

**AKENTEN APPIAH-MENKA UNIVERSITY OF SKILLS TRAINING AND
ENTREPRENEURIAL DEVELOPMENT**

**TECHNO-ECONOMIC ANALYSIS OF HYBRID ENERGY SYSTEM FOR
HOSPITALS
(A CASE STUDY OF WENCHI METHODIST HOSPITAL)**

DANIEL AFRIFA

JULY, 2023

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**A Thesis Submitted to the Department of Electricals and Electronic Technology
Education, Faculty of Technical Education, submitted to the School of Graduate
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Master of Philosophy Electrical Power System Engineering in the Akenten
Appiah-Menka University of Skills Training and Entrepreneurial Development.**

JULY, 2023

DECLARATION

Student's Declaration

I, DANIEL AFRIFA, declare that this thesis, with the exception of quotations and references contained in the published works which have all been identified and duly acknowledged, is entirely my original work, and it has not been submitted, either in part or whole, for another degree elsewhere.

SIGNATURE:

DATE:

Supervisor's Declaration

I hereby declare that the preparation and presentation of this work was supervised in accordance with the guidelines for supervision of thesis as laid down by the **Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development**

DR. KOFFI A. DOTCHE

SIGNATURE:

DATE:

DEDICATION

This scholarly work is especially dedicated to the Almighty God by whose love, grace, have I made it in this life. With you oh Lord, my life has been luxuriantly fruitful, and full of spectacular graces. I love you dearly.

Secondly, I dedicated this dissertation to my favorite one Dr. Linda Maud Naa-Dedei Palm. I love you dearly.

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ABSTRACT

The techno-economic feasibility study presented in this thesis assessed the potential of a hybrid energy system to provide sustainable and reliable electricity to the Wenchi Methodist Hospital in Ghana, while reducing its dependence on the national grid. The HOMER Pro simulation tool was employed to design and simulate different hybrid energy system configurations, taking into account the energy demand of the hospital, the solar irradiation data, and the cost of components. The financial analysis was conducted to evaluate the economic viability of the proposed hybrid energy system.

The simulation results showed that a hybrid energy system consisting of 115 kW photovoltaic system connected to a 500 kW grid line, a 37.5 kW converter, and a 70 kW generator could provide reliable and sustainable electricity to Wenchi Methodist hospital, with a renewable fraction of 96.7% and a capacity shortage of 0%. The system also had the potential to sell excess electricity to the national grid, resulting in significant financial and environmental benefits. The Net present cost (NPC) for the hybrid energy system was estimated to be US\$ 156,358 with an estimated Levelized cost of energy (LCOE) of 0.10\$/kWh and O&M cost of US\$ 10.44 per year

Overall, the results of this study demonstrated the technical and economic feasibility of a hybrid energy system for the Wenchi Methodist Hospital in Ghana. The proposed system had the potential to improve the hospital's access to reliable and sustainable electricity, reduce its operating costs, and contribute to the country's efforts to transition to a low-carbon economy.

CHAPTER ONE

INTRODUCTION

1.0 Background of the study

All around the world, energy access has had huge effect on every nation's socioeconomic development. Thus, a progress of a country is significantly dependent on the total amount of energy accessible for consumption. It is estimated by the United Nations Environment Program (UNEP) that two billion people in villages and developing countries around the world, lack grid-based electricity services (Moses & Shruthi, 2017; (Olatomiwa et al., 2015). Nonetheless, population around the globe keeps increasing, resulting in increased socio-economic activities as such, places a demand on continuous energy supply.

Electricity is considered a key measure to sustainable socio-economic growth necessary for human development (Olatomiwa et al., 2015). This energy which has virtually become a basic requirement for all, is very essential in enhancing income and improving livelihoods across the world (Teklemichael Bahta, 2013), and requires serious attention to be given for continuous supply to all. This energy form has become more accessible with the introduction of renewable energy (RE) resources off-grid through stand-alone hybrid systems. Renewable energy has proven to be a clean source of energy as such, it is necessitating radical transition from conventional non-renewable energy sources by many Countries (Bonah & Nutakor, 2020). With the introduction of these renewable energy sources, other energy sources of CO₂ emissions are cut down and fuel price variations are reduced if not totally avoided.

Besides, renewable source of energy gives better performance and offer affordability of renewable technologies (Bonah & Nutakor, 2020; Díaz, 2017).

With the advantages of RE, more countries are seriously exploring that option. However, the use of renewable energy seems to be focusing so far on a single technology, which may not be sufficient at all time. Examples of solar home systems, solar photovoltaic systems and micro-hydro power have been widely used, but these options are often unable to cater for consumers' needs adequately and reliably, basically due to limited resource availability arising from resource variability (Sen & Bhattacharyya, 2014). Dependence on a single technology generally results in an over-sizing of the system. A hybrid system design is currently the optimal way to overcome the intermittent nature of renewable energy sources, the issue of over-sizing and improvement in supply reliability (Tibiru, 2013). Despite the advantages of hybrid systems, they have received limited attention owing to their increased complications (their technological complexity and cost analysis) (Bonah & Nutakor, 2020; Sen & Bhattacharyya, 2014).

However, lately, many homes in remote islands, cities and towns are adopting the hybrid kind of technology and so are using hybrid RE systems (Ayirewura, 2013). Ghana, like other Countries are in line towards the exploration and use of renewable energy. Adaramola, M. S., Agelin-Chaab, M., & Paul, S. S. (2014) worked on the techno-economic viability of using a hybrid system consisting PV/wind/diesel to power an isolated area, Adafoah in Southern Ghana. Similarly, Bonah & Nutakor (2020) worked at evaluating the techno-economic potential of a PV/wind/DG/Battery and Wind/DG/Battery system for commercial purposes in Mankwadze, also in the

southern part of Ghana. Literature has also revealed the work done to explore the likelihood of integrating PV and biodiesel generators to form a hybrid system to meet water and electricity needs of a particular locality in the northern part of Ghana (Adaramola et al., 2017). With the Addo et al. (2014) team, a research on a PV/wind hybrid system to power a cluster of villages at Bonsaaso in the Ashanti Region of Ghana was undertaken. Work done by Dankwah (2018) in Accra, Ghana, proposed providing the Accra Technical University with a hybrid system configuration to include PV/grid/diesel generator as opposed to the PV/wind/diesel generator done by Adaramola et al. (2014).

1.2 Problem statement

Although Ghana is endowed with abundance renewable energy source for electricity, many communities are still faced with the challenge of being supplied with electricity. Some of these areas which are without constant power supply, house populated work force for the Nation. Wenchi Methodist Hospital faces challenges with supply though connected to the national grid for electricity. They are often faced with intermittent power supply (Dumsor) which sometimes goes off for a whole day.

The provision of reliable and sustainable energy sources in hospitals is a critical issue in many countries, including Ghana. Despite the increasing demand for constant power supply, the energy needs of hospitals are often not met by the traditional grid-connected electricity, which is unreliable and prone to power outages. This can result in significant harm to patients and disrupt the provision of healthcare services.

Moreover, the high costs associated with installation and maintenance of hybrid energy systems, as well as a lack of understanding about the benefits and limitations of these systems, have limited the adoption of hybrid energy systems in hospitals. There is a need for a comprehensive and in-depth analysis of hybrid energy systems for hospitals to identify the most cost-effective and sustainable systems for the region. The purpose of this thesis is to address this gap in knowledge by conducting a techno-economic analysis of hybrid energy systems for hospitals in the Bono region of Ghana.

1.3 Objective

The objective of this thesis is to conduct a techno-economic analysis of hybrid energy systems for hospitals with a focus on Wenchi Methodist Hospital. The specific research objectives are:

- Develop a theoretical model for evaluating hybrid energy supplies
- To assess the energy consumption patterns and sources at Wenchi Methodist Hospital.
- Use relevant metaheuristic optimization techniques to assess optimal design solution
- To evaluate the feasibility of implementing a hybrid energy system in Wenchi Methodist Hospital.
- To conduct a cost-benefit analysis of the hybrid energy system.

