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Submitted by:

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Feasibility of Solid Biomass-Solar Hybrid Standalone System Using HOMER Pro: Grand Bassa, Liberia

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PURPOSE

This research thesis is submitted in partial fulfillment of the requirements for a Master of Science in Energy Engineering at the Pan African University Institute of Water and Energy Sciences (including Climate Change), (PAUWES) at the University of Tlemcen in Algeria.

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DECLARATION

I, **Jackson G. White**, do hereby declare that this thesis is my original work and testify that to the best of my knowledge, it has not been submitted for any award or to another University other than PAUWES.

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CERTIFICATION

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

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ACKNOWLEDGMENT

I dedicate this to my mother, ***Babygirl Flomo***, who passed away before I could get to recognize her.

Glory be to the Almighty for everything. My deepest gratitude to my parents Mr & Mrs. Ignatius White for the prayerful, moral, and financial support they have given me over the years. My success in life hugely depends on their blessings. To my grandma who is always concern about my wellbeing, I love you. To the woman who set me on this path, Aunty Decontee, I am forever grateful. To the man who loves me unconditionally, George Drew, you have a special place in my heart. To my siblings who are always cheering me up and wishing luck, I love you all.

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LIST OF ABBREVIATIONS

AC	Alternating Current
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CH_4	Methane gas
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COVID-19	Corona Virus Disease - 19
CSP	Concentrated Solar Power
DC	Direct Current
EG	Bandgap Energy
ERB	Energy Regulatory Board
ESI	Energy Savings Insurance
GDP	Gross Domestic Product
GEA	Global Energy Assessment
GHG	Green House Gas
GoL	Government of Liberia
GW	Gigawatt
H_2	Hydrogen gas
H_2O	Water
HOMER	Hybrid Optimization Model for Multiple Energy Resources
HTU	Hydrothermal Upgrading

IEA	International Energy Agency
INDC	Intended Nationally Determined Contributions
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
IRENAD	IRENA Document
JFK	John F. Kennedy
kW	Kilowatt
kWh	Kilowatt Hour
LCOE	Levelized Cost of Electricity
LDN	Least Developed Nation
LEC	Liberia Electrical Corporation
LERC	Liberia Electricity Regulatory Commission
LR	Liberia
MCC	Millennium Challenge Corporation
MLME	Ministry of Lands, Mines, and Energy
MW	Megawatt
NACUL	National Charcoal Union of Liberia
NDC	Nationally Determined Contributions
NEEAP	National Energy Efficiency Action Plan
NEP	National Energy Policy
NEPL	National Energy Policy of Liberia
NOCAL	National Oil Company of Liberia
NPC	Net Present Cost

NREL	National Renewable Energy Laboratory
NY	New York
OPEX	Operating Expenditures
PA	Power Africa
PDF	Portable Document Format
PV	Photovoltaic
RE	Renewable Energy
REFUND	Rural Energy Fund
RREA	Rural Renewable Energy Agency
SE4ALL	Sustainable Energy for All
SP	Solar Panel
TFEC	Total Final Energy Consumption
TJ	Terajoule
TP	Technical Performance
TPES	Total Primary Energy Supply
TV	Television
TWh	Terawatt Hour
UK	United Kingdom
UNDP	United Nations Development Program
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USAID	United States Agency for International Development
USD	United States Dollars

WA	Washington
WF	World Food Programme
WMO	World Meteorological Organization

Table of Contents

List of figures

LIST OF TABLES

ABSTRACT

Liberia is a low electricity access nation, wherein only 26.7% of the population has access to modern energy. To improve the huge grid power deficit in the country, the government of Liberia and partners have endeavor to rehabilitate the energy sector through bilateral agreement and private-public partnerships. The government, also in 2009, crafted the National Energy Policy of Liberia (NEPL), a crucial outline the energy action plans for grid-power expansion and microgrid renewable energy programs. The renewable energy sector of Liberia has a promising future because the country can benefit from the six months intensive sunshine for solar power generation, and because the massive forests reserves coupled with a plethora of agricultural provide a considerable potential for bioenergy generation as well.

The general objective of this paper is to encourage the inclusion of renewable energy options in the energy mix of Liberia to increase rural electricity and energy access. The main goal of this thesis is analyzing the energy situation in the community and design a befitting solid biomass-solar hybrid standalone mini-grid system for the Own Your Own Community in rural Liberia; and study and predict the effects such a system would have on the environment, economy, and social aspects of the community. This paper designs a suitable hybrid power system for seventy-six households, one primary school, a church, a community clinic, and marketplace. With a knowledge of the load demand for the case study, and the available renewable energy resources in the region, HOMER Pro was used to perform a techno-economic analysis for seven configurations of the proposed systems. The seven configurations and their respective components are as follows.

- Configuration No. 01: Diesel generator (Base case)
- Configuration No. 02: Diesel generator and Solar PV
- Configuration No. 03: Diesel generator, Solar PV, and Storage
- Configuration No. 04: Diesel generator, Biomass Gasifier, Solar PV, and Storage
- Configuration No. 05: Solar PV and Storage
- Configuration No. 06: Biomass Gasifier, Solar PV, and Storage
- Configuration No. 07: Biomass Gasifier and Storage

The reason behind these varying configurations is to compare the net present costs, levelized costs, and the technical performances of each system within the geographical confines and the climatic zone of the Own Your Own Housing Estate.

After all simulations and analyses, it was found that the system with the least levelized cost of electricity (LCOE), USD 0.46/kWh, is in configuration No. 03 comprising a 17.0 kW diesel generator, a 7.30 kW solar PV, twenty-three (23) strings of 1kWh battery option along with a 9.67 AC-DC converter system. The total annual electricity production for this configuration is 62053 kWh/yr wherein the solar PV system contributes just 12.4% of the annual electricity production, while the diesel generator supplies the rest. The 1kWh lead acid battery of 12 V receives 4378 kWh electricity annually from the PV system, but its energy output 3502 kWh/yr, accounting for a loss of 876 kWh/yr. Unfavorably, this system contains a diesel generator which emits 37139kg/yr of CO_2. However, technically, the best system is in configuration No. 06 containing a 100kW BioGen Fixed Capacity gasifier along with a 24-kW capacity generic flat plate solar PV. The storage option here is a 1kWh generic lead acid battery containing eighty-one strings of batteries; the converter is an 18.3 kW system converter consisting of an inverter and a rectifier. This system's LCOE is USD 0.51/kWh (10.9% higher than configuration No. 03), but with 99.99% reduction in CO_2 and other GHGs emissions compared to the system in configuration No. 03. The solar PV accounts for 44.8% of the annual electrical production, and the biomass gasifier supplies the remainder power need. The total electrical production is 77104 kWh/yr, wherein the AC primary load consumes 78.32% of this amount, with an excess of 5597 kWh/yr of electricity to spare.

Finally, this research climaxes the analyses with miscellaneous findings, detailing the prevailing socio-economic situations in the case study site, including the electricity consumption pattern of the households. The goal is to measure the residents' ability to purchase power, consequently determining the viability of the proposed hybrid energy system at various values of LCOEs.

CHAPTER ONE: GENERAL INTRODUCTION

Contents

1.1 Introduction

This chapter focuses on the fossil fuel consumption of Liberia, including its environmental, economic, and socio-political impacts on the country. Next, this portion of this paper analyses the energy situation in Liberia. Following the energy situation are the *problem statement*, *objectives*, and then, the *scope of the study*.

1.2 Background

In a nation with about 5.058 million people (as of 2020), only about 26.7% of the population has access to electricity. Consequently, the unfortunate 73.3% of the population utilizes unclean and crude sources for electricity production. Those who are financially capable burn gasoline to produce electricity, while the less fortunate ones use candles, lanterns, or the so-called Chinese lights to light up their homes. Due to the absence of clean cooking policies and technologies, a huge portion of the population consumes charcoal or firewood for cooking and space heating purposes. In addition to residential and industrial consumption of fossil fuels, the transport sector in Liberia is entirely dependent on fossil fuels like gasoline, diesel, and kerosene. Hence, with a fast-growing population, it is easy to say that the greenhouse gas (GHG) levels may rise to unacceptable levels shortly.

In 2019, Liberia produced 0.4 TWh of electricity with 99% coming from oil and the rest from solar energy sources [1]. Study shows that the energy sector accounts for 67.5% of the greenhouse gas (GHG) emissions in Liberia, followed by the agricultural sector at 31.9 % and others comprising 0.6%. The massive contribution of the energy sector to GHG emissions confirms to the report that oil and that traditional biomass account for about 99% of electricity production including 100% of the primary energy consumption in the country [2]. Given that estimates reveal that the total population of Liberia could climb to about 10.3 million (M) by 2058, emissions levels could exceed the Paris Agreement target (below 2℃) if this trend in the unsustainable consumption of energy and electricity continues. Society is no stranger to the adverse impacts of climate change on the quality of the environment. Drought, the concentration of GHGs, floods, inconsistent weather, and poor harvest due to extreme climatic conditions, and rising sea levels are just six of the indicators of unfavorable climate change [3]. Specifically, environmental threats looms over Liberia, including disruption of the agricultural sector, degradation in the standard of living, income, and destruction of homes [4]. For instance, Liberia is on the verge of losing the John F. Kennedy (JFK) Memorial hospital and the Redemption hospital to sea encroachment [4].

The environmental impacts of unsustainable energy aside, economic activities also greatly impacted energy access rates and consumption. A country with high modern energy access rates experiences fast economic growth as opposed to a country with low energy consumption rates [5]. From 44% in 2016, studies project that the number of Liberians living on a little over one dollar per day is could reach a staggering 52% this 2021[6]. Such an unfortunate situation can is because of low energy access, exacerbated by the COVID-19 pandemic. According to an IRENA report, electricity access stood at 21.5% in 2017 [7] with a 5.2% increment in 2019, according to World Bank data [8]. During this period, Liberia's GDP increased to 2.5% in 2017 from -1.6% in the previous year. Unfortunately, there was a contraction of -2.5% in 2019 from 1.2% in 2018. Experts agree that this decline in GDP growth rate resulted from the COVID-19 pandemic amongst other economic forces [9]. Energy poverty results to slow economic progress; hence the low standard of living prevalent amongst the Liberian people.

Lastly, the level of access to energy and electricity is crucial to socio-political stability in each region. Citizens in a country with high energy and electricity access rates tend to enjoy their rights to quality education, sound healthcare, comfortable homes, security, clean and safe water, food security, and a peaceful existence [18]. Sadly, the same is barely existent in Liberia. Living conditions in Liberia are below acceptable levels compared to other parts of the globe. Liberia is one of the least developed nations (LDNs) in the world with about 64% of the population living below the poverty line, including about 1.3 million who live in extreme poverty [11]. Besides, 3.7 M Liberians lack access to clean water; 80% are currently food-insecure; child labor rate is at 21%, compounded by a plethora of slum communities [12]. Despite the multitude of challenges facing the economy, the government of Liberia (GoL), in collaboration with international partners, has made immense efforts to alleviate energy poverty and build the economy. Beginning in 2009, GoL crafted the National Energy Policy (NEP), a roadmap for economic and social development through the delivery of modern, dependable, affordable, and environmentally sustainable energy services [13.]. Before 2009, Liberia ratified the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto protocol in 2002. Six years later, GoL developed its National Adaptation Programme of Action which followed its Initial National Communication to the

UNFCCC in 2012 [13]. Three years later, Liberia became a signatory to the Paris Climate Agreement, a huge turning point for the country in the climate-energy sector, resulting in the development of the Intended Nationally Determined Contributions (INDC), finalized in 2015 [14]. These achievements are crucial to the energy sector in that they form the basis for the development of a robust energy action plan, provision of universal electricity access, creation of climate adaptation and mitigation strategy, and the creation of sources of finance for sustainable development.

1.3 Problem statement

Liberia is a country that spans an area of about 38,000 square miles on the west course of Africa. Liberia enjoys an abundance renewable energy resources like biomass, solar radiation, including large, highspeed rivers. Contrarily, Liberia relies heavily on petroleum products for energy and electricity production and consumption. Total primary energy demand is satisfied by the consumption of traditional, unsustainable biomass. Only 26.7% of the entire population have access to electricity, of which, about 95% are situated in Monrovia, leaving the rest of the rural areas a measly 5% of the national share. The absence of electricity and clean cooking technology in Southeastern Liberia mostly responsible for the prevalence of poor education systems and healthcare, a stagnant economy, respiratory and optical related illnesses resulting from the burning of charcoal and firewood. Nonetheless, with its substantial biomass potential, coupled with its massive receipt of solar irradiation, southeastern Liberia stands a chance to benefit from its attractive renewable energy potential. Though solar energy is an intermittent energy resource, coupling it with a constant energy resource biomass can provide affordable, modern, dependable, and undisrupted power to the residents of Buchanan, Grand Bassa County, Southeastern Liberia. Cognizant of these challenges and opportunities, this paper seeks to investigate the feasibility of the development of a hybrid renewable energy system (encompassing biodigester design and solar collectors set up) in the *On Your Own* community on the outskirts of Buchanan city.

1.4 Research question

- What are the electricity and energy need of the research location?
- What is the potential of the resources (biomass and solar irradiation) available in the research location?
- Can hybrid biomass and solar energy economically and sustainably satisfy the energy needs of the On Your Own community?

