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Presented by

Henry Thomas NELSON

ASSESSMENT AND OPTIMIZATION OF FLEXY ENERGY APPROACH
CASE STUDY: BILGO VILLAGE, BURKINA FASO, WEST AFRICA

Defended on 03/09/2019 Before the Following Committee

Chair	Lotfi Baghli	Prof	University of Tlemcen
Supervisor	Daniel Yamegueu	PhD	2iE
External Examiner	Amine Boudghéne Stambouli	Prof	University of Oran
Internal Examiner	Fouad Boukli Hacene	PhD	University of Tlemcen

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BEng Mechanical and Maintenance Engineering (Hon)

A Thesis submitted to the Pan African University Institute for Water and Energy Sciences (Including Climate Change) in Partial Fulfilment of the requirements for the degree of

MASTER OF SCIENCE IN ENERGY ENGINEERING

Supervisor: Dr Daniel Yamegueu

Tlemcen, Algeria

Date: 3rd September 2019

DECLARATION

I, Henry Thomas Nelson, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material, and result from other works Presented here, have been fully cited and references in accordance with the academic rules and ethics.

Henry Thomas Nelson		03/09/2019
(Student)	(Signature)	(Date)

CERTIFICATION

This thesis has been submitted with my approval as a supervisor.

Dr. Daniel Yamegueu		31/07/2019
(Supervisor)	(Signature)	(Date)

ABSTRACT

Access to electricity is essential for infrastructural development, economic growth, and better living standards in any country. However, the access rate to reliable grid electricity services in West Africa remains very low when compared to developed countries in the world. This situation is even worst in rural communities because of the high cost of grid extension. In order to improve electricity access rate to rural communities in Burkina Faso, an approach has been developed known as the flexy energy concept at the International Institute for Water and Environment Engineering (2iE). This concept is composed of a PV/diesel hybrid system without a storage system. The storage unit is excluded due to the high investment cost of batteries and other environmental issues. However, for the management of the system, the storage aspect could be considered to support the load for a few hours of autonomy. In this study, three scenarios were investigated, such as PV/diesel with and without battery storage, and conventional standalone diesel generators for the same load profile by using HOMER software. From the optimization results obtained shows that the best optimal scenario is the PV/diesel/battery hybrid configuration, which has a Levelized Cost of Electricity (LCOE) of US$ 0.524/kWh, and a total net present cost (NPC) of US$ 1,177,376. The storage system for the optimal configuration composed of 72 batteries, which is capable of powering the load for about 8.12 hours of autonomy. Concerning the environmental impact assessment, the CO_2 emission produced by the PV/diesel/battery system was reduced by 29.68% and 23.4% when compared to the scenario with conventional generators and the scenario with PV/diesel hybrid system without storage respectively. Moreover, in order to assess the effect of fuel prices on the LCOE and the NPC for the optimal system, a sensitivity analysis was performed. From the results obtained it is recommended that for energy management of the power plant in Bilgo village it is necessary to include an optimal storage unit in order to reduce the operating and maintenance cost of running diesel generators, reduce the excess electricity produced from the system, and as well minimize the emission produced by the system.

Keywords: Flexy Energy, Hybrid system, Diesel, Photovoltaic Energy Management, Excess electricity production, Levelized Cost of Energy, Net Present Cost

RÉSUMÉ

L'accès à l'électricité est essentiel au développement des infrastructures, à la croissance économique et à l'amélioration du niveau de vie dans tous les pays. Cependant, le taux d'accès à des services fiables de réseau électrique en Afrique de l'Ouest reste très faible par rapport aux pays développés. La situation est encore pire dans les communautés rurales en raison du coût élevé de l'extension du réseau. Pour améliorer le taux d'accès à l'électricité des communautés rurales du Burkina Faso, une approche connue sous le nom de concept d'énergie flexy a été développée à l'Institut international d'ingénierie de l'eau et de l'environnement (2iE). Ce concept est composé d'un système hybride PV/diesel sans système de stockage. La capacité de stockage est réduite en raison du coût d'investissement élevé des batteries et de leur impact sur l'environnement. Cependant, pour la gestion du système, l'aspect stockage pourrait être envisagé pour supporter la charge pendant quelques heures d'autonomie. Dans cette étude, trois scénarios ont été étudiés, tels que PV/diesel avec ou sans stockage sur batterie, et générateurs diesel autonomes conventionnels pour le même profil de charge en utilisant le logiciel HOMER. Les résultats d'optimisation obtenus montrent que le meilleur scénario optimal est la configuration hybride PV/diesel/batterie, qui a un coût de l'électricité nivelé (LCOE) de 0,524 kWh et un coût total net actuel (NPC) de 1 177 376 $US. Le système de stockage pour la configuration optimale composé de 72 batteries, et ils sont capables d'alimenter la charge pour environ 8,12 heures d'autonomie. En ce qui concerne l'étude d'impact environnementale, les émissions de CO_2 produites par le système PV/diesel/batterie ont été réduites de 29,68% et 23,4% par rapport à un scénario avec des générateurs conventionnels et le système hybride PV/diesel sans stockage. De plus, afin d'évaluer l'effet des prix du carburant sur le LCOE et le NPC pour le système optimal, une analyse de sensibilité a été effectuée. A partir des résultats obtenus, il est recommandé, pour la gestion énergétique de la centrale du village de Bilgo, d'inclure une unité de stockage optimale afin de réduire les coûts de fonctionnement et d'entretien des groupes électrogènes diesel, de réduire l'électricité excédentaire produite par le système et de minimiser les émissions produites par celui-ci.

Mots-clés: Flexy Energy, Système hybride, Diesel, Gestion de l'énergie Photovoltaïque, Production Excédentaire d'électricité, Coût nivelé de l'énergie, Coût Actualisé Net

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LIST OF ABBREVIATION

AC	Alternating Current
COE	Cost of Energy
CO_2	Carbon dioxide
CRF	Capital Recovery Factor
DC	Direct Current
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiation
GW	Gigawatt
GWh	Gigawatt hour
HOMER	Hybrid Optimization Model for Electric Renewables
HRES	Hybrid Renewable Energy System
HES	Hybrid Energy System
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
Ktoe	Kilo Tons of Oil Equivalent
kVA	Kilovolt Ampere
kW	Kilowatt
kWh	Kilowatt-hour
kW_p	Kilowatt peak
LCOE	Levelized Cost of Electricity
MW	Megawatt
NASA	National Aeronautics and Space Administration

O&M	Operating and Maintenance cost
PV	Photovoltaic
SOC	State of Charge
2iE	International Institute for Water and Environmental Engineering

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CHAPTER ONE

1. INTRODUCTION

1.1 Background of Study

Access to reliable electricity serves as an essential factor for all kinds of development in any country, such as human development, economic growth, and social development. In sub-Saharan Africa, the electricity access rate is very low when compared to developed countries in the world, which has a negative impact on economic growth and living standard in the region (Mallick et al., 2013).

According to the International Energy Agency (IEA) report in 2017, over 1 billion people in the world do not have access to modern energy services, and approximately less than 1.1 billion people remain without electricity in the world (IEA, 2017). Access to electricity remains a challenge in Sub-Saharan Africa, especially for those living in remote rural and peri-urban communities. In 2014, approximately 620 million people in Sub-Saharan Africa did not have access to electricity, while those with access faced numerous challenges such as unreliable power supply and high electricity cost (IEA, 2014). However, this situation is more critical especially in rural areas in Sub-Saharan Africa, where the projected scenario shows that by 2040, more than 700 million people will remain without access to electricity (IEA, 2018). Moreover, over 730 million people in Sub-Saharan Africa rely on tradition biomass (such as wood fuel, charcoal, and firewood) for cooking which causes a high level of indoor pollutions that have serious health issues and leads to high mortality rate (World Bank, 2017b). According to the International Energy Agency report in 2014, stated that over 600,000 premature deaths occur every year in Sub-Saharan Africa as a result of air pollution from cooking (IEA, 2014).

However, scientists and engineers have been working tirelessly to find an alternative energy solution to reduce the high reliance on fossil fuel sources. Indeed, renewable energy sources have been identified as the most suitable energy alternative to fossil fuel sources for power generation. Renewable energy sources are abundant in nature and environmentally friendly compared to fossil fuel sources (Borhanazad et al., 2014; Chauhan & Saini, 2014). Electricity generation from renewables has been considered the most viable solution for off-grid locations in most developing countries whereby reduces the fuel cost and the challenge due to technical and economic constraints associated with grid expansion systems (Shahzad et al., 2017).

Nevertheless, generating electricity from single renewable sources (for example wind or solar Photovoltaic) comes with several drawbacks such as high initial investment cost and low power reliability due to their intermittent and uncertainty nature, especially when using a single energy source (Smith et al., 2015). However, these challenges can be overcome by adopting the concept of hybrid renewable energy systems (HRES). HRES is a combination of two or more electricity generating sources such as renewable and conventional energy sources to produce reliable energy. In this concept, the different energy sources complement each other when generating power from the system. Hybrid energy systems are mostly implemented in decentralized locations due to the high cost associated with the grid extension network (Oluwarotimi et al., 2019).

1.2 Problem Statement

Access to reliable energy services is considered as the main requirement for agricultural, industrial, and social-economic development (Nouni, Mullick, & Kandpal, 2008). It also constitutes an input for production, whereby contributes immensely to the well-being of the population by providing essential goods and services to meet their needs. In the case of developing countries, electricity crisis is a major barrier towards poverty reduction and economic development (Doll & Pachauri, 2010).

The reason for the low electricity access rate in most rural and peri-urban areas in Burkina Faso is due to the high poverty rate, scattered population, and inadequate transmission and distribution networks. The primary source of lighting in most rural areas rely on oil lamps, candles, dry-cell battery lamps, and small diesel/petrol generators. In Burkina Faso, the current access rate to electricity is about 20%, and for rural areas is only 5% (Ouedraogo & Yamegueu, 2019).

The use of diesel generators remains the most popular electricity generation source in most rural and peri-urban areas in Burkina Faso (Azoumah et al., 2011) due to their affordability and low initial investment. Despite their low initial cost, they possess several drawbacks associated with them, such as high operation and maintenance cost, low power reliability, and their environmental issues. In order to improve electricity access rate in rural areas in Burkina Faso, PV/diesel hybrid system without battery based on the flexy energy concept have been used to generate electricity in off-grid areas. The exclusion of battery storage in this concept was to reduce the cost of batteries replacement and the environmental concerns associated with batteries at the end of their lifetime. Moreover, the elimination of batteries from the PV/diesel system has its drawbacks such as the excess electricity produced by the system is not put into any productive used, stability problems, extended operating hours of diesel generators as well as high O&M costs and short lifetime. However, for the management of the system, the storage aspect could be considered to serve the load for a few hours of autonomy and reduce the excess electricity production from the power plant.

1.3 Research Questions

I. What is the optimal renewable energy fraction for the hybrid system configuration?

II. What is the LCOE from the PV/diesel hybrid system in Bilgo village?

III. What is the optimal storage capacity that should be included in the PV/diesel system for the management of the system?

IV. What are the environmental impacts of a PV/diesel hybrid system?

1.4 Working Hypothesis

PV/diesel/battery hybrid system is considered as the most optimal solution for electricity access in remote areas. Indeed, they provide sustainable and reliable electricity, reduces CO_2 emission, and they are more cost-effective compared to grid extension systems.

1.5 Research Objectives

1.5.1 Primary Objective

The main objective of this study is to assess the techno-economic, and environmental impacts of flexy energy approach based on the case study of the power supply system at Bilgo village in Burkina Faso.

1.5.2 Specific Objectives

I. Identifying the existing approaches used in decentralized electricity production from hybrid systems.

II. Assessing the performance of flexy-energy approach (electricity production cost, renewable energy fraction, CO_2 emission) in the case study of Bilgo village.

III. Identifying the optimal storage unit that should be incorporated for the management of the system.

1.6 Research Methodology

The methodology used in this study is divided into two sections. The first aspect deals with a vivid literature review on existing energy management strategies used in hybrid systems and a brief review of the energy situation in Burkina Faso. The second aspect focus on simulation of different configurations of power production sources inspired by the existing power plant in Bilgo Village. In this study, three scenarios will be considered for the same load profile in Bilgo Village, which are:

- Three conventional diesel generators (20 kVA *2 and 30 kVA)
- Hybrid PV/diesel generators (70 kVA and 30 kWp)
- Hybrid PV/diesel generators/battery (70 kVA, 30 kWp, with sensitivity analysis on the storage capacity)

For simulation and optimization aspect in this work, HOMER Pro 3.10 software will be used to determine the most optimal system configuration based on the following criteria: lowest LCOE, lowest NPC, lowest capacity shortage, lowest excess electricity production, lowest CO_2 emission produced and highest renewable energy fraction.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Geographical and Climatic Overview of Burkina Faso

Burkina Faso is a landlocked country located in West Africa and lies between latitude 12.26° North; and longitude -1.56° East. The country shares international boundaries with Mali, Niger, Benin, Togo, Ghana, and Ivory Coast (GTZ, 2009). It has a total land area of 274,220 square kilometers (UNIDO, 2016) with an estimated population of 19,193,382 in 2017 (World Bank, 2018). The country is divided into 13 administrative regions, 45 provinces, and 351 communes (2iE Foundation & SONABEL, 2012). The country has a tropical climate with two seasons, which are the dry season and rainy season. The dry season lasts for eight months, and the rainy season lasts for four months, with annual precipitation of 1300 millimeters of rainfalls per annum (UNIDO, 2016).

2.2 Economic Situation in Burkina Faso

The economy of Burkina Faso strongly depends on agricultural products such as cotton which is the most economical crop and gold exploitation (Ouédraogo, 2010). Approximately 70% to 80% of the country's population are actively involved in those sectors. Indeed, the highest revenue for the country is obtained from gold exportation, which makes the country more vulnerable to price fluctuation in the global market (African Development Bank, 2017). The current gross domestic product (GDP) in Burkina Faso is estimated at US$ 14.442 billion, with an annual growth rate of 6.51% (World Bank, 2019). The country GDP over the last 12 years had shown a significant growth rate with the except for 2015, when the growth rate declined by 3.895% compared to the growth rate in 2014. Figure 2-1 shows the GDP and its annual growth rate from 2007 to 2018.

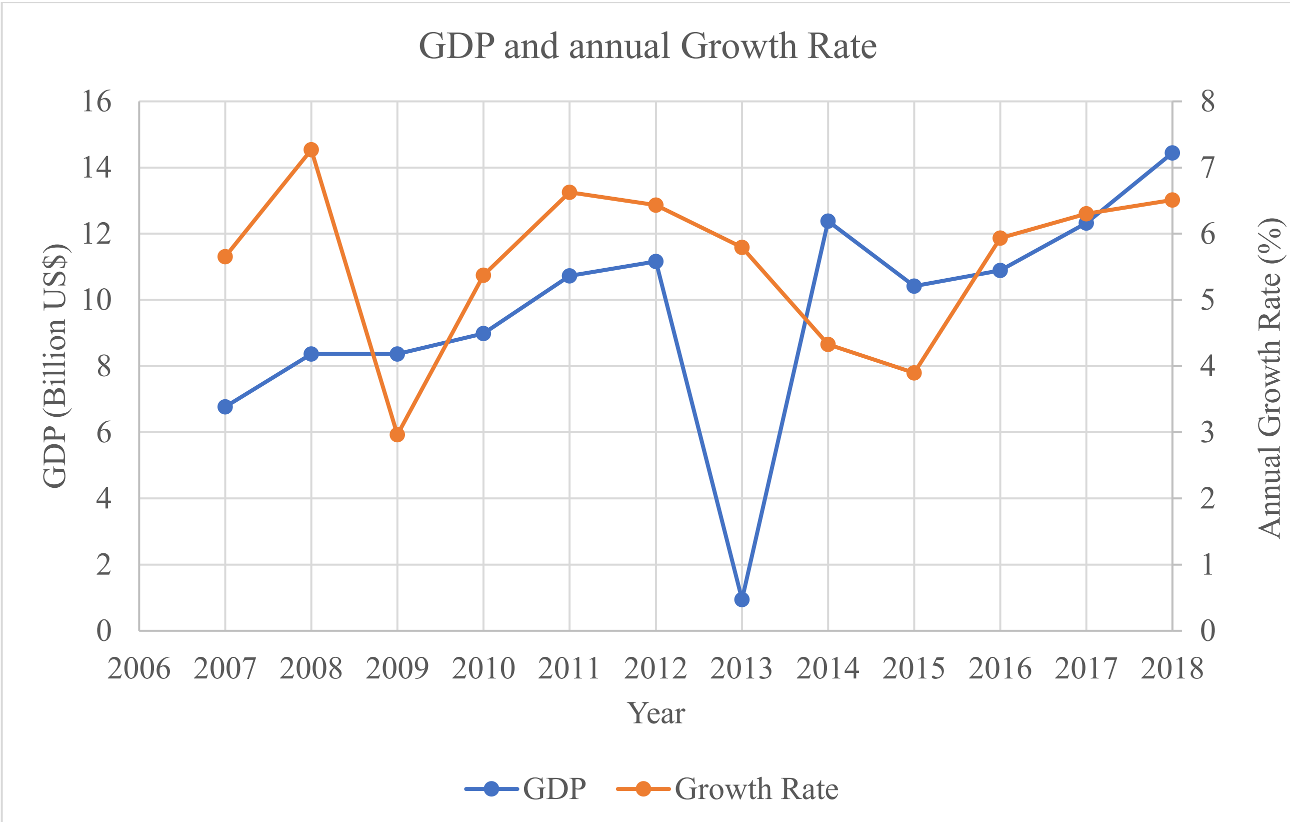

Figure 2-1: GDP and annual Growth rate for Burkina Faso (World Bank, 2019)

2.2.1 Primary Energy Consumption in Burkina Faso

Traditional biomass such as firewood, charcoal, and wood fuel are the most common energy sources consumed by households for cooking purpose in both rural and urban areas in Burkina Faso. In 2008 the total primary energy consumption for Burkina Faso was estimated at 2625 ktoe (kilo tonnes of oil equivalent), biomass accounts for about 82% of the total energy consumption, followed by petroleum product and electricity 16% and 2% respectively (N'tsoukpoe et al., 2015). Figure 2-2, shows the share of the total energy consumption for Burkina Faso in 2008.

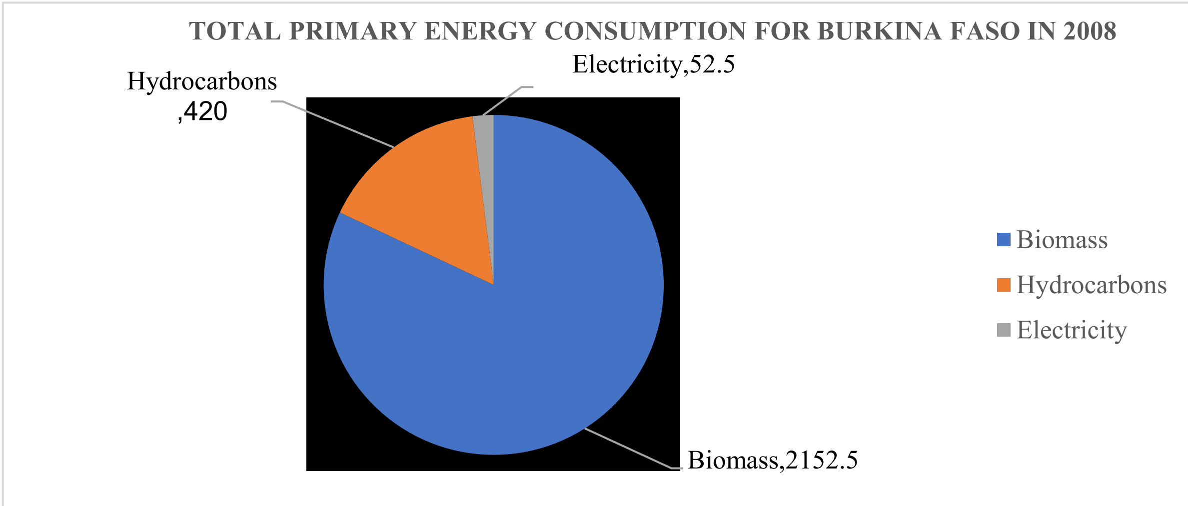

Figure 2-2: Total Primary Energy consumption for Burkina Faso in 2008 (N'tsoukpoe et al., 2015)

2.2.2 Electricity Situation in Burkina Faso

The current electrification rate in Burkina is about 20% (Ouedraogo & Yamegueu, 2019; World Bank, 2018). The electricity access growth rates in both rural and urban areas in 2017 were estimated at 5% and 61% respectively. The electricity access growth rate in Burkina Faso has shown a significant increased from 9.22% in 2000 to 20% in 2017 (World Bank, 2017a) indicating significant progress in the energy sector as shown in Figure 2-3.