1.4 Research questions

- What is the current energy consumption pattern in hospitals and how does it compare with the energy consumption trends in the healthcare sector?

- What is the potential for implementing hybrid energy systems in hospitals, and how does it compare with traditional energy systems?
- What are the capital costs, operating costs, payback period, and life cycle cost of implementing hybrid energy systems in hospitals?

1.5 Significance of the study

The significance of this study lies in its potential to provide valuable insights into the implementation of hybrid energy systems in hospitals. The healthcare sector is a significant contributor to the global energy consumption and has a crucial role in promoting sustainability. By conducting a techno-economic analysis of the implementation of hybrid energy systems in hospitals, this study aims to provide a comprehensive understanding of the feasibility and benefits of such systems.

The results of this study will be of significant importance to policymakers, healthcare administrators, and energy stakeholders. The findings will provide a clear understanding of the potential benefits and limitations of implementing hybrid energy systems in hospitals. The recommendations of this study will also help healthcare administrators to make informed decisions about investing in hybrid energy systems and promote sustainable energy practices in the healthcare sector.

Moreover, this study will contribute to the existing literature on hybrid energy systems and provide a comprehensive analysis of their implementation in the healthcare sector. The findings of this study will also provide a basis for further research and development in this area and help in promoting sustainability in the healthcare sector.

1.6 Limitations of the Study

This research sought to perform and conduct a techno-economic analysis of hybrid energy systems for hospitals with a focus on Wenchi Methodist Hospital. The availability of data on energy consumption patterns in hospitals and techno-economic data of hybrid energy systems may be limited. This could impact the accuracy of the results and the conclusions of the study.

The findings of this study may not be generalizable to all hospitals as they are dependent on the specific characteristics of each hospital, such as its size, location, and energy consumption patterns. The techno-economic analysis of the implementation of hybrid energy systems in hospitals will be based on mathematical models. These models are subject to limitations and assumptions, which could impact the accuracy of the results.

The study will make certain assumptions, such as constant energy consumption patterns and constant technological and economic parameters, which may not reflect the reality in all cases

1.7 Structure of the study

The thesis is organized as follows; Background to the study and objectives are presented in chapter one. The literature review is presented in chapter two. The resources, materials, and methods utilized in this investigation are presented in chapter three. The findings are presented and discussed in chapter four. The research conclusions and recommendations are outlined in chapter five and suggestions for future research.

CHAPTER TWO

LITERATURE REVIEW

Chapter two gives details illustration concerning energy potential and the state of energy in Ghana and globally. In addition, various studies done on hybrid renewable systems in Ghana and elsewhere are enlightened, the components used for the study and their outcome.

2.1 The State of Global Energy Supply

All across the world, energy supply is from both renewable and non-renewable sources with the non-renewable energy source (fossil fuel) accounting for over 80% of world energy use. Specifically, in 2019, about 84% of global primary energy came from fossil fuel (coal, oil and gas) (Apotei, 2019; Ritchie, and Roser, 2017). Electricity, which is one of the components of the world's total energy consumption with the other two being transport and heating, consumed about 64% of fossil fuels in 2019 (Ritchie, and Roser, 2017). Similar to the world's electricity consumption, Ghana also consumed about 65% of the total grid electricity in 2018. This is represented by 10,588.86 GWh of power distributed to their customers, mainly domestic (Energy Commission, 2018). Despite the fact that fossil fuels are relatively inexpensive and easy to identify and transport, recent increases in energy demand have resulted in a fast scarcity of such fuels. Since such fuels are non-renewable, it will take billions of years to be replenished. In years to come, the non-renewability of some energy sources, such as fossil fuels, may result in increase in their fuel prices in areas where they are not economically viable (Apotei, 2019). This will ultimately lead to a shift of renewable energy use. Additionally, the use of fossil fuels in energy

production and use has caused major health and environmental impacts such as air pollution which arises as a result of such releases as SO_x, NO_x, CO₂ (Smith et al., 2015) other greenhouse gas (GHG) emission; carbon monoxide and eventually lead to human health challenges (Murphy et al., 2006). Renewable energy sources such as solar, wind, and biomass are therefore deemed optimum alternative energy source to the conventional fossil fuels in local industries and it is expected to minimize the dependence on the overloaded national electricity grids. It is recognized also that the deployment of renewable energy technologies (RET) for various institutions could make a major contribution to the development of a sustainable energy system in the Country.

2.2 Ghana's Energy profile

Ghana has abundant natural resources such as cocoa, gold, and crude oil, with a total land area of 238,533 square kilometres. Ghana is a low-income developing nation with a GDP of 58.47 billion USD (IEA, 2012) and a population of 26 million (GSS, 2015; Mensah et al., 2017; UNIDO, 2016) and increasing. Though rich in natural resources, Ghana is still facing difficulties such as energy crises (Mensah et al., 2017). Currently, Ghana's grid electricity generation capability includes hydropower plants, thermal power plants, and renewables and is still progressing in its energy accessibility to its citizens. As at 2015, Ghana had an 80 percent electrification rate (Energy Commission, 2019a) which have steadily increased reaching over 85% in 2017 having built on successful electrification initiatives. The country has a diverse energy mix (IEA, 2012).

Over the past few decades, electricity production in Ghana has gradually expanded. With an average growth rate of 7%, total energy generation increased from 11,200 GWh in 2011 to 22,051 GWh in 2021. From the total amount of electricity produced in 2021, 7,521 GWh came from hydropower, 14,408 GWh from thermal power, and 122 GWh from renewable energy sources (Energy Commission, 2022). The installed thermal generation capacity has increased at an average growth rate of 14.3 percent from 2011 to 2021 (Energy Commission, 2022). Ghana has attempted to bring considerable amounts of renewable power to the national energy generation mix, diversifying the country's primary sources of electricity, which have historically been hydro and thermal (Kumi, 2017). About 34.1 percent of the generation mix in 2021 was hydro, compared to 65.3 percent thermal and 0.55 percent renewable energy (Amo-Aidoo et al., 2022; Energy Commission, 2022). The percentage of renewable energy in the generating mix has doubled from its 0.28 percent share in 2020 (Energy Commission, 2022). The use of renewable energy is progressively rising due to ongoing cost reductions and a deliberate attempt to diversify the mix (Ansu-Mensah & Kwakwa, 2021; Lee et al., 2020; Takase et al., 2022). Table 2.1 shows the growth of electricity generating power plants and their installed and reliable generation capabilities in 2021.

Table 2.1 Total Installed and dependable generation capacities in Ghana as of 2021 (Energy Commission, 2022)

| Plant | Installed Capacity | Dependable Capacity |
|------------------------------------|---------------------------|----------------------------|
| Thermal power plant | 3649MW | 3395 MW |
| Hydroelectric Plant | 1580 MW | 1400 MW |
| Other renewable energy (on-grid) | 144.05 MW | 94.65 MW |
| Other renewable energy (off-grid) | 7.44 MW | - |
| Other renewable energy (mini-grid) | 119.865 MW | 94.6 MW |
| Total | 5488.82 MW | 4975.25 MW |

2.2.1 Electricity demand

Energy consumption during the past 20 years has increased along with the generation capacity; between 2000 and 2021, yearly increases in total power usage averaged 4.7 percent. Compared to 30.4 percent and 43 percent of the total power utilized in 2020, the industrial and residential sectors consumed 31.8 percent and 47 percent of the energy in 2021, respectively (Energy Commission, 2022).