1.5 Objectives

1.5.1 General objective

Incorporation of renewable energy options in the energy mix of Liberia to increase rural electricity and energy access

1.5.2 Specific objectives

a. Analyze the energy situation in the community and design a befitting solid biomass-solar hybrid standalone mini-grid system for the Own Your Own Community in rural Liberia.
b. Study and predict the effects such a system would have on the environment, economy, and social aspects of the community.

CHAPTER TWO: LITERATURE REVIEW

Contents

2.1 Introduction

This chapter summarizes Liberia’s fossil fuel consumption, highlights the key energy players in the country, and explains the policies guiding the energy sector in Liberia. This part also presents the energy scenario in Liberia along with the country’s renewable energy (RE) potential. This chapter climaxes with a review of Liberia’s RE programs, including the proposed energy efficiency program aimed at optimizing energy consumption and increasing energy access (expectations of the famous vision 2030).

2.2 Energy profile of Liberia

Liberia is fortunate to have a massive potential in biomass, hydropower, and solar energy. A 2017 IRENA report shows that RE contributes to 85% of Liberia’s total final energy consumption (TFEC). The same report reveals that renewables contribute about 83% to the total primary energy supply, with the remaining 17% coming from oil. However, the country’s RE supply is hugely reliant on biomass (99% of RE supply as of 2017), with solar the only other source of RE. Such is an unfortunate situation for a nation with substantial RE potential. These statistics correspond to the report that electricity access in Liberia is just 27.6% [15] as of 2019 (in a country with a population of about five million people), a 6.1% increase from 2017.

2.2.1 Energy and Development

There is a consensus worldwide that growth and development in a nation's energy sector correlate with overall wealth and prosperity. Hence, it is only wise that the Government of Liberia (GOL) begin to invest more in energy production with a keen emphasis on efficiency. Given that Liberia has no oil reserves coupled with little or no investment in renewable energy, GOL spends millions of dollars on the importation of oil. Importing oil is unfavorable for the economy since it results in the devaluation of the Liberian dollars.

2.2.1.1 Policy Framework, Legal Framework and Strategies for RE Development

Formulation of Liberia's National Energy Policy (NEP) began in 2006 and finalized in 2009. The NEP outlines the nation's vision for development in the energy sector, starting with the emergency phase through capacity building and development phases [13]. In the foreword, the NEP states: "*Therefore, the provision of modern, dependable, affordable, and environmentally sustainable energy services is crucial to the achievement of the Millennium Development Goals and Liberia’s Poverty Reduction Strategy.”* Thus, the NEPL intends to alleviate Liberians from poverty through policies enabling sustainable and equitable distribution of power throughout the country. After completion, the NEPL through MLME developed all legal frameworks allowing the setup of energy and energy-related programs in the country. It is also an embedded objective of Liberia's vision 2030. This vision targets provision of electricity to 70% of Monrovia while connecting 35% of the rural areas to mini-grids or isolated units through 2030 (National policies and commitments, renewables Liberia 2020). At last, Liberia has a reference document that laid out plans and regulations for the energy sector for the first time since independence.

2.2.1.2 Legal Framework

In 2015, the national legislature enacted the legal principle for public-private providers of electricity in Liberia. This principle is now known as the 2015 **Electricity Law of Liberia.** The law provides for the broadening and delivery of off-grid power to rural and isolated regions. This constitutional principle encourages appropriate externalization of institutions that, after LERC accreditation, will qualify to produce, and supply electricity within the specified business space (Liberia's Energy Landscape, renewables Liberia 2020).

Additionally, a **Mini-Grid Code for Liberia** is in the development stages. Upon completion, the ERB wishes to use the Mini-Grid Code to specify pleasantries like legitimacy, specific conditions, the excellence of services, invulnerability and other phenomena needed to check permissions of in-coming service providers. The goal is to ensure that these service providers comply with international best practices.

2.2.1.3 Strategies (*Strategic Roadmap*)

The NEPL relies on three strategies to implement the vision of the energy sector. These strategies emerged from the theme, "*Small light today, big light tomorrow.”* This theme is a phrase by former president Madam Sirleaf at the induction ceremony for the re-ignition of public power distribution in Monrovia in 2006. The plan is to provide ‘small light’ through grant-in-aid capital and GoL’s restricted money. As opposed to the small light, a more sizable portion of the finances required for the 'big light' comes from grants leased from banks. Hence, 'small light' depends on political and commercial activities, while 'big light' relies on bank decisions.

GOL adopted a three-pronged strategy just to realize the goals outlined in NEP. This strategy comprises the short term (emergency phase), the medium-term (capacity building phase), and of course, the long run (development phase). Achieving the goals of these phases is mostly reliant on the responsibility that Liberians must execute the policy regarding energy development dutifully.

- **Emergency Phase-** this phase launched in January 2006, closing with the incorporation of the finalized National Energy Policy in 2009. This period saw the implementation of pilot projects. However, the main goal was the finalization and adoption of the NEP, a plan of action for the energy sector. The pilot projects and other energy-related initiatives primarily served as guides for the drafting of the national energy policy.
- **Capacity Building Phase-** this phase lasted from 2008 to 2015. Its purpose was for setting the stage for the implementation of the energy policy. Setting the stage meant building regional competency for the integration of the plan in implementing energy projects. This phase was heavily dependent on donor assistance with the projects implemented during this period culminating with the then 2015 Millennium Development Goals.
- **Development Phase-** The development phase is ongoing as expected. This phase is hugely dependent on the achievements of the previous stages. For instance, the working institutions set up (of which only about 30% improved) during the capacity building phase are the driving forces in the development of the energy sector of Liberia. Institutions like NOCAL, LEC and LEC are all products of the capacity building phase. However, the full potential of the development phase is still underway due to economic constraints and lack of political commitments. The long-term goals of this phase include mega-scale hydroelectric capacity, the establishment of multifaceted partnerships for leveraging opportunities for foreign exchange of electricity, including the improvement of other vast renewable energy reserves/potential (Strategic Roadmap, NEP 2009).

2.2.1.4 Energy efficiency policy and targets

2.2.1.4.1 Previous milestones and policy actions

The quest for energy efficiency stems from the 2009 national energy policy (NEP) which resulted in the crafting of the National Energy Efficiency Action Plan (NEEAP) of Liberia. Hence, the policy guiding the implementation of the proposed energy efficiency programs closely aligns with that of the NEP. About five years after the development of the National Energy Policy of Liberia (NEPL), GoL established the Rural Renewable Energy Agency (RREA) to implement the commercialization and distribution of sustainable energy services in rural Liberia by the utilization of the renewable resource in the given region. The formation of the RREA also resulted in the establishment of the rural renewable energy fund (REFUND), the financial mechanism through which the RREA assists remote and low-income communities. The arm of the RREA in charge of the REFUND is the Off-Grid and Mini-Grid Unit. In 2015, the national legislature amended chapter 85 of the 1973 Public Authorities Law creating the LEC to draft the 2015 Electricity Law of Liberia. This milestone enabled the government to formulate the legal and regulatory framework for the generation, transmission, distribution, and sale of electricity within the borders of Liberia, including the import and export of the electricity and to facilitate the implementation of the NEP. The 2015 Electricity Law of Liberia also empowered GoL to create the Liberia Electricity Regulatory Commission (LERC) with responsibilities like investigations of alternative forms of regulation like tariffs flexibility, incentive-based regulations, and the use of competitive markets.

2.2.1.4.2 Energy efficiency targets

Studies show that energy efficiency in Liberia is low compared to other regions around the globe. Considering losses ranging from generation to non-technical issues, Liberia lost annually on average about 45% of the power generated during 2010-2015. Coupled with a poor supply-side management program, there is a lack of a demand-side management program. However, as part of the vision 2030 outlined in the NEPL, the GoL has set targets to develop and improve Liberia's energy efficiency standards on a sectoral basis. The sectors of interest are domestic and public buildings, the industries, transport, and agriculture. The goal here is to maximize energy efficiency whilst minimizing energy costs, and their accompanying negative environmental impacts. According to the NEEAP, the overall energy efficiency targets are as follows:

- Reduction of losses in the electric grid.
- Reduction of losses in domestic and public lighting.
- Reduction of losses in the building sector; and
- Reduction of losses in the industrial sector.

Upon achievement of the targets, the energy sector expects to benefit about 461 GWh in energy savings yearly.

2.3 RE potential in Liberia

2.3.1 Bioenergy Potential

Estimated put the total bioenergy capacity of Liberia at 163 $*10^3$ TJ/year (energypedia 2015, Liberia Energy Situation). This follows the fact that about 43% of the country is forest (41,790 km^2) [6]. As a result, Liberia has an abundance of tree crops like rubber, coconut, palm, and cocoa. These serve as a huge reserve of biofuels that could provide a substantial amount of energy when utilized. However, the technology needed to convert these biomasses to clean, and more productive forms of energy are lacking. These locals and petit traders use organic residues to produce charcoal, which is an unclean form of energy. Nonetheless, this huge reserve of biomass presents Liberia with a huge bioenergy potential that may someday a valuable sustainable energy resource.

2.3.2 Charcoal and Firewood

The report shows that Liberians consumed about 225 tons of commercial charcoal in 1999 [17]. Also, the same report revealed that charcoal consumption was a whopping 36,500 tons within six years later [17]. Consequently, the charcoal industry fell a total of 960,000 trees yearly to meet consumers need. NACUL now reports that production and consumption of charcoal are between 235,500 to 285,000 tons per year as of 2010 at a rate of 59 kg/year.

Calculations show that the yearly consumption of firewood is one cubic meter ($1m^3$) per individual [18]. Similar report also reveals that in rural communities, firewood consumption can go up to eighteen cubic meter ($18m^3$) per household. Further, estimates project that annual demand may increase by 0.43 m^3 per person in the coming years. However, community residents usually obtain firewood from the outskirts of their residences and bushes just nearby, consisting primarily of fallen wood, and a bunch of lifeless tree leaves.

2.3.3 Hydropower

Aside from the water accumulated during the rainy season which lasts from April to November, Liberia possesses six rivers and a coast that traverses the entire length of the southern region. Liberia receives an annual rainfall of 509.6 cm (200.6 in) in the coastal areas, 198 cm (˜80 in) in the interior. The mean humidity is about 81.7% along the coast during the wet periods and 77% during the sunny periods [20]. A study by the Rural Energy Strategy and Masterplan conducted in

2013, estimated that hydroelectricity capacity was 2,310 MW in Liberia. These seven large rivers, with high overheads and flows above 50 m^3/s, the country is capable of building and maintaining hydroelectric plants that are 5 MWs and above [24].

2.3.3.1 Generation from Hydro Power Stations

Before the civil war of 1990, Liberia generated half of its energy from Mount Coffee Hydropower located about 27 km northeast of Monrovia, the capital city. Unfortunately, rampant lotting and destruction by armed men damaged the dam was during the prolonged periods of wars in Liberia. While functional, the dam generated a maximum power of 64 MW which accounted for about 35% of all electricity generated in the country [19] [22]. Nonetheless, renovation of the dam began in 2012 and construction works ended in 2018. The experts renovating the dam expected it to be fully functional in late 2020 or early 2021 with a full capacity of 88 MW (Mt. Coffee Hydropower Plant Rehabilitation, renewable-liberia.info) [22].

Apart from the Mt. Coffee Dam, scores of other hydropower projects are in other parts of the county. Among these is the Yandohun Hydropower Mini-Grid in Lofa, the Hydropower-and-Diesel grid for Lofa [25] and the Firestone Plantations Hydropower Plant in Harbel, Margibi.

2.3.4 Solar Energy

On a monthly count, solar radiation on plain surfaces can average around 4 $kWh/m^2/day$ in the wet season (June up to August) to 6 $kWh/m^2/day$ for the high-temperature days in the sunny period (from February to March). This consistency of the elevated level of solar energy potential across the country adds to a mean value of 1,712 $kWh/m^2/year$ and the possibility of harnessing 1,400 to 1,500 kWh/kWp.

2.3.5 Wind Energy

Studies purport that the wind potential for Liberia is insignificant. The windiest day in Liberia is August 7 (10.5 mph wind speed), and the average wind speed is about 7.8 mph [30]. Referencing a 2015 report SE4ALL Action Agenda Report, wind power in Liberia could fall less than 1 GWh (0.48GWh) in 2025 [27]. As a result, there is no plan or recommendation to use wind energy to generate power in the country.

2.4 Bioenergy

Bioenergy is energy derived from biomass, a renewable energy resource originating from plant and algae-based substances listed in the table below.

Table 2.4 ***List of biomass resource***

- Crop wastes
- Forest residues
- Purpose-grown grasses/plants
- Woody energy crops
- Microalgae
- Urban wood waste
- Wood waste

Engineers can use biomass resources to produce transportation fuels, heat for homes and industrial processes, electricity, and products. With the abundant biomass resource available in Liberia, a modern utilization of bioenergy can enhance energy security, ensure sustainability in the energy sector, whilst contributing to the economic growth of the nation. Specifically, the production of renewable bioenergy can yield the following results:

- Clean and relative less costly energy
- Minimum or no need for importing oil
- Jobs creation for locals, especially in rural communities
- Boost in the economic activities of rural settings
- Security and gradual eradication of gender imbalances

A 2009 technical report by Milbrandt for USAID revealed that biomass resources were more than enough to cover the country's annual electricity consumption of 297 GWh, including oil consumption of 206 dam^3 [22]. Further, given that biomass accounts for 99% of the TPES, the need for the modern conversion of biomass to clean fuel for power and heat generation could not be more appealing.

