr as compared to the rectifier with losses of 562 kWh/yr. From Figure 4.15, it depicts that, the inverter function maximum from hours of 7:00 – 16:00 with a capacity in the range of 3 – 7 kW. These are the hours of the day when the PV panels generates DC electricity which is converted into AC electricity to power electrical appliances.

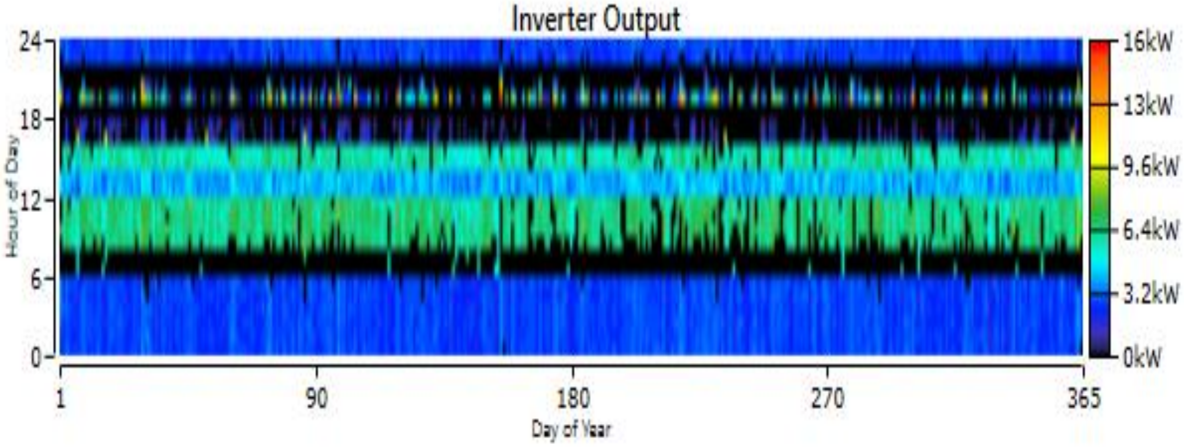


Figure 4.15: Daily performance of inverter

From Figure 4.16, it can be seen that the rectifier function maximum from the hours of 18:00 – 23:00 (during these hours only biogas generator produces AC electricity to meet the community energy demand) and 6:00 – 8:00 (might be due to low solar radiation, thus, making biogas generator function maximum). Moreover, the rectifier also converts excess AC electricity generated from the biogas generator into DC before storing in the battery storage.

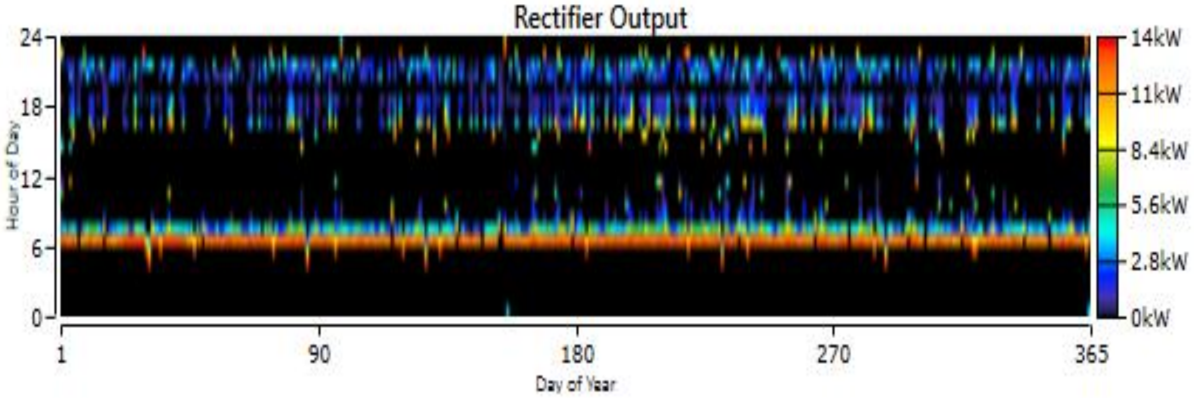


Figure 4.16: Daily performance of rectifier

4.4 Emission analysis

Solar PV emits no pollutants into the atmosphere but biogas emits some portion of pollutants into the atmosphere. The biogas generator will emit 33.6 kg/yr of carbon dioxide, 0.0368 kg/yr of carbon monoxide and 0.023 kg/yr of nitrogen oxide. However, the biogas generator will emit no particulate matter and sulphur dioxide into the atmosphere. However, the carbon dioxide released into the atmosphere will be absorbed by plants through photosynthesis, thus making biogas a clean energy source.

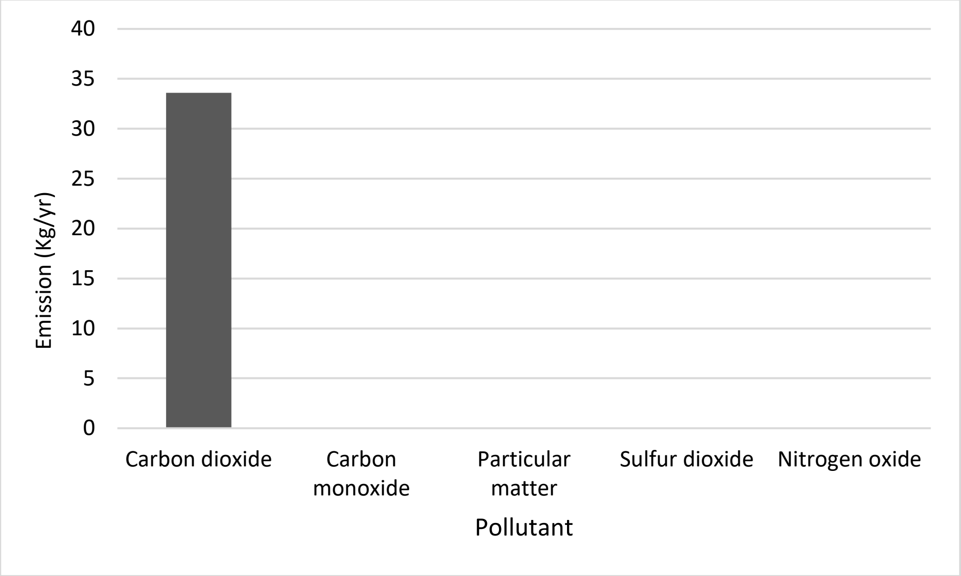


Figure 4.17: Amount of pollutants emitted from the optimal power system

4.5 Economic analysis

4.5.1 Presentation of economic metrics (present worth, annual worth, return of investment, internal rate of return and payback time)

HOMER optimization compared the base and current systems to calculate the key and valuable economic metrics considering the life cycle costs of both systems (see Table 4.2).

Table 4.2: HOMER optimization base and current systems used to calculate valuable economic metrics

	Architecture				Cost	
System	PV Panel (kW)	Biogas Generator (kW)	Battery (kwh)	Converter (kW)	NPC (US$)	Initial Capital (US$)
Base	0	50.0	40	10.2	242,394	80,584
Current	18.6	45.0	62	15.7	219,554	102,247

The optimal solar PV-biogas hybrid power system has a present worth (accounts for the difference between the NPC of the base case system and the current system) of US$ 22,840 with annual worth of US$ 1,867. This positive value of present worth indicates that the current system (solar PV-biogas hybrid power system) saves money over the project lifetimes compared to the base case system. Moreover, the return on investment (ROI) and internal rate of return (IRR) of this project are estimated at 12.4% and 16.5% respectively. Another metric which of economic importance in the feasibility and implementation of a project is the payback time. Nevertheless, the simple and discounted payback time is found to be 3.95 years and 4.49 respectively. In view of this, it will take approximately 4.5 years to recover the total investment cost of this project.

4.5.2 Optimal hybrid system net present cost (NPC) and levilized cost of energy (LCOE)

The optimal solar PV-biogas hybrid power system has overall NPC of US$ 219,554, LCOE of US$ 0.188/kWh and operational cost of US 9,587/yr. Out of the total NPC, biogas generator has the highest NPC of US$ 74,431 representing 34%, followed by battery storage (US$ 63,596) representing 29%, other (cost for construction of biogas digester, mini-grid distribution system etc.) is UDS$ 57,236 representing 26% and converter is US$ 3405 representing 2% respectively (see Figure 4.18 and Figure 4.19). From Figure 4.18, it can be seen that more than half of the hybrid power system NPC is consumed by biogas generator and battery storage. Moreover, biogas generator operating and maintenance cost (O&M) is more than half of the hybrid power system overall O&M. In addition, solar PV panels have very low O&M but high capital cost as compared to biogas generator (see Figure 4.18). Consequently, reducing the storage system, reducing the capacity and minimizing the operation hours of the biogas generator will effectively help reduce the hybrid power system overall cost and make it more cost-effective and cheaper. Additionally, Figure 7.8 in appendix shows the breakdown of the optimal power system annualized cost by components and Figure 7.9 in appendix shows the breakdown of the optimal power system annualized cost by cost type.