Over the past 21 years, Ghana has seen a peak load (system) growth of around 180 percent, which equals a 5% compound annual growth rate (Statistics, 2022). According to Figure. 2.1, it climbed from 1,161 MW in 2000 to 3,246 MW in 2021, reflecting a compound growth rate of 5%. On the other side, peak load (domestic) grew by around 248 percent during that time. The peak load on the system increased by 10.2%, while domestic peak demand in Ghana climbed by 9.3% in 2020 over 2019 (Andoh et al., 2021; Energy Commission, 2022; Thoresen & Skogheim, 2021). Peak demand for the Ghana system is expected to rise from 3,539 MW in 2022 to 4,460 MW in 2026. With power exports to Togo, Benin, Burkina Faso, and Mali included, the total energy demand for Ghana is anticipated to rise (Energy commission, 2021a). It is expected to increase further by 2030, peaking at around 36,500GWh (Andoh et al., 2021; Sasu, 2022)

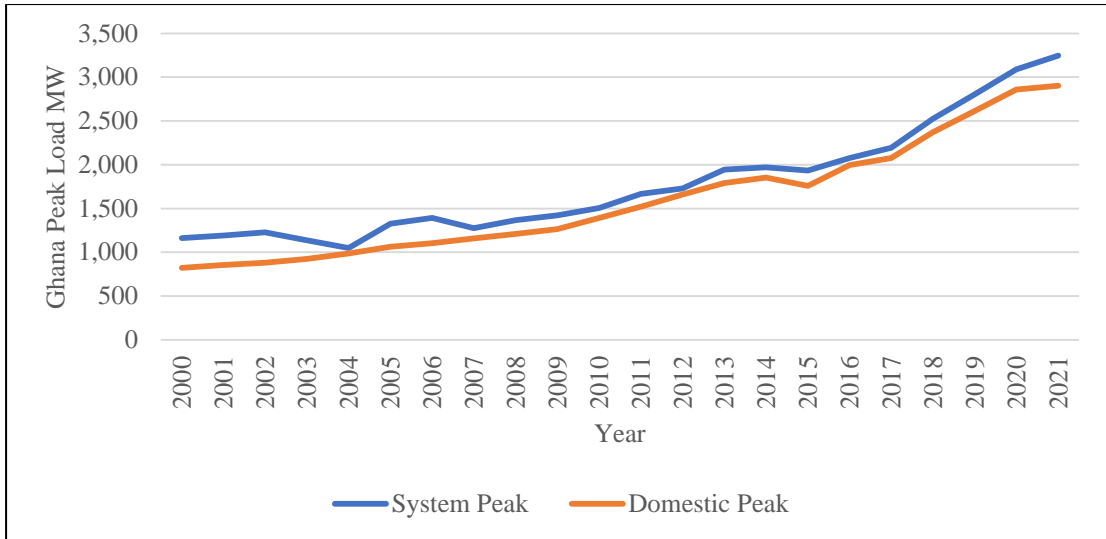


Figure. 2.1 System and Ghana Peak Load (MW) (Energy Commission, 2022)

2.2.2 Transmission losses

The country had continuously relied on the transmission and distribution network for over three decades, starting in 1989 when the NES was implemented. This long and constant dependence on the transmission and distribution system has caused the infrastructure to deteriorate, leading to frequent power outages, high transmission losses, overloaded transformers, etc. (Gyamfi et al., 2015). Between 2000 and 2021, transmission losses increased by nearly 79 percent, from 229 GWh to 1,076 GWh. An estimated 35% of the transmission and distribution systems loss (Energy Commission, 2022; Gyamfi et al., 2015; Twerefou & Abeney, 2020).

The electricity demand projections for the next several decades are staggering, and the electricity grid will have to continue to adapt if we are to meet these demands. By 2030, energy consumption is projected to rise by around 10% annually, reaching 40,000 gigawatt hours (GWh) (Wisdom et al., 2019). According to the Energy Commission, an additional producing capacity of 200 MW per year is needed to meet the anticipated demand. Therefore, examining the potential of renewable energy

resources for electricity generation is necessary to ensure the projected energy demand is met with a sustainable and reliable energy supply.

2.3 Ghana's Renewable Energy legal framework

Ghana has made a commitment to renewable energy production and consumption. As a result, Ghana's government has signed up to a number of policy instruments. Ghana agreed to the Economic Community of West African States' (ECOWAS) White Paper for a Regional policy's energy access goal. This stated that by 2015, the initiative must provide modern electricity access to 50% of West Africa's population (ECOWAS, 2005). The Ghana's Government recommended some renewable energy policies. These were the National Energy Policy (NEP) 2010 (Ministry of Energy, 2010) and Strategic National Energy Plan (SNEP) 2006–2020 (Energy Commission, 2006). In the 2010 NEP, the Government of Ghana (GoG) echoed the country target for RE development for grid power supply. These RE resources include mini-hydro, wind, solar and waste-to-energy (Ministry of Energy, 2010). The SNEP 2006–2020 document shows that the GoG has plans and strategies to grow the country's energy market, which is expected to offer sufficient, feasible, and efficient energy services for socioeconomic growth. This is possible by the design of a complete strategy to identify the best pathway for development, operation and managing of the RE resources (Ministry of Energy, 2010; Obeng-Darko, 2019). In that light, Ghana's goal of increasing the share of renewable energy in the national energy mix to 10% by 2020 was dependent on the development and usage of locally available renewable energy resources for electricity generation (Energy Commission, 2006). As part of Ghana's plan, the government intended to deploy RET to attaining 30% penetration in rural electrification by 2020 (Energy Commission, 2006). The Renewable Energy Act

of 2011 establishes a framework for renewable energy technology development, management, usage, sustainability, and appropriate supply, as well as the development of indigenous capabilities in RE technologies (Government of Ghana, 2011). This aims at enhancing the proportion of renewable energy in Ghana's national energy supply mix for households, agriculture, industries, and transportation while also assisting in the mitigation of climate change-related challenges (Hagan, 2015). Ghana has also been able to ratify a number of other acts to support the development and sustainability of RE. The Energy Fund Act 1997, (Act 541) which promotes the development and efficient use of RE, the Ghana Investment Promotion Council Act 2013 (Act 865) which gives tax incentives for investments situated outside industrial areas and the Value Added Tax Act 2013, (Act 870) which exempts imported renewable energy equipment into the country from tax (ECREEE, 2015).

2.4 Renewable energy targets

In Ghana, the government outlined several objectives and goals for increasing renewable energy generation to 10% by 2020 (IRENA, 2015b; Mensah et al., 2017) and achieving a 30% penetration of rural electrification through the use of RE technologies by 2020 (Energy Commission, 2006). However, about half of Ghana's population, particularly in rural areas still lack access to the national power grid. These can be ascribed to the present policies and strategies, which included lack of a mixture of rational policies, infrastructural and technological limits, budgetary limits, as well as social and cultural challenges (Kuamoah, 2020). The factors for considerations are:

- financial/ budgetary constraints could be explained by the fact that Ghana had an increasing renewable energy technology investments since 2010, but

expenses of electricity production from the renewable energy sources remain high, making funds insufficient for its development (Obeng-Darko, 2019);

- infrastructural and technological constraints could be resided in the cause that Ghana has seen low renewable energy (RE) permeation rate in its energy mix as a result of lack of infrastructure, particularly for an old, underdeveloped national grid system such that the country additionally is disadvantaged by a lack of technical expertise (Kuamoah, 2020);
- Social and cultural challenges could be explained by the ignorance of the People who has difficulties to modify their habits and accept changes for fear of the unknown (Obeng-Darko, 2019).

2.5 Renewable energy potential and opportunities

Ghana is endowed with gold, cocoa, and oil, among other natural resources. Ghana therefore has the potential to harness locally, available renewable energy resources to meet and augment its daily energy consumption and achieve long-term growth. This means that exploiting renewable energy resources to serve Ghanaians with electricity will have significant environmental benefits (Asumadu-Sarkodie & Owusu, 2016; Mensah et al., 2017).