2.4.1 Biomass conversion technologies and RE market

There are three primary conversion pathways for the conversion of biomass to bioenergy: biochemical conversion, thermochemical conversion, and physio-chemical conversion. Biochemical conversion involves two process options: anaerobic digestion to produce biogas, and fermentation to produce bioethanol. The thermochemical conversion process involves combustion, gasification, hydrothermal (liquefaction/HTU) processing and pyrolysis. And the physio-chemical conversion comprises the esterification of plant oil following its extraction from oilseeds [18]. The fuels yielded from these processes can be solid, liquid, or gas depending on the conversion technology employed in the initial stages. Solid biofuels are ideal to produce heat, power, or simply combined heat and power (CHP). Liquid biofuels have huge applications in the transport industry, including minor applications in stationary engines. Lastly, gaseous biofuels have applications in clean cooking, power production, the process industry, and other sets of processes. The biomass conversion technologies and their respective end products are in the figure below.

(Adams)

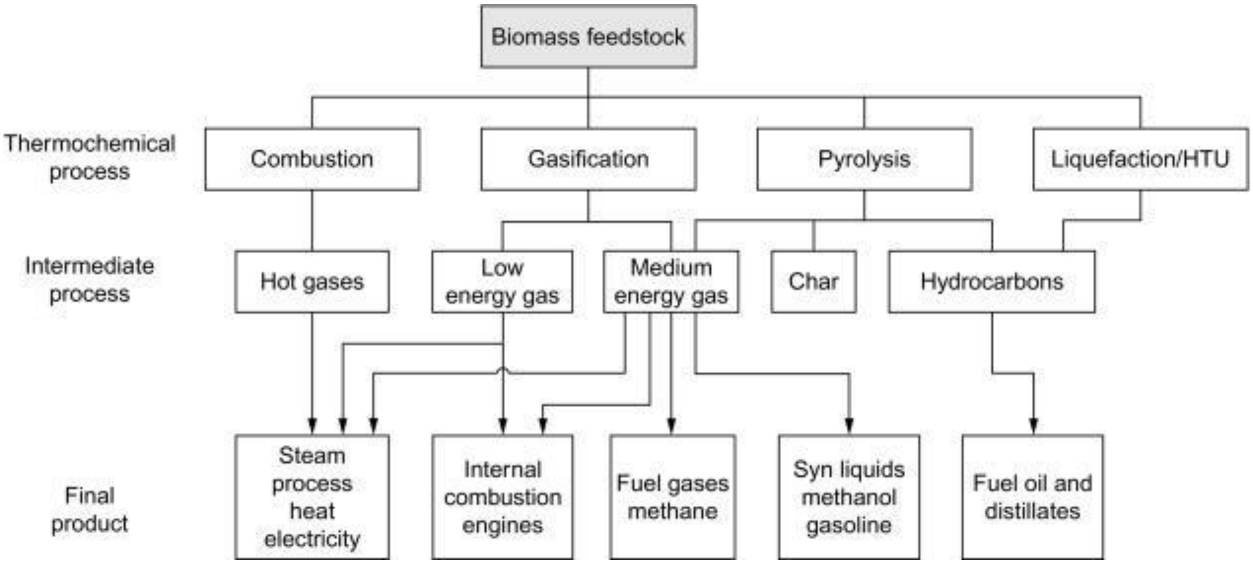

Figure 2.4.1 Biomass conversion processes

It is important to note that the type, quantity, and characteristics of the biomass feedstock, end-use requirements, environmental legislations, economic situation the region, location, and non-technical factors influence the conversion process the engineer employs in each process.

Reports show that the global bioenergy market was worth about USD 344.90 billion in 2019 with forecasts proposing an increase to about USD 642.7 billion by 2027, assuming an 8% compound annual growth rate (CAGR) [20]. Factors responsible for growth in the bioenergy market before COVID-19 include the unfavorable environmental impact resulting from the consumption of fossil fuels, expensive importation of fossil fuel resources for countries lacking these resources, the ever-growing demand for sustainable energy, and the low-cost alternatives provided by the utilization of renewable energy resources. Now, the COVID-19 era has resulted in severe travel restrictions, limited social contacts, and the insurgence of work-from-home. These travel restrictions halt the sales of a huge quantity of gas and oil around the globe since the travel ban includes cargoes in which these suppliers transport these commodities (4% decline in 2020 according to the IEA report). In contrast, the renewable energy sector is unaffected by the pandemic as evident in the 7% installations of additional capacities around the globe. IEA data shows that renewables experienced an overall 3% (330 TWh in solar PV and wind capacities) in 2020. The report revealed that both solar and wind could experience a 17% growth in generation this 2021, and similar growth of 8.3% for hydro and biomass generation in the same year (a 7% increase from 2020. This implies that the share of renewables in total electricity production will reach 30% from less than 27% in 2019.

2.4.2 Working principles

2.4.2.1 Thermochemical conversion: A look at Gasification

Biomass gasification is an advanced technology pathway that utilizes heat, steam, and oxygen to transform biomass into hydrogen and other products (producer gas and syngas) without combustion[1]. This method's net carbon emissions are low because the plants grown as biomass remove carbon dioxide from the atmosphere. When coupled with carbon capture technology, this method yields a negative emissions value eventually.

Biomass gasification, in a way, is different from biogas production, which decomposes wet organic matter like animal dung or sewage sludge by the action of microbial organisms to generate methane gas. Biomass gasification occurs according to the following chemical reaction:

Equation 1

$$Biomass + O2 \ \rightarrow CO + H2 + Heat. \qquad (1)$$

There are four primary steps involved in biomass gasification:

I. Heat & drying – for 10-50% reduction in the moisture content of the biomass. The desired end-product dictates the degree to which the feedstock is dried. A higher moisture content yields higher CO_2 and H_2O in the final mixture, while low per cent of moisture yields the desirables, CO, H_2, and CH_4.

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[1] Office of Energy Efficiency & Renewable Energy, *Hydrogen Production: Biomass Gasification,* 'Biomass Gasification Definition' (2020). Available at https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification

II. Pyrolysis – the speedy breakdown of the organic feedstocks void of oxygen. This process begins at three hundred – five hundred℃, and it releases volatiles and produces permanent gases (CO, CO_2, H_2), which remain suspended even during cooling. The 70-90% of biomass converted to vapor and gases during pyrolysis doubles that converted during the combustion of coal.

III. Gas solid reaction – post pyrolysis, chemical reactions persist between char and the floating gaseous molecules, mostly when C and O_2, CO_2, H_2O, and H_2 react to form CO, 2CO, H_2+CO, and CH_4.

IV. Gas-phase reactions – CO reacts combines with H_2O to yield H_2 + CO and CH_4 + H_2O due to the continuous reaction of the volatiles produced during pyrolysis.

The catalyst needed to kickstart gasification can be air, oxygen, steam, or a combination of these three.

2.5 Solar energy

2.5.1 Working principles

Engineers and scientist call the energy acquired by electrons when radiant light and heat from the sun strikes the earth's surface solar energy. The amount of solar radiation striking a given region of the earth fluctuates due to the following:

- Site location
- Hour of the day
- Season in the year
- Topography of the region
- Weather situation of the region

Also causing variation in solar radiation are phenomena called diffuse solar radiation and direct beam solar radiation. When absorption, dispersion and reflection affect the passage of sunlight in the atmosphere, engineers and scientists call it Diffuse solar radiation. The following entities cause this phenomenon:

- Air molecules
- Water vapors

- Clouds
- Dust
- Pollutants
- Wildfires
- Volcanoes

Direct beam solar radiation is when sunlight reaches the earth’s surface void of any of the above-listed factors. Summation of both the diffuse solar radiation and direct beam solar radiation gives the so-called global solar radiation, expressed as

Equation 2

$$G_{tOt} = Dif_{tOt} + Dir_{tOt} \tag{2}$$

where G_{tot} is the global radiation, Dif_{tot} is the sum of diffuse solar radiation, and Dir_{tot} is the total direct beam solar radiation with all units in kW/m^2. Given that

Equation 3

$$Dif_{\theta,\alpha} \; = R_{glb} * P_{dif} * Dur * SkyGap_{\theta,\alpha} * Weight_{\theta,\alpha} * \\ cos\, cos\, (AngIn_{\theta,\alpha}) \,, \tag{3}$$

and

Equation 4

$$Dir_{\theta,\alpha} = S_{const} * \beta^{m(\theta)} * SunDur_{\theta,\alpha} * SunGap_{\theta,\alpha} * cos\, cos\, (AngIn_{\theta,\alpha}) \,, \tag{4}$$

then

Equation 5

$$\begin{aligned} G_{tOt} = Dif_{tOt} + Dir_{tOt} \\ &= * cos\, cos\, (AngIn_{\theta,\alpha}) \, (R_{glb} * P_{dif} * Dur * SkyGap_{\theta,\alpha} \\ &* Weight_{\theta,\alpha} + S_{const} * \beta^{m(\theta)} * SunDur_{\theta,\alpha} * SunGap_{\theta,\alpha}) \end{aligned} \tag{5}$$

Where R_{glb} is the global normal radiation; P_{dif} the proportion of global normal radiation flux is diffused; Dur the time period for analysis; $SkyGap_{\theta,\alpha}$ the fraction of the sky that is clear; $Weight_{\theta,\alpha}$ the proportion of diffuse radiation emanating from a particular region of the sky relative to others; $AngIn_{\theta,\alpha}$ the angle of incidence between the central region of the sky and the intercepting surface; S_{const} (a value of 1367 W/m^2) is the solar flux outside the atmosphere at the average between the earth and the sun; β the mean transmissivity of the atmosphere considering the shortest path for the radiation; $m(\theta)$ the relative optical path length, measured in proportion to the zenith path length; $SunDur_{\theta,\alpha}$ the day interval in most cases multiplied by the hour interval – angular measurements are considered for regions near the horizon; and $SunGap_{\theta,\alpha}$ the gap faction for the sun map region.

2.5.1.1 Solar radiation conversion mechanisms

Energy experts can utilize the techniques of photoelectric effect to convert solar energy an end-use product primarily via the employment of technologies like solar photovoltaics (PV), solar collectors, and concentrated solar power (CSP). The choice of technology pathway depends on the end-use requirement. These technologies are briefly discussed below.

I. Solar photovoltaics contain a basic component called a photovoltaic cell which converts the radiant energy from the sun to electricity using a set of electrical semiconductors (the n-type semiconductor and the p-type semiconductor), which when joined together gives the p-n junction network. A solar PV setup begins from a cell and ends with a system of arrays. The diagram below illustrates a PV setup.

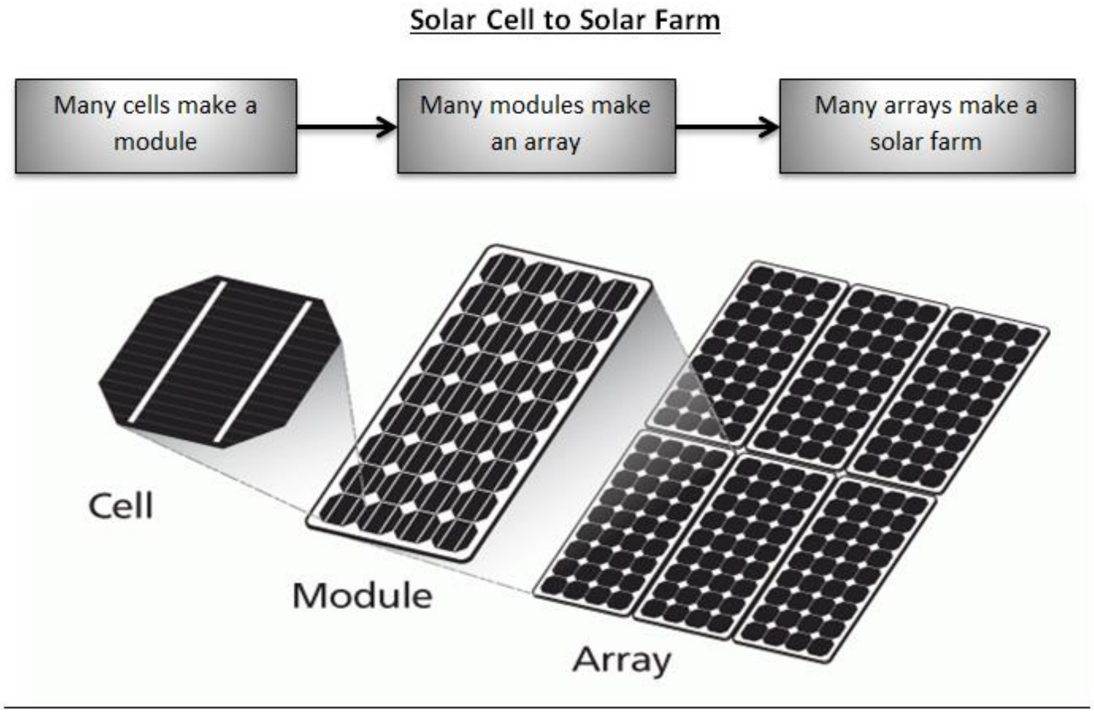


Figure 2.5.1 A typical solar PV build-up

When photons strike and ionize the semiconductor material on the solar panel, the valence electrons get excited and break free of their atomic bonds. The structure of the semiconductors induces a directional motion for the free electrons, causing the flow of electric current. Like all conversion technologies, solar PVs are associated with levels of inefficiency in the form of losses. The losses occurring in a PV cell can be a collection, quantum, reflection, and transmission.

a. Collection losses – as opposed to ideal conditions, the excited electrons are reabsorbed into cell structure, causing the PV output to decrease and the collection efficiency to be less than 100%. In a group of photons with energy E, the energy criteria are set such that EG<E<E*, where EG is the bandgap energy, and E* is characteristic estimated upper-bound specific to the given cell's design.
b. Quantum losses – when the photons have E<EG, they are unable to produce the photoelectric effects, indicating unavailable energy to the system and a reduction in the efficiency. Since the phenomenon is one photo for one electron, irrespective

of the amount of energy in the photon, the excess energy dissipates as heat in this situation.

c. Reflection losses – the glass covering the surface of a PV cell causes a fractional reflection loss $\rho(E)$, where $0 < \rho < 1$. The level of reflection varies with the energy in the photon. To reduce reflection losses, r(E), manufacturers coat PV cells with anti-reflective materials.
d. Transmission losses – PV cells have characteristic height, length, and width. Hence, a photon may travel through the wafer without smashing into an atom in the silicon-doped structure. The free transmittance of photons through the structure results in transmission losses. Transmission losses are a function of the cell's width and the energy of the photon, designated τ(E, W), where $0 < \tau < 1$.