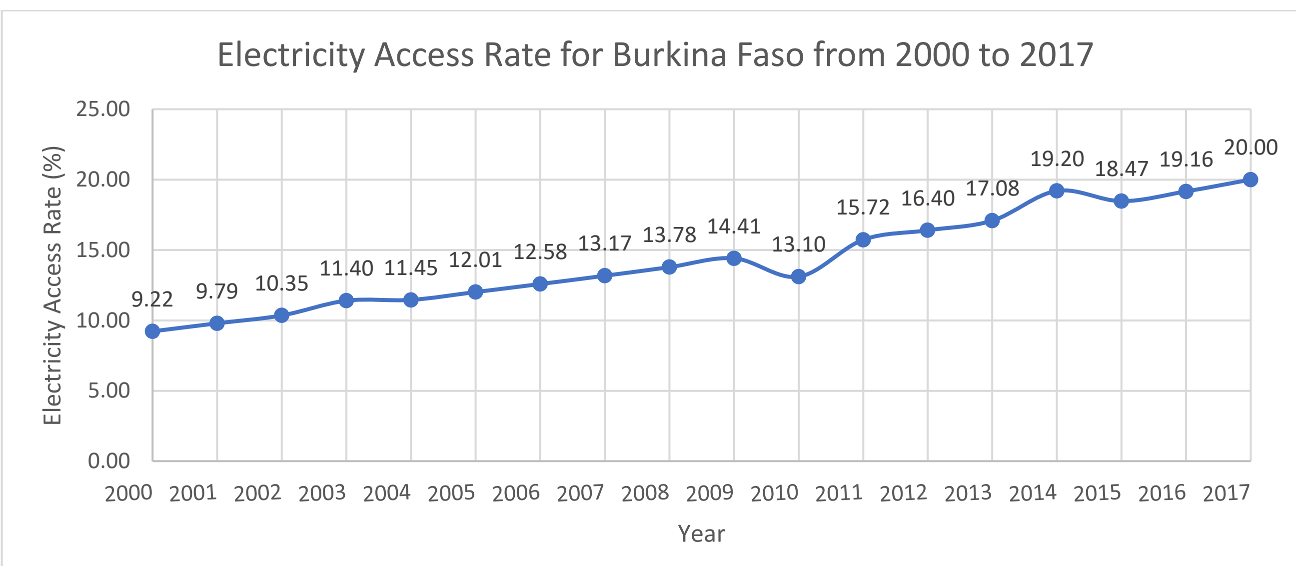

Figure 2-3: Electricity Access rate in Burkina Faso Between 2000 and 2016 (World Bank, 2018)

The national electricity company in Burkina Faso known as SONABEL (Société Nationale d'Electricité du Burkina) is a state institution responsible for electricity generation, production, importation, transportation, distribution in the country. According to SONABEL's annual report in 2017, the total installed capacity in the country was about 355 MW, for which 288 MW was generated from thermal plants, 32.4 MW generated from hydropower plants, and 34.8 MW generated from solar photovoltaic power plants (SONABEL, 2017). The total electricity production in the country in 2017 was estimated at 1095 GWh, with an additional 646 GWh of electricity imported from neighboring countries in particular Ivory Coast, Ghana, and Togo. This importation is set to boost the access rate in the country since the national production is insufficient to meet the demand for the entire country (see Figure 2-4). Moreover, electricity production from renewable sources in 2017 was estimated at 137 GWh representing about 7.86% of the total electricity production (SONABEL, 2017). Figure 2-5 shows the total electricity production for Burkina Faso from 2010 to 2017.

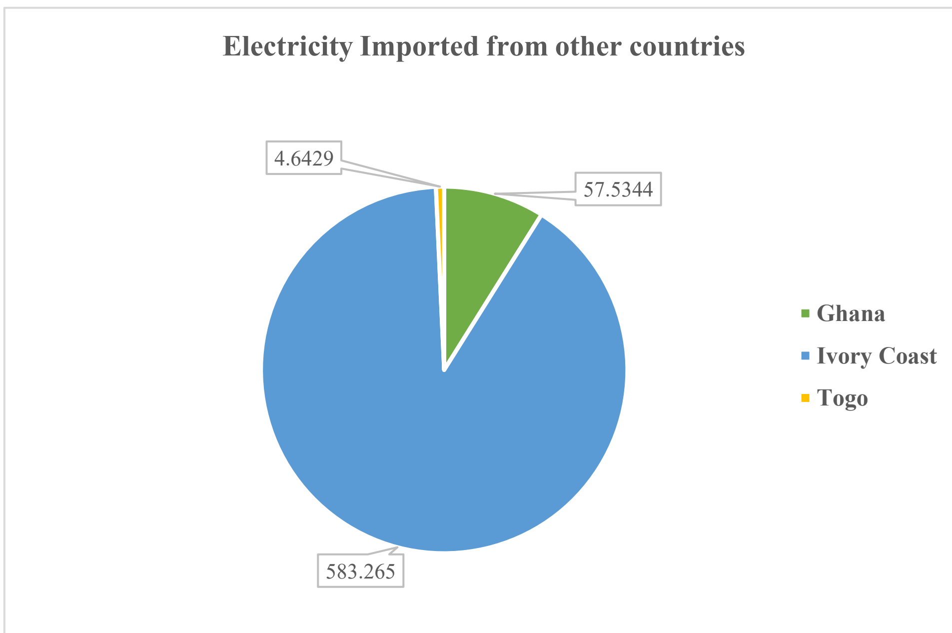

Figure 2-4: Electricity imported from Other Countries(SONABEL, 2017)

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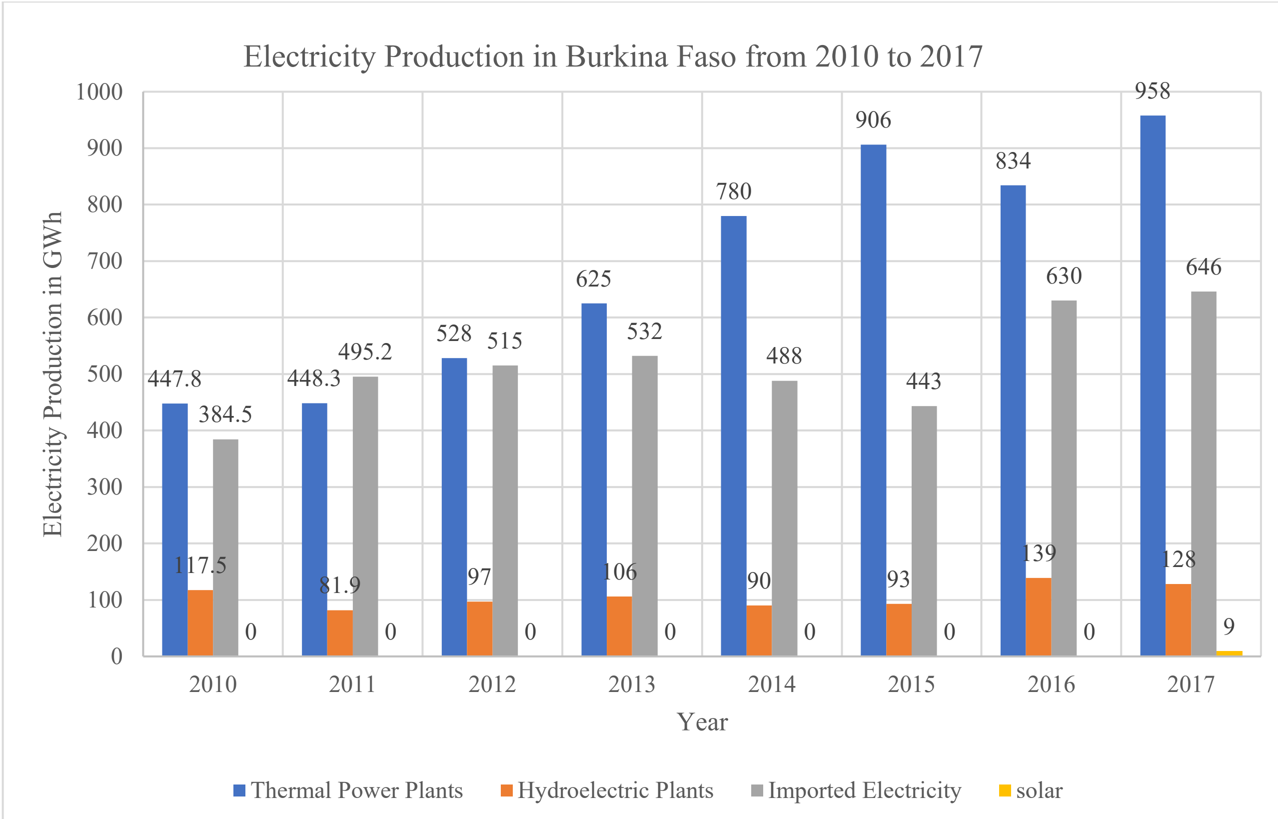

Figure 2-5: Electricity Production in Burkina Faso (SONABEL, 2017)

2.3 Renewable Energy Resources in Burkina Faso

The renewable energy sources available in Burkina Faso are solar, hydro, and biomass. Biomass is mainly used for cooking in both rural and urban areas, and they are rarely used for generating electricity in the country. Indeed, Burkina Faso is well endowed with high potential in solar energy. The country received an average daily solar radiation of 5.5 kWh/m^2/day, with average isolation of 8.3 hours a day and direct sunshine is over 3000 hours per year (Azoumah et al., 2011; N'tsoukpoe et al., 2015; Yamegueu et al., 2011). The Sahel region in the north received the highest solar radiation, which exceeds over 7.5 kWh/m^2/day (African Development Bank, 2017). The daily direct normal irradiance (DNI) in the country ranges from 3.9 kWh/m^2 to 4.5 kWh/m^2 (Azoumah et al., 2010). The Global Horizontal Irradiation (GHI) of Burkina Faso radiation ranges from 5.4 kWh/m^2 to 6.0 kWh/m^2 as one can see in Figure 2-6. Moreover, the hydroelectric potential in the country remains low due to the low annual rainfall pattern, which serves as the main drawback in electricity production from hydropower plants.

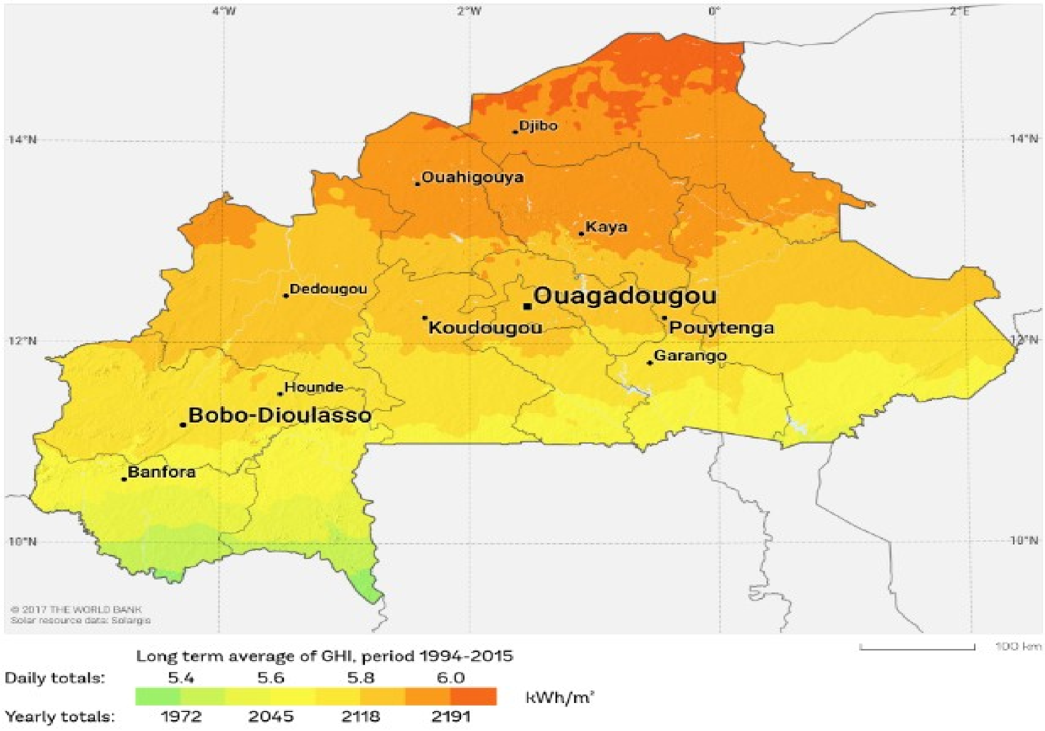

Figure 2-6: Global Horizontal Irradiation for Burkina Faso (SOLARGIS, 2017)

2.4 The Concept of Hybrid Energy Systems

The concept of hybrid energy systems involves the combination of multiple energy sources for power generation. These energy sources can either be from renewable energy sources (solar, wind and hydro) or conventional sources (diesel engines). The main advantages of combining multiple energy sources over a single energy generating source is that they offer a more reliable power supply by ensuring energy balance at all time. However, most hybrid system incorporates the used of battery storage and diesel generators (Adaramola et al., 2014; Borhanazad et al., 2014; Ismail et al., 2013). The role of battery storage and diesel generator in hybrid energy systems is to overcome the intermittent nature of renewable sources such as wind and solar. Over the years, hybrid energy systems have become the most suitable alternative for providing electricity in remote rural areas (Adaramola et al., 2014; Azoumah et al., 2011; Oluwarotimi et al., 2019; Zhang et al,. 2017), whereby offering a reliable and cost-effective solution for the utilization of renewable energy resources (Borhanazad et al., 2014).

2.4.1 Classification of Hybrid Power Systems

Hybrid energy systems can be classified as either pure renewable-based hybrid systems or fossil-renewable based hybrid systems. The pure renewable-based hybrid systems, are systems consisting of two or more renewable sources combined to generates power with or without storage systems (Muh, 2017). While Fossil-Renewable based hybrid systems involve the combination of conventional sources and renewable sources to generate electricity. Fossil-Renewable based hybrid systems are commonly used to generate power in remote areas of developing countries (Kaabeche & Ibtiouen, 2014).

Hybrid energy systems can also be considered as DC-coupled systems or AC coupled systems. For the DC-coupled system, all the power produced from the DC components are directly connected to the DC bus. In the process of supplying power to AC loads the DC power in the bus is converted by an inverter to produce an AC output. Likewise, for the AC coupled hybrid system, all the power produced from the energy sources are connected to the AC bus before supply power to the load. In the AC coupling system, two different inverters are used, which are the grid-tied inverter and the bi-directional inverter. The grid-tied inverter is responsible for converting all the power generated by the DC primary source (solar PV) to AC power before been connected to the AC bus. The bi-directional inverter is used to charge the battery banks when it operates as rectifiers in one hand, and in the hand converter DC power from the PV and the battery when it operates as an inverter to supply power to the load. Figure 2-7 and Figure *2-8* illustrate a schematic of both AC coupling and DC coupling hybrid power systems (Mahmud, 2016).

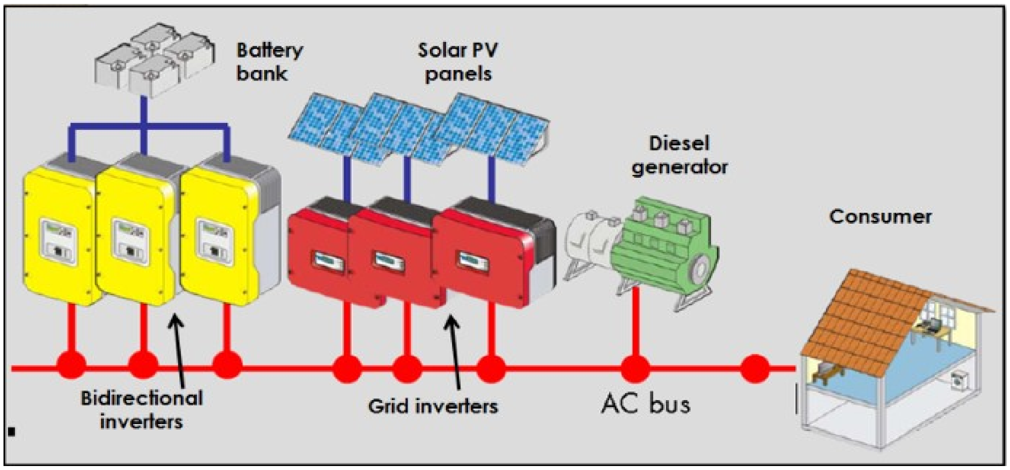

Figure 2-7: Schematic AC coupled PV/Diesel Hybrid System (Mahmud, 2016)

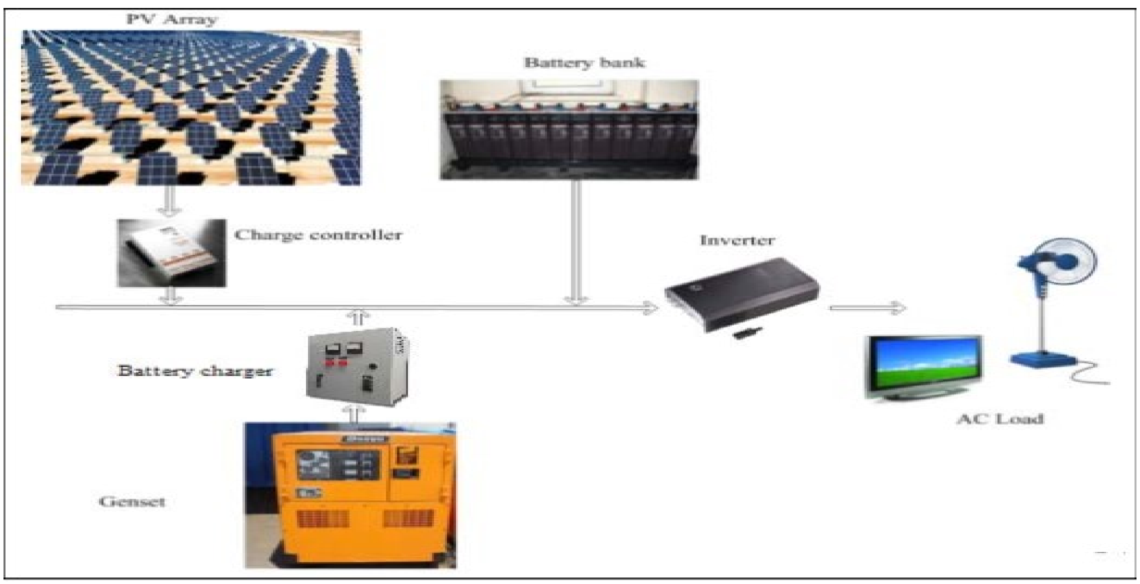

Figure 2-8: Schematic diagram DC Coupled PV/diesel hybrid system with battery storage (Mahmud, 2016)

2.4.2 Configuration of PV/diesel hybrid system

PV/diesel hybrid systems can be configured in three ways based on how the power generating sources are connected to the load. The three methods of PV/diesel hybrid system configuration are as follow:

- Hybrid PV/diesel series system
- Hybrid PV/diesel parallel system
- Hybrid PV/diesel switched system

2.4.2.1 Hybrid PV/diesel series system

In a series PV/diesel hybrid system, all the power generated by the diesel generator is first converted to DC power through a rectifier to the DC bus and then converted back to AC before supplying power to the load. The DC power produced by the PV array and batteries in the DC bus is converted to AC power by an inverter to serve the AC primary load. In the series type configuration, when the energy produced by the PV and the batteries are capable of satisfying the load, the diesel generator is disconnected from the system. The role of the diesel generator in the series configuration is supplied power when the production from the PV and the batteries cannot meet the load demand. At this state, the diesel generator is allowed to operate at its rated capacity to meet the peak demand. Moreover, the PV arrays are responsible for charging the battery bank instead of the diesel generator during excess electricity production from the system PV (Azoumah et al.,2011). Also, the series hybrid configuration can be operated into either manual or automatic mode.

Advantages of Hybrid PV/diesel Series Systems

- The power supplied to the load does not cause interruption when the generator starts to operate.
- There is no switching of AC power between the different energy sources required.
- The load demand can be met by the PV array and the battery bank.
- The diesel generator can be sized to be optimally loaded while supplying the load and charging the batteries.

Disadvantages of hybrid PV/diesel Series System

- Decrease in the lifetime of the batteries because of the number of charging and discharging.
- Power to the load is interrupted momentarily when the AC power source is transferred.
- The efficient of the system at load operation is low because the diesel generator supplies

power to a series of rectifiers.

- Power conversion losses from the diesel generators.

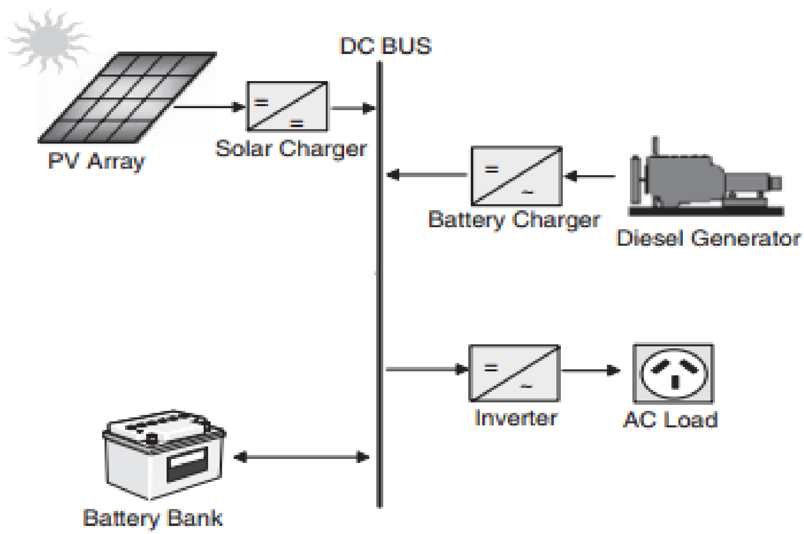

Figure 2-9: PV-Diesel Series Hybrid System Configuration (Rashid, 2011)

2.4.2.2 Hybrid PV/diesel Parallel Systems

In a parallel hybrid system configuration, the PV array and the diesel generator are connected in parallel, whereby each energy source is capable of supplying the load separately when loads are ranging from low to medium demand to peak demand. In the case of peak demand, the two power sources are combined to meet the load demand. The parallel hybrid configuration can be classified as either a DC or an AC couplings system. In this type of system configuration, the diesel generator is directly connected to the AC bus while, and the PV array and the battery bank are connected to the DC bus. However, in other to ensure synchronization between the two buses, a bi-directional converter is used, which functions as a rectifier when charging the batteries during low demand when the diesel generator produces excess energy. The two main advantage of the parallel hybrid configuration over the series and switch hybrid systems configurations are:

- The combination of the bi-converter and the diesel generator are capable of supplying maximum power to load rather than power supply by each component alone. In Principles, the capacity is doubled in this hybrid configuration.