2.5.1 Solar energy

Solar energy is viewed as a national and international sustainable option capable of meeting rising energy demands due to population and economic growth, as well as industrialisation (Samu & Fahrioglu, 2017). Ghana has ample solar energy, which spans across the country, with a solar energy potential of 35 EJ (Exajoules) (Eshun & Amoako-Tuffour, 2016). The country's solar irradiation level ranges from about 4000

to 6500 Wh/m²/day with the maximum irradiation level identified to be arising in the northern half of the country (Awopone 2021; Gyamfi et al., 2018; Asumadu-Sarkodie & Owusu, 2016). Ghana’s annual solar hours (1800 to 3000 hr/yr) provides the country with high potential for grid electricity connection (Kemausuor et al., 2011; UNIDO, 2016). In recent times, the GoG has undertaken several solar energy system deployment initiatives, with some success (Hagan, 2015). About 42.5 MW of electricity generation from solar power plants have been added to the utility grid. Some rooftop PV systems have also been installed countrywide and solar lanterns have been distributed to communities in rural and distant areas (Energy Commission, 2019b). Some solar PV installation states or architecture in Ghana are indicated in Table 2.2 (Asumadu-sarkodie & Owusu, 2016a)

Table 2.2 Solar PV installations in Ghana (*Asumadu-sarkodie & Owusu, 2016b*)

| Solar PV systems | Installed capacity (kW) | Generation (GWh) |
|------------------------------------|--------------------------------|-------------------------|
| Rural home system | 250 | 0.70-0.90 |
| Urban home system | 20 | 0.05-0.06 |
| School system | 15 | 0.01-0.02 |
| System for lighting health centers | 6 | 0.01-0.10 |
| Vaccine refrigeration | 42 | 0.08-0.09 |
| Water pumping | 120 | 0.24-0.25 |
| Telecommunication | 100 | 0.10-0.20 |
| Battery charging system | 10 | 0.01-0.02 |
| Grid connected system | 60 | 0.10-0.12 |
| Solar streetlights | 10 | 0.04-0.06 |
| Total | 833 | 1.34-1.83 |

Mathematical modelling of Solar PV

The solar irradiance and the ambient conditions given by the PV have been combined into a mathematical model of the PV subsystem (Algieri et al., 2020a). In precise, the electric power of the PV subsystem is calculated on an hourly basis as

$$P_{PV} = \eta_m \eta_o \eta_R \eta_T G N A_m \quad (2.1)$$

where:

G : the global irradiance,

N : the modules number,

A_m : the area of the single module.

η_m : the effectiveness of the module,

η_o : the efficiency of other components (e.g., cables, inverters),

η_R : the reflectance efficiency

η_T :the temperature efficiency

$$\eta_T = 1 + k_T [T_a + (T_{NOCT} - 20) \times \frac{G}{800} - T_{NOCT}] \quad (2.2)$$

where:

k_T : the temperature coefficient,

T_{NOCT} : the nominal operating temperature of the module and

T_a : the ambient temperature.

Mathematical Photovoltaic Energy Modelling

The design of the photovoltaic system consists of determining the appropriate number of PV modules that convert sunlight directly into direct current (DC) power. A photovoltaic (PV) module is an assembly of PV cells. The output power of each PV module at hour (t) ($P_{pv}(t)$) can be expressed as

$$P_{pv(t)} = I_{(t)} \cdot A \cdot \eta_{pv} \quad (2.3)$$

where:

$I_{(t)}$: the solar insolation (kW/m^2) at hour t .

A : the PV module area (m^2),

η_{pv} : the efficiency of the PV module. In this study,

The assumption is that, the PV modules have a maximum power point tracking (MPPT) system and ignored the temperature effects. Considering N_{PV} as the number of PV modules, the overall produced power can be calculated as follows:

$$P_{pv(t)} = N_{pv} \times p_{PV(t)} \quad (2.4)$$

where:

$p_{PV(t)}$: the output power of PV at time t

N_{pv} : the number of PV

2.5.2 Wind energy

Wind energy has a high potential for seaport applications (IRENA, 2015b). Wind energy is produced from the kinetic energy (energy of motion) of the wind moving across the earth surface. The wind turbines convert the kinetic energy of the wind into useful electrical energy. A study conducted to identify locations suitable for wind farms shows that Ghana has a limited number of site suitable for the operation of wind farms. Furthermore, the potential for wind energy is located especially in coastal areas and upland areas as shown in Figure 2.2.

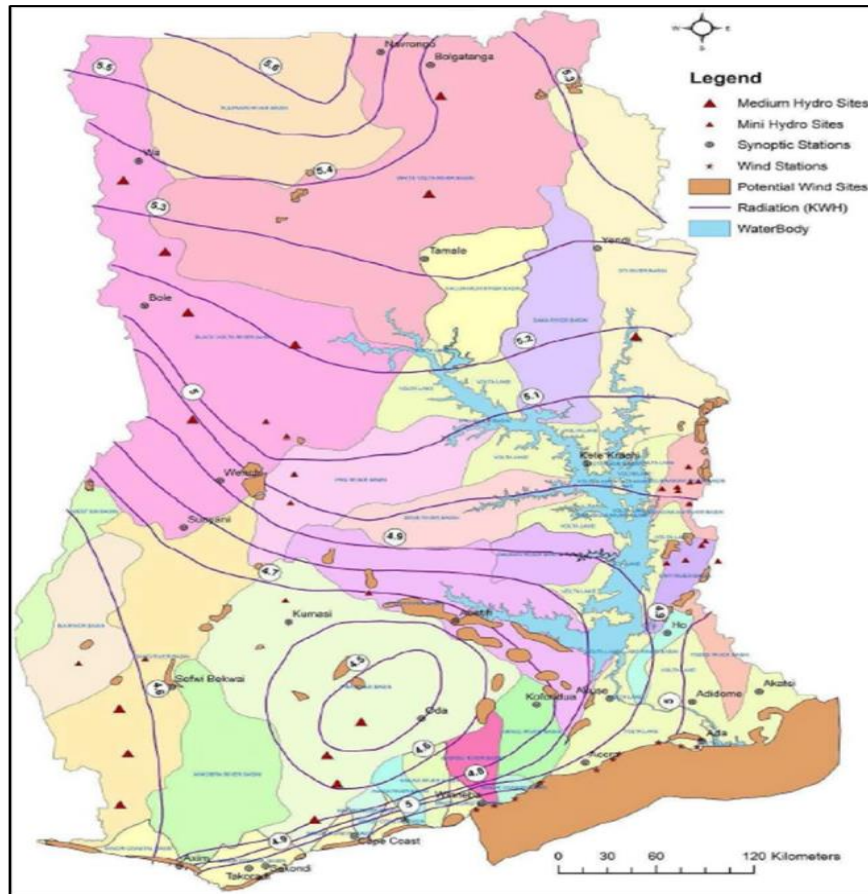


Figure 2.2 (Renewable energy map of Ghana with wind farms potential (Mahou & Madjinou, 2012))

Though Ghana has no commercial wind turbine deployed, about 1,000 km² of the land area is available for a moderate wind resource potential development (Adaramola et al., 2014; Park et al., 2009). The country has already conducted a wind resource assessment at fifteen (15) sites, and these sites have the potential to generate 1,100 MW in total (Hagan, 2015). The Energy Commission recorded the highest annual wind speed of 6.08 m/s measured at across 16 different sites in the country. Additionally, a study conducted by Acakpovi et al., (2018) revealed that the low wind speed at Wenchi for the year 2013 was estimated at 3.77 m/s while that of Wa at 8.24 m/s, but these were not coastal areas. The highest wind speed is along the coast east of

the Greenwich Meridian (Energy Commission, 2019b). With currently available technology, the wind speed level is said to be suitable for generating electricity as well as for direct use in water pumping (Energy Commission, 2019b).

Wind Energy Converters Regulation Mechanism

Wind turbines are devices that generate electricity by harnessing the power of wind to drive an electric generator. The machines that convert wind energy into electrical energy extract kinetic energy from the wind's swept area by creating pressure differences across the turbine blades, activating the electrical generator to generate electricity. The components of a wind turbine include the tower, rotor, nacelle, and turbine rotor control assembly or yawing mechanism. The tower serves as the foundation for the wind turbine, housing the gearbox and electric generator located in the nacelle. The yawing mechanism is a crucial element of wind turbines used to orient the turbine rotor in the direction of the wind flow to capture the wind's kinetic energy. The torque generated by the wind turbine is transmitted to the gearbox and subsequently to the electrical generator, as depicted in Figure 2.3. The electrical generator transforms the converted mechanical energy into electricity (Teklemichael Bahta, 2013).