Consequently, solar PVs have efficiencies in the range of 15-20%, with reported efficiencies of 42% (Vourvoulias). The diagram below shows varying crystalline-silicon PV and their corresponding efficiencies.

CHAPTER THREE: METHODOLOGY

Contents

3.1 Introduction

Here, the software tool employed for the simulations is described, followed by examinations of the weather and load profile of the research site. The hybrid system is designed and sized according to the available energy potential and electricity consumption rates. For economic and environmental analysis, the proposed systems are modelled in HOMER and simulated in seven configurations. Finally, this section ends with descriptions of the different configurations.

HOMER Software

Hybrid Optimization Model for Multiple Energy Resources (HOMER) software is a tool that design and plan power systems. HOMER also designs Hybrid Renewable Energy Systems (HRESs). The software determines optimal size of the system components by performing a techno-economic analysis. HOMER requires the following six types of input data: meteorological, load profile, equipment characteristics, search space, economic, and technical characteristics.

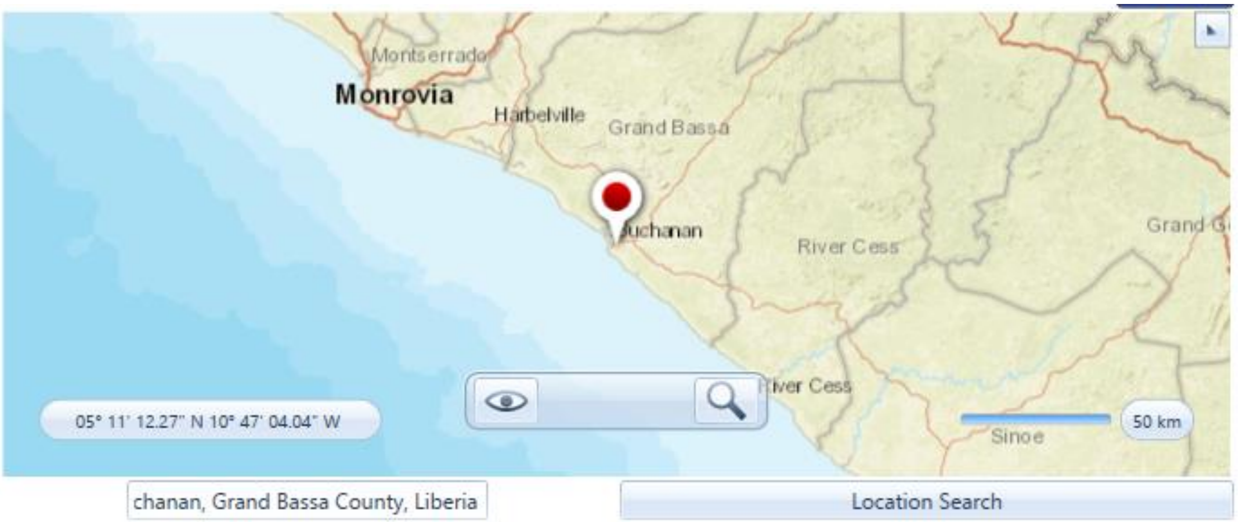
Typical meteorological data include solar radiation, temperature, and wind speed (though we are not considering wind speed in this research). The load profile was fed into HOMER as daily profile and HOMER the used the workforce balance constraints. The equipment characteristics were also inputted to the software to determine the level of efficiency for the system operation. He also fed economic data such as operation and maintenance, capital and replacement costs, fuel price, real interest rates, project lifetime, system fixed capital cost to HOMER software to determine the Net Present Cost (NPC) of the hybrid system.

HOMER can perform a sensitivity analysis that could be with variables having a range of values instead of a specific number.

For this paper, a techno-economic study was conducted for the electrification and delivery of clean energy for a remote region. In most so-called interior parts of Liberia, electricity access is unbearably low. Like other rural communities, the Own Your Own Housing estate lacks grid connectivity. Clean cooking is non-existent. Only a handful of the residences have managed to obtain electricity from an independent power producer (IPP) who is generating power via a diesel generator. Nonetheless, utilizing renewable energy resources could help overcome these challenges. Renewable resources are not just sustainable, but they are also local, plentiful, and clean. The site under consideration is the Own Your Own housing estate located in Grand Bassa County, Southwestern Liberia.

Case Study: The Own Your Own Housing Estate in Grand Bassa County

The Own Your Own Housing Estate contains seventy-six households, a public school, a market building, a church, and community clinic. The average daily load for the estate is 165.44 kWh with a peak load of 14.95 kW during the year.



05° 11' 12.27" N 10° 47' 04.04" W

chanan, Grand Bassa County, Liberia

Figure .1 Case study location

To determine the daily load, hourly load assessments were performed. Further, the load estimations were divided into two periods: the dry (sunny) season, from October to March, and the rainy season, from April to September. This is because these two seasons are determining factors to the daily activities of the residents. Tables 3.3.1 – 3.3.5 give details of the load demands for the households and the other units of the case study.

Table 3.3.1 Household load estimation

	Households						**76**	
	Devices/appliances	**indoors lights**	**outside lights**	**fans**	**TV**	**refrigerator**	**mobile phones**	
	rated power (W)	60	80	75	80	100	5	
	quantity	7	5	3	1	1	4	
	estimated duration (h) of use	1	1	1	1	1	1	
	no usage time (h)	0	0	0	0	0	0	
Time								**Total Wh per day**
0:00		420	400	225	80	100	20	1245
1:00		420	400	225	80	100	20	1245
2:00		0	400	225	0	100	20	745
3:00		0	400	225	0	100	20	745
4:00		0	400	225	0	100	20	745
5:00		0	400	225	0	100	20	745
6:00		0	400	0	0	100	20	520
7:00		0	0	0	0	100	0	100
8:00		0	0	0	0	100	0	100
9:00		0	0	0	80	0	0	80
10:00		0	0	0	80	0	0	80
11:00		0	0	0	80	0	20	100
12:00		0	0	225	80	100	20	425
13:00		0	0	225	0	100	0	325
14:00		0	0	225	0	100	0	325
15:00		0	0	225	0	100	0	325

16:00		420	0	225	0	100	20	765
17:00		420	0	225	0	100	20	765
18:00		420	400	225	0	100	0	1145
19:00		420	400	225	0	0	0	1045
20:00		420	400	225	80	0	20	1145
21:00		420	400	225	80	0	20	1145
22:00		420	400	0	80	100	0	1000
23:00		420	400	0	80	100	0	1000

Table 3.3.1 School building daily load

School building					**1**		
indoors lights	**outside lights**	**water dispenser**	**desktop computer**	**laptop computer**	**ceiling fans**	**mobile phones**	
60	90	80	120	60	45	5	
28	6	5	2	4	12	13	
1	1	1	1	1	1	1	
0	0	0	0	0	0	0	
							Total Wh per day
0	540	0	0	0	0	0	540
0	540	0	0	0	0	0	540
0	540	0	0	0	0	0	540
0	540	0	0	0	0	0	540
0	540	0	0	0	0	0	540

0	540	0	0	0	0	0	540
0	540	0	0	0	0	0	540
0	540	400	240	240	540	0	1960
1680	0	400	240	240	540	65	3165
1680	0	400	240	240	540	65	3165
1680	0	400	240	240	540	65	3165
1680	0	400	240	240	540	65	3165
1680	0	400	240	240	540	65	3165
1680	0	400	240	240	540	65	3165
1680	0	400	240	240	540	65	3165
0	0	0	240	240	0	0	480
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	540	0	0	0	0	0	540
0	540	0	0	0	0	0	540
0	540	0	0	0	0	0	540
0	540	0	0	0	0	0	540
0	540	0	0	0	0	0	540
0	540	0	0	0	0	0	540

Table 3.3.2 Church building daily load

Church building	**1**	

indoors lights	outside lights	water dispenser	desktop computer	laptop computer	ceiling fans	mobile phones	sound system	
60	90	80	120	60	45	5	1500	
4	6	2	1	3	6	60	1	
1	1	1	1	1	1	1	1	
0	0	0	0	0	0	0	0	
								Total Wh per day
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
240	0	160	120	180	270	300	1500	2530

240	0	160	120	180	270	300	1500	2530
240	0	160	120	180	270	300	1500	2530
240	0	160	120	180	270	300	1500	2530
240	0	160	120	180	270	300	1500	2530
240	0	160	120	180	270	300	1500	2530
240	0	160	120	180	270	300	1500	2530
240	0	160	120	180	270	300	1500	2530
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540
0	540	0	0	0	0	0	0	540

Table 3.3.3 Marketplace daily load

Marketplace		**1**			
inside lights	**outside lights**	**mobile phones**	**ceiling fans**	**salon**	
60	90	5	45	1000	
4	4	20	4	1	
1	1	1	1	1	
0	0	0	0	0	
					Total Wh per day
0	360	0	0	0	360
0	360	0	0	0	360
0	360	0	0	0	360
0	360	0	0	0	360
0	360	0	0	0	360
0	360	0	0	0	360
0	360	0	0	0	360
240	0	0	0	0	240
240	0	100	180	1000	1520
240	0	100	180	1000	1520
240	0	100	180	1000	1520
240	0	100	180	1000	1520
240	0	100	180	1000	1520
240	0	100	180	1000	1520
240	0	100	180	1000	1520
240	0	100	180	1000	1520
240	0	100	180	1000	1520
240	0	100	180	1000	1520
240	360	0	0	0	600
0	360	0	0	0	360
0	360	0	0	0	360
0	360	0	0	0	360
0	360	0	0	0	360
0	360	0	0	0	360

Table 3.3.4 Clinic daily load

Community clinic			**1**				
ceiling fans	**tv**	**inside lights**	**outside lights**	**desktop computer**	**laptop computer**	**water dispenser**	
45	80	60	90	120	60	80	
6	1	12	6	1	2	2	
1	1	1	1	1	1	1	
0	0	0	0	0	0	0	
							Total Wh per day
0	0	0	540	120	0	160	820
0	0	0	540	120	0	160	820
0	0	0	540	120	0	160	820
0	0	0	540	120	0	160	820
0	0	0	540	120	0	160	820
0	0	720	540	120	0	160	1540
0	0	720	540	120	120	160	1660
270	80	720	540	120	120	160	2010
270	80	720	0	120	120	160	1470
270	80	720	0	120	120	160	1470
270	80	720	0	120	120	160	1470
270	80	720	0	120	120	160	1470
270	80	720	0	120	120	160	1470
270	80	720	0	120	120	160	1470

270	80	720	0	120	120	160	1470
270	80	720	0	120	120	160	1470
270	80	720	0	120	120	160	1470
270	80	720	0	120	120	160	1470
270	80	720	0	120	120	160	1470
270	80	720	540	120	120	160	2010
270	80	720	540	120	120	160	2010
0	80	720	540	120	120	160	1740
0	80	720	540	120	120	160	1740
0	80	720	540	120	120	160	1740

The demand of electricity is model to reflect the reduced need for cooling during the rainy season. The need for heating is absence since locals use firewood for space heating. Nonetheless, the energy demand for heating was highlighted in the bioenergy model. Also, the demand for electricity dropped slightly during the rainy season because Ministry of Education (MOE) mandate the closure of schools for a couple of months during this period. The summary of electricity consumption during both dry season and rainy season is given below in the tables 3.3.5 and 3.3.6.