- This configuration can synchronize the output voltage of the inverter and that of the diesel generator, whereby enhancing greater flexibility to optimize the operation of the system.

Advantages of Hybrid PV/diesel Parallel System

- The efficiency of the diesel generator is increased since there is no conversion of power by the generator.
- This configuration reduces the number of the electronic converters and also reduces the initial capital investment of sting up the hybrid system
- The cost of maintenance of the diesel generator is reduced.
- The initial failure of the power converter does not interrupt the power in feeding the load.
- The optimal system load can be satisfied since power is generated simultaneously by the two energy sources.

Disadvantages of Hybrid PV/diesel Parallel System

The automatic control system is mandatory for reliable operation of the hybrid system.

- The converter must provide a sinusoidal voltage so that to enhance synchronization with the diesel generator.
- System operation is very complicated to untrained users.

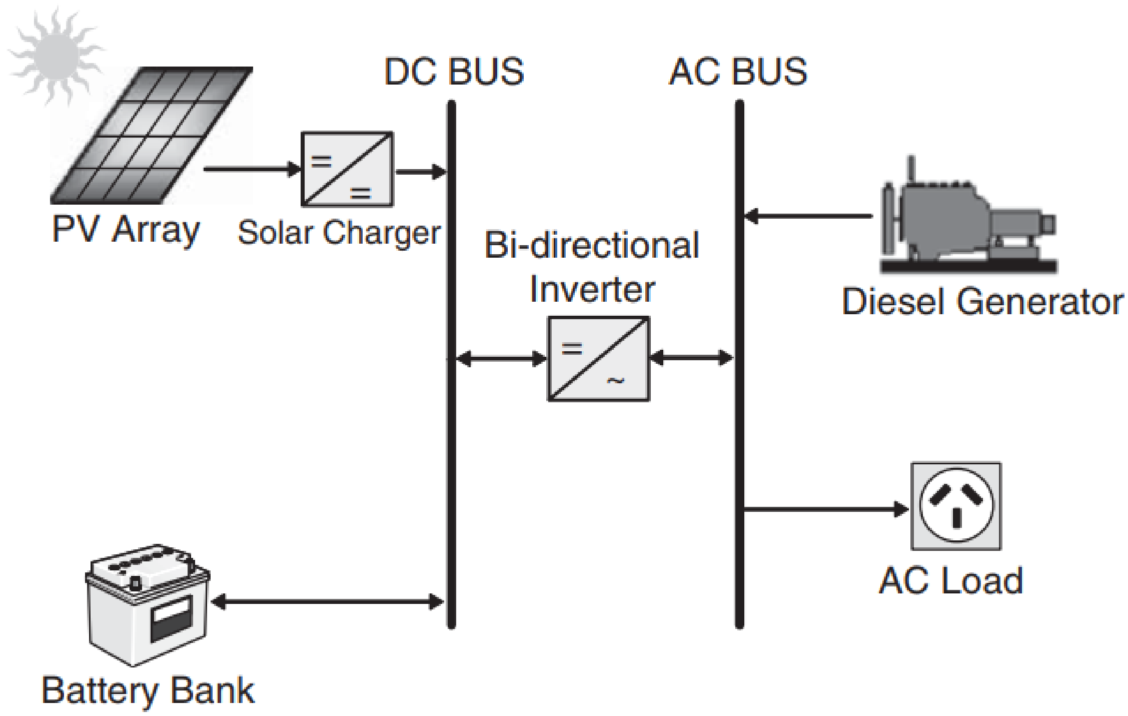

Figure 2-10: Parallel PV-diesel hybrid energy system (Rashid, 2011)

2.4.2.3 Hybrid PV/diesel Switched System

This type of PV-diesel hybrid configuration system is common in developing countries (Azoumah et al., 2011). In the operation of PV/diesel switched hybrid system, the load demand can be met by the diesel generator or by the PV arrays and the battery banks via the inverter, since there is no parallel operation by the power generating sources. The advantage of switched hybrid configuration over the series and parallel configurations is that the diesel generator is capable of supply the load directly without any power interruption and as well increases in the overall conversion efficiency and reduces fuel consumption of the diesel generator. The control management strategies for this hybrid configuration is as follow: when the energy produced by the PV array exceeds the load demand, the excess energy is used for charging the battery, and the diesel generator remains off. The diesel generator is only allowed to operates when the load demand is high such that the power produced from the PV arrays and the batteries cannot satisfy the load. The switched hybrid configuration system can only operate in automatic mode instead of manual mode, which makes the system more complicated to operate (Azoumah et al., 2011; Rashid, 2011).

Advantages of hybrid PV/diesel Switched system

- No need for power synchronization in switching energy sources.
- Unexpected failure by the power inverter cannot shut down the system completely, because the diesel generator can still meet the energy demand.
- The generator can generate a sinusoidal wave depending on the application.
- Reduce fuel cost and maintenance cost of the diesel generator

Disadvantages of hybrid PV/diesel Switched system

- Power interruption is experienced, especially switching from one source to another.
- The diesel generator and the inverter are typically sized to meet the peak load demand; thus, reducing their efficiency at part load operation
- The system is very complex to control in automatic mode.
- Switched PV/diesel hybrid energy system requires more components and result in high investment cost.

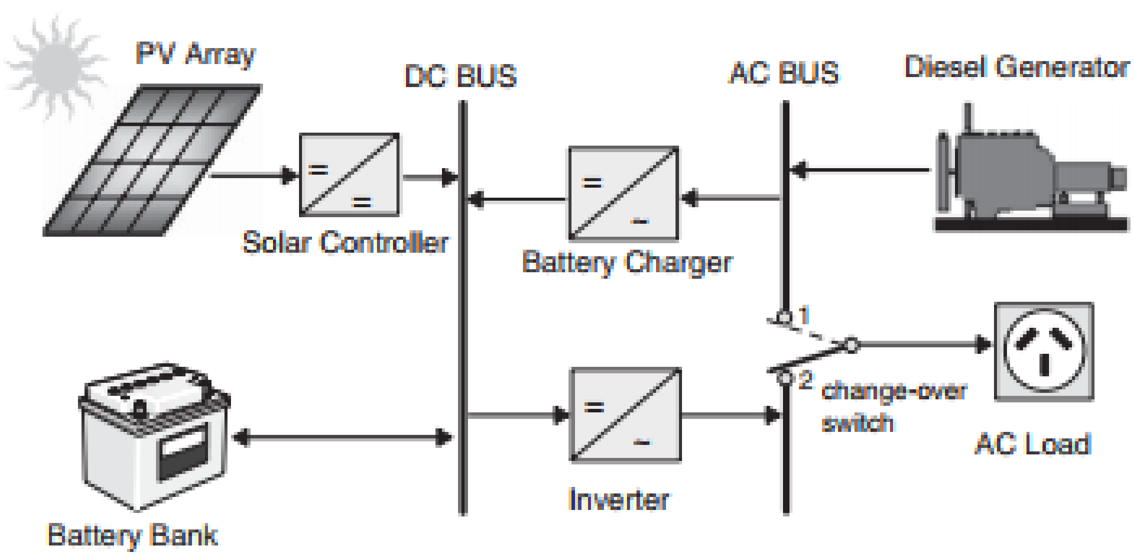

Figure 16: Switched PV-diesel hybrid energy system (Rashid, 2011)

2.5 Previous Literature on Hybrid Power System

Many studies have been carried out over the years on hybrid power generation systems for decentralized applications. Some of these studies focused on assessing the techno-economic feasibilities and viability, performance optimization, and power plant reliabilities of hybrid systems. Adaramola et., (2014a), in Southern Ghana carried out a study on a PV-wind-diesel-battery hybrid systems, from their analyses they reported that for 80 kW PV array, 100 kW wind turbine, two diesel generator with combined capacity of 100 kW, 60 kW converter, and a 60 Surrette 4KS25P battery of nominal capacity of 1904 Ah at 100 h was able to produce 791.1 MWh of electricity on a yearly basis. They also found the cost of energy to be $0.281/kWh for this hybrid configuration rather than generating electricity from a single generating source.

Shaahid & El-Amin (2009), carried out a comparative techno-economic feasibility study in a remote community in The Kingdom of Saudi Arabia. In that study, three different scenarios were analyzed, such as PV/diesel generator with and without storage and stand-alone diesel generators. From their finding, it was observed that the standalone conventional diesel generators system has the lowest LCOE, which is due to low fuel cost in the country. However, PV-diesel-battery is the most optimum configuration in that study was mainly focused on the environmental impact related to the three scenarios, and the fuel-saving cost of running diesel generators. They also reported that the contribution from the PV and the battery reduces the operating hours of the diesel generators, which result to a high cost of fuel-saving and the amount of CO_2 emission into the atmosphere was reduced by 24%. The cost of energy for the PV/diesel/battery system was found to be $ 170/kWh, with a renewable penetration of 27%. They concluded that by running the diesel generators alone, it is more expensive when considering the high operating and maintenance cost associated with them.

Ismail et al. in 2013, performed techno-economic analyses on hybrid systems for powering remote tropical village in Malaysia. In that study, three different scenarios were considered, such as PV arrays with a battery bank, conventional diesel generators only, and PV/diesel/battery system. They used a genetic algorithm for simulating the three scenarios, in order to determine the most optimal system configuration based on lowest energy cost and lowest emission for the same load profile of the village. From their analyses, they reported that the most optimal system with the lowest cost of energy was the scenario with PV/diesel/battery system configuration. The LCOE for the optimal system was found to be $0.239 /kWh with 90% of the PV contribution and 0.4 days of autonomy. They also revealed that the CO_2 emission from the optimal system was drastically minimized and as well reduced the operation hours of the diesel generators. In conclusion, they reported that PV/diesel/battery hybrid system is the best solution for electricity generation in remote areas of Malaysia.

Adaramola et al. (2014b) assessed the possibility of generating electricity from solar PV/diesel hybrid power system for rural and semi-urban areas in Northern Nigeria, using HOMER software. They reported that PV/diesel generator/battery hybrid configuration is the most economical and more suitable option for generating electricity for that particular location. The LCOE obtained from simulation results were highly influenced by the interest rate, whereby the cost of energy for the PV/diesel/battery hybrid system varies between $0.348/kWh and $0.378/kWh compared to diesel generator only (without battery) which varies between $0.417/kWh and $0.423/kWh.

Adaramola et al. (2017) in another study, used HOMER to perform a feasibility study of a hybrid system consisting of solar PV and biodiesel generator power system to generate electricity for domestic purposes (such as household lighting), small businesses and water pumping system in the Upper West region in Ghana. They considered five investment scenarios during this study: 100%, 75%, 50%, 25% and 0%. The optimum configuration from the simulation comprised of 30 kWp of solar PV, 364.8 kWh of battery storage, 30 kW converter, and 10 kW biodiesel generator. The investment cost, the net present cost (NPC) and the Least Cost of Energy (LCOE) were US$ 243200, US$ 412,104 and US$ 0.76/kWh at 100% cost without any aid from government or donor partners. However, the LCOE was reduced to US$ 0.20/kWh with NPC US$109520 when compared with US$ 169046.94 for a grid-based system, with 100% capital investment support from government or donor partners

Borhanazad et al. (2014), performed an optimization on hybrid micro-grid systems for three locations in Iran. In that study, a hybrid PV/wind/diesel/battery system was investigated. The power management algorithm was applied to the load, whereby a technique known as the Multi-Objective Particle Swarm Optimization (MOPSO) was used to find the optimal system sized components for the three locations. At the end of the optimization, they were able to propose a control strategy for the hybrid micro-grid for maintaining the continuous power supply to the load under different operational modes.

2.6 The Flexy Energy Concept

Most studies on PV/diesel hybrid systems in existing literature incorporates battery storage in order to supply power to the load and as well maintain energy balance during high peak when the production from PV cannot meet the demand. However, the used of battery storage systems come with several drawbacks such as; shorter lifetime, high replacement cost, and other environmental issues associated with them. In most developed countries, batteries are usually recycled at the end of their life instead of been disposed into the environment. Moreover, in the case of developing countries, it is a big challenge to handle batteries when they run out since there are no facilities in place for recycling, especially in rural and areas. Some studies reported that the cost of batteries storage could represent about 16% -20% of the total net present cost of the system (Yamegueu et al., 2011).

Over the years an approach has been developed by researchers at the International Institute of Water, and Environment Engineering (2iE) in Burkina Faso known as the flexy energy concept. The flexy energy concept composed of a PV/diesel hybrid system without battery storage, the batteries are excluded because of their high investment cost and the environmental issues associated with them. The flexy concept maximize the use of local mix energy resources for the management of the load to be supplied; via a smart control unit (Azoumah et al., 2011; Tsuanyo et al., 2015)

However, this concept aims at providing sustainable electricity supply for people living in rural and peri-urban areas in West Africa. The first prototype based on this concept was implemented at the 2iE K1 Site in Kamboinsé, Burkina Faso. The prototype composed of a diesel generator with a rated capacity of 11.5 kVA, solar PV with a capacity of 2.85 kW_p, and a single-phase inverter of 3.3 kW. This concept has also been implemented in Bilgo village in Burkina Faso and Siby commune in Mali, in order to respond to the challenges encountered in decentralized electricity production, especially in rural and peri-urban areas.

Over the years, studies have been carried out based on the flexy energy ranging from modeling, experimentations and techno-economic analyses. Azoumah et al. in 2011, carried out a study on sustainable energy generation in rural and peri-urban areas in West Africa based on the concept of flexy energy. From their study, they performed simulation on three power generating scenarios such as (diesel generators only, PV and battery, and a PV/diesel hybrid system). From their analyses the reported that the PV diesel hybrid system was the most optimal system over the other two systems in terms of cost, and the amount of CO_2 emission into the atmosphere was reduced by 86.7%. They concluded that PV/diesel hybrid based on the flexy energy concept could be a better alternative in rural and peri-urban areas if their design management is improved.

Yamegueuet al. carried out experimental work on PV/diesel system without battery storage on the prototype installed at 2iE site K-1. The study assesses the behavior of the PV/diesel hybrid system for different ranges of load profiles corresponding to different nominal power the diesel generators such as (40%, 62%, 82%, and 105%). It is found that the contribution of the PV array affects the output performance of the diesel generators because the generators were operating at a lower-rated capacity, which results in high fuel consumption. They also found out that in order to ensure high power reliability, the rated power from the diesel generators must be equal to the peak load. They concluded that for higher load demand and high solar irradiation, the PV/diesel system is more reliable and efficient.

Tsuanyo et al. in 2015, carried a techno-economic modelling on PV/diesel hybrid system without battery storage installed at 2iE K-1 campus in Kamboinsé. In their study, two cases were considered. The first one is composed of PV with identical diesel generators capacities while the second case comprised of PV with different generators capacities. Both cases were compared with conventional diesel generators. They used HOMER software for simulation and optimization in order to find out the most optimal system with the lowest LCOE. The study shown two possible optimization solutions: the first solution composed of seven identical diesel generators of 26 kW capacity which was coupled up with a PV generator of capacity120 kWp, the second solution three diesel generator with capacities of 35 kW, 54 kW and 75 kW respectively, were coupled with PV generator of 150 kWp. The LCOE for the two optimal solutions were found to be 0.285 €/kWh when compared with to the conventional diesel generators which were found to be 0.32 €/kWh.

With all these positive contribution mentions in the previous paragraphs about this concept, a major drawback has been identified due to the energy management of the PV/diesel power plant. One of these drawbacks which have been identified in this study is related to the excess electricity production by the system during low demand, which has not been considered.

In this context, this study seeks to identify the most optimal storage capacity that can be incorporated into the hybrid PV/diesel configuration, which is capable of storing all the excess electricity produced. Furthermore, the inclusion of storage system will help to reduce the extended operating hours of the diesel generators in order to minimize the operating and maintenance cost of the system.

2.7 Economic Modelling

The economic parameters are also used to make a financial assessment for the entire lifetime of the project. The economic parameters consider in this study are; the levelized cost of energy (LCOE), net present cost (NPC), annualization cost (AC), internal rate of returns (IRR), salvage value (SV), discount rate.

2.7.1 Levelized Cost of Electricity (LCOE)

The LCOE is the most transparent metric and commonly used tool to evaluate the cost of electric power generation when comparing different energy technologies (Branker et al., 2011). The LCOE is a measure of the marginal cost (which is the cost required to produce one additional unit) of electricity over an extended period (Hearps & McConnell, 2011). The LCOE can be defined by the average cost of electricity per kWh of useful electrical energy produced by a system; it can be calculated as the total annualized cost of producing electricity by the total load served (Lambert, Gilman, & Lilienthal, 2006).

$$LCOE = \frac{C_{ann\ tot}}{E_{served}} \qquad \text{Equation 1}$$

Where:

$C_{ann\ tot}$ = total annualized cost in \$/yr and

E_{served} = total electrical load served in kWh/yr.

2.7.2 Net Present Cost (NPC)

The net present cost consists of all the incomes and outlay cost that is used in the entire project lifetime, including the future cash flows discounted back to the present. The NPC takes into account the capital investment cost of the system components, replacement cost, maintenance and fuel cost and savages cost of components (which is the net worth remaining of the system component after the system lifetime) during the lifetime of the project. It can be calculated by the equation (Chauhan & Saini, 2014):

$$Net\ Present\ Cost\ = \frac{Total\ Annualised\ Cost}{Capital\ Recovery\ Factor}$$ Equation 2

$$Capital\ Recovery\ Factor\ = \frac{i(1+i)^N}{(1+i)^N - 1}$$

Equation 3

2.7.3 Salvage Value

The salvage value of the system (S) is the value remaining in the component of a power system at the end of the projected time. The salvage value depends on the replacement cost instead of the initial capital cost. It is calculated using the following equation (HOMER, 2016):

$$S = C_{rep} \frac{R_{rem}}{R_{comp}}$$ Equation 4

The remaining life (R_{rem}) of the component at the end of the projected lifetime is given by:

$$\mathrm{R_{rem}} = \mathrm{R_{comp}} - \left(\mathrm{R_{project}} - \mathrm{R_{rep}}\right)$$ Equation 5

The replacement cost (R_{rep}) duration is given by:

$$R_{rep} = R_{comp}\ INT\left[\frac{R_{proj}}{R_{comp}}\right]$$ Equation 6

Where C_{rep} is the component replacement cost, R_{rem} is the remaining life of component (t), R_{comp} is the lifetime of the component (t), and INT ( ) is a function that returns the integer amount of a real number.

2.7.4 Real Discount Rate

The real discount rate is used to convert between one-time costs and annualized cost. The real discount rate can be computed from the nominal discount rate and the expected inflation rate in HOMER. It can be expressed in the following equation (HOMER, 2016):

$$R = \frac{r-f}{1+f} \qquad \text{Equation 7}$$

Where: R is the real discounted rate; r is the nominal discounted rate; f is the expected inflation rate

2.7.5 Annualized Cost

The Annualized cost is the annual cost of components which include the annualized capital cost (C_{cap}), the annualized replacement cost (C_{rep}) and the operation and maintenance cost ($C_{O\&M}$) throughout the lifetime of the project. It can be calculated as the net present cost of components multiply by the capital recovery factor (HOMER, 2016; Yang, Wei, & Chengzhi, 2009):

$$C_{ann} = CRF(i, N) \times C_{NPC} \qquad \text{Equation 8}$$

The total annualized cost is the annualized value of the total net present cost, and can be calculated in the equation below (HOMER, 2016):

$$C_{ann} = CRF_{tot}(i, N) \times C_{tot\ NPC} \qquad \text{Equation 9}$$

Where:

C_{ann} = Annualized cost ($); i= real inflation rate (%); N= Projected lifetime (years); C_{NPC} = Net Present Cost of components ($).

2.8 Energy Management Strategy (EMS)

To ensure reliability in power production from hybrid power systems, it is essential to have a management strategy that will guarantee a smooth running of the power plant. Energy management strategy is a systematic use to control the operation of the power plant in order to ensure the flow of energy from each power generating components (Olatomiwa, Mekhilef, Ismail, & Moghavvemi, 2016). The main roles of EMS in PV/diesel hybrid power systems are:

- To ensures the continuity in power supply to the load at all conditions whereby maximizing the use of energy resources.

- To minimize the cost of energy production during system optimization
- To protect the power plant from been damage due to overloading and stability issues

According to Kaabeche & Ibtiouen (2014), the energy management strategy for PV/diesel hybrid systems can be done using two approaches:

For the first approach, when the power production by the hybrid system is more than the energy demand, the excess energy generated from the hybrid system is used for charging the battery bank to its maximum state of charge (SOC) or power dump load if available. In this situation, the diesel generator does not operate and result in high fuel-saving and as well reduces the operational cost of the hybrid system. For the second method, when the power required by the load demand exceeds the power supply from the hybrid system results in energy deficiency; thus, two possible solutions can be used to meet the load demand. Firstly, the battery banks are used to supply power to the load, but SOC must be at the maximum level. Secondly, in the situation when the state of charge of the battery decreased to its minimum level, the diesel generator is turned on and operates at it rated capacity to supply enough power to meet the load requirement and as well charge the battery banks to their maximum SOC.

2.9 Energy Dispatch Strategies

Energy dispatch strategies are used in HOMER to control the operation of power generating components such as PV, diesel generators, and the batteries. The most commonly used dispatch strategy adopted in by many authors are:

- Load Following Strategy
- Cycle Charging Strategy

2.9.1 Load Following dispatch strategy

This strategy only allows the power generated from the renewable sources to charge the batteries whereby the generators do not. The batteries are charged with the excess energy generated from the renewable sources during the low demand period. This strategy maintains the cost of charging batteries at zero and help to increase the cost of fuel-saving. In the LF strategy when the difference between the power generated from the renewable sources and the load demand at a particular time is greater than zero, the battery bank is charged until it reaches the maximum

SOC. At the maximum SOC, the continuous power generated from the renewable sources are considered as excess load. When the difference between the power generated from the renewable sources and the load is less than zero, the energy stored in the battery is discharged until it reaches its minimum SOC. When the battery can no longer supply energy to the load, the generator is turned and supply enough energy to meet the load demand. In a situation where both sources failed to meet the load demand, an unmet load exists (Olatunde, 2017).