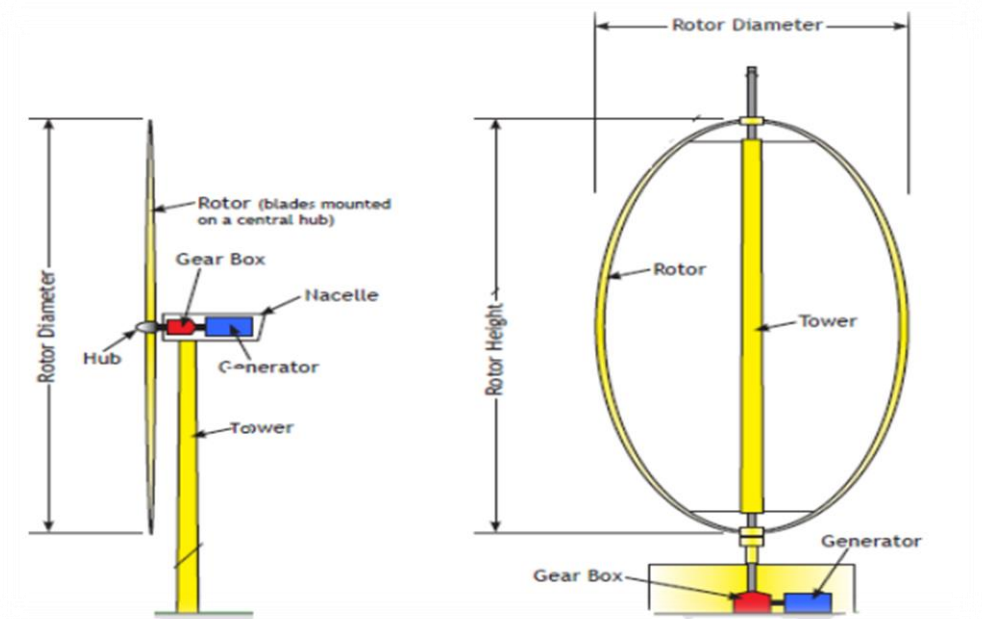


Figure 2.3 Typical wind energy converter

Mathematical modelling of a wind energy

Wind turbines turn wind energy into mechanical power, which is subsequently converted into electrical power (Algieri et al., 2020b). Mechanical power over an area (A) is calculated using

$$P_m = \frac{1}{2} \cdot \rho \cdot A \cdot V^3 \quad (2.5)$$

where:

P_m : Mechanical power

ρ : Air density (1.225 kg/m³)

A: The Area m²

V: Wind speed (m/sec)

Similarly, the electrical power of the wind energy conversion system is given as

$$P_w = \frac{1}{2} \cdot \rho \cdot C_e \cdot A \cdot V^3 \quad (2.6)$$

Where C_e is the maximum power extraction efficiency of the wind generator and other electrical mechanisms connected to the generator.

Wind turbine power modelling

When the wind speed exceeds the cut-in velocity (V_{ci}), the power delivered by the generator increases proportionally to the cube of the wind speed (v). Once the wind speed surpasses the rated velocity (V_r), the generator produces constant power that equals the rated power (P_r). However, if the wind speed exceeds the cut-out value (V_{co}), the turbine shuts down to protect the generator, resulting in zero power output. Mathematically, the power generated by a wind turbine (PWT) at any given time (t) can be expressed as follows:

$$PWT^{(t)} = \begin{cases} 0 & v(t) \leq V_{ci} \text{ or } v(t) \geq V_{co} \\ P_r \cdot \frac{v^3(t) - v_{ci}^3}{v_r^3 - v_{ci}^3} & V_{ci} < v(t) < V_r \\ P_r & V_r < v(t) < V_{co} \end{cases} \quad (2.7)$$

The wind turbine selected for the site has a rated power of 500 kW and a rotor diameter of 33.2m. In addition, the wind speed at the hub height is calculated using the power law as:

$$V_{hub} = V_{anem} \left(\frac{Z_{hub}}{Z_{anem}} \right)^\alpha \quad (2.8)$$

where:

V_{anem} and V_{hub} : the wind speeds at the anemometer,

(Z_{anem} and Z_{hub}): the hub height

α : the power-law exponent, set at 0.2.

The overall amount of power produced is expressed as:

$$PWT^{(t)} = N_{WT(t)} \times p_{WT(t)} \quad (2.9)$$

where:

$p_{WT(t)}$: the wind turbine power at a time (t)

$N_{WT(t)}$: the number of wind turbine

2.5.3 Bio Energy/ Biofuel

Another renewable energy source that could help the country's electricity system is bioenergy. Biomass, biofuel, and municipal waste-to-energy are all included in the term "bio energy". Waste-to-energy is another renewable option for the Country. It is known that the organic composition makes up more than 60 percent of the total waste in Ghana (NEA, 2016). Biogas technology is seen as an alternative energy to help in environmental pollution reduction. Biogas is produced through an anaerobic activity. It is produced basically from the fermentation of organic matter/materials (Nasution & Hidayat, 2020). Biomass is the feed stocks for biogas production and is usually acquired from livestock manure, human waste or from processing certain plants (Nasution & Hidayat, 2020). The exploitation of biomass for bioenergy in Ghana was inadequate, except for direct use as charcoal and firewood, according to the Strategic National Energy Plan. However, data show that their usage for such exploit is falling which is revealing an alignment with the government's long-term goal (Energy Commission, 2006). Work done in 2011, by Kemausuor et al. (2014) on the maximum potential of bioenergy technically produced from animal manure, wood residues, crop residues, municipal solid wastes and municipal liquid waste in Ghana amounted to 2700 Mm³ of biogas or 2300 ML cellulosic ethanol and corresponds to 97 PJ of heat energy or to 52 PJ of liquid fuel energy respectively. But some studies show that Ghana has significant feed stocks for the generation of biogas both at household and institutional levels (Doghle, 2018). Ideally, any type of biomass can be degraded to biogas (Rasimphi et al., 2018). However, biogas service companies in Ghana so far are faced with numerous challenges. These include, high costs of biogas digesters, low commitment from government, lack of concrete policy, low level of follow-up services from the biogas companies, and poor image of biogas as a new

energy source. Notably is the socio-cultural hindrance of using ‘faecal gas’ for cooking. There is also the lack of well-tested standardized designs, and lack of microfinance schemes for cattle farmers interested in biogas digesters (Bensah et al., 2011).

Bio fuel from alcohol

Another form of energy generated from biological material is biofuel, basically from fuel alcohol. In theory, any food or cellulosic material that can be turned into sugars can be used to produce fuel alcohol. The term "first generation alcohol" refers to ethanol obtained from food sources such as sugarcane, cassava, corn, millet, sugar beet etc. “Second generation alcohol” refers to products made from cellulosic resources. “Third generation” products are occasionally used to describe alcohol can also be created from algae (Okuley, 2019; US EPA, 2010). Processes that use cellulose and algae as raw materials are currently in the early stages of development and are not economically competitive (Afrane, 2012).

2.5.4 Mini-hydro Energy

Mini-hydro energy source is a small-scale version of hydroelectric power, usually made for the local community or a particular industry or to contribute to the energy distribution grid. About 40% of Ghana’s hydropower potential estimated from mini-hydropower plants (Gyamfi et al., 2015) which are projected to provide a total electricity generation capacity of 740 MW. This energy is to be harnessed from about 63 potential mini-hydro sites in the country. There is ongoing feasibility assessment on sites such as Daboya, Pwalugu, Juale and Kulpawn by the Volta River Authority whereas the Ministry of Energy is working on the Hemang site (IRENA, 2015a).

Volta region holds the greatest share of these mini-hydro sites in Ghana followed by the northern region as shown in Figure 2.4.