Table 3.3.5 Dry season electricity demand

	Units	Aggregate daily consumption (kWh/day)
October - March	Households	219978.2
	School building	4362.87
	Community clinic	6336.4
	Marketplace	3298.32
	Church building	444.8
	Total	234420.59

Table 3.3.6 Rainy Season Electricity demand

	Units	Aggregate daily consumption (kWh/day)
April - September	Households	157563.2
	School building	2047.125
	Community clinic	5646.55
	Marketplace	3006.72
	Church building	410.24
	Total	168673.835

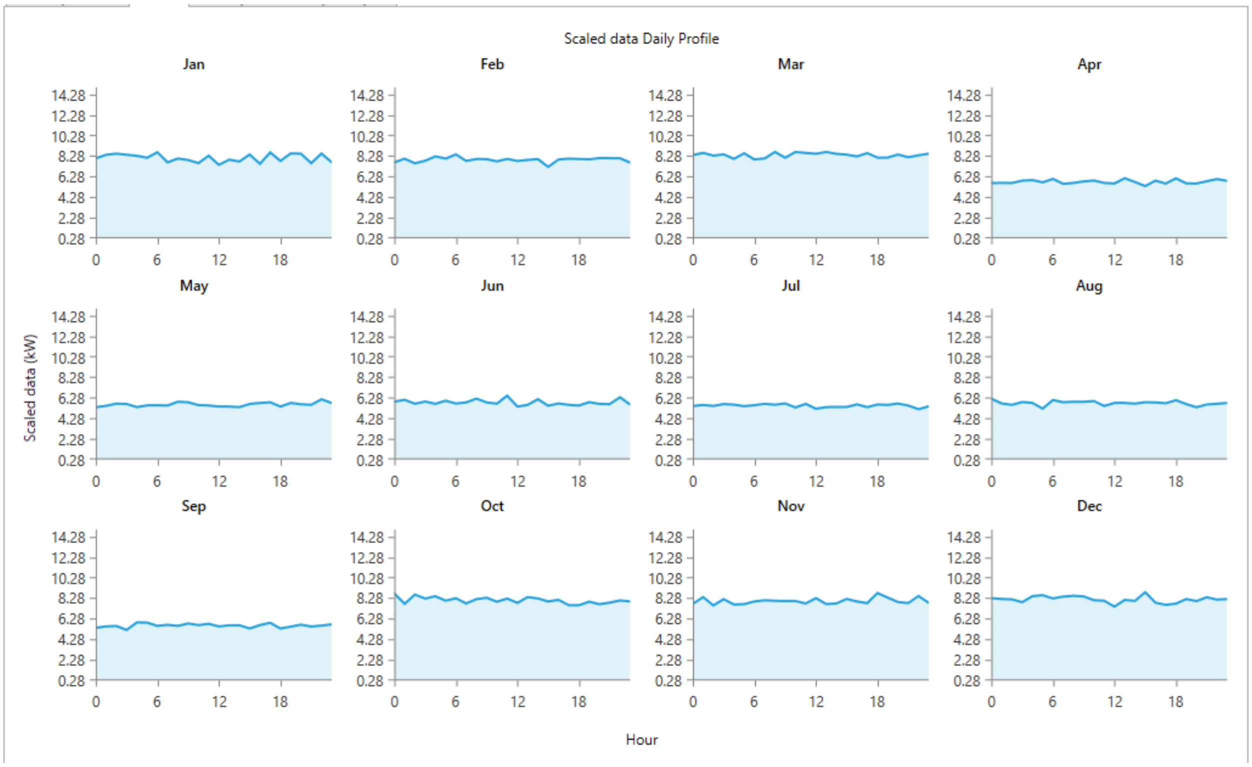


Figure .2 Monthly hourly load

3.3.1 Climatic conditions and solar energy potential

The case study along with its proposed system set up is located at 5-degree, 53.2 minutes north latitude and 10-degree, 1.8 minutes west longitude. The monthly solar irradiation for the case study, including the biomass resources data in figures 3.3-3 and 3.3-4. The peak temperatures from February to May is 27.31 degrees Celsius.

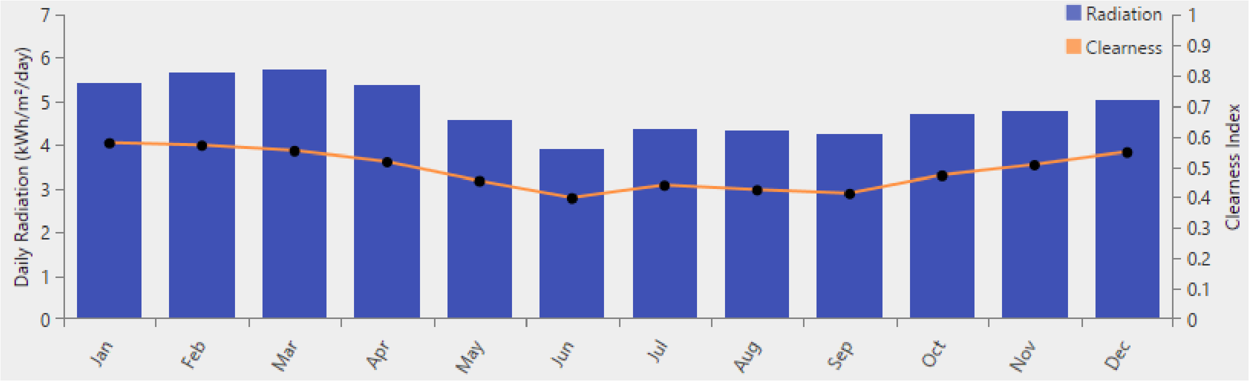


Figure .3 Average monthly solar irradiation

The highest solar irradiation for the research site in March at 5.720 kWh/m^2/day with the annual average being a moderate 4.84 kWh/m^2/day. The annual average clearness index is low (about 44.5%). The moderate solar irradiation of the case study coupled with its low clearness index implies a low solar energy potential for the case study.

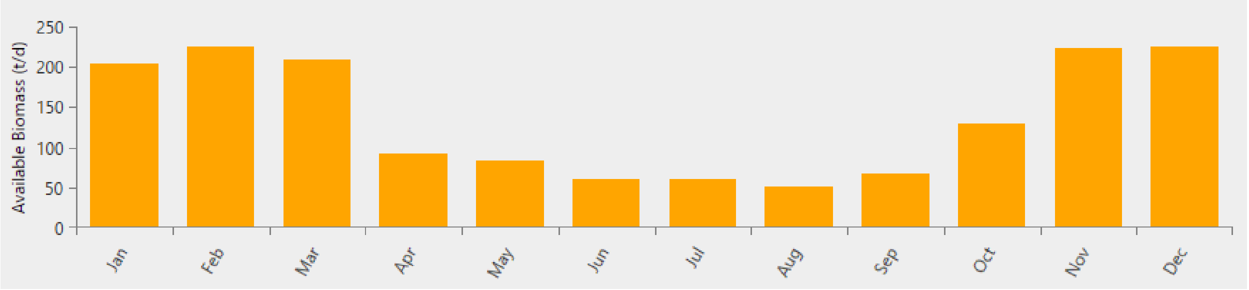


Figure .4 Average monthly biomass resource

The annual average biomass resource for the case is 136.17 t/d, with the highest values reported in February, November, and December as 225 t/d, 223 t/d, and 226 t/d, respectively.

Sizing of components, and the simulations

To determine the suitable power system for the case study, seven (7) simulations with varying combinations of the components and resources required for the base case as well as the proposed case were performed. Following are detailed descriptions of the choice of components utilized in the system design.

Solar PV details and cost

The chosen solar PV panel is a *generic flat plate PV* with 1 kWh rated capacity. The cost of this 1 kWh solar PV system is 2500 USD, and the O&M is 0.4% of the capital cost. The lifetime of the solar panel is 25 years void of a tracking system. The essential characteristics of the chosen solar panel is the figure

Table 3.3.7.1 Solar PV technical characteristics

Solar panel rated power	24.2 kW
Lifetime	25 years
Derating factor	80%
Tracking system	No
Efficiency	15%
Ground reflectance	20%

Batteries details and cost

Batteries are storage options that ensure the continuous supply of power during periods of outages, including during the absence of renewable resource like solar energy. The battery of choice is a *generic 1 kWh Lead Acid battery (Kinetic battery model).* The cost of a single model is 300 USD with the O&M being about 3.33% of the capital cost. The replacement is the same as that of the model cost (USD 300), and the lifespan of the battery is 10 years. The important characteristics of the batteries are in figure.

Table 3.3.8 Storage option technical characteristics

Nominal voltage	**12 V**
Maximum capacity	83.4 Ah
Roundtrip efficiency	80%
Maximum charge current	16.7 A
Maximum discharge current	24.3 A

Converter details and cost

The converter of choice is the system's AC-DC converter with an 18.3 kW capacity rated capacity. The capital cost is USD 300 with 0-dollar O&M cost. The converter efficiency is 95%, and it consists of an inverter and rectifier, boosting a 15-year lifespan.

Biomass Gasifier details and cost

The biomass gasifier of choice is a *BioGen 100 kW Fixed Capacity Genset* with a USD 40000.00 initial capital cost. The replacement cost is also USD 40000.00, and the O&M cost is USD 2.00 per operation hours. The lifetime of the BioGen set is 15000.00 hours and its engine efficiency is 80%. The cost of the biofuel equated to the price per kg of biomass which is USD 0.84 per kg. The penalties for emitting GHGs into the atmosphere and the environment are as follow: CO_2 it is USD 30 per ton according to international standards; for sulfur dioxide is USD 2.12, and for nitrogen dioxide is USD 15.10.

Configuration No. 01: Diesel generator only (base case)

The first configuration, the operating system comprises only a diesel generator. The generator size is 17.0 kW. The system's LCOE is USD 0.54 per kWh, the total NPC is USD 420,148.20; the CAPEX is USD 8500.00, and the OPEX is USD 31843.00.

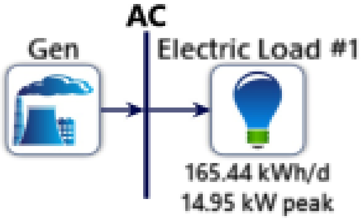


Figure 3.3.4.1 Configuration No. 01

Configuration No. 02: Diesel generator and Solar PV

In this configuration, the system comprises a 17.0 kW diesel generator, and a 11.2 kW solar panel along with a 3.23 kW system converter. The system's total NPC is USD 342,857.40; the LCOE is USD 0.62 per kWh; the CAPEX is USD 44853.00 with an OPEX of USD 32337.00.

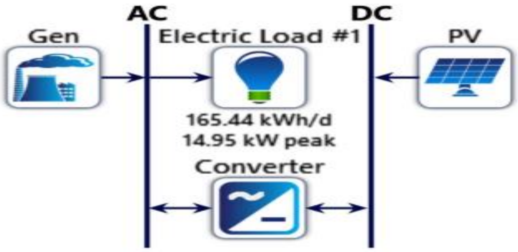


Figure 3.3.4.2 Configuration No. 02

Configuration No. 03: Diesel generator, Solar PV, and Storage

The proposed system here comprises a 17.0 kW diesel generator, a 23.2 kW generic flat plate PV, along with a 13.0 kW system converter, and a Generic 1kWh Lead Acid battery as a power storage option for instances of power outages and absences of solar energy resources. The 12 V capacity of the storage system dictates that thirty-nine strings of batteries to meet the backup demand. The total NPC is USD 335435.30, and the LCOE is USD 0.46 per kWh. The CAPEX and OPEX are USD 75149 and USD 21681, respectively.

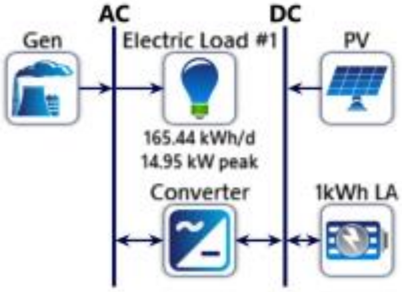


Figure 3.3.4.3 Configuration No. 03

Configuration No. 04: Diesel generator, Biomass gasifier, Solar PV, and Storage

This version of the system consists of a 17.0 kW diesel generator, a 200-kW generic biomass gasifier, a 23.7 kW generic flat plate PV with a 13.2 kW system converter. The accompanying battery has a 1kWh rated capacity with one string in series and forty-one strings in parallel. The voltage of the battery is 12 V. The system’s total NPC is USD 371274.20, its LCOE is USD 0.48 per kWh of electricity. Both the CAPEX and OPEX are USD 83967.00 and USD 45263.00, respectively.

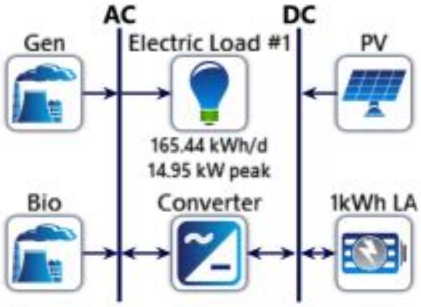


Figure 3.3.4.4 Configuration No. 04

Configuration No. 05: Solar PV and Storage

The combination of components here includes a 101-kW generic flat plate solar PV, a rated 1kWh generic Lead Acid battery comprising 591 strings of batteries with a 47.1 kW system converter. The system total NPC is USD 672390.00 with a LCOE of USD 0.86 per kWh of electricity. The CAPEX stands at USD 442728.00 while the OPEX is at USD 17765.00.