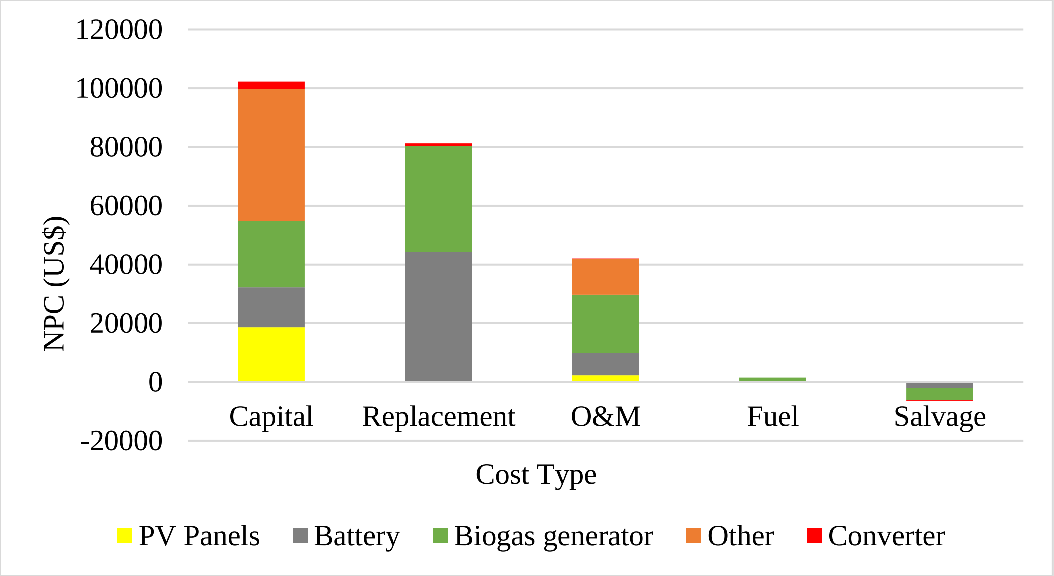


Figure 4.18: Breakdown optimal power system NPC by components

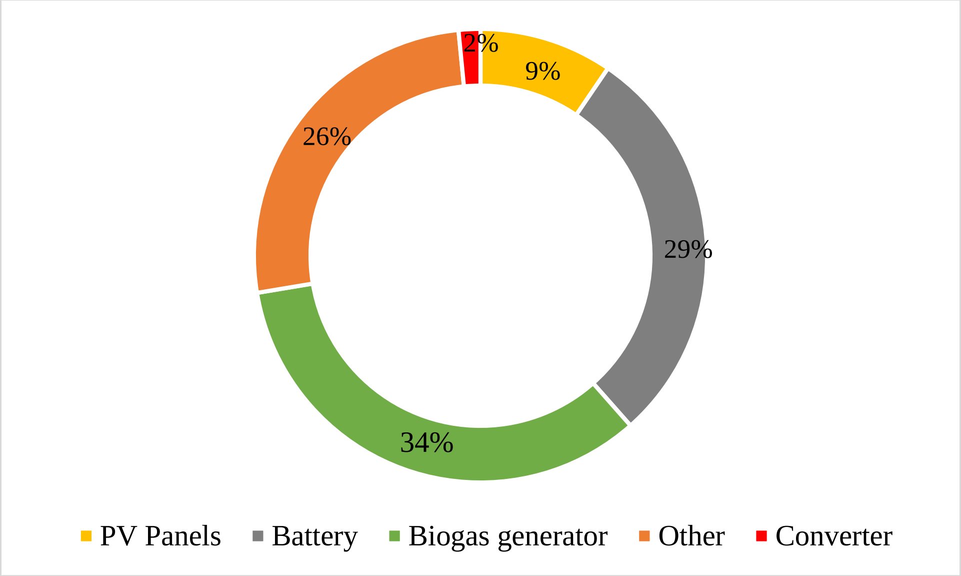


Figure 4.19: Percent share of optimal power system NPC by components

4.6 Cash flows output for the project

HOMER optimization results displays the optimal cash flow of the project. It displays the cash flows in either component types (converter, other, biogas generator, battery and PV panel) with nominal cash flows or discounted cash flows from year 0 to year 25 (project lifetime). The nominal cash flow refers to the actual income minus cost that HOMER anticipates in a particular year whiles discounted cash flow refers to nominal cash flow discounted to year zero (Lambert et al., 2006). Figure 4.20 displays that the project has negative cash flows from year 0 to year 24. These negative values represent an outflow which refers to capital, replacement and O&M cost for component types and cost of fuel during the running of the project. At year 0, the project has the highest cash outflows because of high initial capital (US$ 102,247) needed to initiate the project. The outflow values start to depreciate from year1 to year 24. From year 1 to year 25, the battery storage will be replaced every 4 years and biogas generator will be replaced in every 6 years, and converter will only be replaced in year 15 and year 25. In addition, see Figure 7.10 in appendix for cash flow of cost type with discounted cash flow.

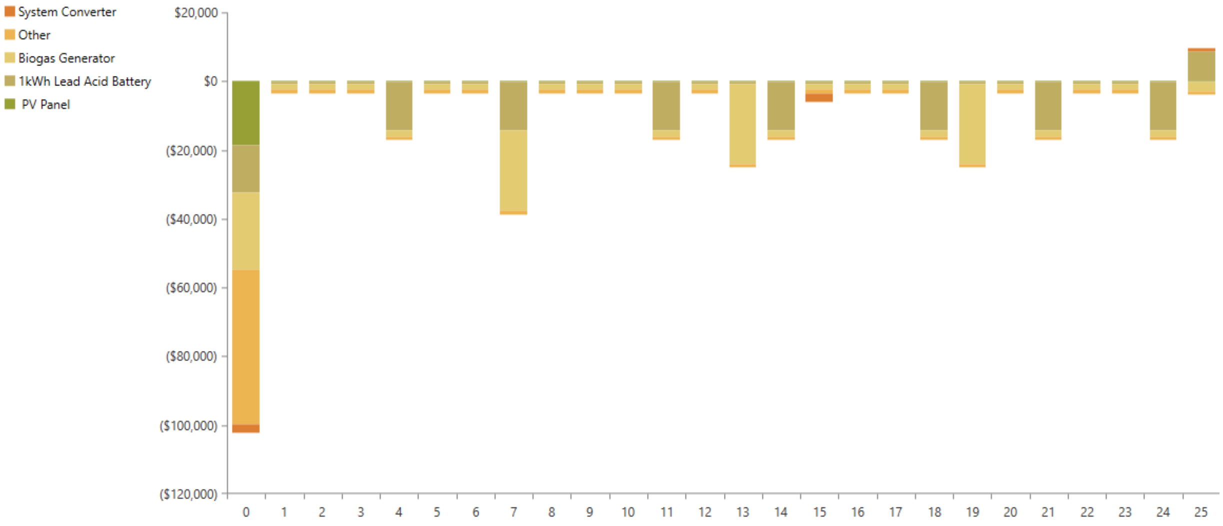


Figure 4.20: Cash flow of component type with nominal cash flow

From Figure 4.21, it shows that at the project lifetime (year 25), the project has a positive inflow value of US$1,839. This inflow value is originating from the savage value of components such as battery storage, biogas generator and converter at the end of the project lifetime. In addition, see Figure 7.11 in appendix for cash flow of cost type with discounted cash flow.

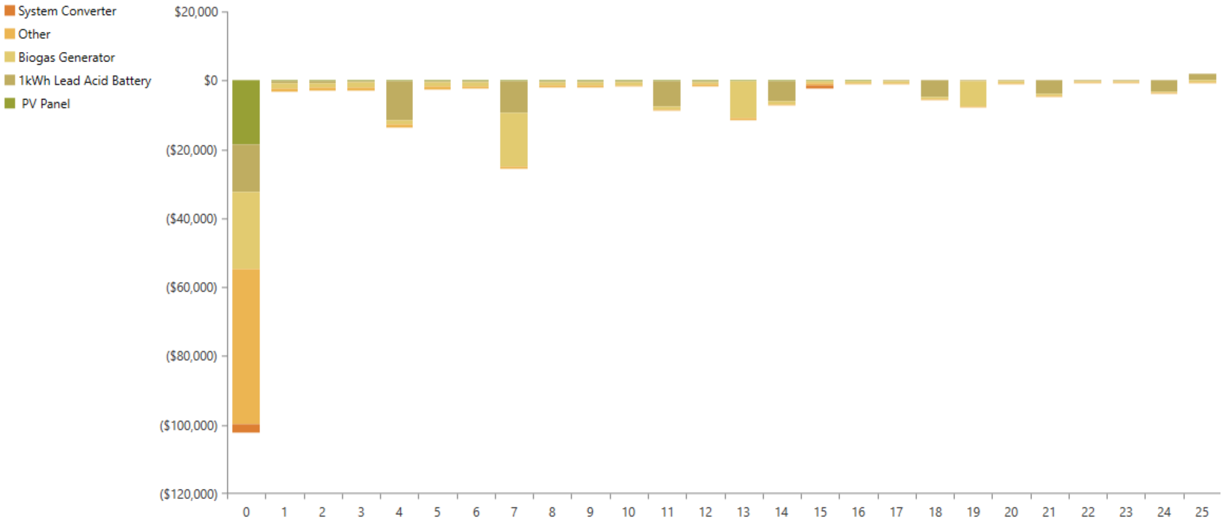


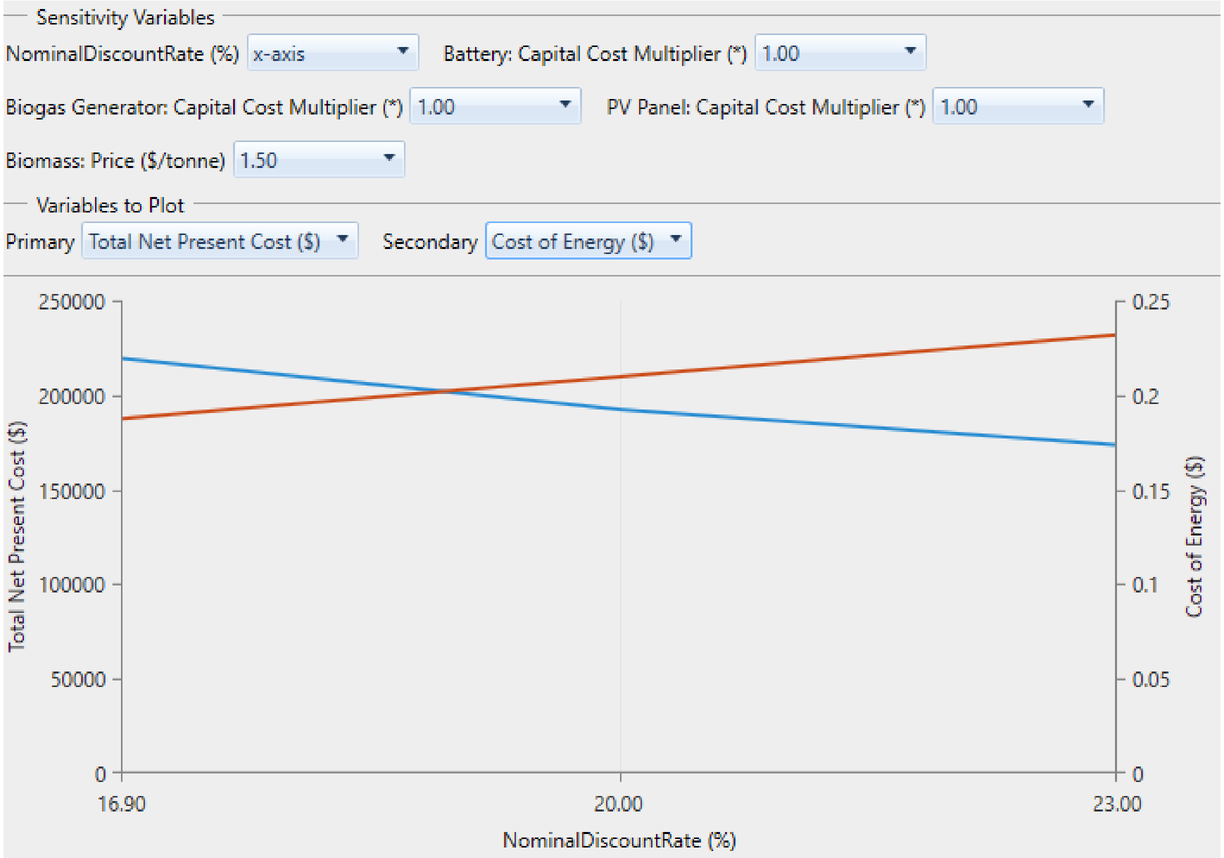
Figure 4.21: Cash flow of component type with discounted cash flow