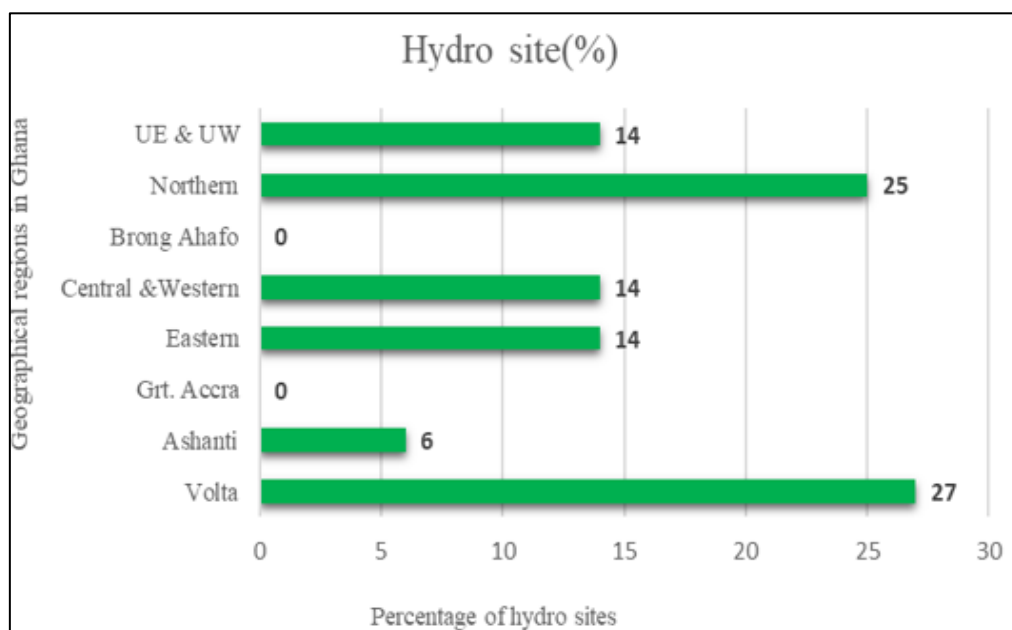


Figure 2.4 Mini-hydro potential sites in Ghana’s geographical regions (IRENA, 2015a)

2.6 Renewable energy systems

Renewable energy systems can be model as a single power source or coupled to other energy systems to form a hybrid power system.

2.6.1 Stand-alone Energy Systems

Stand-alone powers systems (SPS) is a power system not connected to a utility grid or electricity distribution system. It is mostly utilized for locations isolated from the grid (off-grid). A SPS consists of one or more energy generation sources. Most off-grid locations are powered with diesel generators; however, diesel generators are disadvantageous compared to solar standalone systems. The negative effect of diesel generators is linked to fluctuations in fuel price, lack of subsidies, operational and

maintenance costs, greenhouse (GHG) emissions, inefficiency and penalties for CO₂ emissions (Díaz, 2017). Renewable hybrid power systems have massive potential growth for the future. Hybrid renewable energy/power systems (HRES) are therefore gaining grounds due to their advantages over the stand-alone power systems. They happen to present the ports with environmentally friendly options; reduced CO₂ emissions, no issues of subsidies, available renewable resource (Díaz, 2017).

It is identified that, when two or more renewable energy resources merged, it has the potential to meet individual and global energy demand (Díaz, 2017; Muhammad-Sukki et al., 2010). This is because some of these renewable energy sources can be unpredictable and unreliable. For example, a stand-alone solar energy system can support electricity for just a period and not around the clock all through the year (Adaramola et al., 2017). The sun is available during the day but not at night and during the year, some seasons may see cloudy days and there will be no sunlight. Likewise, a stand-alone wind energy system may not produce usable energy for a considerable time frame during the year owing to relatively high cut-in wind speed (Adaramola et al., 2014). The inconveniences faced with hybrid renewable energy resource (HRES) such as the variability of renewable resources availability and startup /acquisition cost can easily be dealt with using optimize designs and system controls (Díaz, 2017). The solution is to combine different technologies to form a hybrid system such as solar/wind/biofuel, wind/hydro, solar/wind/diesel.

2.6.2 Diesel Generator

Renewable energy systems have intermittent output characteristics, but they may be combined with conventional power sources to provide a consistent power output.

Diesel generator (DG) serves as a constant source of power in a variety of HRES. The DG systems are intended to provide power to the load (Olatomiwa et al., 2015)

$$F_G = B_G \cdot P_{G-rated} + A_G \cdot P_{G-out} \quad (2.12)$$

where:

$P_{G-rated}$: the nominal power of the DG,

P_{G-out} : the output power,

A_G and B_G : the coefficients of fuel consumption curve (L/kWh)

The initial capital cost of the DG is assumed \$16,602.55 for 70 kW. Replacement and operational costs were assumed \$16,702.55 for 70 kW and \$6.00/h, respectively. The operating lifetime was also considered 15,000 h. In July 2021, per litre price of diesel in Ghana is US \$1.03. In this study, 70 kW sizes of DG is considered for the simulation. Initial capital cost and cost of installation are all included in the LCC. Over the course or period of the system's life, both capital and operating expenses will be incurred. HOMER conducts simulations to meet the specified demand. HOMER considers such two factors as alternative technology options and resource availability. The entire net present cost (NPC) of the project is calculated using HOMER.

$$NPC = \frac{C_{tot}}{CRF(i, T_P)} \quad (2.13)$$

where:

C_{tot} : signifies the total annual cost of the system (US\$/year),

i : the annual interest rate (%),

T_P : the lifetime of the work, and CRF the capital recovery factor, the capital factor is

$$CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2.14)$$

Where, n is symbolizes the number of years in the work. In HOMER, the salvage cost (SC) is calculated as

$$SC = C_{RC} \left(\frac{T_{rem}}{T_{com}} \right) \quad (2.15)$$

where:

C_{RC} : the replacement cost of the equipment (US\$),

T_{rem} : the remaining lifetime of the equipment (years),

T_{com} : the lifetime of the component (years). Levelized cost of energy (COE) is evaluated as

$$COE = \frac{C_{tot}}{E_{tot}} \quad (2.16)$$

Where the E_{tot} represents the total annual electricity consumption (kWh/year), and C_{tot} signifies total annual cost of the system (US\$/year).

In operating a system, economics are an important part of the simulation. HOMER attempts to reduce total net present cost (NPC) both in determining the best system architecture. The best-suited configuration is chosen based on the simulation findings. All economic computations are carried out in constant dollars (Moses & Shruthi, 2017a).

2.6.3 Hybrid energy systems

A hybrid electrical system is a system that combines two electrical technologies to provide energy and heat. It is a total electrical configuration system that can be built or designed to meet a power requirement either locally or remotely (Dankwah, 2018). Hybrid Renewable Energy Systems (HRES) is a combination of two or more renewable energy sources or renewable sources joined with fossil fuels (Díaz, 2017). HRES can be deployed as a standalone system, micro-grid/mini-grid and grid-connected system in urban, peri-urban and rural locations across the globe (Díaz, 2017). The practicability, dependability or consistency and economic evaluations of hybrid power systems make it more dependable and cost-effective than one source power system (Ajao et al., 2011; Nema et al., 2009). Globally, several notable studies have been conducted on renewable

hybrid energy systems. Nfah & Ngundam (2008) modelled a hybrid power system using wind, diesel and battery for power supply to remote areas in Cameroon. In Chile, Caballero et al. (2013) designed a small grid-connected hybrid energy system, which comprises solar and wind sources for electrification. Ismail et al. (2013) also performed techno-economic analysis on a hybrid system which comprises photovoltaic panels, battery system and diesel generator for a typical Malaysian village household.