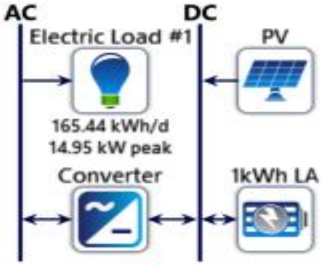


Figure 3.3.4.5 Configuration No. 05

Configuration No. 06: Biomass Gasifier, Solar PV, and Storage

This configuration utilizes a rated 100kW BioGen Fixed Capacity gasifier along with a 24-kW capacity generic flat plate solar PV. Like in configuration No. 05, the storage option here is a 1kWh generic lead acid battery containing eighty-one strings of batteries; the converter is an 18.3 kW system converter consisting of an inverter and a rectifier. The system total NPC USD 397953.50 with a LCOE of USD 0.51 per kWh of electricity. The CAPEX is USD 130411.00, while the OPEX is USD 20696.00.

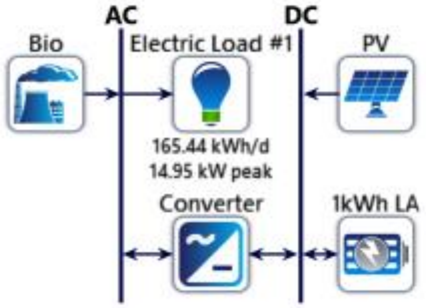


Figure 3.3.4.6 Configuration No. 06

Configuration No. 07: Biomass Gasifier and Storage

Here, the configuration employs a rated 100kW BioGen Fixed Capacity gasifier. Like in configuration No. 05, the storage option here is a 1kWh generic lead acid battery containing eighty-one (81) strings of batteries; the converter is an 18.0 kW system converter consisting of an inverter and a rectifier. The total NPC for the proposed system is USD 492979.60 with a LCOE of USD 0.63 per kWh of electricity. The system's CAPEX is USD 69691.00, and its OPEX is USD 32743.00.

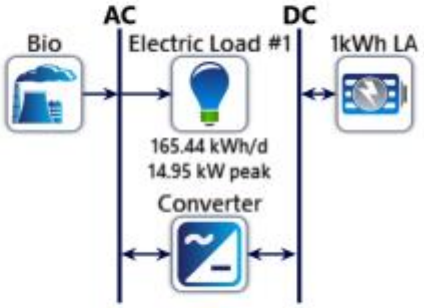


Figure 3.3.4.7 Configuration No. 07

CHAPTER FOUR: RESULTS AND DISCUSSION

Contents

4.1 Introduction

This chapter summarizes the different results obtained for the different configurations of the components for the case study. The discussions begin with the electrical output of the system for the various configurations, followed by the outputs and share of electricity production generated by each component. Also analyzed are the total NPCs and the LCOEs. This chapter highlights the cost contributions of each component to the capital cost, O&M cost, replacement cost, and salvage value. Next under discussion are evaluations the economic viability of the different configurations. The best technology option is then determined considering cost and other key sustainability variables. The chapter ends with the discussion of other key findings from the survey.

4.2 Case Study: Own Your Own Housing Estate site

- **Configuration No. 01: Diesel Generator**

The system optimized for this configuration is in figure. Here, the diesel generator size is 17.0kW. The diesel accounts for 100% of the annual electricity production which stands at 60788 kWh/yr. The mean electrical output along with the minimum and maximum output are report in figure 4.2.1.

Table 4.2.1 Diesel Generator technical characteristics

Quantity	Value	Units
Electrical production	60788	kWh/yr
Mean Electrical Output	6.94	kW
Minimum Electrical Output	4.25	kW
Maximum Electrical Output	15.0	kW

The system's total NPC is USD 420,148.20; the CAPEX is USD 8500.00, and the OPEX is USD 31843.00. Being the sole component, the diesel generator accounts for 100% of the system's NPC. The figure following shows the breakdown of the NPC into the CAPEX, OPEX, replacement, salvage, and resource costs.

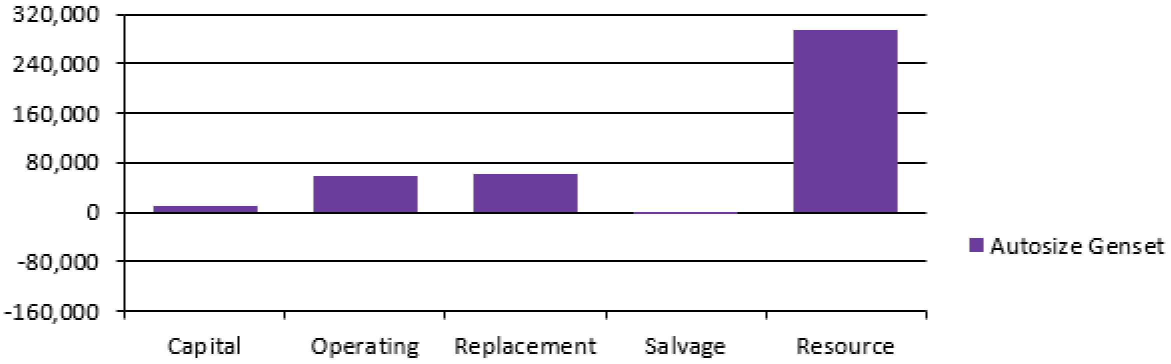


Figure 4.2.1.1 Costs summary

As shown above in the resource (diesel fuel) accounts for the largest portion of the NPCs at about 69.75%, followed by the replacement costs at 14.68%.

- **Configuration No. 02: Diesel Generator and Solar PV**

The proposed system for this configuration is in figure 4.2.0.1. The diesel generator size is 17.0 Kw, the solar PV is 11.2 kW, and converter is 3.23 kW. Here, the diesel generator accounts for 85.4% of the total annual electrical production, with the total annual electrical production standing at 63572 kWh/yr. The summaries of the electrical production for both components are in figures 4.2.2 and 4.2.3.

Table 4.2.2 Diesel Generator production summary

Quantity	Value	Units
Electrical production	54344	kWh/yr
Mean Electrical Output	6.20	kW
Minimum Electrical Output	4.25	kW
Maximum Electrical Output	15.0	kW

Table 4.2.3 Solar PV production summary

Quantity	*Value*	*Units*
Minimum Electrical Output	0	kW
Maximum Electrical Output	3.00	kW
PV Penetration	15.3	%
Hours of Operation	4353	Hrs/yr
Levelized Cost	0.450	$/kWh

The system costs USD 342,857.40; the CAPEX is USD 44853.00 with an OPEX of USD 32337.00. In this configuration, the diesel generator contributes about 84% to the system costs, wherein the resource (diesel fuel) dominates this value with about 67.68% of the total annual cost of the diesel generator. The solar PV system accounts for about 11.51% of the system costs. The figure shows the distribution of the system costs among the components making up the system.

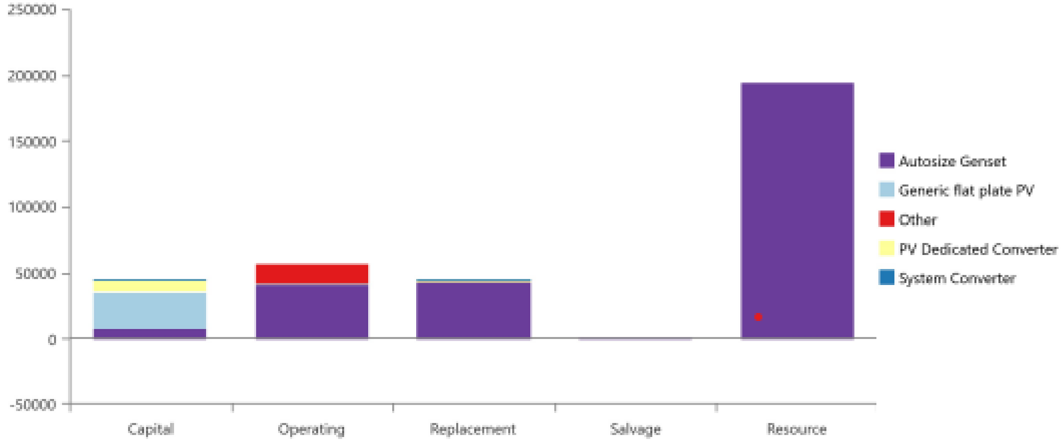


Figure 4.2.1.2 Costs summary

As the chart above shows, the generic flat plate PV accounts for more than half of the system capital costs (about 51.01% of the capital costs), while the diesel generator contributes about 71.12% of the system operating costs. However, as expected, the diesel fuel cost accounts for 100% of the system resource costs, since the solar irradiation is free. Consequently, reducing the diesel fuel by 50% could cause the system costs to diminish by USD 105093.62, a 30.7% decrease in total system costs. Such decrease could consequently lead to a drop in the system LCOE, a favorable situation for the residents of the case study.

- **Configuration No. 03: Diesel Generator, Solar PV, and Storage**

Figure 4.2.0.4 depicts the desired system for this configuration. The system uses a 17.0 kW diesel generator, a 7.30 kW solar PV, twenty-three (23) strings of 1kWh battery option along with a 9.67

AC-DC converter system. The total annual electricity production for this configuration is 62053 kWh/yr wherein the solar PV system contributes just 12.4% of the annual electricity production, while the diesel generator supplies the rest. The 1kWh lead acid battery of 12 V receives 4378 kWh electricity annually from the PV system, but its energy output 3502 kWh/yr, accounting for a loss of 876 kWh/yr. the next four tables show summaries of the electrical characteristics of the various components.

Table 4.2.4 System production summary

Component	*Production (kWh/yr)*	*Percent*
Generic flat plate PV	7723	12.4
Diesel Generator	54331	87.6
Total	62053	100

Table 4.2.5 Diesel Generator production summary

Quantity	*Value*	*Units*
Electrical Production	54331	kWh/yr
Mean Electrical Output	7.17	kW
Minimum Electrical Output	4.25	kW
Maximum Electrical Output	15.1	kW

Table 4.2.6 Solar PV production summary

Quantity	*Value*	*Units*
Minimum Electrical Output	0	kW
Maximum Electrical Output	3.00	kW
PV Penetration	12.8	%
Hours of Operation	4353	Hrs/yr
Levelized Cost	0.398	$/kWh

Table 4.2.7 Storage production summary

Quantity	*Value*	*Units*
Average Energy Cost	0.298	$/kWh
Energy In	4378	kWh/yr
Energy Out	3502	kWh/yr
Storage Depletion	0.0183	kWh/yr
Losses	876	kWh/yr
Annual Throughput	3916	kWh/yr

The system costs comprise the CAPEX, OPEX, and the replacement costs, the salvage value, and resource costs. Figure 4.2.1.3 illustrates contributions of each of these components to the system.

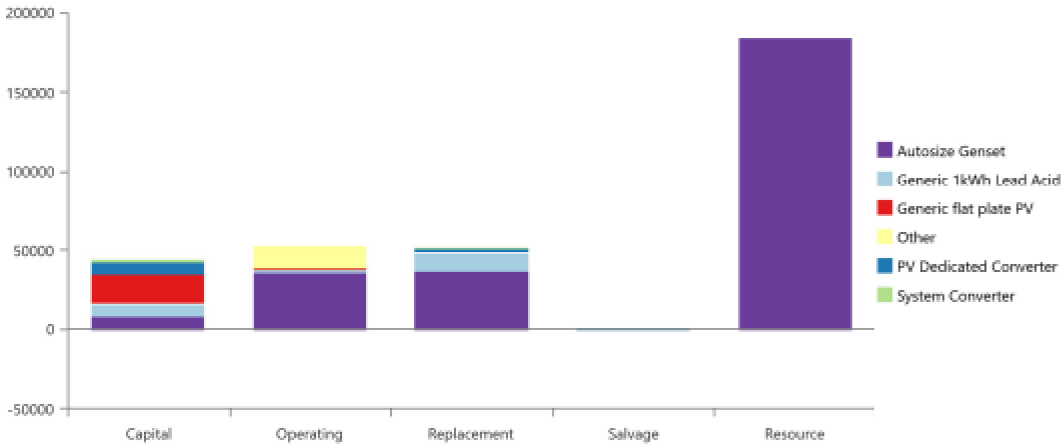


Figure 4.2.1.3 Costs summary

As shown, the resource for the diesel generator constitutes a huge portion of the system costs (55.8% of the total cost), and specifically accounting for about 69.5% of the costs for running the diesel generator. As also illustrated, the solar PV accounts for a greater percentage of the CAPEX with it USD 18250.00 value (about 42.3% of the CAPEX). The diesel generator dominates both the OPEX and replacement costs with USD 35607.00 (66.8% of the OPEX) and USD 37255.00 (71.40% of the replacement) respectively. Following the value of the replacement costs for the generator is the battery's USD 11114.00 (approx. 21.92% of the replacement costs). Hence, the annual cost of the diesel generator is the primary contributor to the high system costs for this configuration. However, a 50% government subsidy to the generator resource cost could potentially yield about 27.9% reduction in annual system costs, saving about USD 92224.57 in the process.