4.7 Results for sensitivity analysis

The sensitivity variables are plotted using HOMER surface plot and line plot. HOMER surface plot displays the total net present cost (NPC) on the surface plot and levilized cost of energy (LCOE) as superimposed plot. Also, HOMER line plot displays NPC and LCOE on the vertical axis against the sensitivity variable on the horizontal axis. The effect of nominal discount rate, components (PV panels, battery and biogas generator) capital cost and price of biomass feedstock on the optimal system NPC and LCOE are analysed using HOMER surface plots and line plots.

4.7.1 Effect of nominal discount rate on system NPC and LCOE

Sensitivity analysis was performed on two different nominal discount rate scenarios: 20% and 23% with respect to current nominal discount rate (16.9%). From Figure 4.22 and 4.23, as the nominal discount rate increases from 16.9% to 20%, the system LCOE rises from US$ 0.188/kWh to US$ 0.210/kWh (LCOE increases by 11.7%) and NPC falls from US$ 219,544 to US$ 190,000. Similarly, with sudden drastic increase in nominal discount rate from 16.9% to 23% will increase the LCOE of the system from US$ 0.188/kWh to US$ 0.232/kWh (LCOE increases by 23.4%). This new LCOE of US$ 0.210/kWh and US$ 0.232/kWh is 23.5% and 36.47 % higher than the current LCOE (US$ 0.17/kWh) for residential households in Ghana. This means that, high nominal discount rate will negatively affect the LCOE of the system and will make it very expensive for the community. Also, it will not attract investment to implement the project. However, this sensitivity results shows that the optimal power system LCOE is only 24 – 35% higher than current LCOE for residential tariffs in Ghana, thus, making this optimal power system cost-effective compared to electricity from the national grid.



Sensitivity Variables

NominalDiscountRate (%): x-axis

Battery: Capital Cost Multiplier (*): 1.00

Biogas Generator: Capital Cost Multiplier (*): 1.00

PV Panel: Capital Cost Multiplier (*): 1.00

Biomass: Price ($/tonne): 1.50

Variables to Plot

Primary: Total Net Present Cost ($)

Secondary: Cost of Energy ($)

Figure 4.22: Effect of nominal discount rate on the system NPC and LCOE

4.7.2 Effect of PV capital cost on system NPC and LCOE

PV capital cost which consists of PV panels and mounting structure (depends on efficiency and manufacturer), installation and labour cost (depends on quality of technicians), cables and wires (type and quality) varies from one company to another in Ghana, hence, sensitivity analysis was performed on four different PV capital cost scenarios: US$1250/kW, US$1500/kW, US$1500/kW and US$2000/kW compared to PV initial cost (US$1000/kW) used for stimulation and optimization in this study. From Figure 4.22 and Figure 4.23, as the PV capital cost changes from US$1000/kW to US$1250 kW, the optimal power system LCOE rises from US$ 0.188/kWh to US$0.191/kWh (1.6% higher) and NPC rises from US$ 219,544 to US$ 221,000. Similarly, with US$ 1500/kW as PV panel capital cost, the LCOE rises from US$ 0.188/kWh to US$ 0.194/kWh (3.19% higher) and NPC rises from US$ 219,544 to US$ 223,000. With a high PV capital cost of US2,000/kWh, the optimal system LCOE rises from US$ 0.188/kWh to US$ 0.20/kWh (6.38% higher) and NPC rises from US$ 219,544 to US 230,000. These results justify that the LCOE from PV panel capacities of US$ 1,250/kW, US$1,500/kW, US$ 1,725/kW and US$ 2,000/kW will be 10.6%, 12.4%, 14.1%, 15.9% and 17.7% respectively higher than the LCOE (US$ 0.17/kWh) for residential tariffs in Ghana. From these sensitivity results, it implies that, with sudden increased in PV panel capital cost, there is only slight change in the optimal power system LCOE and NPC of the project since the PV panels lifetime equals the project lifetime (no replacement cost).

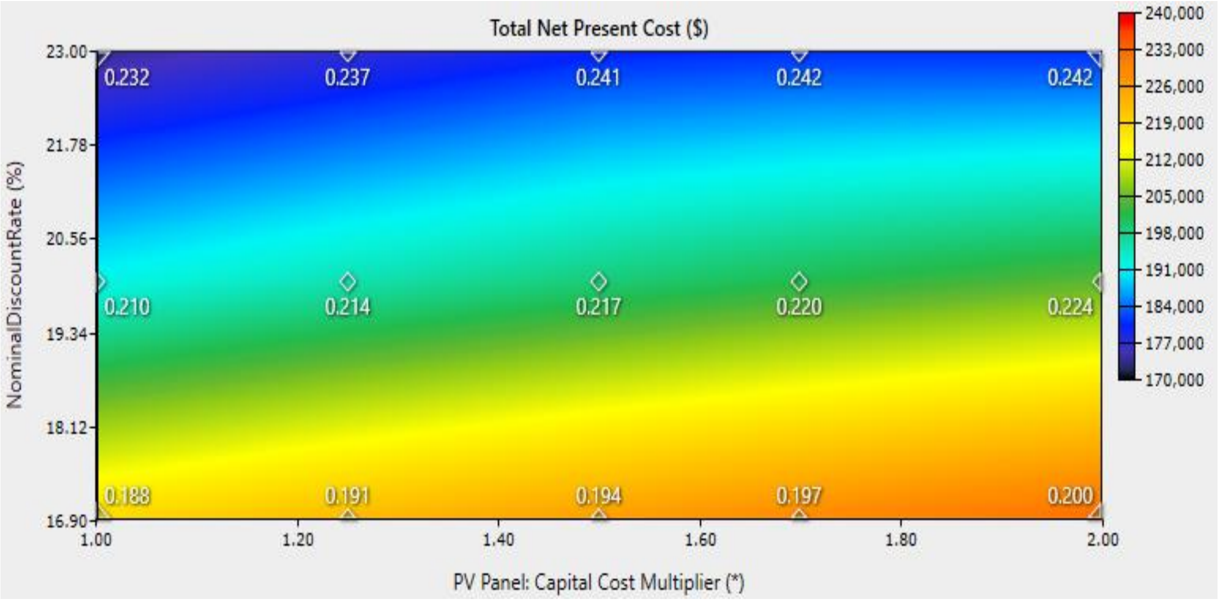


Figure 4.23: Effect of nominal discount rate and PV capital cost on NPC and LCOE

4.7.3 Effect of battery capital cost on system NPC and LCOE

At a (nominal discount rate of 16.9%, biomass price of US$1.5/tonnes, converter price of US$500/kW and biogas generator cost of US$750/kW), as the battery capital cost decrease by 10%, the system LCOE will drop from US$ 0.188/kWh to US$0.186/kWh (1.06% decrease) and NPC will drop from US$ US$ 219,544 to US$ 216,9000. Similarly, as the battery capital cost decrease by 20%, the system LCOE will fall from US$ 0.188/kWh to US$0.185/kWh (1.6% decrease) and NPC will fall from US$ 219,544 to US$215,000 (see Figure 4.24). Moreover, this 10% and 20% decrease in battery capital cost will cause the LCOE of the system to only be 8.8% and 9.4% higher than that LCOE (US$0.17/kWh) for residential tariffs in Ghana.

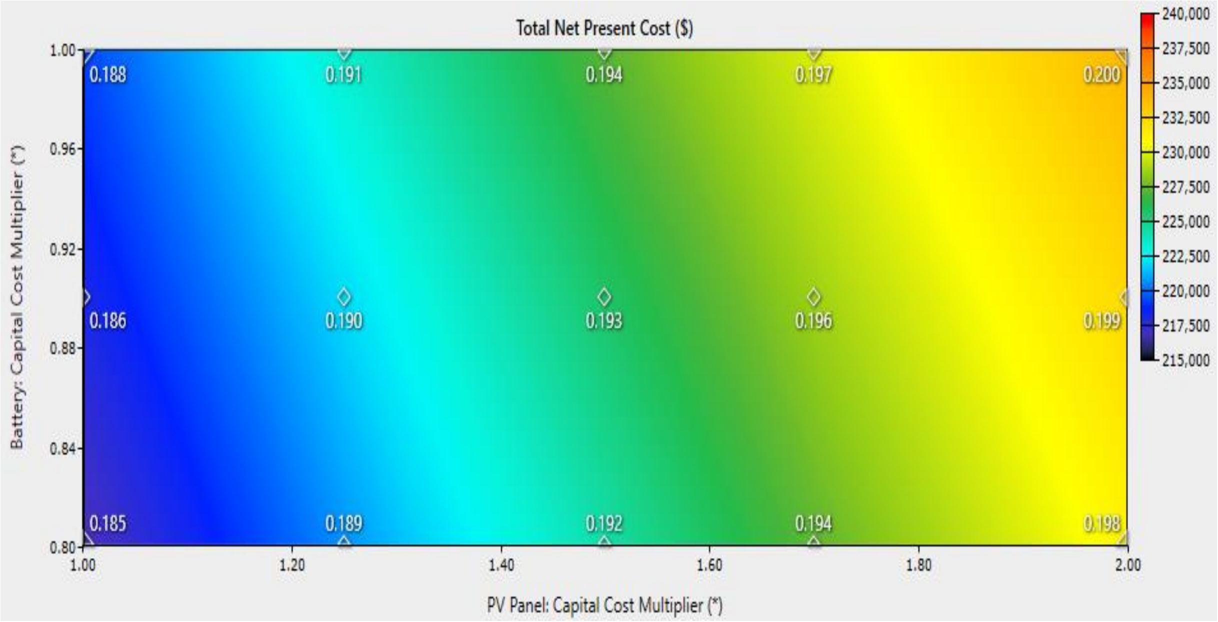


Figure 4.24: Effect of components capital cost (battery and PV panels) on NPC and LCOE