2.9.2 Cycle Charging

In this type of discharge strategy, the generator is allowed to operate to its rated capacity to supply power to the load, and the excess energy produced is used for battery charging (Aziz, Tajuddin, Adzman, Ramli, & Mekhilef, 2019). This strategy consumes more fuel because of the operation of the generator, and the cost of charging batteries is not zero as compared to the LF strategy.

CHAPTER THREE

3. RESEARCH METHODOLOGY

3.1 Study Area

Bilgo village is the selected location for this study. Bilgo village is located in the commune of Pabre, which is a section of Kadiogo Province in the Central Region of Burkina Faso. The village is located about 30 km from the capital city Ouagadougou and lies between latitude 12° 31.8 N and longitude1° 40.8 W. According to the 2006 general population and household census report there were about 303 households with 2008 inhabitants in Bilgo (SONABEL; & 2iE Foundation, 2012). The village is accessible in both seasons because it is connected with the main road leading from Kamboinsé to Ouagadougou. The main sources of households earning in Bilgo village depend on agricultural activities and livestock rearing.

Access to electricity in Bilgo village was a challenge before the installation of the PV/diesel hybrid power plant since there was no access for electricity grid extension leading towards the village. Most of the households were relying on inefficient sources for lighting such as (touch light, oil lamps, candles, and small thermal generators). The problem of electricity access in the village was serving as a major setback towards the quality of living, better health services, quality education, water supply, and small businesses. Previous feasibility studies reported that the need for electricity in the village was timely and welcoming to the people of Bilgo village, and the commissioning of the power plant will foster development in the village. Figure 3-1 presents the geographical location of Bilgo village.

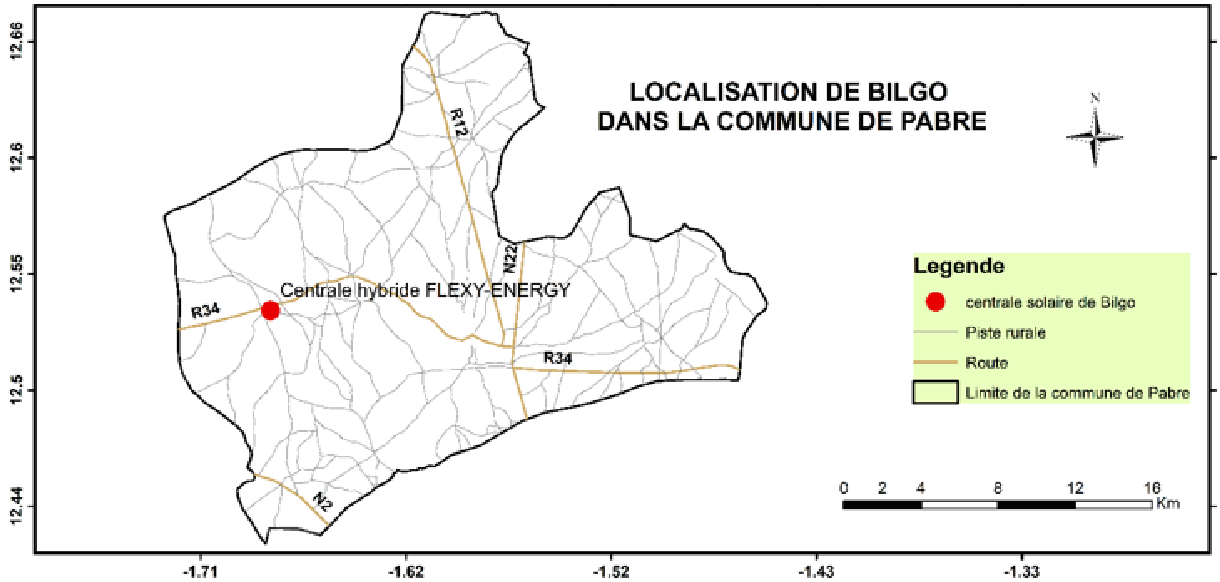

Figure 3-1: A map of Bilgo village showing the exact location of the power plant

3.2 Configuration of the PV/diesel Hybrid Power System in Bilgo Village

This study is based on the existing PV/diesel hybrid power system without battery storage system installed in Bilgo village. This hybrid power plant was designed to meet the electrical load demand in Bilgo village based on the previous feasibility study. The power plant relies on the contribution from both power sources for the load profile of the village. In the case of this power plant, a parallel AC hybrid configuration was adopted. The power plant composed of 30 kW_p solar PV capacity, which is sub-divided into five arrays (three with 5 kW_p and two with 7.5 kW_p). The PV arrays were coupled with three diesel generators with a total capacity of 70 kVA (two with 20 kVA and one with 30 kVA). The parallel operation of this hybrid system makes it possible for either of the power generating sources capable of supplying power to the load based on the demand and can also operate simultaneously during peak demand.

The parallel hybrid configuration of PV/diesel hybrid setup is illustrated in Figure 3-2. The five PV arrays are all connected to DC protection buses, to ensure safety interruption of electricity flowing from the PV array to the inverters. The DC buses were connected to five grid-tied inverters (three with 5 kW capacity and two with 7 kW capacity). The grid-tied inverters were used to reduce the losses and as well reduces the size of the DC components in the connection box. The inverters were also connected to multiple circuit breakers in order to ensure maximum system protection. The measuring meters were used to measure the intensity, voltage, current, and power output from the inverter before they were connected to the AC bus. The three generators are directly connected to the AC bus since the output it produces is AC. The AC bus is connected to a central control unit, which contains multiple components that control the entire operation of the power plant.

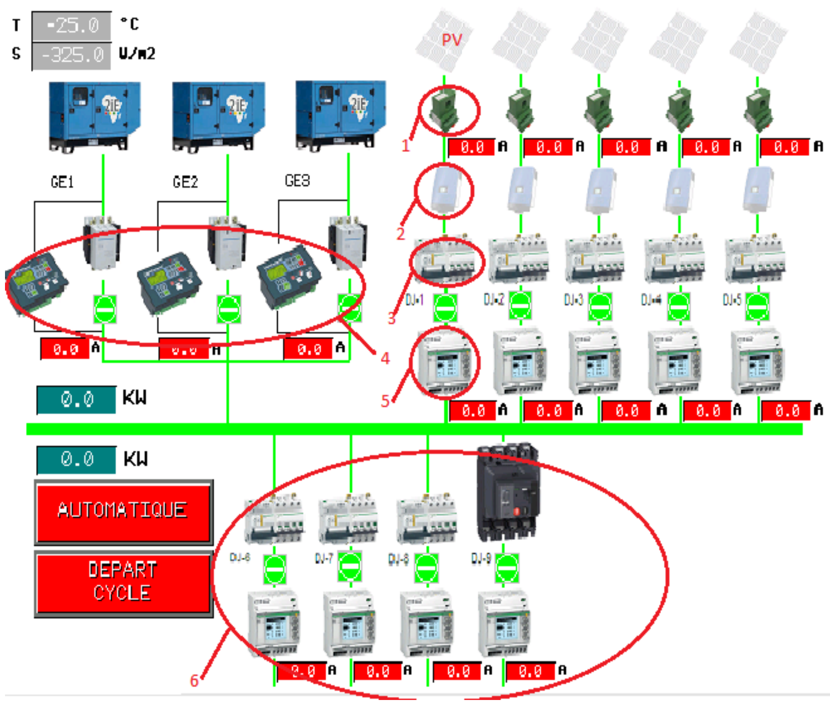

Figure 3-2: Architect of the PV/Diesel Hybrid configuration of Bilgo Power Plant

Key: 1 = DC protection bus; 2= DC/AC inverters; 3 =Circuit breakers; 4 = Generator controller; 5= Sensitivity Meters; 6= Consumer distribution line.

3.3 Software used in Modelling of Hybrid Energy System

Software tools are mostly used in the hybrid systems for simulating, optimizing, and sizing of systems. Some of these tools used in existing literature are HOMER, RETScreen, HYBRIDS, HOGA, Hybrid2, SOMES, ARES, SOLSIM, RAPSIM, IPSYS, SOLSIM, DESIGN PRO (Borhanazad et al., 2014; Sinha & Chandel, 2014). From all the software tools mention, HOMER has been considered as the most widely used tool used for simulation and optimization of hybrid systems. This tool is capable of simulating different energy sources and also perform sensitivity analysis to determine the robustness of the hybrid system. (Adaramola et al., 2014; Muh, 2017; Niyomugabo, 2018; Sinha & Chandel, 2014). The advantage of HOMER over the other hybrid designing tools is that it is capable of combining multiple energy systems by making a comparative analysis based on technical and economic parameters.

3.3.1 Description of Simulation and Optimization Software (HOMER)

Hybrid Optimization Model for Electric Renewables (HOMER) is a powerful simulation tool developed by National Renewable Energy Laboratory (NREL) in the United States of America. This tool has been commonly used to perform simulation optimization and sensitivity analysis on different hybrid system configurations by analyzing the behavior and performance of the system based on technical viability and economic feasibility (Adaramola, Agelin-Chaab, et al., 2014; Niyomugabo, 2018; Zala & Jain, 2017).

In the simulation process, the software model the performance of the hybrid power system configuration by making an energy balance calculation in each timestep of the year in order to determine the technical and economic feasibility of a particular hybrid system configuration. The software also calculates the energy supply to the load from the various energy generating sources as well as the energy flow from each component. The simulation process in HOMER has two determinations: firstly, the software determines whether the system is feasible or not. For a system to be feasible, it must adequately serve electrical loads and satisfy all other constraints considered by the designer. The second determination estimate the economic aspect of the hybrid configuration by taking into consideration the life-cycle cost of the system, which includes the total cost of installation and the operation of the system over its lifetime. (Niyomugabo, 2018).

In the process of optimization, the software performs numerous simulation and searches for the most optimal system configuration based on technical and economic constraints such as the lowest life-cycle cost and the least cost of energy. Sensitivity analysis is used to examine the effect of uncertainty or change in model input variables that are uncontrollable such as (solar irradiation, wind speed, fuel price) after HOMER has performed various optimizations under a specified range of input data (Adaramola, Agelin-Chaab, et al., 2014). Figure 3-3 is a schematic diagram of HOMER software employed in the methodology of the work.

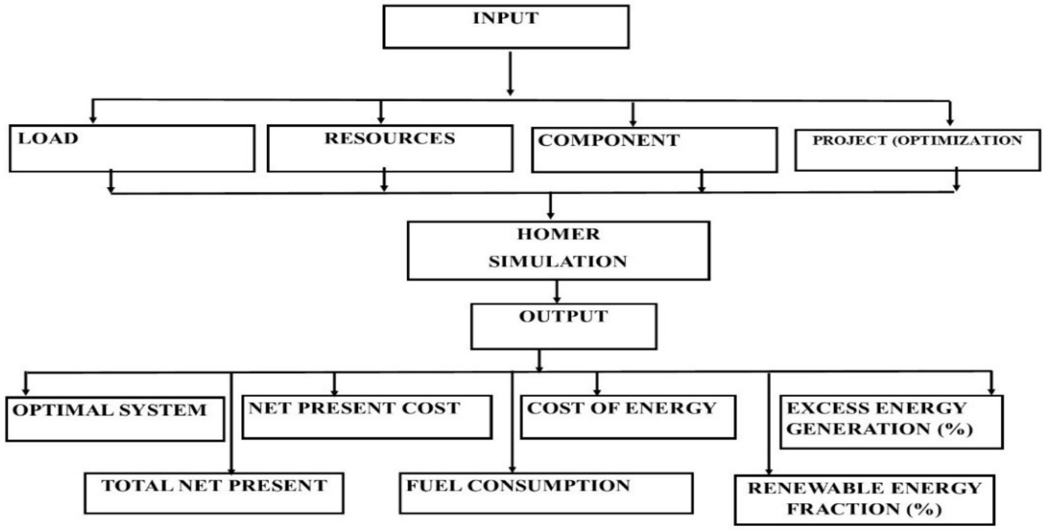

Figure 3-3: Representation of HOMER software

3.4 Simulation Input Parameters

The following input parameters are required in order to run different simulation models in HOMER Pro software.

3.4.1 Load Assessment

The electrical load requirement for Bilgo village was obtained from a previous socio-economic feasibility study conducted by 2iE foundation in 2012, through a field survey for household energy consumption patterns in the village. It was considered that each household in the village has the same energy consumption at the same time duration, which means a load calculation for a single household was estimated, and the value was multiply by the number of households in the village.

3.4.2 Daily Load Profile

The daily electric load profile for Bilgo village in Figure 3-4 is estimated at 430.55 kWh/d with a peak load of 47.636 kW which occur between 20:00-21:21:00 in the evening. The load demand is high between 18:00 to 00:00, because almost all the villagers are at home, and most of their electrical appliances are operating. The low load demand periods occur during the day between 14:00-16:00 when most of the villagers are not around, and most appliances are not in use.

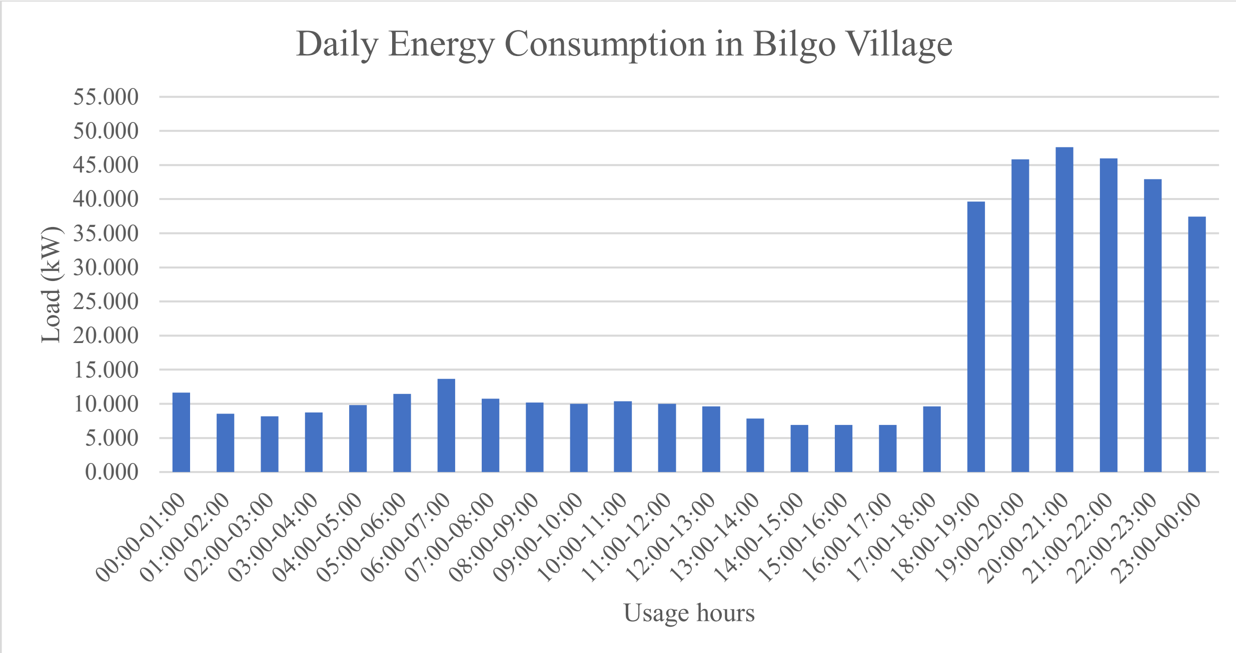

Figure 3-4: Daily Load Profile Trend in Bilgo Village

For the simulation process in this study, a day to day and time step variability of 5% was taken into consideration, in order to ensure randomness to the load profile and to make it more data realistic throughout the year. The random variability is used to satisfy the 10% operating reserve to provide a maximum safety margin to ensure the reliability of electricity supply regardless of the sudden change in electrical loads or sudden decrease in renewable output (HOMER, 2016). Based on the random variability for the system, the peak load increases from 47.634 kW to 58.26 kW, with an annual AC primary load of about 157,149 kWh/yr.

3.4.3 Solar Resources in Bilgo Village

The solar resource data for this study in Figure 3-5, is obtained from the National Aeronautics and Space Administration (NASA) database for the given latitude of Bilgo Village. The monthly solar radiation for the site location ranges between 5.09 to 6.43 kWh/m^2/day, with an annual average solar radiation of 5.76 kWh/m^2/day. The average clearness index for the location was found to be 0.59, which indicates a good potential for PV system application.

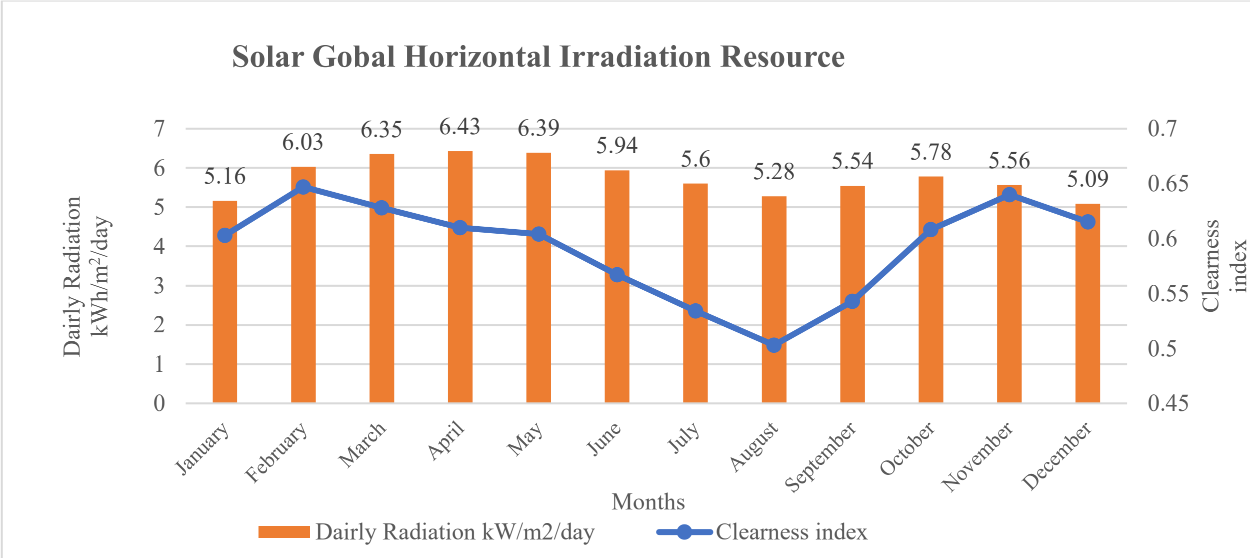

Figure 3-5: Monthly solar radiation for Bilgo village (NASA,2019)

3.4.4 Temperature Resources

Temperature is another factor that influences the production energy from the PV array, and it varies from place to place. The temperature resource data for this study was also obtained from NASA based on the latitude of the location. The temperature for the location ranges between (25.19 °C to 31.5 °C), with an average annual temperature of 27.67 °C. The highest temperature for the location experiences in April as one can see in Figure 3-6.

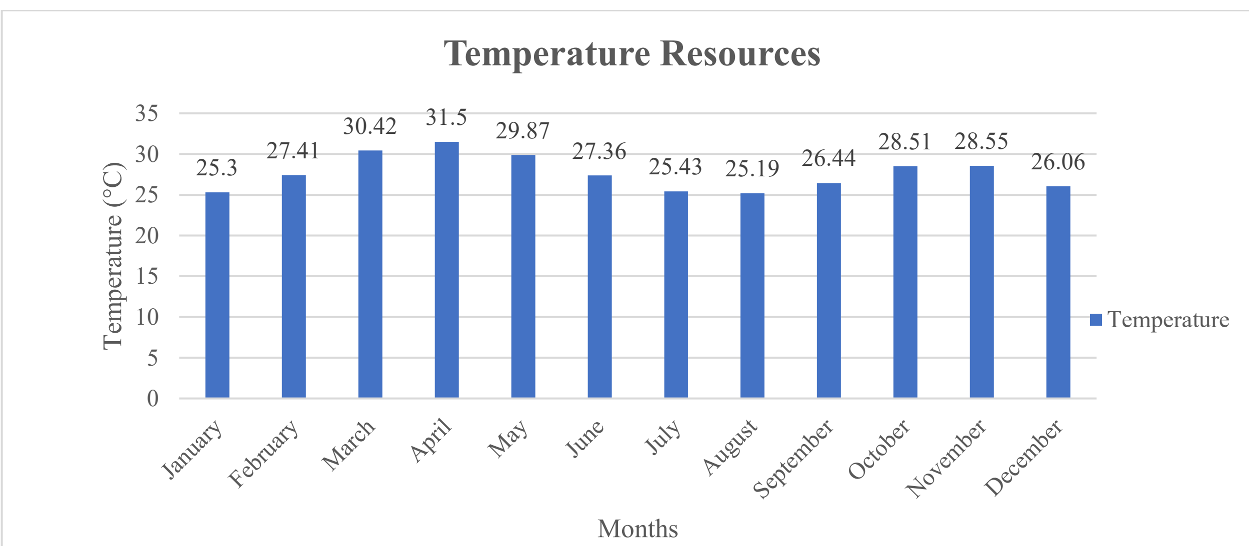

Figure 3-6: Temperature Resources in Burkina Faso (NASA,2019)

3.4.5 Components Assessment and Costing

The components considered in this study were, solar PV modules, converters, diesel generator, and controllers and battery. The technical data for all the components were based on the manufacturer specification, and the costs of components such as (PV modules, diesel generators, grid-tied inverter, and controller) were obtained from the cost they were acquired before the commissioning of the project.