- **Configuration No. 04: Diesel generator, Biomass gasifier, Solar PV, and Storage**

This version of the system consists of a 17.0 kW diesel generator, a 200-kW generic biomass gasifier, a 23.7 kW generic flat plate PV with a 13.2 kW system converter. Also included are forty-one strings of a 1kWh lead acid battery. The total annual electrical production for the system is in the table 4.2.8.

Table 4.2.8 System electrical production

Component	Production (kWh/yr)	Percent
Solar PV	**33720**	**47.9**
Diesel generator (combined with gasifier)	**36615**	**52.1**
Total	**70335**	**100**

The system costs include the CAPEX, OPEX, replacement, salvage, and resource costs. The following figure reveals the contributions of each cost's component to the overall cost.

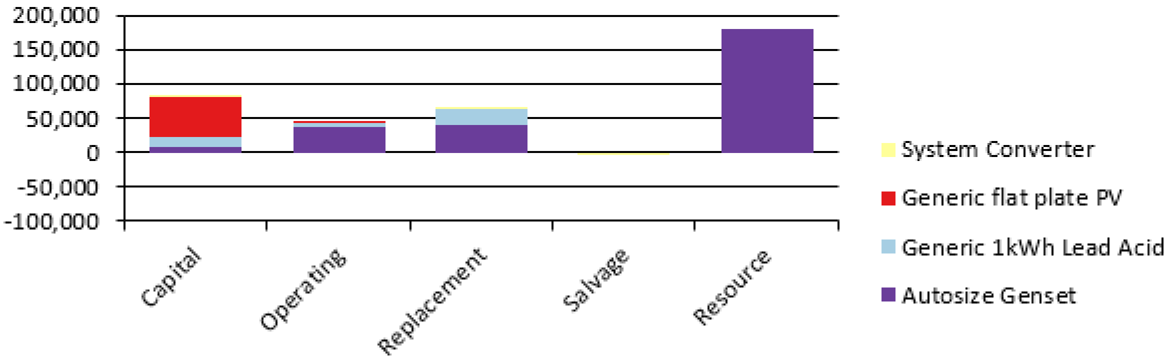


Figure 4.2.1.4 Costs summary

Like in previous cases, the resource cost is accounts for. 68.6% of the diesel generator costs with a USD 180448 value. The solar PV contributes about 70.5% to the total capital costs of USD 83967.00. On the other hand, the diesel generator dominates the system operating costs (USD 45263.00), accounting for 81.5% of the total costs for this category. Yet again, the diesel generator is the principal contributing to the total annual system cost, holding about 70.8% share of the overall system costs of USD 371274.00.

- **Configuration No. 05: Solar PV and Storage**

The configuration of this system comprises three components: a solar PV, the 1kWh lead acid battery, and a system converter. Table 4.2.9 displays the technical characteristics of these components below.

Table 4.2.9 System technical characteristics

Component	Name	Size	Unit
PV	Generic flat plate PV	101	kW
Storage	Generic 1kWh Lead Acid	591	strings
System converter	System converter	47.1	kW
Dispatch strategy	Homer Cycle Charging		

Here, the solar PV replaces the diesel generator with a 101kW capacity, accounting for 100% power supply to the AC load, including the DC storage system of the batteries. The 12 V capacity of the 1kWh lead acid battery supplies 7092 volts of backup power. The 47.1 kW system converter serves both as an inverter for the storage charge control, and as a rectifier for the AC load distribution.

Next is the system annual costs. The annual costs contain CAPEX, OPEX, replacement, salvage, and resource costs. Figure 4.2.0-5 reveals the contributions of each component to the overall system costs in the chart below.

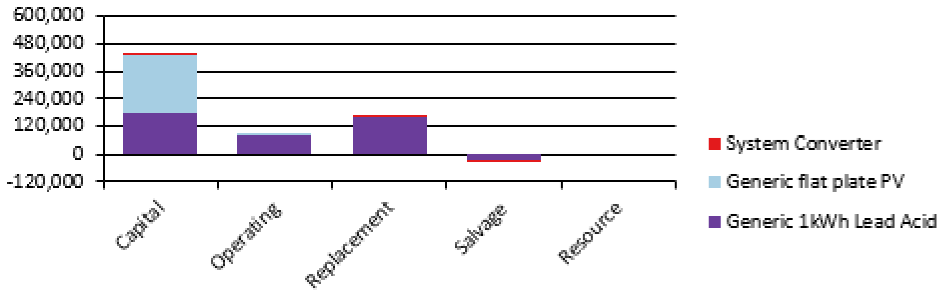


Figure 4.2.1.5 Costs summary

Unlike previous configurations, the resource contributes 0% to the overall system costs, because the resource needed for this configuration, solar radiation energy, is free. Nonetheless, the solar PV dominates the system CAPEX a 56.76% (USD 251289.00) contribution, followed by the 1kWh lead acid battery with about 40.05% (USD 177300.00). On the other side, the lead acid battery accounts for 85.46% of the OPEX (USD 76402.00) of the total. The lead acid battery is also the main contributor to the replacement cost with USD 156633.00, constituting about 96.31% of the total. Finally, though the solar PV accounts for 56.76% the CAPEX, the lead acid battery dominates in most of the remaining categories. Holding about 57.87% of the overall system costs, followed by the solar PV at 39.3%, the storage system becomes the principal contributor to the overall system costs. This result is acceptable because the batteries have a short lifetime (15 years) compared to the solar PV's 25-year time of use, resulting in an ever-compounding replacement costs and maintaining fees.

- **Configuration No. 06: Biomass Gasifier, Solar PV, and Storage**

This configuration of the system includes biomass gasifier (100kW fixed capacity biogas Genset), a set of solar PV panels, a system converter, and a lead acid storage option. The technical characteristics of the components in table 4.2.1.1.

Table 4.2.1.1 System technical characteristics

Component	Name	Size	Unit
Generator	BioGen 100kW Fixed Capacity Genset	100	kW
PV	Generic flat plate PV	24.2	kW
Storage	Generic 1kWh Lead Acid	81	Strings
System converter	System converter	18.3	kW
Dispatch strategy	HOMER Load Following		

Here, both the Biomass Gasifier and solar PV satisfy 100% of the load requirement. The solar PV accounts for 44.8% of the annual electrical production, and the lead acid battery rest supplies the backup power. The total electrical production is 77104 kWh/yr, wherein the AC primary load consumes 78.32% of this amount, with an excess of 5597 kWh/yr of electricity to spare. Reported in tables 4.2.1.2 and 4.2.1.3 are the production summary and the consumption summary, respectively.

Table 4.2.1.2 System production summary

Component	Production (kWh/yr)	Percent
Generic flat plate	34529	**44.8**
BioGen 100kW Capacity	42575	**55.2**
Total	**77104**	**100**

Table 4.2.1.3 System consumption summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	60386	100
DC Primary Load	0	0
Deferable Load	0	0
Total	60386	100

Further reports on the Biogas Genset reveal 22.2 tons/yr in fuel consumption is a low fuel consumption of 0.365 kg/kWh. Also, the stats for the biogas genset show that it operates for 1703 hrs/yr, with a 4.86 capacity factor, and a marginal cost of USD 0.0302/kWh. CO_2 emitted is a measly 3.45kg/r from a high of 17.7kg/yr reported for the base case, an 80.5% reduction in the annual greenhouse gas emissions. Table 4.2.1.4 details the technical characteristics and emission values for this configuration.

Table 4.2.1.4 technical characteristics and emissions

Quantity	Value	Units
Fuel consumption	22.2	tons/yr
Specific fuel consumption	0.365	kg/kWh
Fuel energy input	23741	kWh/yr
Hours of operation	1703	hrs/yr
Operational life	8.81	yr
Capacity factor	4.86	%
Fixed generation cost	5.00	$/hr
Marginal cost	0.0302	$/kWh
Avg feedstock per day	0.0608	tons/day
Avg feedstock per hour		tons/hour
Pollutant	**Quantity**	**Unit**
CO_2	3.45	kg/yr
CO	0.395	kg/yr
Unburned Hydrocarbons	0.0160	kg/yr
Particulate matter	0.00158	kg/yr
Sulfur dioxide	0	kg/yr
Nitrogen oxides	0.0316	kg/yr

The system costs contain the following components: CAPEX, OPEX, replacement, salvage value, and resource costs. The chart following reveals contributions of each cost component to the overall cost.

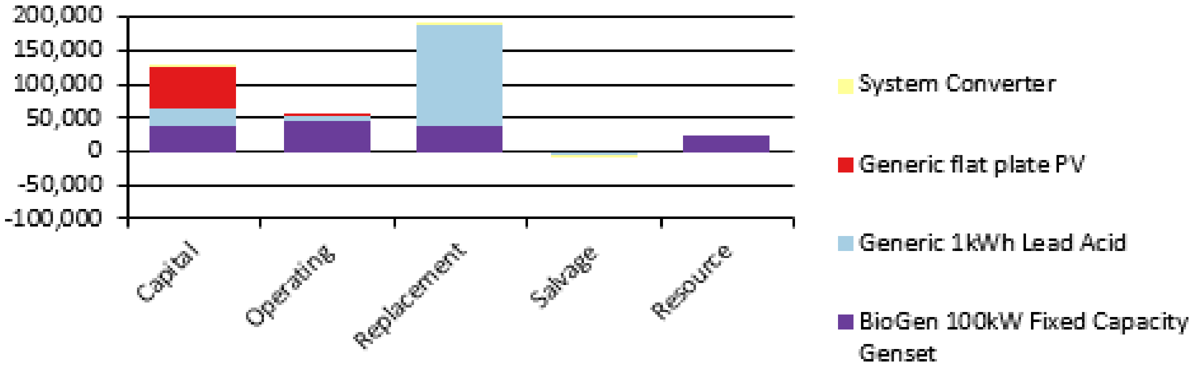


Figure 4.2.1.6 Costs summary

Contrary to configuration N0. 05, the resource costs contribute about 6.02%% to the overall system costs, because though solar radiation energy is free, there are costs associated with biomass resources. The costs associated with biomass can include land cost, feedstock price, and labor cost. Nonetheless, the solar PV dominates the system CAPEX a 46.49% (USD 60624.00) contribution, followed by the BioGen 100kW Fixed Capacity Genset with about 30.67% (USD 40000.00). In the OPEX category, the BioGen 100kW Fixed Capacity Genset for 76.39% of the OPEX (USD 44031.00) of the total. For the replacement costs, the lead acid battery dominates with USD 149736.00 value representing 78.45% of the total. And as expected, the BioGen 100kW genset is the only contributor to the resource costs with USD 23964.00. Finally, despite contributing the highest amount in a single category, the lead acid battery tops the list for the highest contributor to the overall system costs by accounting for about 45.63% of the annual total, followed by the BioGen 100kW Fixed Capacity Genset 36.50%. This result is factual because the batteries have a short two-year lifespan in this scenario compared to the solar PV's 25-year time of use and the BioGen Genset's 8.81 years, resulting in an ever-compounding replacement costs and maintaining fees.

- **Configuration No. 07: Biomass Gasifier and Storage**

This configuration of the system includes biomass gasifier (100kW fixed capacity biogas Genset), a system converter, and a lead acid storage option. The technical characteristics of the components in table 4.2.1.5.

Table 4.2.1.5 System technical characteristics

Component	Name	Size	Unit
Generator	BioGen 100kW Fixed Capacity Genset	100	kW
Storage	Generic 1kWh Lead Acid	81	Strings
System converter	System Converter	18.0	kW
Dispatch strategy	HOMER Load Following		

Here, the BioGen 100kW Fixed Capacity Genset satisfy 100% of the load requirement since it also supplies the storage system. The total electrical production is 75650 kWh/yr, wherein the AC primary load consumes 79.82% of this amount, with an excess of 768 kWh/yr of electricity to spare. Both the production summary and consumption summary are in accompanying tables 4.2.1.6 and 4.2.1.7, respectively.

Table 4.2.1.6 Biomass Gasifier production

Component	Production (kWh/yr)	Percent
BioGen 100kW Fixed Capacity Genset	75650	100
Total	75650	100

Table 4.2.1.7 System consumption summary

Component	Consumption (kWh/yr)	Percent
AC Primary	60386	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	60386	100

Further reports on the Biogas Genset reveal 39.4 tons/yr in fuel consumption, with a low specific fuel consumption of 0.365 kg/kWh. Also, the stats for the biogas genset show that it operates for 3026 hrs/yr, with an 8.64 capacity factor, and a marginal cost of USD 0.0302/kWh. CO_2 emitted is modest 6.12kg/r from a high of 17.7kg/yr reported for the base case, a 65.4% reduction in the annual greenhouse gas emissions. Table 4.2.1.8 reports the full details.