4.7.4 Effect of biogas generator capital cost on system NPC and LCOE

From Figure 4.25, as biogas generator capital cost increase by 100%, the system LCOE rises from US$0.188/kWh to US$0.207/kWh and NPC rises from US$ 219,544 to US$ 242,000. Similarly, when PV capital cost increase by 100% (US1000/kW to US2000/kW) at initial biogas generator capital cost, the LCOE of the system changes to US$0.200/kWh which is 3.5% lower than the LCOE from the biogas generator. This sensitivity results implies that increasing the PV panel capital cost and decreasing the biogas generator capital cost will decrease the LCOE of the system, thus, making it cost-effective.

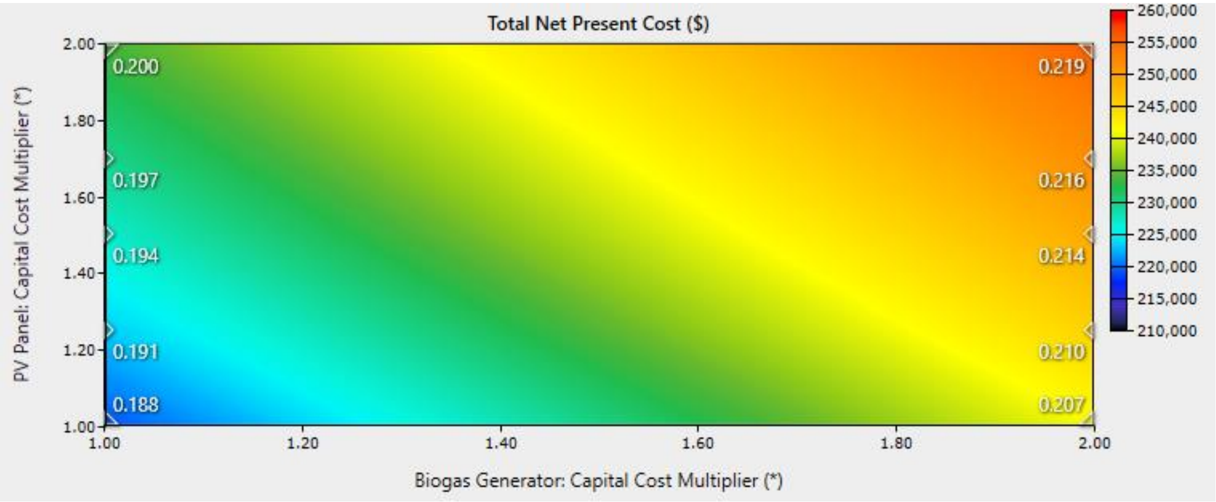


Figure 4.25: Effect of components cost (PV panel and biogas generator) on the system NPC and LCOE

4.7.5 Effect of price of biomass on system NPC and LCOE

At constant (nominal discount rate, PV panel capital cost and battery capital cost), when the biomass price is increased from US$ 1.50/tonnes to US$ 2.50/tonnes, there is only an infinitesimal change in the LCOE but NPC remains constant. This implies that price of biomass does not greatly influence the change of LCOE and NPC of the system (see Figure 4.26 and Figure 4.27).

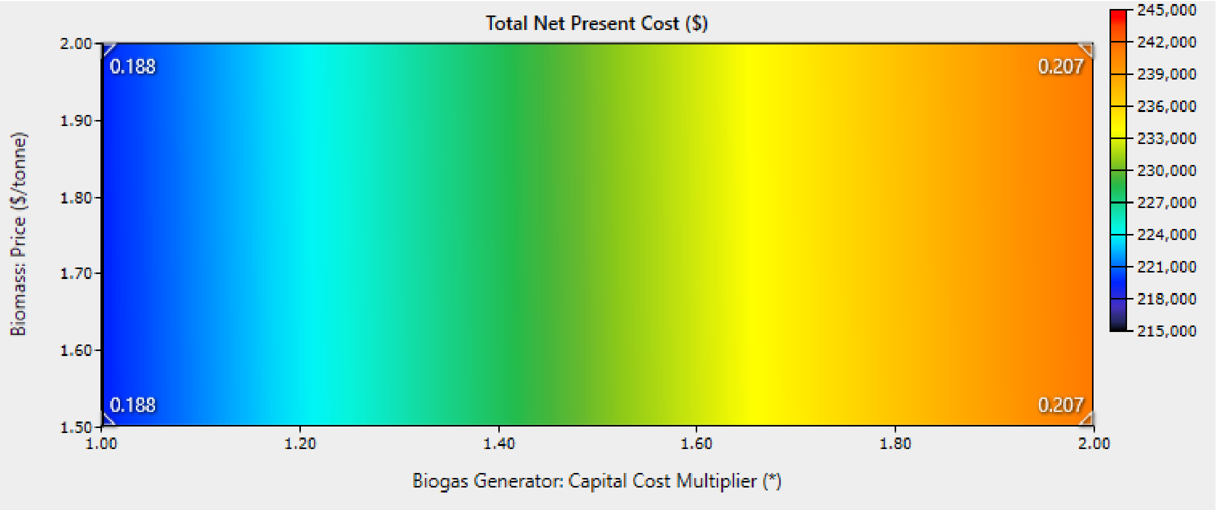


Figure 4.26: Effect of price of biomass and biogas generator capital cost on system NPC and LCOE

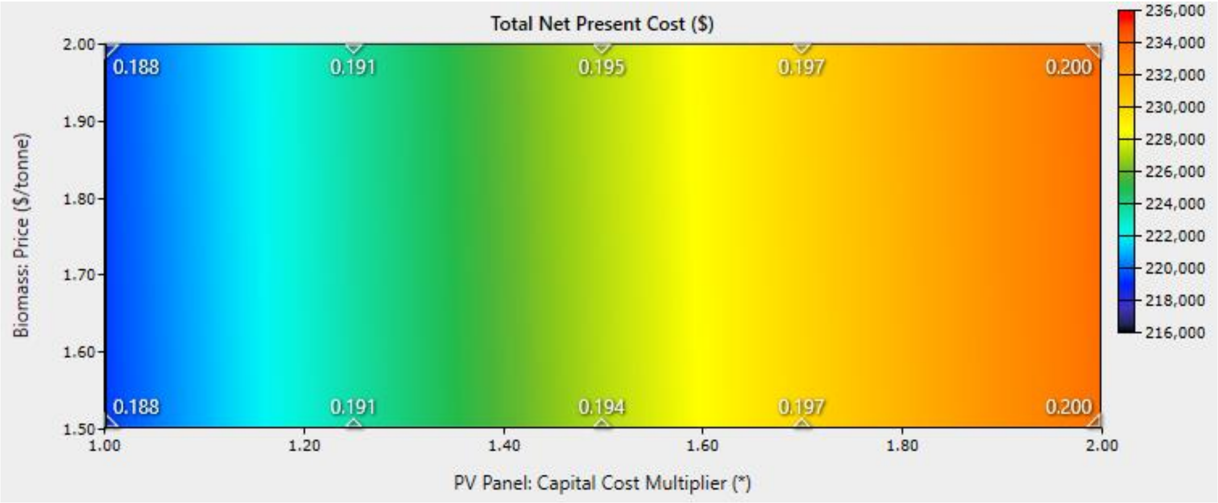


Figure 4.27: Effect of price of biomass price and PV panels capital cost on system NPC and LCOE

CHAPTER 5

5 Conclusion and Recommendations

5.1 Conclusion

Globally, the transition from fossil fuels to clean fuels has impelled a recent keen interest in renewable energy sources for energy activities. The Government of Ghana policy to increase the share of renewables in national energy mix to 10% and 100% universal access to electricity in the country by 2020 has prompted research into the analysis and development of reliable and cost-effective energy from renewable energy sources.

In this study, a hybrid power system which consist of solar PV and biogas generator has been modelled and optimized successfully. The technical potential of crop residues and animal manure available in Mankramso community for biogas production was assessed. In addition, solar global horizontal irradiance data for Mankramso was retrieved from NASA Surface Meteorology Database. HOMER software was used to carry out design, simulation and optimization of the solar PV-biogas hybrid power system.

Results from HOMER optimization depicted that the hybrid power system which comprises of PV panels capacity of 18.6 kW, biogas generator capacity of 45 kW, battery storage capacity of 62 kWh and converter capacity of 15.7 kW is the optimal and ideal power system that can meet Mankramso's daily electricity consumption of 262.05 kWh/d without intermittency. The technical, economic and greenhouse emission analysis shows that this optimal power system will annually produce 105,479 kWh/yr of electricity and 95,633 kWh will be consumed by Mankramso community AC loads with an electricity excess of 4,676 kWh/yr. The PV panels will produce 23% and biogas generator will produce 77% of this annual electricity. PV panels will emit no pollutants but biogas generator will emit small quantities of pollutants such as carbon dioxide (33.6 kg/yr), carbon monoxide (0.0368 kg/yr) and nitrogen oxides (0.0230 kg/yr). Nevertheless, the carbon dioxide emitted will be absorbed by plants through photosynthesis, thus, making biogas a clean energy. Moreover, the optimal power system has a NPC of US$219,442 which will yield a LCOE of US$ 0.188/kWh. However, this LCOE is about 10.6% higher than residential tariffs (US$ 0.17/kWh) in Ghana. Furthermore, sensitivity analysis performed on this power system shows that high discount rate increases the LCOE and NPC of this system, hence, current discount rate affects the LCOE and NPC of this system. In addition, the sensitivity analysis on components (PV panels and biogas generator) capital cost depicted that increasing the PV panel capital cost and decreasing the biogas generator capital will decrease the LCOE of the system, thus, making it cost-effective. With the project lifetime of 25 years, the return on investment and internal rate of return of this project was estimated at 12.4% and 16.5% respectively. Moreover, it will take investors approximately 4.5 years to recover the total investment cost of this project.