2.7 Hybrid Renewable Energy System Applications in Ghana

In recent years, hybrid technology has seen development and upgrades of its role in the RE sector. The benefits produced by the hybrid technology for autonomous power production are unparalleled. Currently, many houses in rural and urban areas use hybrid systems and many isolated islands are adopting the hybrid kind of technology because of the benefits received in comparison with a single renewable system (Ayirewura, 2013). Studies on hybrid systems for Ghana have been conducted and documented in the literature. For instance, Adaramola et al. (2014) performed techno-economic viability of using PV/wind/diesel to power a remote location in Southern Ghana. Similarly, Adaramola et al. (2017) investigated the possibility of integrating PV and biodiesel generators to form a hybrid system to meet electricity and water needs of a particular community in the northern part of Ghana. Dankwah (2018) proposed a hybrid system configuration which comprises PV/grid/diesel generator for the Accra Technical University. Addo et al. (2014) carried out an analysis by utilizing an iterative algorithm design a PV/wind hybrid system to power a cluster of villages at Bonsaaso in the Ashanti Region of Ghana. Awopne (2021) conducted a feasibility study for a rural area in northern part of Ghana, a stand-alone hybrid system consisting of PV/DG/Battery with the outcome of NPC and COE of \$ 296,552 and 0.399\$/kWh respectively.

2.8 Hybrid Energy System Component

Various hybrid energy models can be built by coupling existing individual potential energy systems. Some of which are as follows: solar PV/wind hybrid energy system, wind/hydro hybrid energy system, solar/wind/hydro hybrid energy system.

Inverter and Converters

To convert DC power from sources like wind turbines, PV panels, and batteries into AC power for meeting AC load demand in a hybrid AC/DC power system, power converters are essential. Inverters are required as the output power of these sources is in DC. The rated power of the inverter, P_{inv} , was calculated based on the peak AC load demand, P_{peakAC} , using the following formula

$$P_{inv} = (P_{peakAC}) / \eta_{inv} \quad (2.17)$$

where:

η_{inv} : the inverter efficiency

P_{inv} : the rated power of inverter

P_{peakAC} : the peak AC load demand

The generic converter power model with an average capital unit cost of 50 USD/kW and a lifetime of 10 years was considered.

2.9 Cost involved in Installing Power Schemes

2.9.1 Initial Capital Cost of Solar PV

The capital cost of the solar PV is given base on the purchase cost at the time, US \$1 = 6 Ghana Cedis in August, 2021. In addition, the cost is for 1kW solar PV. The initial cost is calculated showing the detail of the factors considered

$$C_{In} = C_{pv} + C_{install} + C_{mount} \quad (2.18)$$

where:

C_{In} : Initial capital cost

C_{pv} : Cost of solar PV

$C_{install}$: Cost of installation of the solar PV

C_{mount} : Cost of mounting structure

Replacement cost (C_{Rep}) of Solar PV

The cost of replacement of Solar PV is calculated using the following factors.

$$C_{Rep} = C_{install} + C_{Decom} + C_{pv} \quad (2.19)$$

where:

C_{Rep} : Replacement cost

$C_{install}$: Cost of Installation

C_{Decom} : Cost of Decompose

C_{pv} : Cost of pv

Operation and Maintenance cost (C_{OM}) of Solar PV

The cost of replacement of Solar PV is calculated using the following factors.

$$C_{OM} = C_{ope} + C_{service} \quad (2.20)$$

where:

C_{ope} : Cost of operation

$C_{service}$: cost of service

2.9.2 Cost of Wind Turbine

Initial capital cost for wind turbine (C_{IC})

Initial cost for the wind turbine is calculated using the formula

$$C_{IC} = C_{WT} + C_C + C_{OC} \quad (2.21)$$

where:

C_{IC} : Initial capital Cost

C_{WT} : Wind turbine Cost

C_C : Construction Cost

C_{OC} : Other capital cost

Replacement cost (C_{REP}) for Wind turbine

The cost of replacement for wind turbine is calculated using the following considerations.

$$C_{REP} = C_{WT} + C_{DECOM} + C_{install} \quad (2.22)$$

where:

C_{WT} : wind turbine cost

C_{DECOM} : Cost of Decompose

$C_{install}$: cost of installation

Operation and Maintenance cost (C_{COM}) of Wind Turbine

The operation and maintenance cost of wind turbine is calculated using the formula

$$C_{COM} = C_{op} + C_{service} \quad (2.23)$$

where:

C_{op} : Operation cost

$C_{service}$: Service cost

2.9.3 Capital cost of Diesel Generator

Initial capital cost (C_{DGIn})

The initial capital cost for diesel generator is calculated showing the detail of the factors considered.

$$C_{DGIn} = C_{DG} + C_{DGT} + C_{DGInst} \quad (2.24)$$

where:

C_{DG} : cost of generator

C_{DGT} : cost of transportation

C_{DGInst} : cost of installation

Replacement cost of Diesel Generator (C_{DGR})

The cost of replacement for diesel generator (C_{DGR}) is determined using the following considerations.

$$C_{DGR} = C_{DG} + C_T + C_{DGInst} + C_{DGD} \quad (2.25)$$

where:

C_{DGSer} : cost of service for diesel generator

C_{DGrop} : cost of operation of diesel generator

2.9.5 Capital cost of Converter

The capital cost of the converter is calculated per 1kW

Initial Capital cost of Converter (C_{CONIn})

The initial capital cost of converter takes into consideration the cost of the following parameters; converter cost of installation of the converter, cost of mounting structure.

$$C_{CONIn} = C_{CON} + C_{CONInst} + C_{CONmount} \quad (2.30)$$

where:

C_{CONIn} : Initial capital cost of Converter

C_{CON} : Cost of Converter

$C_{CONInst}$: Cost of installation of the Converter

$C_{CONmount}$: Cost of mounting structure

Replacement cost (C_{CONR}) of Converter

The replacement cost of a Converter in the choice of hybrid energy systems is usually checked using the parameters following.

$$C_{CONR} = C_{CONInst} + C_{COND} + C_{CON} \quad (2.31)$$

where:

C_{CONR} : Replacement cost of converter

$C_{CONInst}$: Cost of installation of converter

C_{COND} : Cost of decompose

C_{CON} : Cost of converter

Operation and Maintenance cost (C_{COM}) of Converter

The operational and maintenance cost (CCOM) of Converter is determined using the parameters following.

$$C_{COM} = C_{COPE} + C_{CONservice} \quad (2.32)$$

where:

C_{COPE} : Cost of operation

$C_{CONservice}$: Cost of service

2.10 Market Prices of the Components Used for the Hybrid System

The market prices of the various component used in the study were considered in different market across the globe. Alibaba express, ghanabuysell are some of the marketing companies considered to check the components from. These prices are clearly shown in table 2.3

Solar PV power generation installation cost in Africa has decrease 61% in terms of it price since 2012. The price is US \$1.30/Watt in Africa, compared to the global average of US \$1.80 per watt (IRENA, 2016).

In Africa, for system larger than 200kW, the cost of installation is US \$1.90 per watt. In addition, it is estimated that, the utility-scale PV could fall to US \$0.80/W in 2025 which will be 57% reduction with reference to the cost of installation in a year 2015 at the price of US \$1.80 (IRENA, 2016).

Table 2.3 Some market prices of solar PV

| Description | Value | Cost | Reference |
|-----------------------|--|-------------|--------------|
| Solar panel | 260 watts | \$150.00 | GhanaBuySell |
| Yingli Solar panel | 330WP polycrystalline | \$120.00 | |
| Solar system | 1kW with 1kW inverter 10a charge controller- 100ah | \$666.67 | |
| Complete solar system | 1Kw | \$1,599.83 | |
| Sunfuture solar panel | | | |
| Factory price | 500kW | \$94,166.67 | Alibaba.com |

2.11 Renewable Fraction (RF) Calculation in HOMER Pro 3.14.2

The renewable fraction is the fraction of the energy delivered to the load that originated from renewable power sources.

Type: Output Variable

Units: None

Symbol: f_{ren}

HOMER calculates the renewable fraction using the following equation:

$$f_{ren} = 1 - \frac{E_{nonren} + H_{nonren}}{E_{served} + H_{served}} \quad (2.33)$$

where:

E_{nonren} = non-renewable electrical production [kWh/yr]

H_{nonren} = non-renewable thermal production [kWh/yr]

E_{served} = total electrical load served [kWh/yr]

H_{served} = total thermal load served [kWh/yr]

HOMER abbreviates the renewable fraction as "Ren. Frac." in the Sensitivity and Optimization Results tables.