3.4.5.1 PV Modules Assessment

The PV array consists of 120 polycrystalline flat plates with a rating of 250 W_p. The total rating of the PV modules is 30 kW_p DC, (with an irradiance of 1000 W/m^2, solar cell temperature of 25 °C and Air mass (AM) of 1.5 under Standard Test Condition). The modules were inclined at a slope of 15° relative to the latitude of the location. The azimuth angle of the PV module was zero, and the panels were oriented toward the south in order to capture the maximum amount of solar radiation during the day. The lifetime of the modules is 25 years and the derating factor is 85%, which account for all the losses due to the effect of temperature, wiring losses, shading, snow cover and aging which reduces the power output of the panels when compared to the rated power of the PV panel (HOMER, 2016). The capital and replacement costs of the modules was estimated to US$1062.61 /kW, which includes shipping cost and installation and taxes, and the O&M cost was considered to be 1% of the total capital cost. Table 3-1 shows the technical specification of the module:

Table 3-1: Technical Specification of the 250 W PV module

Technical Specification	
Manufacturer	**Yingli Energy (China)**
Rated Power	**250 W**
Rated Voltage (V)	**29.8 V**
Rated Current	**8.39 A**
Open Circuit Voltage (V_{OC})	**37.6 V**
Short Circuit Current (I_{SC})	**8.39 A**
Maximum Voltage (V_{max})	**1000 V**
The temperature of the Solar Cell	**44.8 °C**
Temperature Coefficient	**-0.4586**
Derating Factor	**85%**
Efficiency	**13%**

3.4.5.2 Inverters and DC Protections Assessment

The grid-tied inverters were used to convert the DC output from the PV arrays to the AC bus. In the installed system, each grid-tied inverter was connected to an array to ensure full power supply to the AC bus. The use of grid-tied inverters for this system is to reduce the number of combiner boxes and enhance easy troubleshooting and system monitoring (Mahmud, 2016). The selected inverters used in this study is SMA TriPower 5000TL, and 7000TL, the rated input voltage (V_{mpp}) for the inverters is 580V, with a maximum voltage (V_{max}) of 1000V. The maximum efficiency of the inverters is 98%. The capital and replacement costs of the inverter, including DC protections, were estimated at US$1770.76 /kW and the operation and maintenance cost of the inverter is assumed to be US$ 10 /yr, with an operational lifetime of the inverter is 15 years.

3.4.5.3 Diesel Generator Assessment

Diesel generators are commonly used as a backup power generation system. The role of diesel generators in hybrid power systems is to ensure reliability and effectiveness in power supply Diesel generators in hybrid power system are usually sized to meet the peak load demand

(Adaramola et al., 2014) when other renewable sources failed to meet the demand. The minimum load ratio of the generator was set at 20%, and the operating lifetime of the diesel generators is 15000 hours. The capital and replacement costs for the diesel generators is US$1894.55/kW, and the operation and maintenance (O&M) cost was US$ 0.02/hr. The minimum load ratio considered for this study is set at 25%.

3.4.5.4 System Control Unit Assessment

The control system central control system is considered as the brain which composed of different components such (transducers, circuits breakers, regulators, generator controllers) installed in it. It controls, regulates, and creates a means of communication between all the components involved in the hybrid systems to ensure a smooth operation of the power plant. The dispatch strategy used in this study is the Load Following. The total capital and replacement costs for the system control unit, including all other component embedded in it, cost US$ 59,292.75, and the operation maintenance cost is taken as US$ 100/year. The lifetime of the system controller is 25 years.

3.4.5.5 Battery Storage Assessment

The Trojan SPRE 02 1255 was the selected battery model for the simulation in this study. The battery has a nominal voltage of 2V and a nominal capacity of 1270Ah. The batteries were connected in three strings and each string size composed of 24 batteries. The series connection of the battery was to increase the bus voltage to 48 V, and the parallel connection of the batteries increase the capacity to 3810 Ah. The battery has an efficiency of 80%, with a throughput of 2024 kWh. The maximum charge current and the maximum discharge current of the battery are 222A and 300A, respectively. The capital (including shipping cost and installation cost) and replacement cost of the battery were US$ 600, and the operation and maintenance cost was considered as 1% of the capital cost.

3.4.5.6 System Converter Assessment

The selected converter used in the simulation is SMA Sunny Island 8.0 H bi-directional inverters, with a total rated capacity of 30 kW and the efficiency of 95.8. The maximum AC power input of the converter is 11500 W_p, and maximum AC input current is 48V. The converter has a DC input voltage of 48V, and the maximum charging current is 140A. The capital cost (includes installation cost) and replacement cost of the system converter is US$ 900/kW, and the operational maintenance cost was taken as 1% of the capital cost. The lifetime of the converter is 15 yrs.

3.4.6 Economic Input Parameters

The lifetime of the project has been taken as 25 years. The discount rates in Burkina Faso range between 6% and10%, which have been estimated by authors (Ouedraogo & Yamegueu, 2019; Tsuanyo et al., 2015). The escalated inflation rates range between 1% and 3%, which was estimated by (Ouedraogo & Yamegueu (2019). For the study, the discount rate and the inflation rate will be taken as 8% and 3% respectively, and the real discount rate is estimated at 4.85% by using the Fishers expression. The price for diesel around the world as of June 10 was estimated at US$ 1.03, and in Burkina Faso was about US$ 0.99/L (CFA 577.88 per liter) according to the Global Petrol Price (2019). Since the country is a net importer of petroleum product from neighboring countries, which makes the country more vulnerable to oil prices fluctuation in the world market. During scarcity in the country, the price fuel in rural areas is drastically increasing, which make it more expensive to operate a power plant running on diesel engines. For this study, an investigation will be conducted to know the effect of changes in fuel prices in on hybrid power system and the cost of producing electricity in Bilgo village. The fuel prices were varied between US$ 0.86/L to US$ 1.28/L.

3.4.7 System Simulation Constraints

In order to ensure a smooth operation of the system, specific conditions must be satisfied when modelling a hybrid power system. However, if these specific conditions are not met the software will reject the systems during optimization. For this study, two main constraints were considered, such as the operating reserve and the maximum annual capacity shortage. The operating reserve is the surplus operating capacity that instantly responds to a sudden increase in the electrical load demand or a decrease in the output power from renewable sources. For this study, in order to ensure a reliable power supply for the given load profile an operating reserve of 10% as recommended by Adaramola et al. (2014). The capacity shortage is the shortfall in that occurs between the actual operating capacity and the actual amount of operating capacity the system can provide, while maximum annual capacity shortage is a total shortfall that occurs throughout the year. The accepted maximum allowable annual capacity shortage reported by

Adaramola et al. (2014) ranges from 0.5% to 5%. In this study to ensure that there is no shortfall, the maximum capacity shortage of 1% was considered.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Optimization Scenarios

In this study, three power generation scenarios were simulated, as shown in Table 4-1. The scenarios were analyzed by using HOMER software in order to determine the most optimal system with the lowest net present value, the lowest levelized cost of energy, the lowest CO_2 emission, lowest capacity shortage, lowest excess electricity production and the highest renewable energy fraction.

Table 4-1: Optimization Scenarios for the three power generating system

System Configuration	Scenarios
Conventional Diesel Generators only	A
Diesel Generator and PV array without Storage	B
Diesel Generator /PV array/ Battery storage	C

4.1.1 Convention Diesel Generators only (Scenario A)

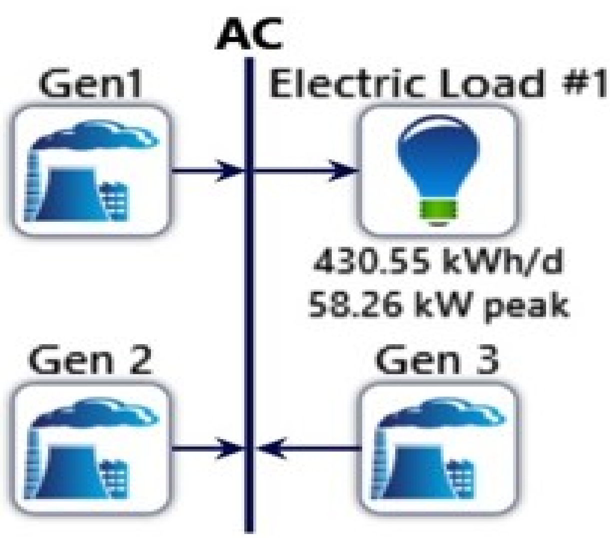

Figure 4-1: Schematic of the Diesel Generators

In scenario A, three conventional diesel generators (2*16 kW and 24 kW) are used to supply power to the given load profile in Bilgo village. The optimization result shows that the annual electricity production by the power plant is estimated at 157,145 kWh/yr, with a contribution from each generator represented in Figure 4-2.

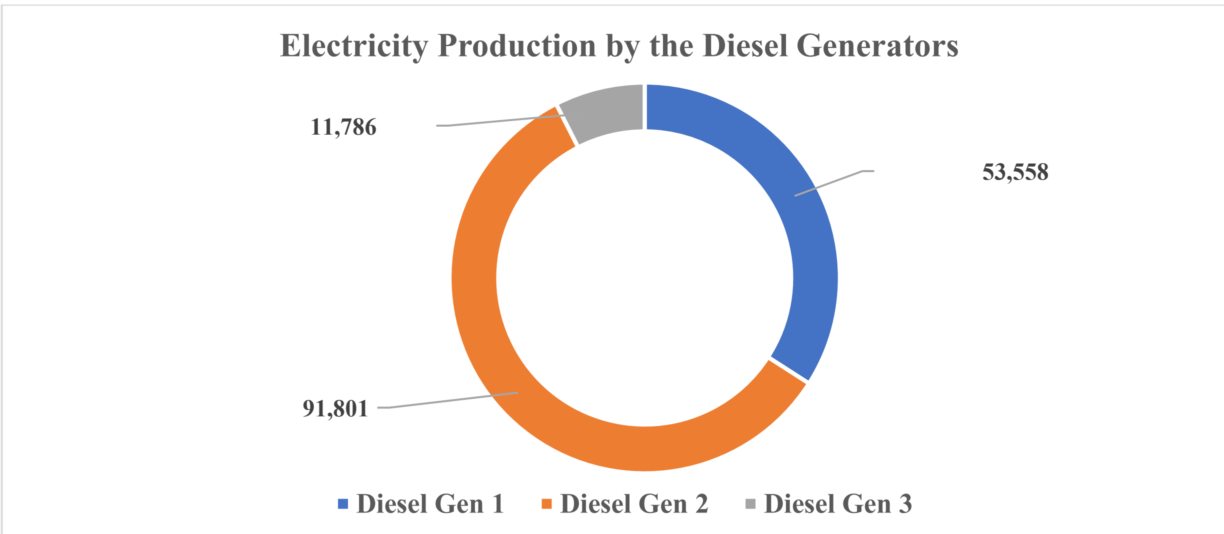

Figure 4-2: Total Electricity Production by the diesel generators annually

The total annual unmet load which the power plant was unable to serve that occurs when the demand exceeds the operating capacity is found to be 4.32 kW/yr, with an annual capacity shortage of 194 kW/yr due to the shortfall between the required operating capacity and the capacity supply by the system. The LCOE in this scenario is US$ 0.5816/kWh, with a total NPC of US$ 1,307,126.00 (see Figure 4-3). The operating and maintenance cost of the system over the entire lifetime of the project is US$ 65, 942.43, with a capital investment of US$ 165,387.80. Since the power plant only operates on diesel engines, the annual fuel consumed for electricity production throughout the year is 51,232 L, which account for about 55.5% of the total system cost. The specific fuel consumption for the three generators (DG-1, DG-2, and DG-3) are 0.271 L/kWh, 0.343 L/kWh and 0.447 L/kWh, respectively. The lifetime for the three diesel generators is found to be 6.65 years for DG-1, 1.73 years for DG-2 and 7.28 years for DG-3. The annual CO_2 emission produced from the system is estimated at 134,116 kg/yr due to the long operating hours of the diesel generators.

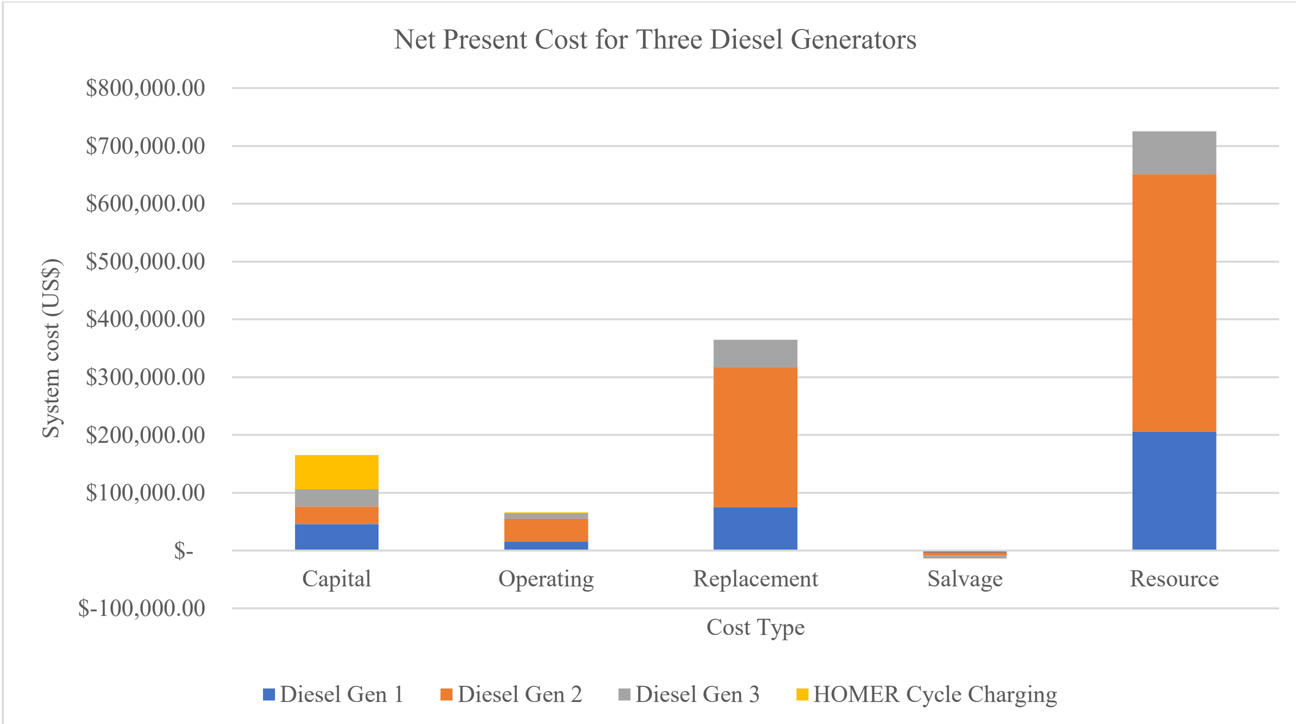

Figure 4-3: total NPC for Scenario A

4.1.2 Solar PV / Diesel generator Configuration (Scenario B)

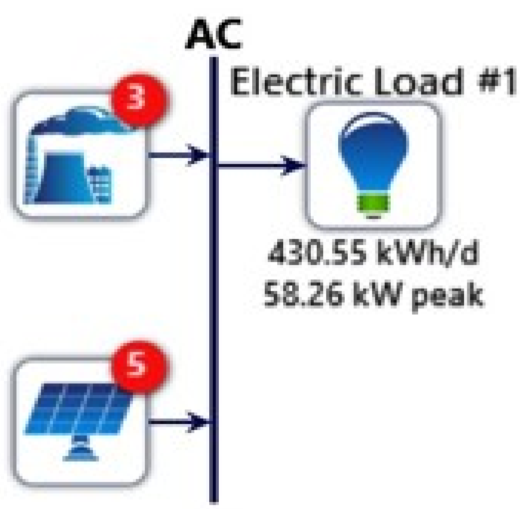

Figure 4-4: Schematic of the PV / Diesel Hybrid System without Battery storage (Flexy Energy Concept)

Scenario B is composed of PV/diesel hybrid system without battery storage. This configuration demonstrates the impact of the renewable energy source in the electricity production from the power plant. The optimization result shows that the total annual electricity production is 186,877 kWh/yr. The electricity production by the PV array and the diesel generators are 48,406 kWh/yr and 138,472 kWh/yr respectively (Figure 4-5), with a total renewable penetration of 30.79%, and renewable fraction is11.9% from the PV array.

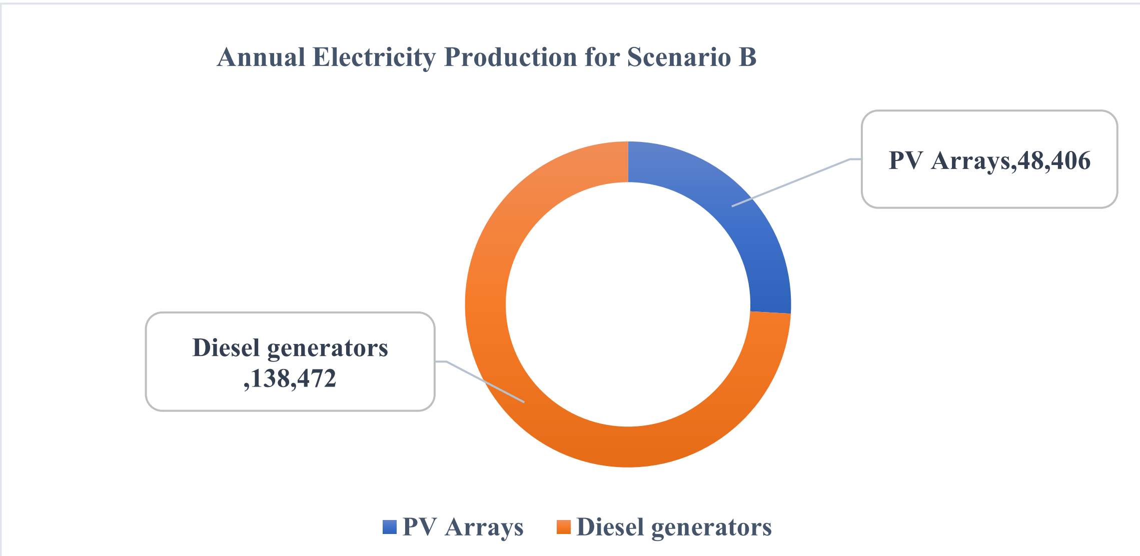

Figure 4-5: Total electricity production for Scenario B

The annual excess electricity production by the system is 29,732 kWh/yr, which exceeds the load demand of the village by 15.9%. Moreover, the annual unmet load the system was unable to serve that occurs as a sudden change in the peak load is 4.37 kWh/yr, with an annual capacity shortage of 194 kWh/yr.

The LCOE for this scenario is found to be US$ 0.604/kWh, with a total NPC and operating cost are US$ 1,357,160 and US$ 74,341.70 respectively. Before the energy generated from the PV arrays, the annual fuel consumed by the diesel generators is estimated at 46,932 L/yr, which accounts for about 49% of the total system cost. The specific fuel consumption by the three generators (DG-1, DG-2, and DG-3) are 0.271 L/kWh, 0.333 L/kWh and 0.49 L/kWh, respectively. The amount CO_2 produced from the system is estimated at 122,871 kg/yr, which is mainly associated with the diesel generator since the PV arrays do not emit any pollutants into the atmosphere.