5.2 Recommendations

- The Government can consolidate with potential investors for the implementation of this project since the government wants to increase the share of renewables in the national energy mix to 10% and increase electricity access to 100% in the country by 2020.
- Government should use cross-subsidy to ensure tariff parity among grid and off-grid community schemes in the country, so that rural communities are not unduly disadvantaged.
- This study used secondary solar GHI data from NASA. Therefore, ground data for solar irradiation from the study site should be used for future studies to achieve more accurate results.

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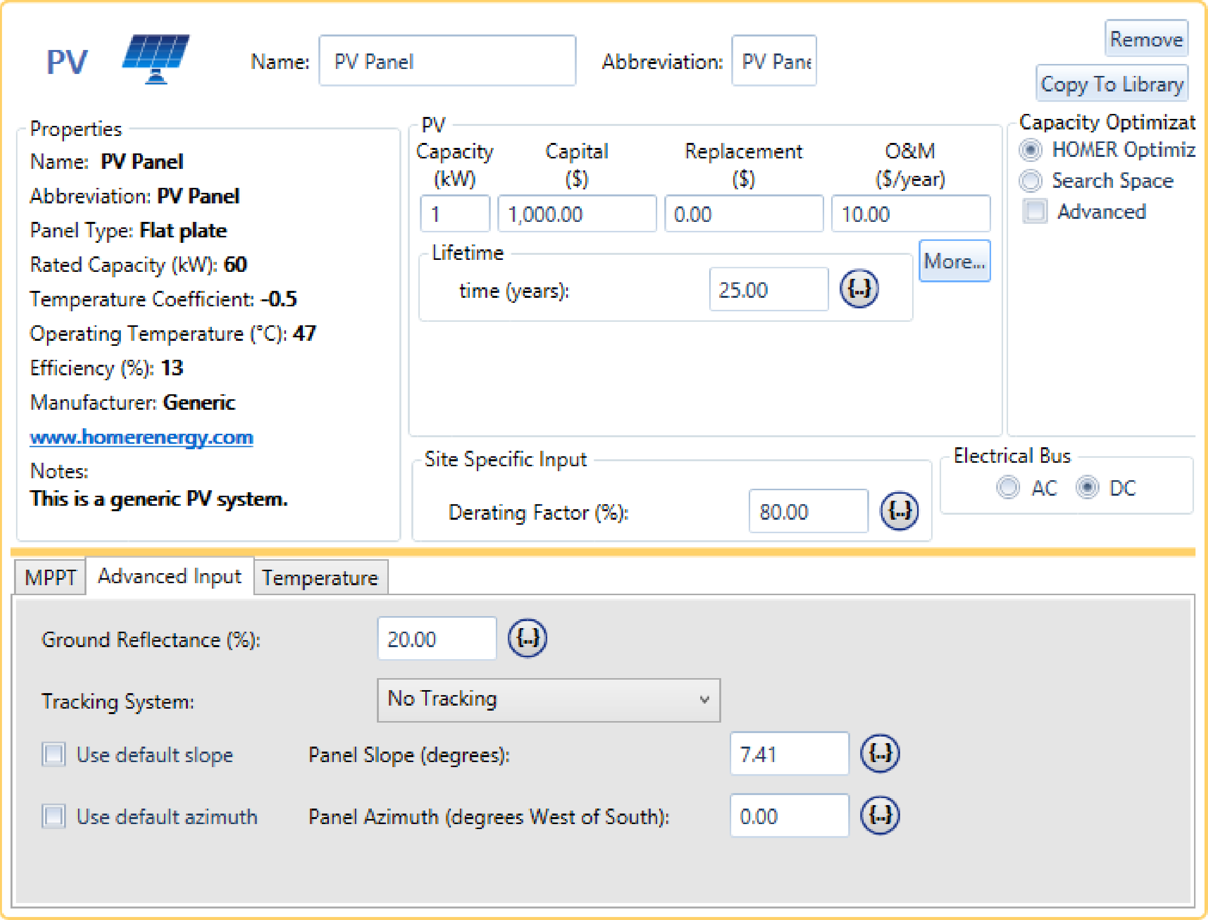
7 Appendix

HOMER stimulation and optimization procedure



Name: PV Panel

Abbreviation: PV Pane

Properties

Name: **PV Panel**

Abbreviation: **PV Panel**

Panel Type: **Flat plate**

Rated Capacity (kW): **60**

Temperature Coefficient: **-0.5**

Operating Temperature (°C): **47**

Efficiency (%): **13**

Manufacturer: **Generic**

www.homerenergy.com

Notes:

This is a generic PV system.

PV

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
1	1,000.00	0.00	10.00

Lifetime

time (years): 25.00

Capacity Optimizat

● HOMER Optimiz

○ Search Space

☐ Advanced

Site Specific Input

Derating Factor (%): 80.00

Electrical Bus

○ AC ● DC

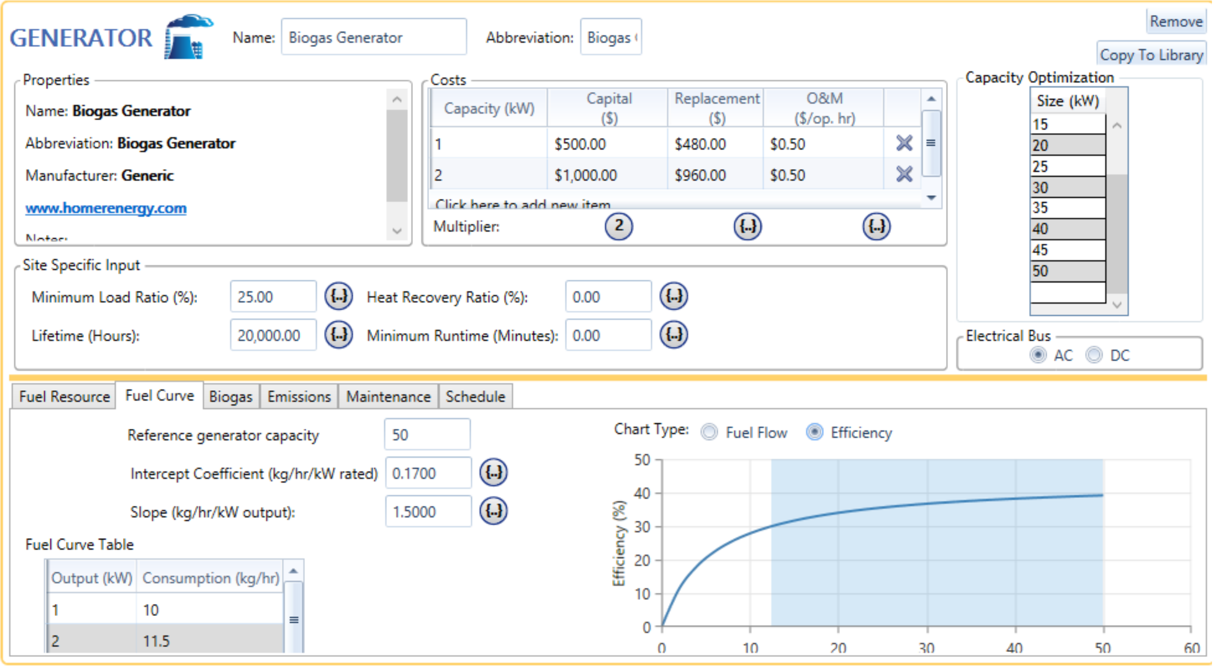
Ground Reflectance (%): 20.00

Tracking System: No Tracking

☐ Use default slope Panel Slope (degrees): 7.41

☐ Use default azimuth Panel Azimuth (degrees West of South): 0.00

Figure 5.1: PV panel input parameters



Name: Biogas Generator

Abbreviation: Biogas

Properties

Name: **Biogas Generator**

Abbreviation: **Biogas Generator**

Manufacturer: **Generic**

www.homerenergy.com

Notes:

Costs

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/op. hr)
1	$500.00	$480.00	$0.50
2	$1,000.00	$960.00	$0.50