Table 4.2.1.8 technical characteristics and emissions

Quantity	**Value**	**Units**
Fuel consumption	39.4	tons/yr
Specific fuel consumption	0.365	kg/kWh
Fuel energy input	42185	kWh/yr
Hours of operation	3026	hrs/yr
Operational life	4.96	yr
Capacity factor	8.64	%
Fixed generation cost	5.00	$/hr
Marginal cost	0.0302	$/kWh
Avg feedstock per day	0.108	tons/day
Avg feedstock per hour	0.00450	tons/hour
Pollutant	**Quantity**	**Unit**
CO_2	6.12	kg/yr
CO	0.702	kg/yr
Unburned Hydrocarbons	0.0284	kg/yr
Particulate matter	0.00281	kg/yr
Sulfur dioxide	0	kg/yr
Nitrogen oxides	0.0562	kg/yr

The system costs comprise the following: CAPEX, OPEX, replacement, salvage value, and resource costs. The following chart display the value of each cost component.

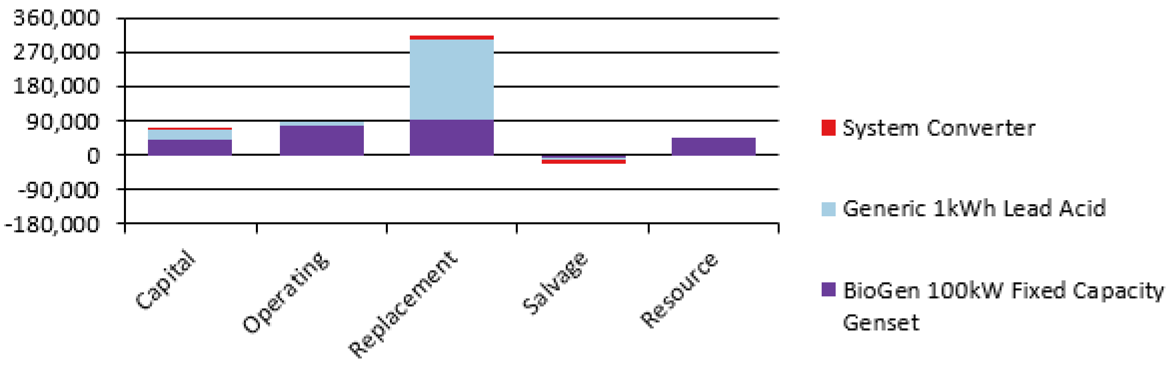


Figure 4.2.1.7 Costs summary

In this configuration, the resource costs contribute about 8.64%% to the overall system costs, solely contributed by the biomass resources. The costs associated with biomass can include land cost, feedstock price, and labor cost. The CAPEX of the BioGen 100kW Fixed Capacity Genset in this system is the same as in configuration No. 06, but constitutes 57.40% of the total USD 69691.00, followed by the lead acid battery with about 34.87% (USD 24,300.00). In the OPEX category, the BioGen 100kW Fixed Capacity Genset also accounts for 88.20% of the OPEX with (USD 78237.00) of the total USD 88709.00. Like the replacement costs in configuration No. 06, the lead acid battery here dominates with USD 211786.00 value representing 69.08% of the total USD 306576.00. And as expected, the BioGen 100kW genset is the only contributor to the resource costs with USD 42580.00, also doubling that of configuration No. 06. Finally, unsurprisingly, the BioGen 100kW Fixed Capacity Genset tops the list for the highest contributor to the overall system costs by accounting for about 49.53% of the annual total USD 492980, slightly above the Lead Acid Battery by a 0.53% margin. Lastly, the storage dominance in the OPEX category results from the fact that the batteries have a short 1.46-year lifespan in this scenario compared to the BioGen Genset's 4.96 years, resulting in an ever-compounding replacement costs and maintaining fees.

4.2.1 Miscellaneous Findings

Personal Info of the respondents

- The findings share lights on the prevailing socio-economic situations in the case study site, including the electricity consumption pattern of the households. For the first component of the survey the questionnaire was focused on the social relationship trend in the area. The figures below summarize important variables considered.

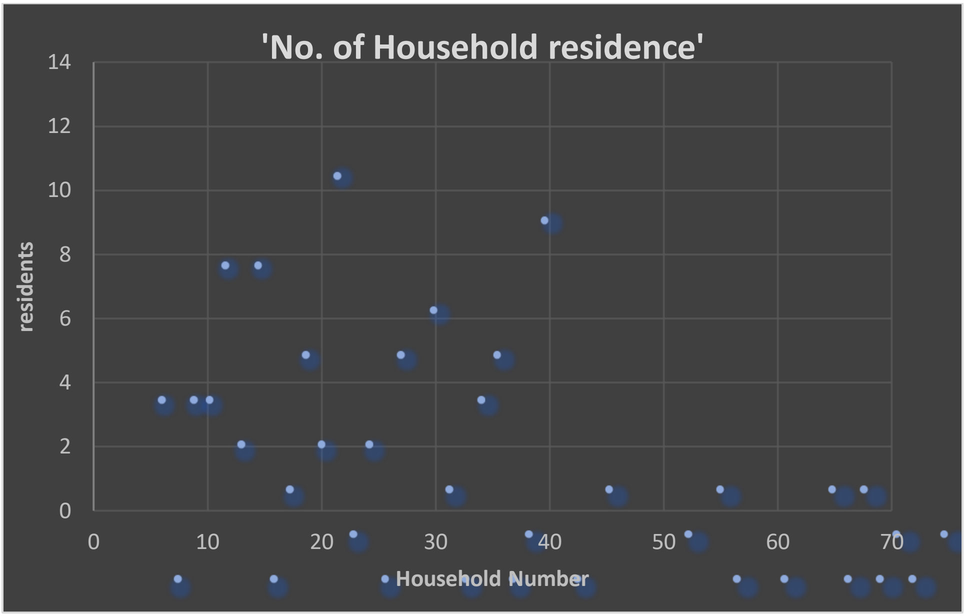


Figure 4.2.2.1 *per household distribution of residence*

The figure above reveals that the household No. 13 (as reported by the respondent #13), holds the highest number of residents (12 persons), followed by households No.26 & No. 06 with 11 and 10 residents, respectively. In terms of energy needs, one can expect that these households will demand more electricity, and therefore, will bear the huge costs associated with increased power consumption. On the other side, four households reported just one resident each; thirteen houses reported hosting two residents each, while another thirteen revealed hosting three residents each. Similarly, the household reporting such low figures should have a significantly lower incurred energy costs compared to their counterparts with higher number of residents. To put this into perspective, assume the following.

- equal non-human load for all household
- One mobile phone for every two residents

- One laptop computer for every four residents

Given that the base rated power for a mobile is 5W and for a laptop is 60W, then the additional load for household No. 13 becomes (½) *(12) *(5W) *(1h) + (1/2) *(12) *(60W) *(1h) = 390Wh, and for households No. 06 & No. 26, it becomes (1/2) *(10) *(5W) *(1h) + (1/2) *(10) *(60W) *(1h) = 325Wh each. Based on the assumptions, there is a null additional load for a household with one resident. However, household with two residents will incur an additional load of 65Wh, and a household of three residents will incur 97.5Wh additional load. Take $0.03/Wh for the average cost for electricity and realize the cost difference between both sets of houses.

Also captured under this category is the respondents' sexual profile. The total number of respondents is sixty-two, with the females constituting about 53% of the total respondents. The following table summarizes the sex distribution in the case study area.

Table 4.2.2.2 Sex distribution among respondents

		Percent of respondent
No. of females	33	53%
No. of males	29	47%

The average age of the population is 34 years, a potential for industrial and economic growth.

- **Economic status**

The key components here are the employment rate, total earnings for the case, and the distributed liquid capital among the residents. The next table show the employment status as revealed by the respondents.

Table 4.2.2.3 case study employment status

		Percent of the population
No. of employed respondent	21	34%
no. of unemployed respondent	41	66%

The 66% unemployment rate in the case study is alarming as people without jobs are vulnerable poor living standards and insecurity. This prominent level of unemployment can also impair most of the residents' ability to purchase electricity. Yet still, the average monthly earning for the employed portion of the population is LRD 55857.14 (about USD 328.57). When spread across the entire population, this value drops to a mere 900.92 (USD 5.30). Given that the average monthly cost of electricity is LRD 5100.00 (USD 30.00), it becomes clear how challenging it must be for the residents to gain access to electricity. Nonetheless, an increase in job opportunities for a young population could boost the economy of the region, improve living conditions, while enabling residents to afford their energy needs.

- **Electricity profile**

The electricity profile includes the electricity access rate, the average cost of electricity, and the share of electricity by source. CDG is for community diesel generator, CLL is Chinese led light, KL is kerosene lantern, PDG is personal diesel generator, and SP is solar panel. Table 4.2.2.4 shows levels of electricity access as observed during the survey and revealed by the respondents.

Table 4.2.2.4 Electricity access

		Percent
Respondents with electricity access	31	50%
Respondents without electricity access	31	50%

With only half the population having electricity access, the other half endures the unbearable darkness and to exists in a below standard life. Notwithstanding, introduction of alternative energy modern sources could significantly reduce energy cost and eventually alleviate energy poverty in the region. A look at the share of electricity access from various sources unveiled the following as reported in table 4.2.2.3.

Table 4.2.2.5 Sources of electricity

Electricity access		**Other means of lighting**	
Source	Percent of respondents	Source	Percent of respondents
CDG	71%	Candles	6%
PDG	16%	CLL	71%
SP	13%	KL	23%

Bulk of the residents rely on CDG for electricity, with only 13% of the total getting power SP systems. Those without electricity access depend principally on CLL for lights at night, with only 6% of the other relying on candles, a potentially dangerous source of light.

Lastly, the school, church, and the community clinic, among other service centers all lack access to electricity. Hence, these facilities render limited services to the residents. The results are slow personal growth, a stagnant economy, suppression of innovation and increased poverty.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This paper intended to design a sustainable hybrid energy system for the off-grid community of Own Your Own Housing Estate. The estate contains seventy-six (76) households, a primary public school, a church, a community clinic, and a marketplace. To determine the suitable hybrid energy system for the case study, seven configurations were simulated comprising the various proposed systems. A techno-economic analysis was performed, followed by the discussion of the survey results for the case study, to compare each system to choose the most suitable power system, with regards to the residents economic and social characteristics.

The seven configurations and their respective components are as follow.

- Configuration No. 01: Diesel generator (Base case)
- Configuration No. 02: Diesel generator and Solar PV
- Configuration No. 03: Diesel generator, Solar PV, and Storage
- Configuration No. 04: Diesel generator, Biomass Gasifier, Solar PV, and Storage
- Configuration No. 05: Solar PV and Storage
- Configuration No. 06: Biomass Gasifier, Solar PV, and Storage
- Configuration No. 07: Biomass Gasifier and Storage

HOMER Pro Software was employed to design and set optimizations parameter of the seven (7) proposed configurations. The systems design took into consideration the techno-economic characteristics of each component including load demands, climatic characteristics of case study site, and the components costs. The load requirements accounted for the seventy-six households in the case study boundaries, the primary school, the church, community clinic, and the marketplace. The loads assessment also covered both climatic periods: the Dry Season and the Rainy Season. The average total daily load is 165.44kWh with a peak value of 14.95kW.

Comparisons among the seven configurations reveal that the configurations with the lowest LCOEs (a value showing how much a kWh of electricity costs) are configuration No. 03 with \$0.46/kWh, configuration No. 04 with \$0.48/kWh, and configuration No. 06 with \$0.51/kWh. However, configuration No. 03 have an associated emission value of CO_2 37139kg/yr, followed by configuration No. 04 with 36538kg/yr of CO_2. Compared to these two configurations, configuration No. 06 yields 99.99% reduction in annual CO_2 emissions. Therefore, considering the narrow price gap both configurations No. 03 & 04, and configuration No. 06, Configuration No. 06, comprising a biomass gasifier (100kW fixed capacity biogas Genset), a set of solar PV panels (24.2kW), a system converter (18kW), and a lead acid storage option (81 strings), is technically the best energy system option for the case study with SDG7 in mind. However, considering the economic status of the residence coupled with the need for low-cost electricity for all, Configuration No. 03 (the lowest LCOE) is the best energy system option. Even still, with just a 5% decrease in its NPC, Configuration No. 06 could become more affordable than its competitors. Also, increase in employment rates of the residents can improve their ability to afford the cost of power from Configuration No. 06.

5.2 Recommendation

Electricity access is crucial to the growth and development of the case study area. The site receives a moderate daily solar irradiation (4.84kWh/m^2/day), coupled with an abundance of biomass resources. Sadly only 50% of the population has electricity, of which diesel generator supply 100%. Additionally, the employment rate is low, resulting to a meager financial potential for the residents. Cognizant of these factors, the following are recommended:

- The adoption of a hybrid energy system of Biomass Gasifier, Solar PV and a storage system as specified in configuration No. 06.
- An alternative is the temporary adoption of the system proposed in configuration No. 03 to provide more affordable power, followed by its replacement with that of configuration No. 06 to safe of carbon emissions.
- The need for capacity building for the locals to enable eventually manage and maintain the renewable hybrid energy system is crucial to job creation and the sustainability of the project.
- The creation of gender-inclusive job opportunities is essential to the residents to afford power and to live comfortably
- Encouragement of private-public partnership in the development of any off-grid microgrid in the case study area to ensure equity distribution for the project.

- Government willingness to equally subsidize the development of the recommended power system to ensure fair competition with diesel-based power systems.
- Finally, the need for further research in the case study to determine the detailed technical potential for both solar power and biomass resources.

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