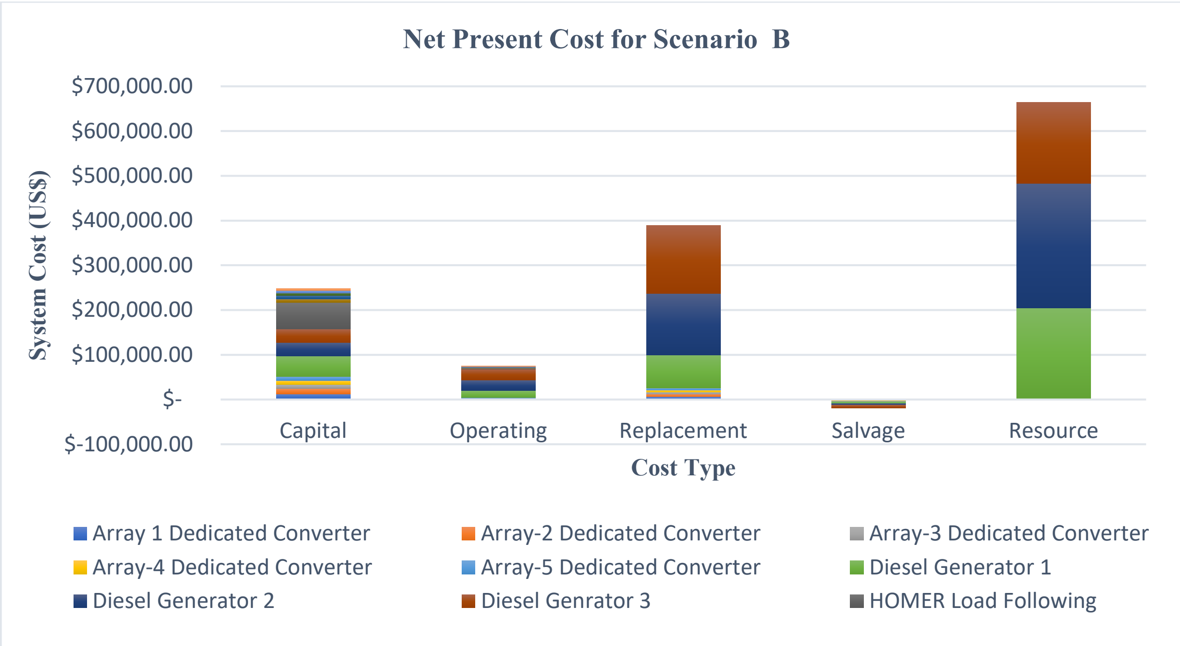

Figure 4-6: Total NPC for Scenario B

4.1.3 Solar PV/Diesel/Battery Configuration (Scenario C)

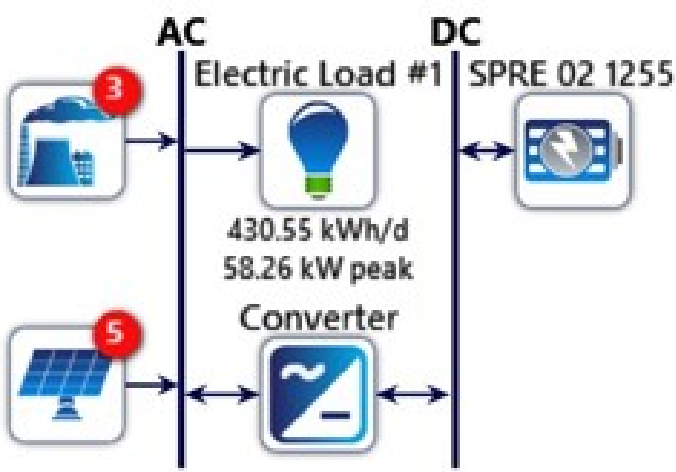

Figure 4-7: Schematic of PV/diesel/battery hybrid system (Scenario C)

Scenario C composed of PV/diesel/battery hybrid system. The inclusion of storage batteries in the system configuration is to store the excess electricity produced by the system and in order to reduce the operating hours of the diesel generators. The total annual electricity production by the system is 162,940 kWh/yr, with a 30% contribution from solar PV arrays and 70% contribution from the diesel generators (see Figure 4-8). The PV/diesel/battery system provides a reliable power supply, with 100% met load with no excess electricity generated. The excess electricity produced by the system is stored in batteries which can be used to support the other generating components during high peak or when the production from the PV array is low. The total renewable fraction is found to be 27.1%, indicating a significant contribution from renewables.

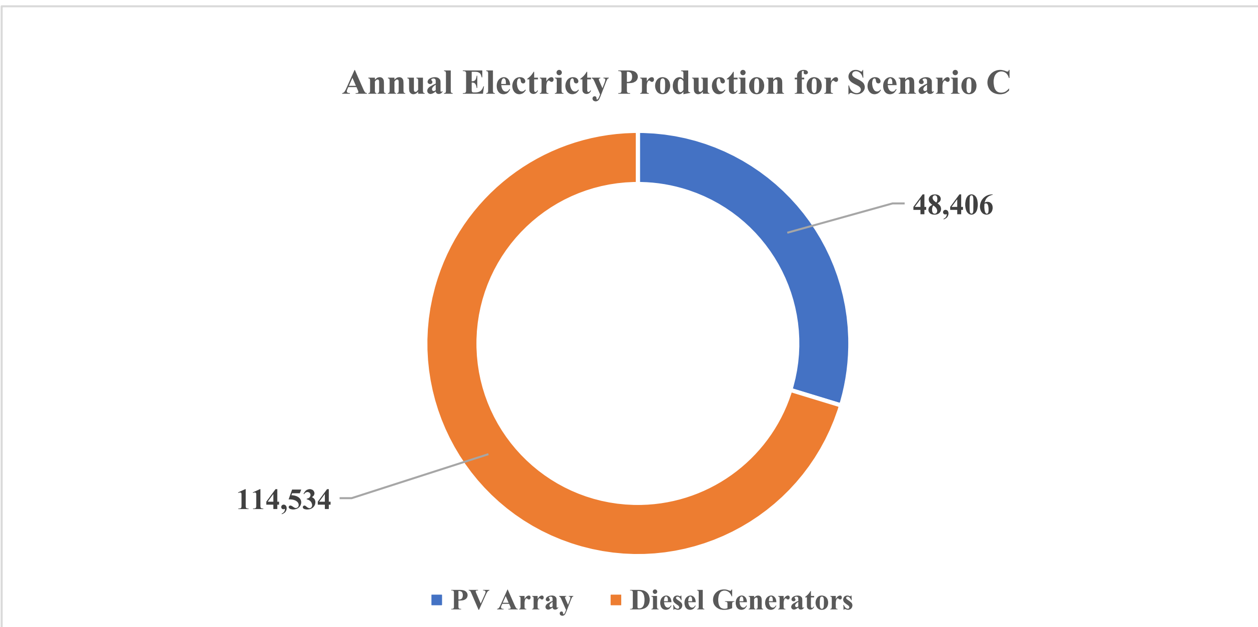

Figure 4-8: Total Electricity Production from Scenario C

The LCOE obtained from the optimization result is US$ 0.524/ kWh, with a total NPC and operating cost of US$ 1,177,376 and US$ 62,889.82, respectively. The annual fuel consumed by the diesel generators is estimated at 36,023 L, and the specific fuel consumption by the three generators (DG-1, DG-2, and DG-3) are found to be 0.270 L/kWh, 0.326 L/kWh and 0.435 L/kWh respectively. In addition, the annual CO_2 emission produced from the diesel generators is 94,304 kg/yr.

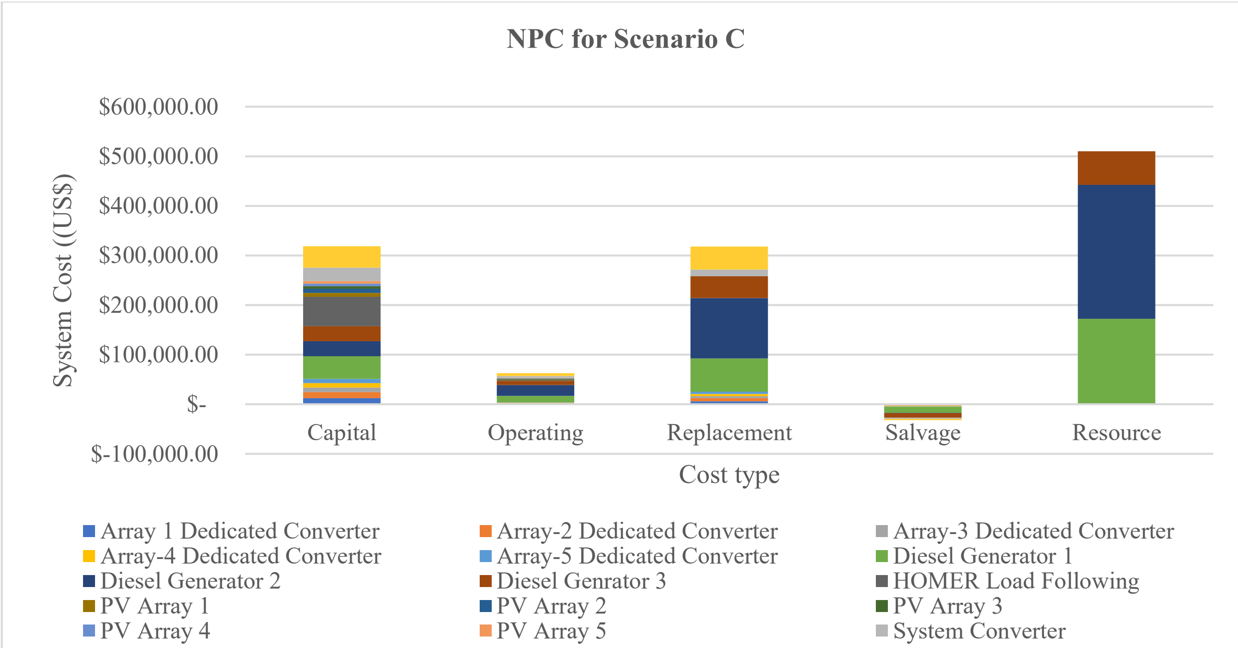

Figure 4-9: Total NPC for scenario C

4.2 Comparative analysis of the different scenarios

In the previous section, the three scenarios were analyzed based on technical, economic and environmental parameters, in order to search for the most optimal system configuration to meet the electricity demand for the given load profile in Bilgo village. Table 4-2 shows a comparative analysis of the three scenarios analyzed in the previous sections.

Table 4-2: Summary of Optimization Scenario for the hybrid power system for Bilgo village

System configuration Scenario	Electricity production (kWh/yr)	Annual fuel Consumption (L)	LCOE (US$ /kWh)	NPC (US$)	Excess Electricity Production (kWh/yr)	Renewable Energy Fraction (%)	Annual CO_2 Emission (kg/yr)
Diesel generators only (A)	157,154	51,232	0.5816	1,307,126	0	0	134,116
PV/diesel generators (B)	186,877	46,932	0.604	1,357,160	29,732	11.9	122,861.00
PV/diesel/battery (C)	162,940	36,023	0.524	1,177,376	0	27.1	94,304.00

From Table 4-2, the most optimal system with the lowest energy cost and the lowest NPC is scenario C, which is composed of 30 kWp PV array, 30 kW inverter, 56 kW diesel generators combined capacity and 72 batteries, with a LCOE of US$ 0.524/kW and a NPC of US$ 1,177,376. Although the initial investment cost in the optimal scenario is high, which is about US$ 318,818, because of the initial acquisition of components, but has the lowest operating and maintenance cost of US$ 62,890. Also, the optimal system has the lowest replacement cost of components of US$ 318,023 and lowest fuel cost of US$ 510,052 when compared to the other configuration. However, the optimal system has the highest initial investment cost because of additional components used in the configuration such as batteries and system converter but has the least operating and maintenance cost.

The net present costs for the three scenarios given in Figure 4-10, shows that scenario B has the highest NPC compared to the other two scenarios due to its high operating cost of US$ 74,342 and replacement cost of US$ 364,381. Scenario A has the lowest capital cost of US$ 165,358 compared to the other two scenarios but also has the highest fuel consumption cost of US$ 725,3758 due to the long operating hours of the diesel generators.

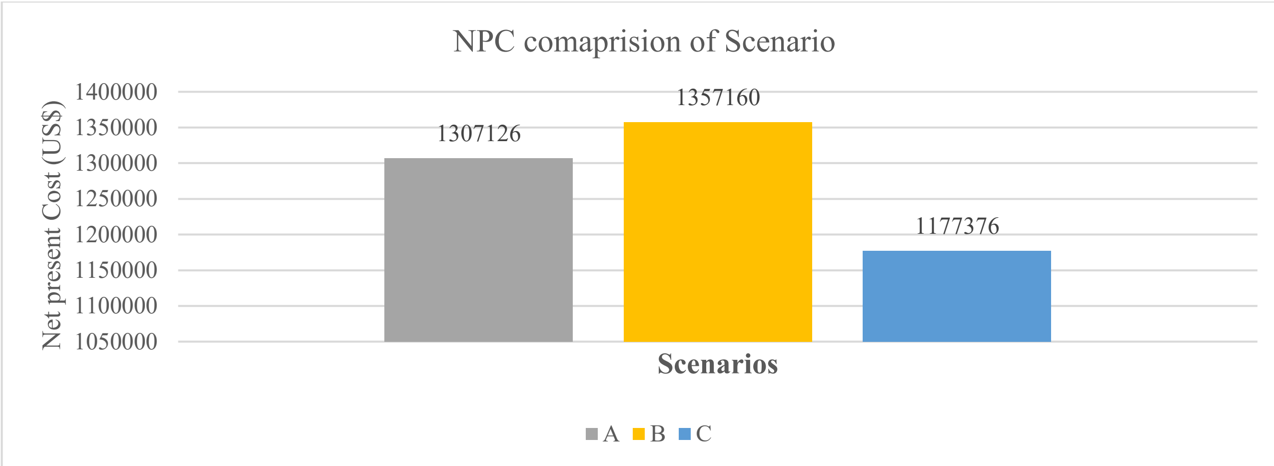

Figure 4-10: Total NPC comparison of Scenarios

4.2.1 Electricity Production and Battery autonomy Comparison

The annual electricity production of the optimal system is 162,940 kWh/yr, which exceeds the required for the given load profile of the village, which is about 157,145 kWh/yr. However, the excess electricity produced by the optimal system is stored in batteries, and it is also capable of serving the load for about 8.12 hours of autonomy, and as well reduces the extended operating hours of the diesel generators. In scenario A, the generators were sized based on the load profile of the village, likewise, for scenario B the total electricity production exceeds the load demand of the village by a far margin and represent 15.9%.

Figure 4-11 shows the electricity production for the three scenarios.

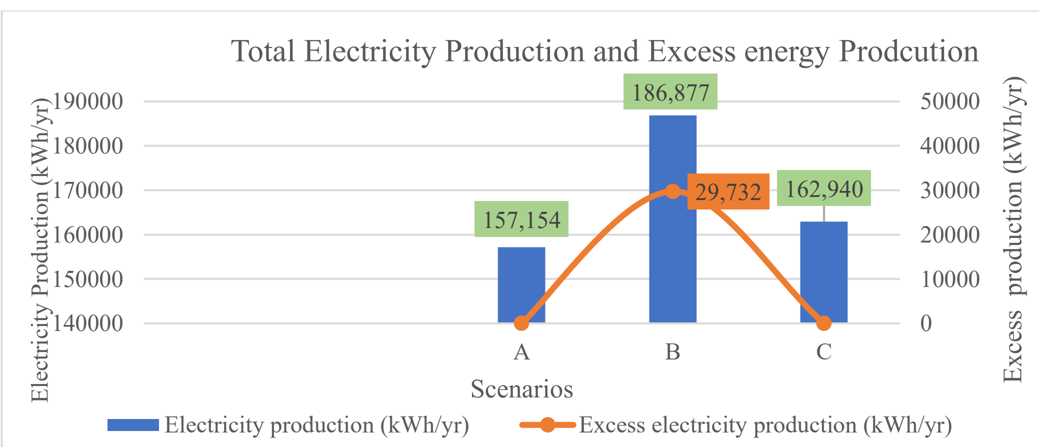

Figure 4-11: Comparison of scenario-based on excess energy production and annual electricity production

Table 4-3: Storage Management of batteries

Number of Battery	LCOE (US$/kWh)	Autonomy (Hours)	Excess Electricity Production (%)
0	0.604	0	15.9
24	0.5151	2.71	3.83
48	0.5172	5.42	0.0538
72	0.5239	8.12	0
96	0.5266	10.8	1.8
120	0.5279	13.5	0.748
144	0.5305	16.2	0.266
168	0.5331	19	0.0586
192	0.5357	21.7	0
126	0.54	24.4	0
240	0.5449	27.1	0

Figure 4-12 and Table 4-3 illustrates the impact of storage autonomy hours on the LCOE. For the scenario B without batteries, it is observed that the LCOE is very high, about US$ 0.604/kWh and the excess electricity production is about 15.9%. However, for autonomy less than 6 hours the LCOE is lower, and only 48 batteries are required (Table 4-3), but all the excess electricity produced by the system cannot be stored in the batteries due to the lower capacity to store more energy and require more batteries. For less than 10 hours of autonomy, the load profile requires only 72 batteries to store the excess electricity produced by the system. Moreover, for over 10 hours of autonomy, the load profile requires more 72 batteries. Hence for longer hours of autonomy, the LCOE and the total NPC of system increases but the lifetime of batteries are shorten due to deep discharging for longer hours.

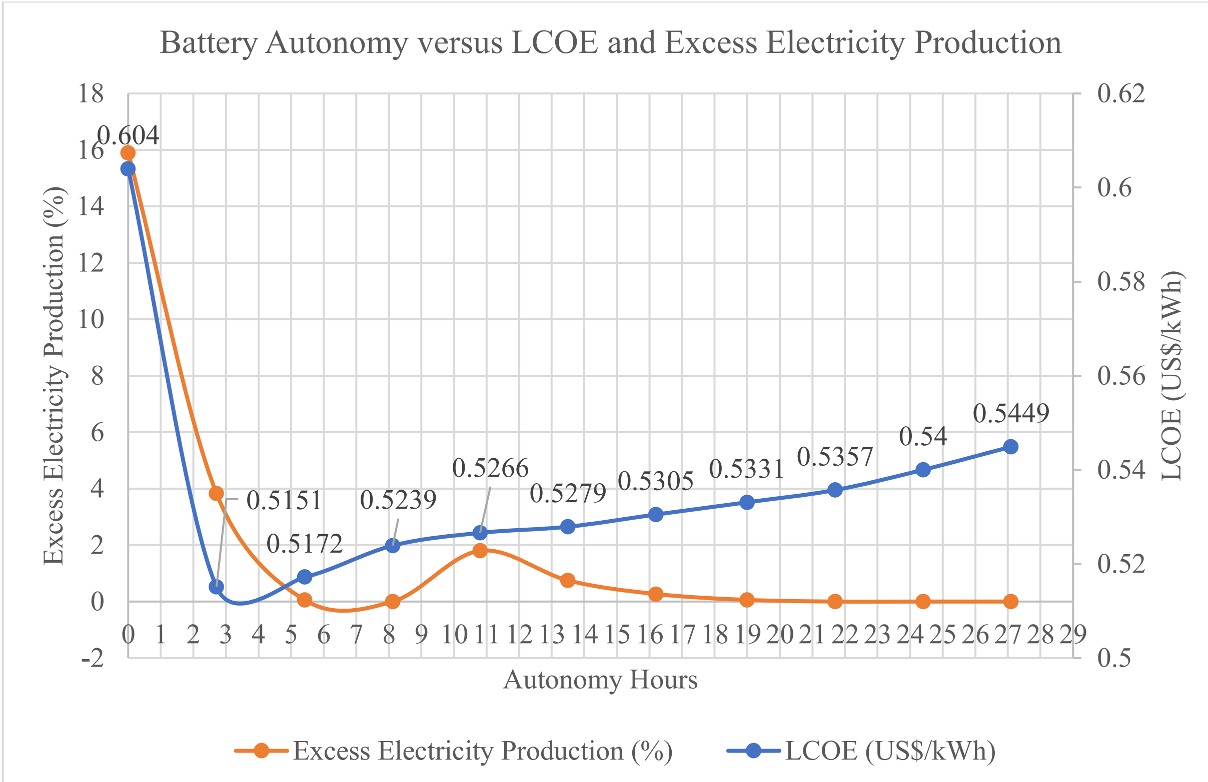

Figure 4-12: The effect of battery autonomy hours on LCOE

4.2.2 Renewable Fraction and Annual Emission Produced from the System

The optimal system has the highest renewable energy fraction of about 27.1%, followed by scenario B with 11.9%, and is scenario A is zero, due to the absence of renewable power source in it configuration system. The integration of renewable in the optimal system reduces the operating hours of the diesel generators by 34.8% and also reduce the amount of emission produced by 29.68% and 23.24% annually compared to scenario A and B respectively. In the case of scenario B, the annual fuel consumption and the emission produced from the system were reduced by 9.16% and 8.4% respectively compared to the scenario with conventional diesel generators only due of the PV contribution. Figure 4-13, shows a comparison between LCOE and the renewable energy fraction for the three scenarios. Figure 4-14 shows the comparison based on fuel consumption and emission produced in each scenario.