Click here to add new item

Multiplier: 2

Capacity Optimization

Size (kW)
15
20
25
30
35
40
45
50

Site Specific Input

Minimum Load Ratio (%): 25.00

Heat Recovery Ratio (%): 0.00

Lifetime (Hours): 20,000.00

Minimum Runtime (Minutes): 0.00

Electrical Bus: ● AC ○ DC

Reference generator capacity: 50

Intercept Coefficient (kg/hr/kW rated): 0.1700

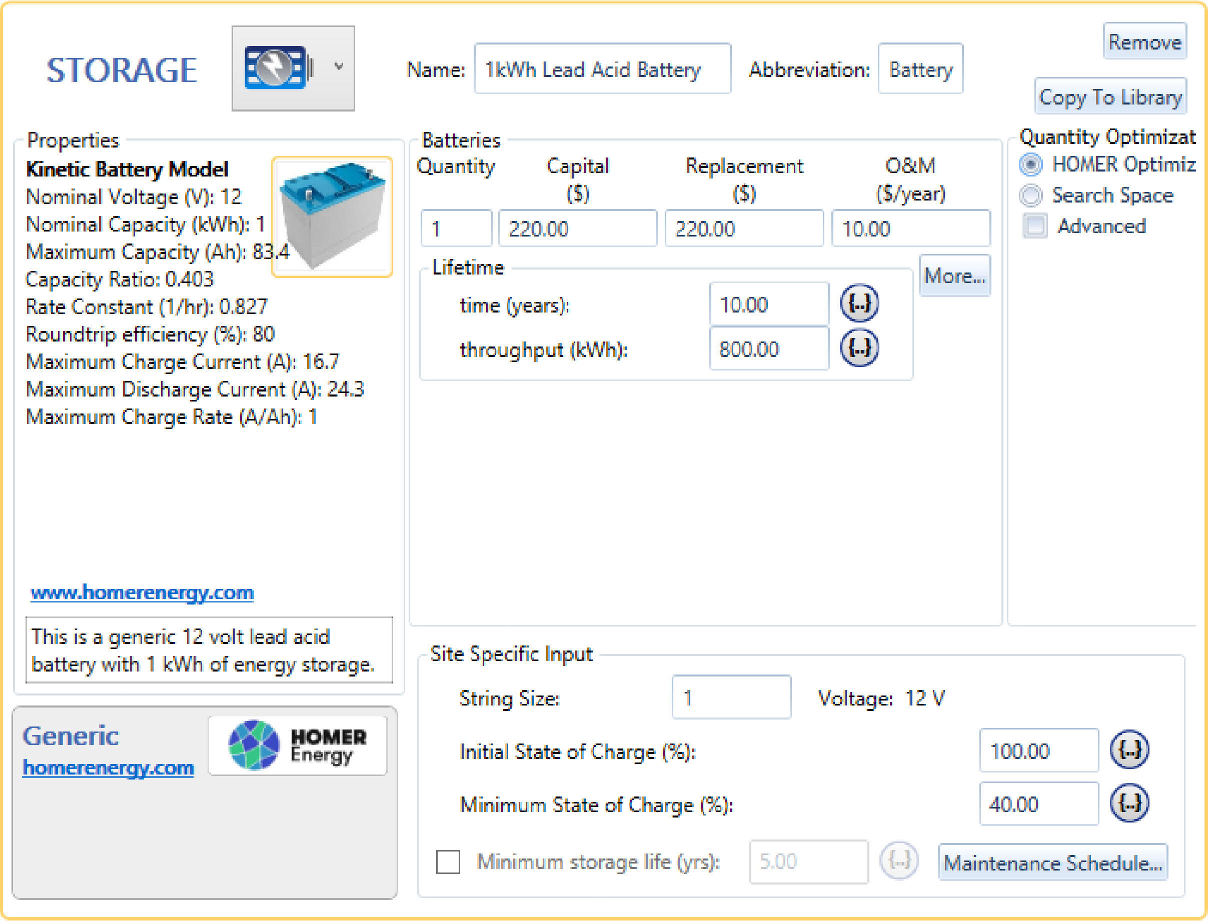
Slope (kg/hr/kW output): 1.5000

Fuel Curve Table

Output (kW)	Consumption (kg/hr)
1	10
2	11.5

Chart Type: ○ Fuel Flow ● Efficiency

Figure 5.2: Biogas generator input parameters



Name: 1kWh Lead Acid Battery

Abbreviation: Battery

Properties

Kinetic Battery Model

Nominal Voltage (V): 12

Nominal Capacity (kWh): 1

Maximum Capacity (Ah): 83.4

Capacity Ratio: 0.403

Rate Constant (1/hr): 0.827

Roundtrip efficiency (%): 80

Maximum Charge Current (A): 16.7

Maximum Discharge Current (A): 24.3

Maximum Charge Rate (A/Ah): 1

www.homerenergy.com

This is a generic 12 volt lead acid battery with 1 kWh of energy storage.

Batteries

Quantity	Capital ($)	Replacement ($)	O&M ($/year)
1	220.00	220.00	10.00

Lifetime

time (years): 10.00

throughput (kWh): 800.00

Quantity Optimizat

● HOMER Optimiz

○ Search Space

☐ Advanced

Site Specific Input

String Size: 1

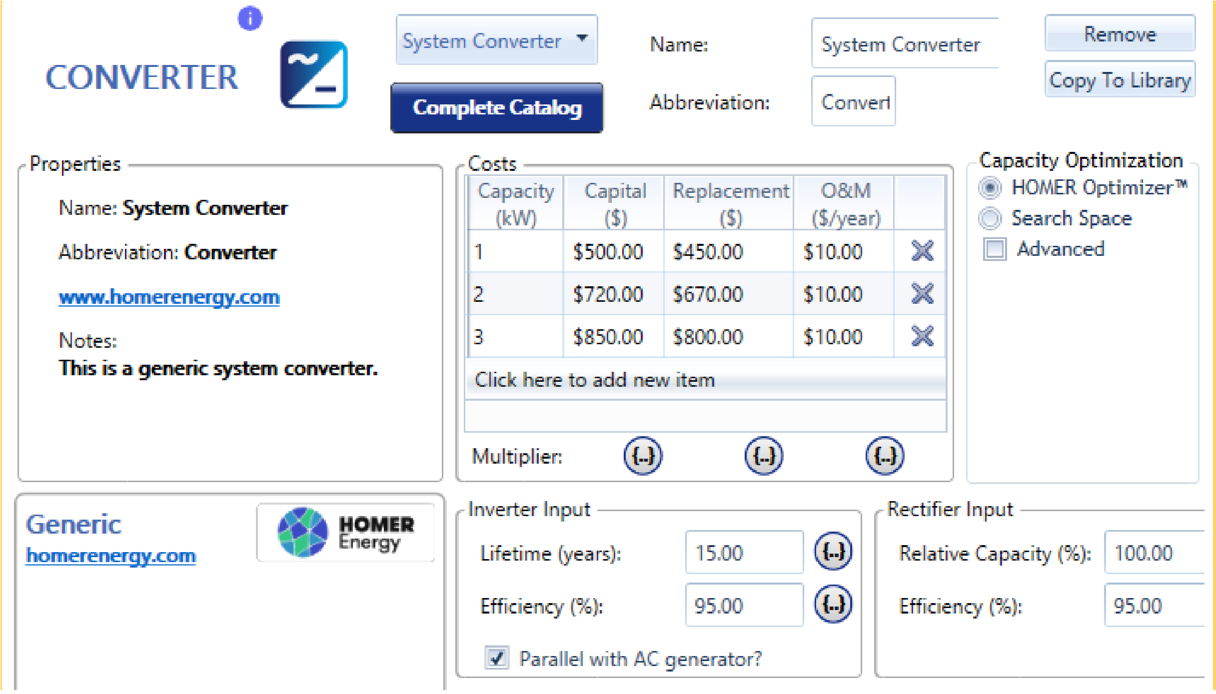
Voltage: 12 V

Initial State of Charge (%): 100.00

Minimum State of Charge (%): 40.00

☐ Minimum storage life (yrs): 5.00

Figure 5.3: Battery storage input parameters



Name: System Converter

Abbreviation: Convert

Properties

Name: **System Converter**

Abbreviation: **Converter**

www.homerenergy.com

Notes:
This is a generic system converter.

Costs

Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)	
1	$500.00	$450.00	$10.00	☒
2	$720.00	$670.00	$10.00	☒
3	$850.00	$800.00	$10.00	☒
Click here to add new item				

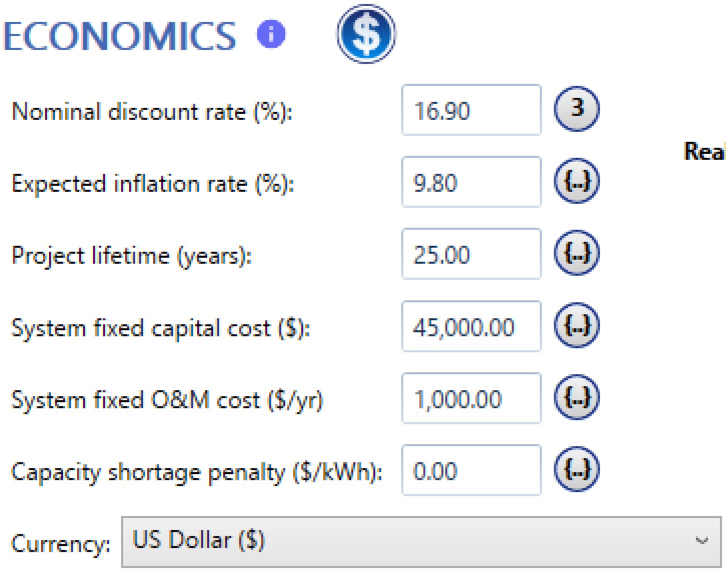
Multiplier: {..} {..} {..}

Capacity Optimization
● HOMER Optimizer™
○ Search Space
☐ Advanced

Inverter Input
Lifetime (years): 15.00
Efficiency (%): 95.00
☑ Parallel with AC generator?

Rectifier Input
Relative Capacity (%): 100.00
Efficiency (%): 95.00

Figure 5.4: Converter input parameters



Nominal discount rate (%): 16.90

Expected inflation rate (%): 9.80

Project lifetime (years): 25.00

System fixed capital cost ($): 45,000.00

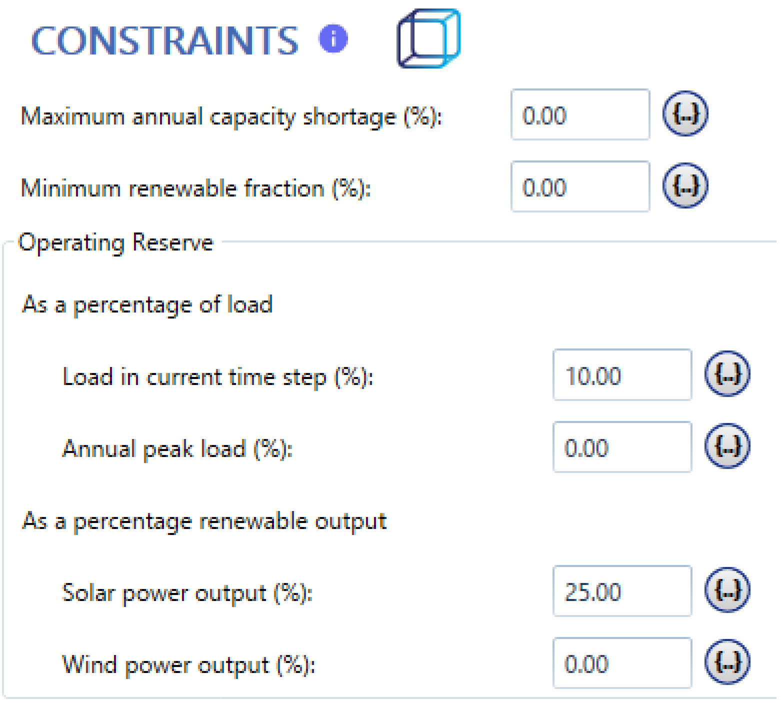
System fixed O&M cost ($/yr): 1,000.00

Capacity shortage penalty ($/kWh): 0.00

Currency: US Dollar ($)

Real discount rate (%): 6.47

Figure 5.5: Economic input variables



CONSTRAINTS

Maximum annual capacity shortage (%): 0.00

Minimum renewable fraction (%): 0.00

Operating Reserve

As a percentage of load

Load in current time step (%): 10.00

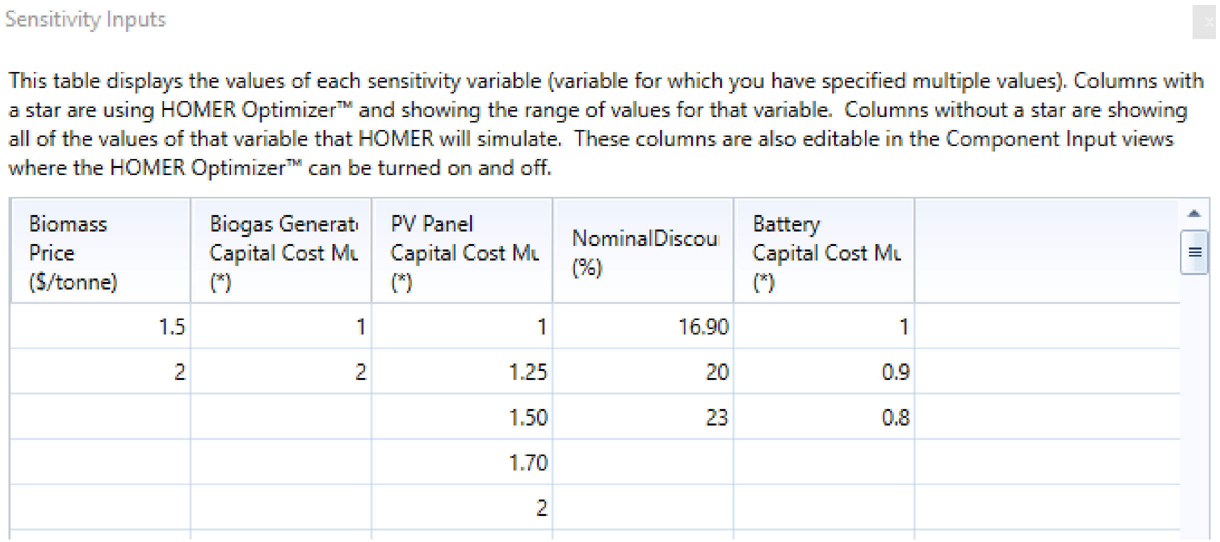
Annual peak load (%): 0.00

As a percentage renewable output

Solar power output (%): 25.00

Wind power output (%): 0.00

Figure 5.6: System constraints input parameters

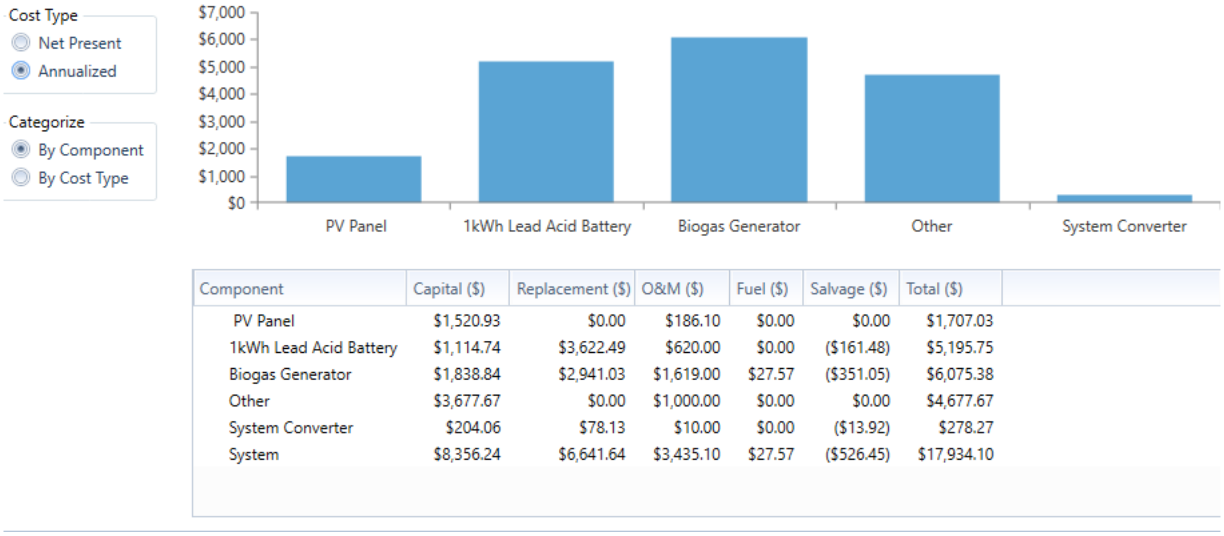


Sensitivity Inputs

This table displays the values of each sensitivity variable (variable for which you have specified multiple values). Columns with a star are using HOMER Optimizer™ and showing the range of values for that variable. Columns without a star are showing all of the values of that variable that HOMER will simulate. These columns are also editable in the Component Input views where the HOMER Optimizer™ can be turned on and off.

Biomass Price ($/tonne)	Biogas Generat Capital Cost Mu (*)	PV Panel Capital Cost Mu (*)	NominalDiscou (%)	Battery Capital Cost Mu (*)
1.5	1	1	16.90	1
2	2	1.25	20	0.9
		1.50	23	0.8
		1.70		
		2		

Figure 5.7: Sensitivity analysis input parameters

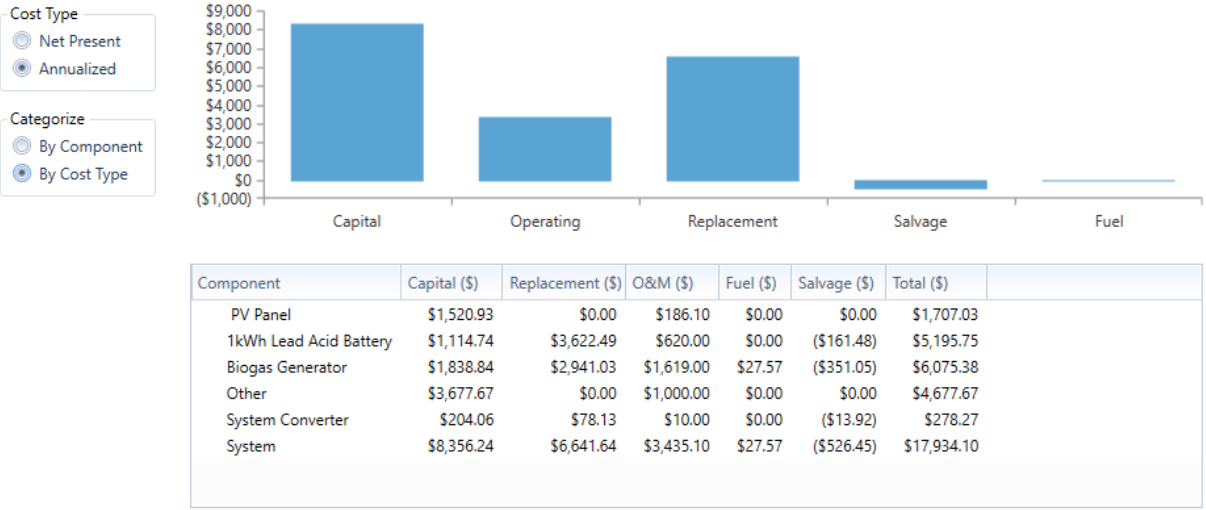


Cost Type
○ Net Present
● Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV Panel	$1,520.93	$0.00	$186.10	$0.00	$0.00	$1,707.03
1kWh Lead Acid Battery	$1,114.74	$3,622.49	$620.00	$0.00	($161.48)	$5,195.75
Biogas Generator	$1,838.84	$2,941.03	$1,619.00	$27.57	($351.05)	$6,075.38
Other	$3,677.67	$0.00	$1,000.00	$0.00	$0.00	$4,677.67
System Converter	$204.06	$78.13	$10.00	$0.00	($13.92)	$278.27
System	$8,356.24	$6,641.64	$3,435.10	$27.57	($526.45)	$17,934.10

Figure 5.8: Breakdown of optimal system annualized cost by components



Cost Type
○ Net Present
● Annualized

Categorize
○ By Component
● By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV Panel	$1,520.93	$0.00	$186.10	$0.00	$0.00	$1,707.03
1kWh Lead Acid Battery	$1,114.74	$3,622.49	$620.00	$0.00	($161.48)	$5,195.75
Biogas Generator	$1,838.84	$2,941.03	$1,619.00	$27.57	($351.05)	$6,075.38
Other	$3,677.67	$0.00	$1,000.00	$0.00	$0.00	$4,677.67
System Converter	$204.06	$78.13	$10.00	$0.00	($13.92)	$278.27
System	$8,356.24	$6,641.64	$3,435.10	$27.57	($526.45)	$17,934.10