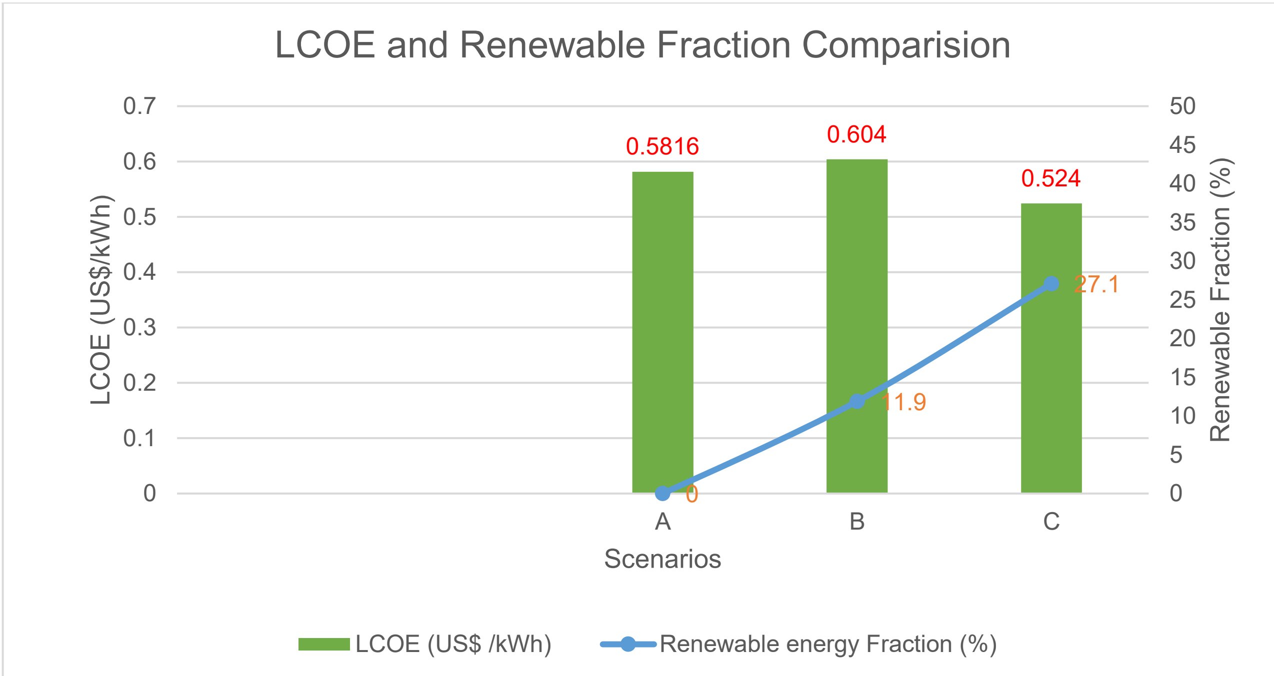

Figure 4-13: Scenario Comparison Based on LCOE and Renewable energy fraction

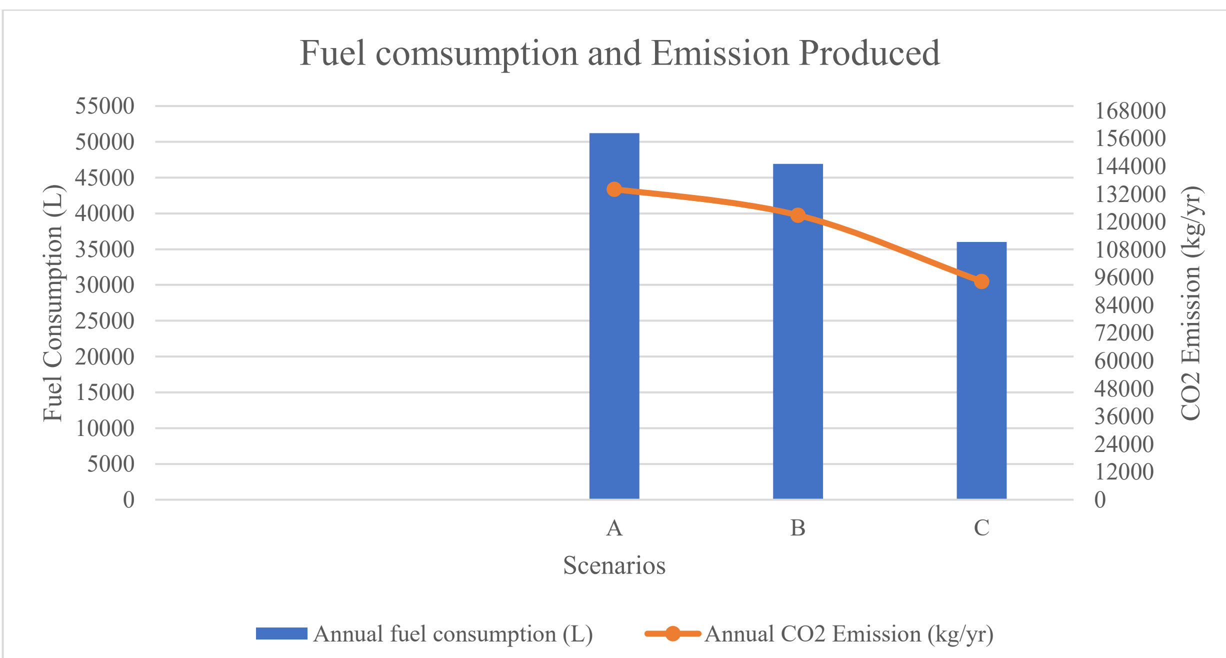

Figure 4-14: Scenario-based on Fuel consumption and CO2 emission

4.3 Optimal Operation and Performance of The PV Arrays

The total rated capacity of the PV arrays for the optimal system is 30 kWp with a total mean electrical output of 132.7 kWh/day, and a capacity factor of 18.4%. The total annual electricity production by the PV arrays is 48,406 kWh/yr and have a renewable energy penetration of 30.79%. The regular operating hours of the PV array throughout the year is 4364 hrs/yr. Also, the levelized energy cost for the PV array is estimated at US$ 0.165/kWh. The PV arrays start producing from 06:00 in the morning to 17:00. In Figure 4-15, it is observed that the peak production occurs at noon and the months with the highest energy production are March, April, and May when the radiation is high. Figure 4-16 shows the production from the PV array for a particular day in the year.

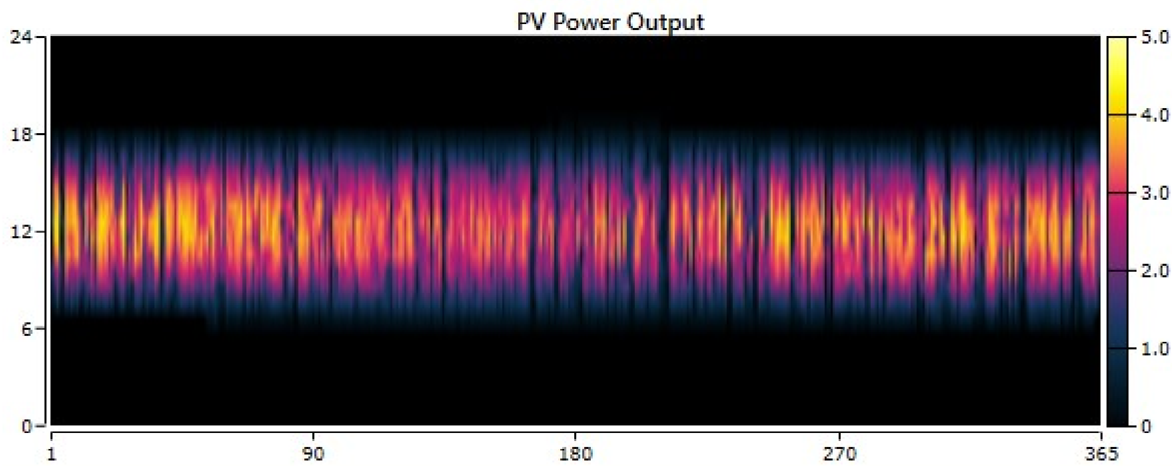

Figure 4-15: PV production for the optimal scenario.

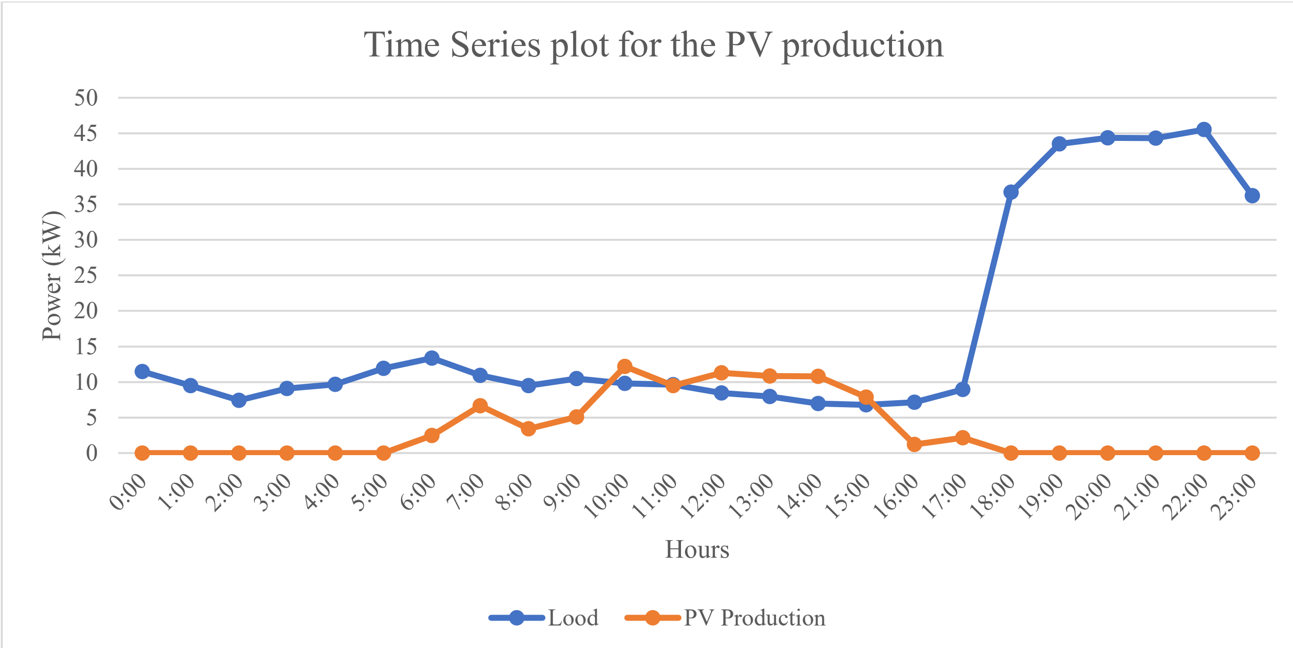

Figure 4-16: Time Series Analysis for the Power Production by the PV Arrays

4.4 Optimal Operation and Performance of Diesel Generators

The maximum rated capacity of the diesel generator is 56 kW, with annual electricity production of about 114,534 kWh/yr representing 70% of the total energy production by the hybrid power plant. The mean electric output of the generators is 42.3 kW. The operating hours for DG-1 DG-2 DG-3 are 1875 hr/yr, 4770 hrs/yr, and 1809 hr/yr. The annual energy fuel input of the generators is estimated at 344,468 kWh/yr. DG-2 has the least operational life of 3.14 yr because of its high operating hours as compared to the other two generators. Figure 4-17 shows the time series plot obtained from the daily production of the diesel generators for a particular day in the year. According to the operating hour for DG-1 is from 18:00 to 23: 00, for DG-2, it starts to operate from 00:00 to 06:00 and 18:00 to 23, and DG-3 operate from 07:00 to 12:00 and from 18:00 to 00:00. DG-2 has a high operating and maintenance cost, replacement cost, fuel cost compared to the other two generators, and represent about 37.6% of the total NPC for the system.

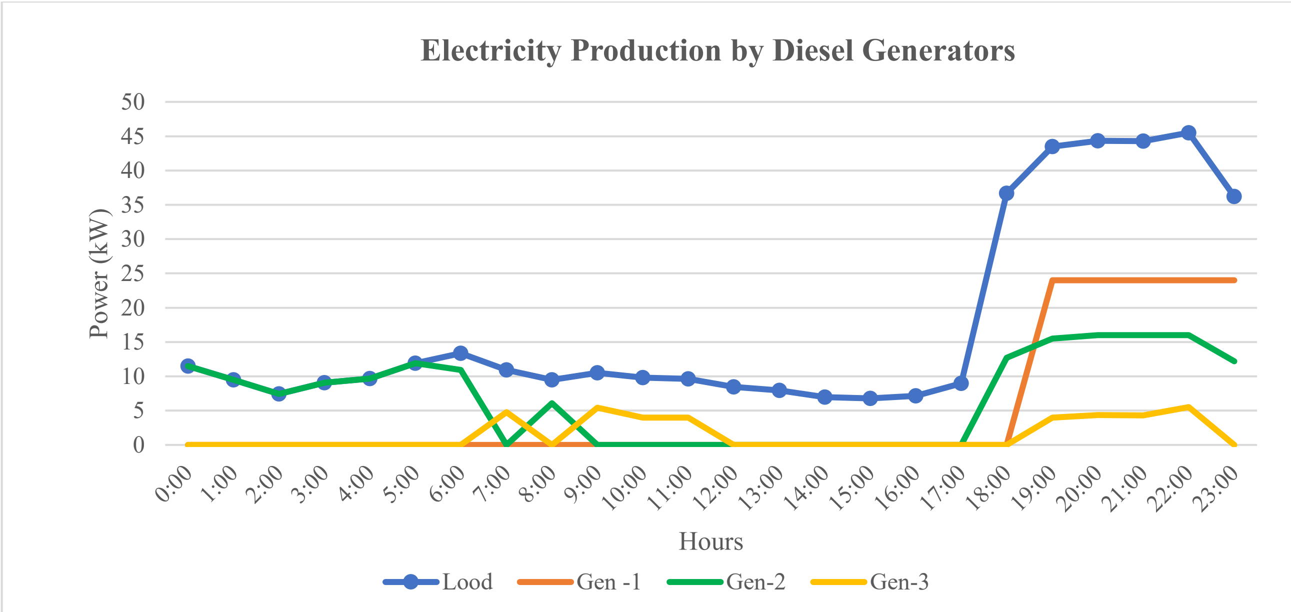

Figure 4-17: Time Series Analysis for the power production by the three conventional diesel generators

4.5 Optimal operation and Performance of Battery

The battery storage incorporated into the optimal system has a nominal voltage of 2V and nominal capacity of 1270 Ah. The batteries are connected in three parallel strings, and each string size composed of twenty-four batteries connected in series to obtained a bus voltage of 48V. Each battery string is capable of producing about 60.96 kWh of electricity. The total energy stored in the batteries and the total energy discharge from the batteries are found to be 18,068 kWh/yr and 14,580 kWh/yr respectively. The optimal autonomy hours of the storage capacity is 8.12 hours, which implies that battery storage is capable of meeting the demand when there is no power supply from both the PV arrays and the diesel generators. The battery storage has a nominal capacity and usable nominal capacity of 182 kWh/year and 146 kWh/yr respectively. However, the annual losses from the battery bank and annual throughput of the battery are estimated at 3,628 kWh/yr and 16,301 kWh/yr respectively. The storage wear cost for the battery storage is estimated at US$ 0.331/kWh. The expected lifetime of the battery storage is 8.94 years, and the lifetime throughput of the battery storage is 145,728 kWh.

The battery has a maximum SOC of 100%, and a minimum SOC of 20%. The batteries start to charge from 09:00 to 16:00. The SOC of the batteries from 00:00 to 09:00 is 21.07%, and between the hours of 09:00 to 13:00 the SOC ranges from 21.07% to 30.38%. However, the SOC of batteries from 17:00 to 23:00 is 22.66% as one can see in Figure 4-18.

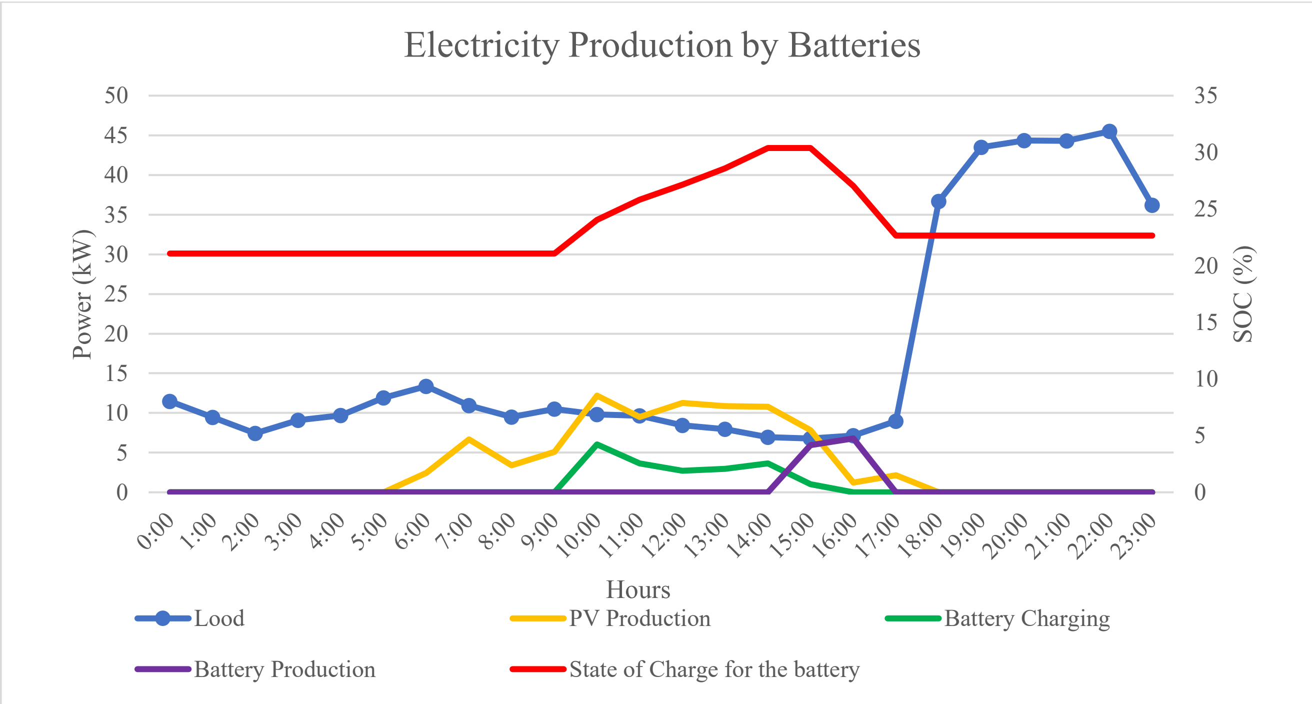

Figure 4-18: Time Series Analysis for the Optimal System Batteries Production

4.6 Optimum Operation and Performance of The Converter

The converter selected for optimal hybrid system behaves as an inverter when converting the DC output from the batteries to power the AC primary load and as well behave as a rectifier to charge the battery by converting the AC power generated from the diesel generators to DC power. The converter has an inverter efficiency and rectifier efficiency of 98.0% and 90.0%, with a capacity factor of 5.44 % and 6.89 % respectively. The annual operating hours of the inverter and the rectifier are 1,692 hrs/yr and 3,023 hrs/yr respectively. The energy out and the energy in of the inverter are 14,297 kWh/yr, and 14,588 kWh/yr, and for the rectifier are 18,079 kWh/yr and 20,087 kWh/yr. The annual losses from the inverter and the rectifier were estimated at 292 kWh/yr and 2,009 kWh/yr. For maximum power supply to the load, the inverter has an output power of 24.9 kW. The inverter operating hours is from 18:00 to 0:00 at a capacity range from 5.6 kW to 24.9 kW, and for rectifier is from 07:00 to 17:00, with a capacity ranging from 5 kW to 15 kW which is used to charge the storage.

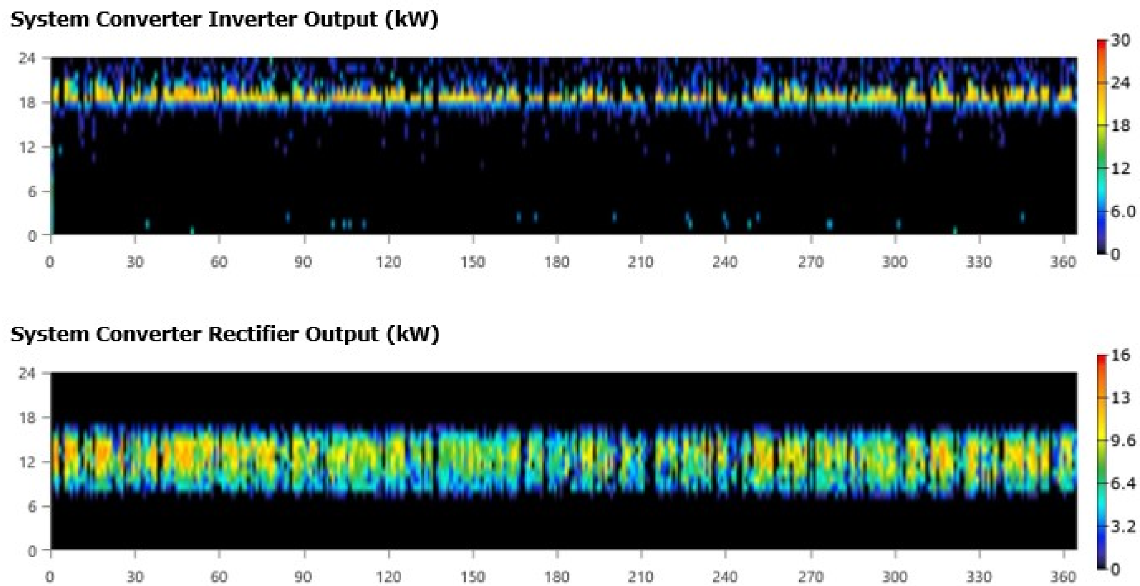

Figure 4-19: Daily operation of the converter.

4.7 Cost Breakdown for the Optimal System by Component and Cost Types

The cost breakdown for the optimal system in Table 4-4 shows the total investment involved from the start to the end of the project. According to Figure 4-20, shows a share of the capital investment cost for each component involves in the optimal system configuration. The share of the capital cost for diesel generators accounted for about 33% of the initial investment cost, and the PV modules represent about 10%. The storage unit (batteries) for the optimal system represents about 14% of the initial investment. The capital investment on for the other component such as the grid-tied inverters, system controller and system converter costs are 16%, 19%, and 8% respectively.