Figure 5.9: Breakdown of optimal system annualized cost by cost type

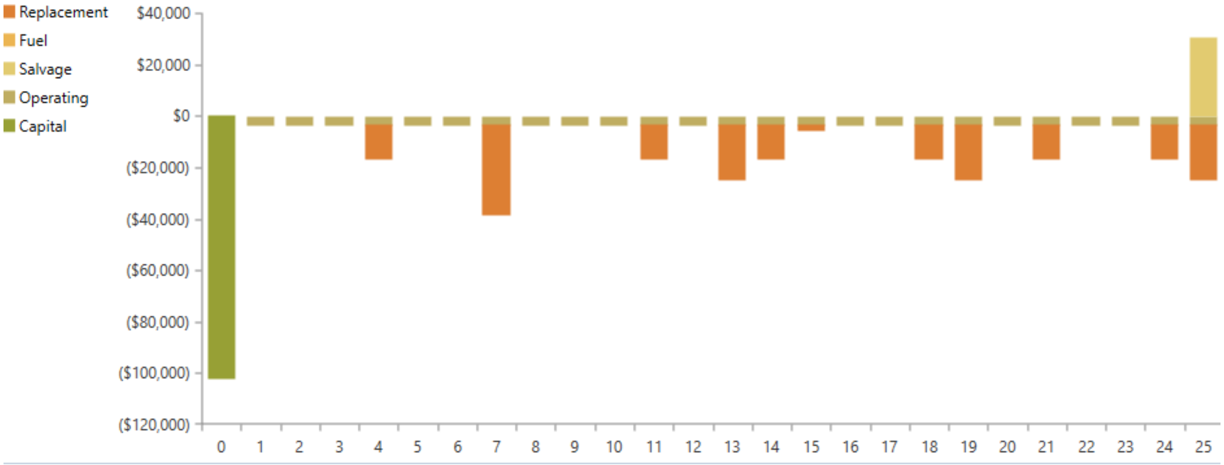


Figure 5.10: Cash flow of cost type with nominal cash flow

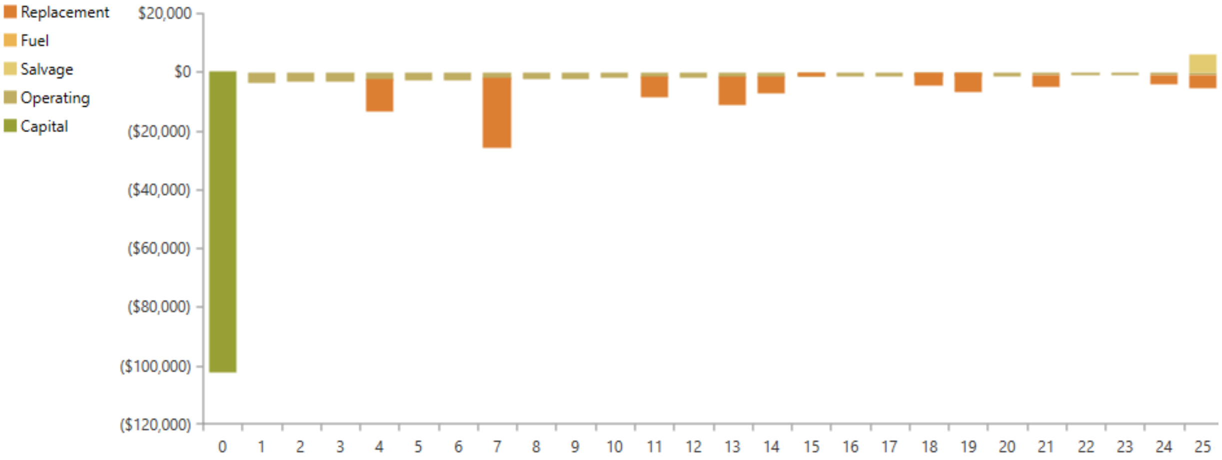


Figure 5.11: Cash flow of cost type with discounted cash flow

Questionnaire for data collection

Design of Solar PV-Biogas Hybrid Power System for Rural Electrification in Ghana Questionnaire for farmers (Crops and Animals) in Mankramso Community in the Offinso-North District

April – June, 2018

Questionnaire number: **Name of Community: Mankramso**

We are designing a Solar PV and Biogas Hybrid Power System for Rural Electrification in Mankramso Community located in the Offinso-North district. Solar PV system converts the sun light into direct current through photoelectric effect. Anaerobic digestion is the fermentation of organic wastes in the absence of free oxygen. The products of anaerobic digestion are an energy-rich biogas (methane and carbon dioxide) and nutrient-rich digestate (waste liquor and solid waste), which is typically applied as a fertilizer. The Biogas can be used to produce electricity. Of interest to us is the possibility of electricity as well as the employment and income gains that such a scheme could bring to this community.

PART 1: GENERAL INFORMATION

Date:	Start time:	Name of interviewer:
Farmer's name:		Farmer's age:
Contact No.:		Educational background:
Location of homestead:		

1.1 General Household Information

Question	**Response (circle or enter)**
Gender of respondent	1. Male 2. Female
What is your marital status:	1. Married/Cohabiting 2. Single/Never married 3. Divorced/separated 4. Widow/Widower
What relationship do you have with the head of household?	1. Wife 2. Son 3. Daughter 4. Other relative 5. Self
How many people live in this household:	Enter number:
What is this household's main source of income?	

PART 2: Information on Animals Reared

2.1 Which livestock do you rear? How many do you have?

Livestock reared by farmers	**Quantity**
Cattle	
Goat	
Sheep	
Pig	
Poultry	
Others, Specify	

2.2 Where do keep these livestock's?

Home	**Farm**	**Roam in the community**	**Other, specify**

2.3 Use of animal residues

Animal type	**Residue type**	**Point of generation, esp. of process residues (home or farm)**	**Amount use(%)**	**What happens to unused residues?**
Cattle				
Goat				
Sheep				
Pig				
Poultry				
Other				

PART 3: Information on Maize and Cassava cultivated

Plots cultivated by farmer	**Plot 1**	**Plot 2**	**Plot 3**	**Plot 4**
Size of plot (acres)				
Production per crop season(s) [eg. 10000 tonnes]				
How many seasons is plot cultivated per year?				

3.1 Use of crop residues

Crop type	**Residue type**	**Point of generation, esp. of process residues (home or farm)**	**Amount used (%)**	**What happens to unused residues?**
Maize	Stalks			
	Husks			
	Cobs			
Cassava	Stalks			
	Peelings			

PART 4: Land ownership and accessibility

Plot ownership and accessibility	**Plot 1**	**Plot 2**	**Plot 3**	**Plot 4**
Distance of plot from community center? (use GPS device)				
How accessible is plot from community center? (E.g. accessible by truck, tractor, motorbike, footpath)				

4.1 Existing Residue Uses

Do you usually use the manure? ☐Yes ☐ No

If YES, what percentage do you use? ____
If NO, which of the following do you use the manure for and what amount in percentage:
☐ Organic fertilizer ________%
☐ Fuel (including charcoal) ________%
☐ Other ________%
Do you burn the residue on the field? ☐Yes ☐ No
If YES, what percentage do you burn on the field? __________________________________
If NO, which of the following do you use the residue for and what amount in percentage:
☐ Animal feed and bedding ________%
☐ Fuel (including charcoal) ________%
☐ Construction ________%
☐ Industry ________%
☐ Other ________%
Do you intentionally leave the residues as organic fertilizer? ☐Yes ☐ No
If YES, what percentage do you use? _______________________
When ploughing, do you remove left over residue or is it ploughed into the soil?_________________
Would you have any objection to residues being lifted from your farm for energy purposes? ☐Yes☐ No
Would you sell the residues or give it out for free? _________________________________
What percentage of field-based residues would you allow for removal? ______________________
Why this amount? ____
How do you think that would affect the nutrient levels in your farmland? _______________

4.2 Willingness to use and pay for Solar PV-Biogas Hybrid Power Plant– first explain importance of the technologies.

What is your current source of power?...
How much do you spend per month? GHC...
If crop and animal residues were processed into electricity, would you like it? ☐Yes ☐ No
Would you be willing to pay for it (especially if you gave out the residues for free)? ☐Yes ☐ No
Would you be willing to pay 80Gp per kWh (Explain to the farmer)? ☐Yes ☐ No
If NO, how much would you be willing to pay?_____________________________
Why would you not want to pay?____

Part 5: Employment / job creation – explain that residues are available for collection at the end of the farming season when most farmers wouldn’t be engaged in farm activities. This section intends to ascertain farmers’ availability during the off-farm season for possible employment**.**

Are you available to collect the residues for the plant? ☐Yes ☐ No
What income generating activities are available to you during the off-farming season? ________________
____
Are you engaged in other jobs during the off-farming season?☐Yes ☐ No

Period	Daily activity including actual times engaged
Farming season 1 (March - August)	
Farming season 2 (August – November)	
Off-season (December – February)	

If available, would you want to be engaged to collect residues for income? ☐Yes ☐ No

5.1 Savings

Are you able to make savings at the end of the year/farming season? ☐Yes ☐ No

From your experience, how much savings do you make at the end of the year? _______________

Part 6: Electronic equipment owned by the household: Village daily Load estimation

Type of equipment	Quantity
Radio	
Mobile phone	
Car battery	
Generator	
Refrigerator	
Bulbs (CFL)	
Bulbs (Incandescent)	
Fridge	
TV(LED)	
TV (CRT)	
DVD player	
Fan (standing/Ceiling)	
Desktop Computer	
Other (specify)	
Other (specify)	
Other (specify)	
Other (specify)	

Table 5.1: Research internship and Master thesis expenses

*Note that some items were paid in US$, Algeria DA and GHS cedis.

PAUWES

Master Thesis Expenditure

MSc. Energy Engineering

Item	Qty	Unit Price GHS	Unit Price US$	Total Price GHS	Total Price DZ	Total Price US$
Research Material-Software						
[1]Software License for Designing+Modelling (3 months subscription)	3		185			555
Research Material						
Internet (4 months subscription)	4	260		1040		241.86
Travelling Expenses						
Flight ticket for Research (Round Way)	1				128,662	1205.90
Local transport from Tlemcen to Algiers	1				5000	47
[2]Local transport for data collection (In & Out for 20 days)	40	70		2800		600.17
Local transport from Accra (Airport) to Kumasi (Internship city)	1	145		145		33.73
Local transport from Kumasi (internship city) to Accra (Airport)	1	145		145		33.73
Printing						
[3]Printing of questionnaires for data collection (200 x 4 pages)	800	0.98		784		182.33
[4]Printing of Master Thesis+Binding (110 pages x 4 copies)	440	0.98		431.2		100.28
						Total = $ 3000.00

Explanation:

[1] Software license cost $185/month, 4 months monthly subscription was purchased but only 3 months cost is included in this master thesis expendinture as shown in Qty above.

[2] The total number of questionnaires for data collection was 200 and each questionnaire had 4 pages which gives a total of 800 pages as shown in Qty above.

[3] 2 (Transport In & Transport Out) x 20 (number of days used for data collection) = 40 as shown in Qty above.

[4] The master thesis has a total of 110 pages and 4 copies were printed for defence which gives a total of 440 pages as shown in Qty above.