Table 4-4: Cost Breakdown of the Optimal System by Components and Cost types

Components	Capital cost (US$)	Replacement cost (US$)	Operating cost (US$)	Salvage (US$)	Resource (US$)
PV Modules	31879	0	4291.3	0	0
Grid-inverter	51352	25220	4147.3	-5232.87	0
Diesel Generators	106095	232738	42982	-21755.38	510053
System Converter	27000	13261	3862	-2752	0
System Controller	59293	0	1430	0	0
Batteries	43200	46803	6178	-2667	0
System	**318819**	**318022**	**62890.6**	**-32407.25**	**510053**

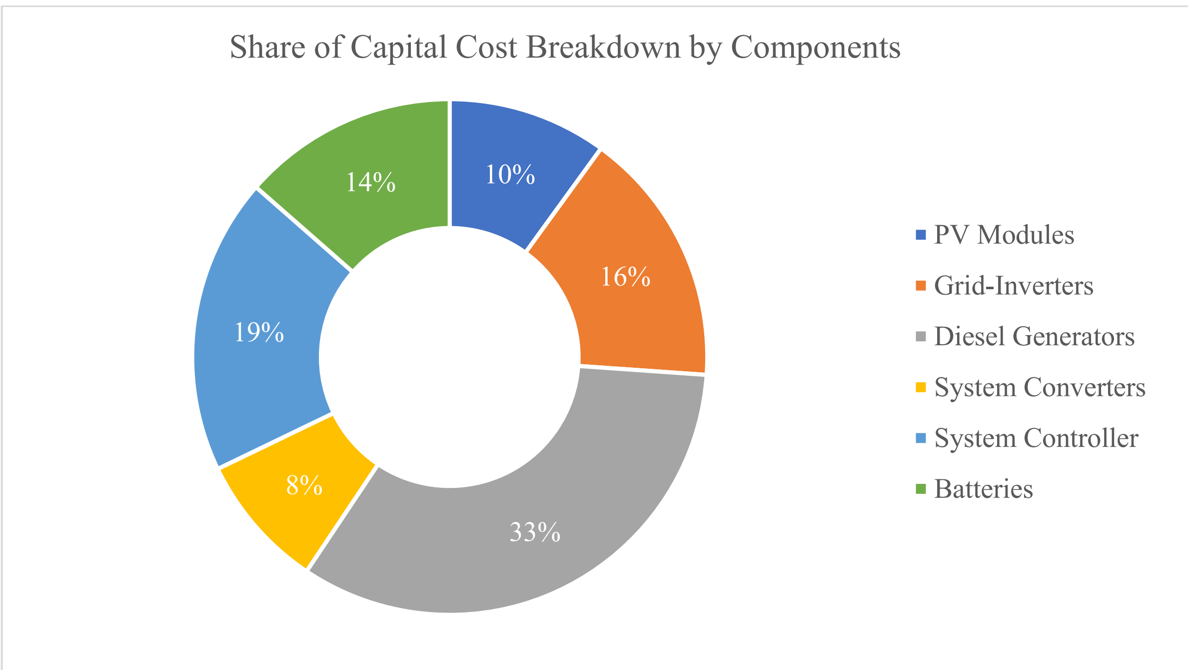

Figure 4-20: Cost Breakdown for the Optimal hybrid Power system

4.8 Sensitivity Analysis

Sensitivity is a technique used in HOMER to check the robustness of the system when specific input parameters are changed. The essence of sensitivity analysis is to predict the effect of uncertainties over the project lifetime. In this study, a sensitivity analysis was carried out on the optimal hybrid system configuration discussed in the previous section. In order to assess the sensitivity of the optimization result, one parameter is changed at a time while the other parameters remain constants (Ouedraogo & Yamegueu, 2019). For this study, a sensitivity analysis was performed on the optimal system based on the two different fuel price scenarios: US$ 0.86/L and US$ 1.28/L with reference to the current fuel price in Burkina Faso, which is US$ 0.99/L. The sensitivity analysis result shows that when the fuel price decreases from US$ 0.99/L to US$ 0.86/L, the LCOE for the optimal system decrease from US$ 0.524/kWh to US$ 0.492/kWh which indicates a significant decrease in LCOE by 6.1%. The total NPC falls from US$ 1,177,376 to US$ 1,106,786 represent a reduction in the NPC by 6%. However, when the price sudden increases from US$ 0.99/L to US$ 1.28/L. The LCOE of energy rises from US$ 0.524/kWh to US$ 0.590/kWh, which represent a 12.6% increase in the LCOE. Similarly, the NPC also increase from US$ 1,177,376 to US$ 1,326,066 indicates a rise in the NPC by 12.6%. The result indicates the LCOE and the NPC depend on the fuel price, that is if the fuel price increases the LCOE, and the NPC will increase as well. The fuel price affects both the NPC and the LCOE because of the high amount of fuel consumed by the generators during power generation. Figure 4-21 shows the effect of fuel price on the optimal hybrid system LCOE and NPC.

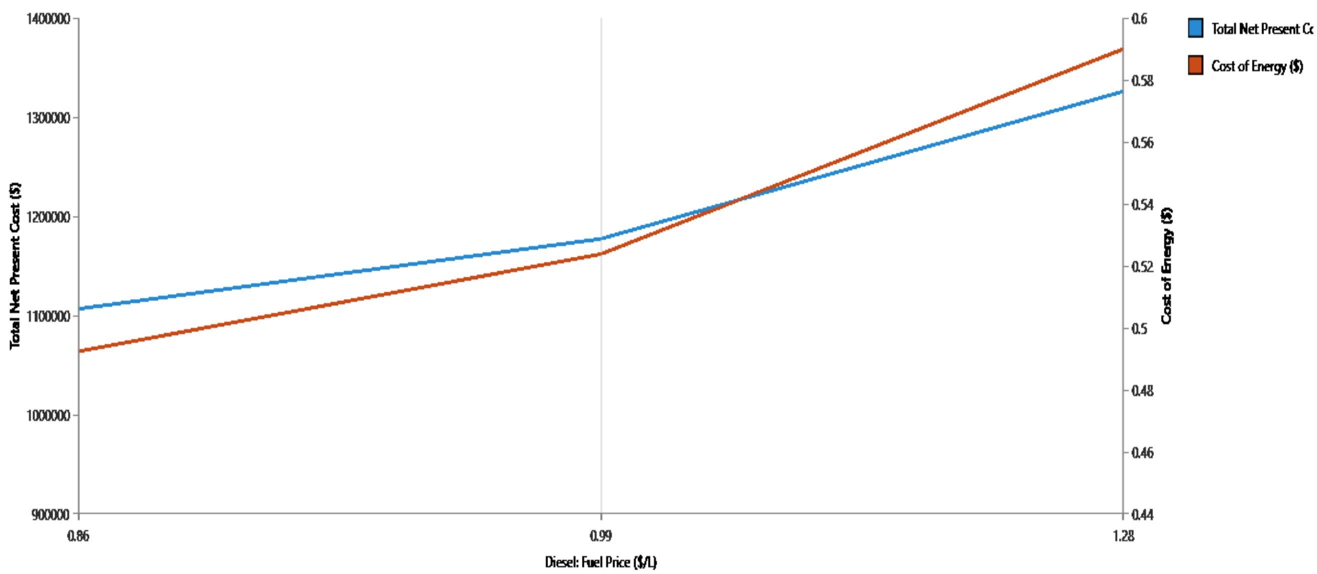

Figure 4-21: The effect of Fuel Price on the system NPC and LCOE

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The main objective for this study was to find an optimal storage capacity that should be included in the PV/ diesel hybrid system based on the concept of flexy energy at Bilgo village. Although the use of battery storage is not included in this approach because of their relatively high cost and the environmental problems associated with them. However, for the management of the system, the use of battery storage unit is not excluded and could be considered if materials it is made-of has less environmental impacts.

In this study, three scenarios were considered: PV/diesel with and without battery and conventional diesel generators for the same load profile, and HOMER software was used for the simulation and optimization process. The optimization result was analyzed based on the system configuration with the lowest LCOE, lowest NPC, lowest CO_2 emission, lowest excess energy production, and high renewable fraction. From the optimization results obtained, the most optimal system configuration was found to be the PV/diesel/battery with LCOE of US$ 0.524/kWh, which shows a significant decrease in the energy cost by 13.24% and 9.9% when compared to the scenarios with PV/diesel without battery and the convention diesel generators respectively.

In terms of financial assessment over the entire lifetime of the system, the optimization results revealed that the total NPC for the optimal system was reduced by 13.25% and 9.93% when compared to the scenarios PV/diesel without battery and diesel generators respectively. With regards to the environment aspect considered in the study, the amount of CO_2 produced by the optimal system was reduced by 29.68% annually because of the less operating hours of the diesel generators. The renewable fraction for the optimal system is found to be 27.1%, which shows high penetration of renewable contribution in the hybrid system. Furthermore, the storage system used in the optimal system configuration was capable of storing all the excess energy produced by the hybrid system and can also supply power the load demand for about 8.12 hours.

The sensitivity analysis carried out on the optimal system based on the extreme limit fuel price in Burkina Faso. This analysis was done in order to know the influence of fuel prices on the

LCOE and the NPC. It was observed that for lower fuel price in Burkina Faso the LCOE and the NPC of the optimal system will decrease, likewise, for high fuel price there is an increase in LCOE and the NPC as well. Hence, this indicates that the NPC and the LCOE depend on the price of fuel in the country.

In conclusion, the inclusion of storage system on the PV/diesel hybrid system seems to be more economical whereby reducing the operating hours and maintenance cost of running diesel generators and as well minimizes the emission produced by the system.

5.2 Recommendations

This study recommends that for the energy management for the PV/diesel hybrid in Bilgo village; it is essential to include a battery storage unit with a capacity that can meet the demand for about 6-8hrs of autonomy.

Moreover, this study considered an operation and maintenance cost for all diesel generators to be 0.02 kWh/hr, but for further studies on this topic, it would be attractive if the O&M cost of the diesel generators varies above 0.02 kW/hr.

The study proposed that further studies should be considered using other energy dispatch strategies in other to make a comparison with the one used in this study.

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7. APPENDIX

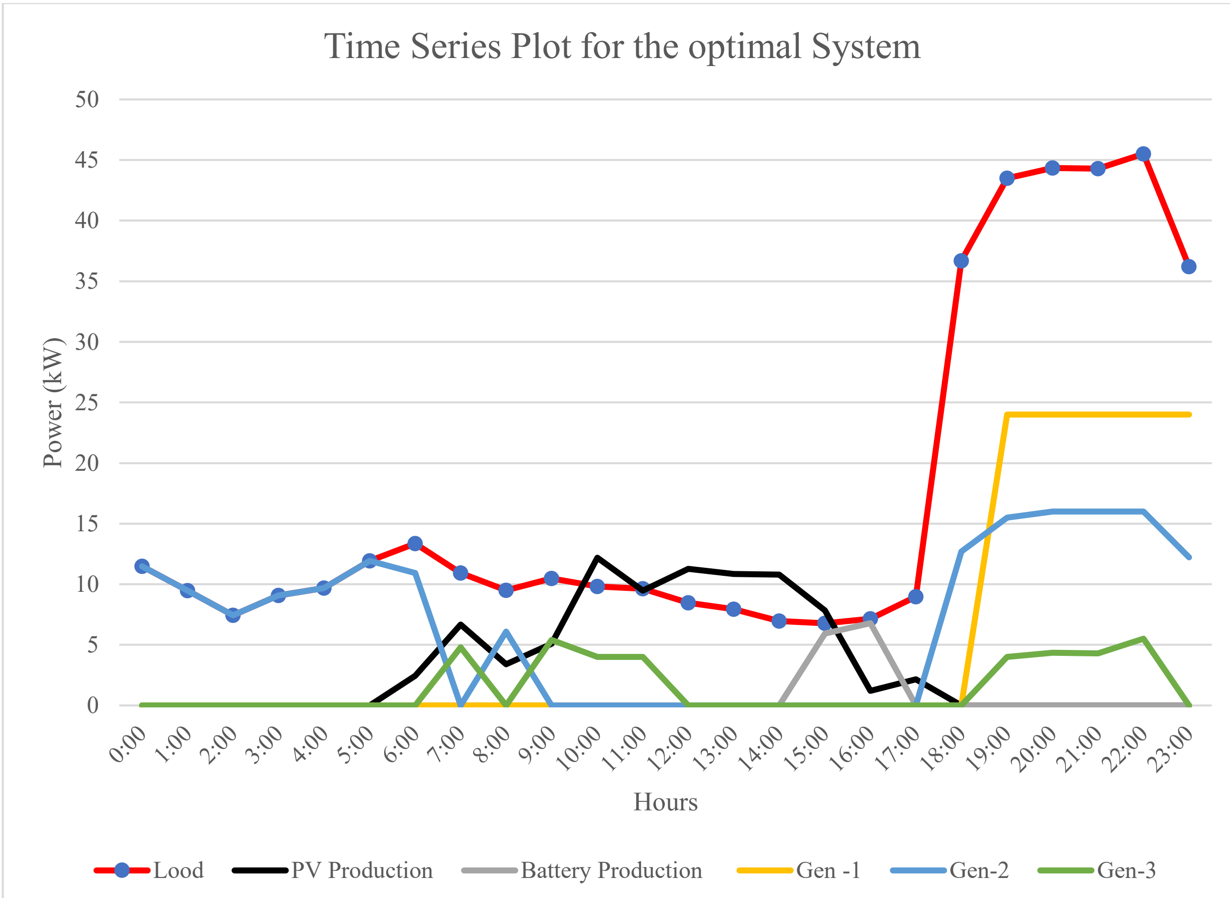
APPENDIX I: Mathematical Modelling of Components

COMPONENT	EQUATIONS
Solar PV	$$P_{output} = \gamma_{PV} f_{PV} \left(\frac{\overline{G_T}}{G_{T,STC}}\right)\left[1 + \alpha_p\left(T_c - T_{C,STC}\right)\right]$$ $$P_{output} = Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{G_{T,STC}}\right)$$ $$T_c = T_{amb} + \left[\left(\frac{\overline{G_T}}{0.8}\right)\right](NOCT - 20\,°C)$$
	Where: γ PV = power output of PV module (kW), f_{PV}= PV derating factor (%),$\overline{G_T}$ = Solar incident radiation on the module (kW/m^2) $G_{T,\ STC}$: Incident solar radiation at STC (1000 W/m^2); α_p: temperature coefficient of power (%/ºC); T_c: PV cell temperature in(°C) and $T_{c,\ STC}$: PV cell temperature under STC (25 ºC), T_{amb} is the ambient temperature, NOCT is the nominal operating cell temperature (ºC)

COMPONENT	EQUATIONS
Power Converter/Inverter	$$\eta_{inverter} = \frac{P_{inv\ AC}}{P_{PV\ output}}$$ $$P_{inv} = \eta_{inv} \times Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{G_{T,STC}}\right)$$ (Yamegueu et al., 2011)
	Where: $P_{inv\ AC}$ is the out power of the inverter in watt; $P_{PV\ output}$ = is the output power generated by the PV array in watt.

COMPONENT	EQUATIONS
Diesel Generator	$P_{DG} = \frac{Maximum\ energy\ demand}{Maximum\ operating\ hours\ per\ day\ \times Maximum\ load\ factor}$ (Kolhe et al., 2002): $q(t) = aP_r + bP(t)$ (Borhanazad et al., 2014; Roy & Kulkarni, 2015; Yamegueu et al., 2013)
	Where: q(t) is the fuel consumption (l/h); P(t) is the generated power in the time step (kW); P_r is the rated power of the generator (kW); a is the fuel curve interception coefficient in (l/kWh rated), and b is fuel curve slope (l/kWh output).

COMPONENT	EQUATIONS
Battery Bank	$RB_{cap} = \frac{E_{AC\ load} \times A_d}{DOD_{max} n_{inv} C_t}$ (Muh, 2017) $SOC\ (t) = \frac{C_B\ (t)}{C_{B\ max}(t)}$ $0 \ll SOC\ (t) \ll 1$ $Autonomy\ day = \frac{N_B \times V_{nor} \times C_{nor}\left(1 - \frac{q_{min}}{100}\right)(24\ h/day)}{L_{AC}(1000\ Wh/kWh)}$ (HOMER, 2016)
	Where: RB_{cap} = is the required battery capacity in (Ah); $E_{AC\ load}$ = is the total AC load in (Ah); A_d = day of autonomy; DOD_{max} is the maximum depth of discharge (%); η_{inv} = inverter efficiency (%); and C_t = temperature correction factor, SOC= state of Charge , C_B (t) = the battery capacity at a time (t) and $C_{B\ max}$(t) is the maximum battery capacity at time t. N_B = is the number of batteries in the storage bank; V_{nor} = nominal voltage of single storage (V); C_{nor} = nominal capacity of single storage (Ah); q_{min} = minimum state of charge of the storage bank (%) and; L_{AC} is the average AC primary load.



APPENDIX II: Time Series Analysis for the Optimal System Configuration

APPENDIX III: Emissions by the optimal system

Pollutant	Quantity	Unit
Carbon Dioxide	94,304	kg/yr
Carbon Monoxide	589	kg/yr
Unburned Hydrocarbons	25.9	kg/yr
Particulate Matter	3.53	kg/yr
Sulfur Dioxide	231	kg/yr
Nitrogen Oxides	553	kg/yr

APPENDIX IV: SMA Grid-tied Inverter Specification (SMA Solar Technology, 2017)

Technical Data	Sunny Tripower 5000TL	Sunny Tripower 6000TL
Input (DC)		
Max. generator power	9000 Wp	9000 Wp
Max. input voltage	1000 V	1000 V
MPP voltage range / rated input voltage	245 V to 800 V/580 V	295 V to 800 V/580 V
Min. input voltage / start input voltage	150 V / 188 V	150 V / 188 V
Max. input current input A / input B	11 A / 10 A	11 A / 10 A
Max. short-circuit current input A / input B	17 A / 15 A	17 A / 15 A
Number of independent MPP inputs / strings per MPP input	2 / A:2; B:2	2 / A:2; B:2
Output (AC)		
Rated power (at 230 V, 50 Hz)	5000 W	6000 W
Max. AC apparent power	5000 VA	6000 VA
Nominal AC voltage	3 / N / PE; 230 / 400 V	3 / N / PE; 230 / 400 V
AC grid frequency / range	50 Hz / -5 Hz to +5 Hz	50 Hz / -5 Hz to +5 Hz
Rated power frequency / rated grid voltage	50 Hz / 230 V	50 Hz / 230 V
Max. output current	7.3 A	8.7 A
Power factor at rated power	1	1
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited	0.8 overexcited to 0.8 underexcited
Feed-in phases / connection phases	3 / 3	3 / 3
Efficiency		
Max. efficiency / European efficiency	98 % / 97.1 %	98 % / 97.4 %
Protective devices		
DC disconnect device	●	●
Ground fault monitoring / grid monitoring	● / ●	● / ●
DC reverse polarity protection / AC short-circuit current capability / galvanically isolated	● / ● / –	● / ● / –
All-pole sensitive residual-current monitoring unit	●	●
Protection class (according to IEC 62103)/overvoltage category (according to IEC 60664-1)	I / III	I / III
General data		
Dimensions (W / H / D)	470 / 730 / 240 mm (18.5 / 28.7 / 9.5 inch)	470 / 730 / 240 mm (18.5 / 28.7 / 9.5 inch)
Weight	37 kg (81.6 lb)	37 kg (81.6 lb)
Operating temperature range	-25 °C to +60 °C (-13 °F to +140 °F)	-25 °C to +60 °C (-13 °F to +140 °F)
Noise emission (typical)	40 dB(A)	40 dB(A)

APPENDIX V: Datasheet for SMA Sunny Island Battery Inverter (SMA Solar Technology, 2017)

Technical Data	Sunny Island 4.4M	Sunny Island 6.0H	Sunny Island 8.0H
Operation on the utility grid or generator			
Rated grid voltage / AC voltage range	230 V / 172.5 V to 264.5 V		
Rated grid frequency / permitted frequency range	50 Hz / 40 Hz to 70 Hz		
Maximum AC current for increased self-consumption (grid operation)	14.5 A	20 A	26 A
Maximum AC power for increased self-consumption (grid operation)	3.3 kVA	4.6 kVA	6 kVA
Maximum AC input current	50 A	50 A	50 A
Maximum AC input power	11500 W	11500 W	11500 W
Stand-alone or emergency power operation			
Rated grid voltage / AC voltage range	230 V / 202 V to 253 V		
Rated frequency / frequency range (adjustable)	50 Hz / 45 Hz to 65 Hz		
Rated power (at Unom, fnom / 25 °C / cos φ = 1)	3300 W	4600 W	6000 W
AC power at 25 °C for 30 min / 5 min / 3 sec	4400 W / 4600 W / 5500 W	6000 W / 6800 W / 11000 W	8000 W / 9100 W / 11000 W
AC power at 45 °C continuously	3000 W	3700 W	5430 W
Rated current / maximum output current (peak)	14.5 A / 60 A	20 A / 120 A	26 A / 120 A
Total harmonic distortion output voltage / power factor at rated power	< 5% / −1 to +1	< 1.5% / −1 to +1	< 1.5% / −1 to +1
Battery DC input			
Rated input voltage / DC voltage range	48 V / 41 V to 63 V	48 V / 41 V to 63 V	48 V / 41 V to 63 V
Maximum battery charging current / rated DC charging current / DC discharging current	75 A / 63 A /75 A	110 A / 90 A / 103 A	140 A / 115 A /130 A
Battery type / battery capacity (range)	Li-Ion[1], FLA, VRLA / 100 Ah to 10000 Ah (lead-acid) 50 Ah to 10000 Ah (li-Ion)		
Charge control	IUoU charge procedure with automatic full charge and equalization charge		
Efficiency / self-consumption of the device			
Maximum efficiency	95.5%	95.8%	95.8%
No-load consumption / standby	18 W / 6.8 W	25.8 W / 6.5 W	25.8 W / 6.5 W
Protective devices (equipment)			
AC short-circuit / AC overload	● / ●		
DC reverse polarity protection / DC fuse	– / –		
Overtemperature / battery deep discharge	● / ●		
Overvoltage category as per IEC 60664-1	III		
General Data			
Dimensions (W / H / D)	467 mm / 612 mm / 242 mm (18.4 inches / 21.1 inches / 9.5 inches)		
Weight	44 kg (97 lbs)	63 kg (138.9 lbs)	63 kg (138.9 lbs)
Operating temperature range	−25 °C to +60 °C (−13 °F to +140 °F)		
Protection class in accordance with IEC 62103	I		
Climatic category as per IEC 60721	3K6		
Degree of protection according to IEC 60529	IP54		

THESIS APPROVAL

<u>TITLE</u>

ASSESSMENT AND OPTIMIZATION OF FLEXY ENERGY APPROACH CASE STUDY: BILGO VILLAGE, BURKINA FASO, WEST AFRICA

Submitted by

Henry Thomas Nelson	Signature	Date

Approved by Examining Board

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Name of Examiner	Signature	Date

Thesis/ Dissertation Advisors

Name of Advisor	Signature	Date
____________________	____________________	________________
Name of Co-Advisor	Signature	Date

Institute Dean

____________________	____________________	________________
Name of Dean	Signature	Date

Pan African University

____________________	____________________	________________
Name of Rector	Signature	Date