2.12 Empirical review

In the field of renewable energy, several previous studies have explored the sizing and optimization of Hybrid Energy Systems (HES). These studies have employed various methodologies to determine the most suitable configuration of renewable energy sources and storage components. The review highlights the strengths and drawbacks of these studies, paving the way for justification of the current study.

Firstly, Chowdhury et al. (2021) aimed to design a stand-alone system for a temporary health care centre on Saint Martin Island, Bangladesh. Remarkably, this study was the first of its kind to highlight power management of a hospital load. The proposed HES configuration comprised PV, Converter, Wind, Battery, and Generator components. Utilizing Homer Pro software, the authors observed that the Levelized cost of the proposed system was \$0.4688. Additionally, the HES demonstrated a 35% lower Levelized cost of energy (LCOE) compared to the solar home system (SHS). Moreover, the system generated 27% less CO₂ emissions than a diesel-based fuel system.

Furthermore, Usman et al. (2018) focused on the optimization of hybrid energy system models consisting of solar PV, diesel generators, and grid integration in India. The study aimed to make renewable energy competitive with fossil-based options like coal and oil. Notably, techno-economic analysis using HOMER software was employed to compare the per unit cost of electrical energy production, operating cost of fossil fuel-based sources, and reduction in greenhouse gases. The study showcased the potential of HES in making renewable energy more viable and environmentally friendly.

Additionally, Islam et al. (2022a) conducted a techno-economic performance assessment of a hybrid renewable energy system for a rural health care center in Bangladesh's Rangpur district. This health care centre, located in Gangachara Upazila, utilized a microgrid solar hybrid photovoltaic system comprising solar panels, a bi-directional inverter, and a generator. Interestingly, the state-of-the-art PV design software, HOMER Powering Health Tool, was utilized for load estimation and techno-economic evaluation. Consequently, the study revealed that a 32 kW grid-connected solar PV system was required for the health care centre, with an estimated Levelized cost of energy (LCOE) of US\$ 0.022.

In addition, Alsagri et al. (2021) conducted a study focusing on health clinics in remote areas, where energy and freshwater supply are critical challenges. The researchers considered a hybrid energy system with photovoltaic panels, a diesel generator, and a battery bank to provide electrical demand for a health clinic. Furthermore, the lack of proper access to fuel in standalone systems posed a challenge in desert remote areas, impacting electricity management. Accordingly, three excess electricity management methods, including increasing annual fuel availability, using a combination of fuel cell/electrolyser, and considering annual capacity shortage, were

compared to each other. The proposed hybrid system exhibited an energy cost of 0.105 \$/kWh, with more than 30% renewable fraction, showcasing the high capability of off-grid development for small loads.

Lastly, Mat Isa et al. (2017), analysed the economic aspects of a grid-connected photovoltaic (GCPV) system for a hospital building in Malaysia. The study emphasized the use of the Levelized Cost of Energy (LCOE) and total Net Present Post (TNPC) in regards to the annual interest rate. Additionally, utilizing HOMER software, the authors conducted optimization and sensitivity analysis to evaluate the impact of the grid-connected PV system. Furthermore, the study also discussed the benefits of the Net Metering (NeM) mechanism.

The reviewed studies have shown the potential of hybrid energy systems in addressing the energy challenges faced by healthcare sectors and rural health facilities. The optimization of renewable energy-based standalone or grid connected systems have proven to be economically viable and environmentally sustainable. The integration of solar PV, wind, battery storage, and backup generators has led to significant cost savings, reduced emissions, and improved energy resilience for healthcare centres worldwide. However, some challenges, such as high initial investment and system complexity, have been noted in previous studies. In the context of increasing energy demand and depletion of conventional resources, promoting renewable energy has become imperative. This study focuses on conducting a techno-economic analysis of hybrid energy systems for hospitals with a focus on Wenchi Methodist Hospital.

2.12.1 Empirical Gap

This thesis addresses a significant empirical gap in the field of hybrid energy systems by offering a specialized and tailored solution for Wenchi Methodist Hospital. The

primary objective is to create an efficient and sustainable power supply for Wenchi Methodist Hospital by integrating solar PV, wind, grid, battery storage, and a generator. By doing so, the study aims to reduce reliance on fossil fuels and grid electricity, providing a reliable and resilient energy management solution for temporary healthcare centres. The unique and novel aspect of this analysis lies in its specific focus on the energy management of the hospital facility. By exploring the optimization of hybrid energy systems for Wenchi Methodist Hospital, this study contributes to the existing body of knowledge in the field and offers valuable insights into addressing the energy challenges faced by healthcare facilities during times of increased pressure and demand.

2.12.2 Justification

Given the ongoing global initiatives to encourage renewable energy adoption, the proposed HES aligns with the Government of Ghana's schemes to promote clean energy. By optimizing multiple HES models with solar PV, diesel generators, and grid integration, the study aims to provide an economically viable and environmentally sustainable energy solution. The comparison based on the per unit cost of energy production, operating cost, and greenhouse gas reduction emphasizes the benefits of HES over conventional fossil fuel-based systems.

CHAPTER THREE

MATERIALS AND METHODS

This chapter focuses on the methods used in this study. It includes taking various data and using HOMER software to select the appropriate Renewable Energy Technology (RET) feasible for the Wenchi Methodist Hospital in Ghana.

3.1 Theoretical Model for Evaluating Hybrid Energy Supplies

To conduct a comprehensive evaluation of hybrid energy supplies for the healthcare center, a theoretical model is developed. This model encompasses various components, methodologies, and performance parameters to assess the techno-economic feasibility and environmental impact of the proposed hybrid energy system.

The steps involved in the theoretical model are as follows:

Step 1: Energy Demand Analysis

The first step involves conducting a detailed analysis of the energy demand of Wenchi Methodist Hospital. Historical data, peak load requirements, and specific energy needs of various departments are taken into account to understand the hospital's electricity consumption patterns accurately.

Step 2: Selection of Energy Sources

Based on the energy demand analysis, appropriate energy sources are selected for the hybrid system. The primary sources considered include solar photovoltaic (PV) panels, wind turbines, battery storage, and a diesel generator as a backup source.

Step 3: Homer Pro Simulation

The Homer Pro simulation software is utilized to model and optimize the hybrid energy system configuration. The software takes into account various parameters such as solar irradiance, wind speed, equipment specifications, and costs to determine the most efficient and cost-effective system design.

Step 4: Technical and Economic Parameters

Technical and economic parameters for each component of the hybrid system are determined. This includes the capacity, efficiency, cost, lifetime, and maintenance expenses of solar PV panels, wind turbines, batteries, and the diesel generator.

Step 5: Performance Analysis

The performance of the hybrid energy system is assessed based on various metrics. The capacity factor, levelized cost of energy (LCOE), net present cost (NPC), payback period (PB), rate of investment (ROI), and internal rate of return (IRR) are calculated to evaluate the system's effectiveness and profitability.

Step 6: Sensitivity Analysis

To account for uncertainties and variations, a sensitivity analysis is conducted by considering different scenarios with varying factors such as solar PV price, diesel fuel price, inflation rate, and discount rate. This helps in understanding the robustness and resilience of the proposed system under changing conditions.

Step 7: Comparison with Alternative Solutions

The theoretical model also includes a comparison of the hybrid energy system with alternative energy supply solutions, such as standalone solar or wind systems, to determine the most optimal and viable option for Wenchi Methodist Hospital.

The theoretical model presented in figure 3.1 provides a systematic approach to evaluate the feasibility and benefits of hybrid energy supplies for Wenchi Methodist Hospital. By integrating renewable energy sources and advanced power management techniques, this model aims to optimize energy utilization, minimize dependence on fossil fuels, and enhance the overall energy resilience and sustainability of the healthcare facility.

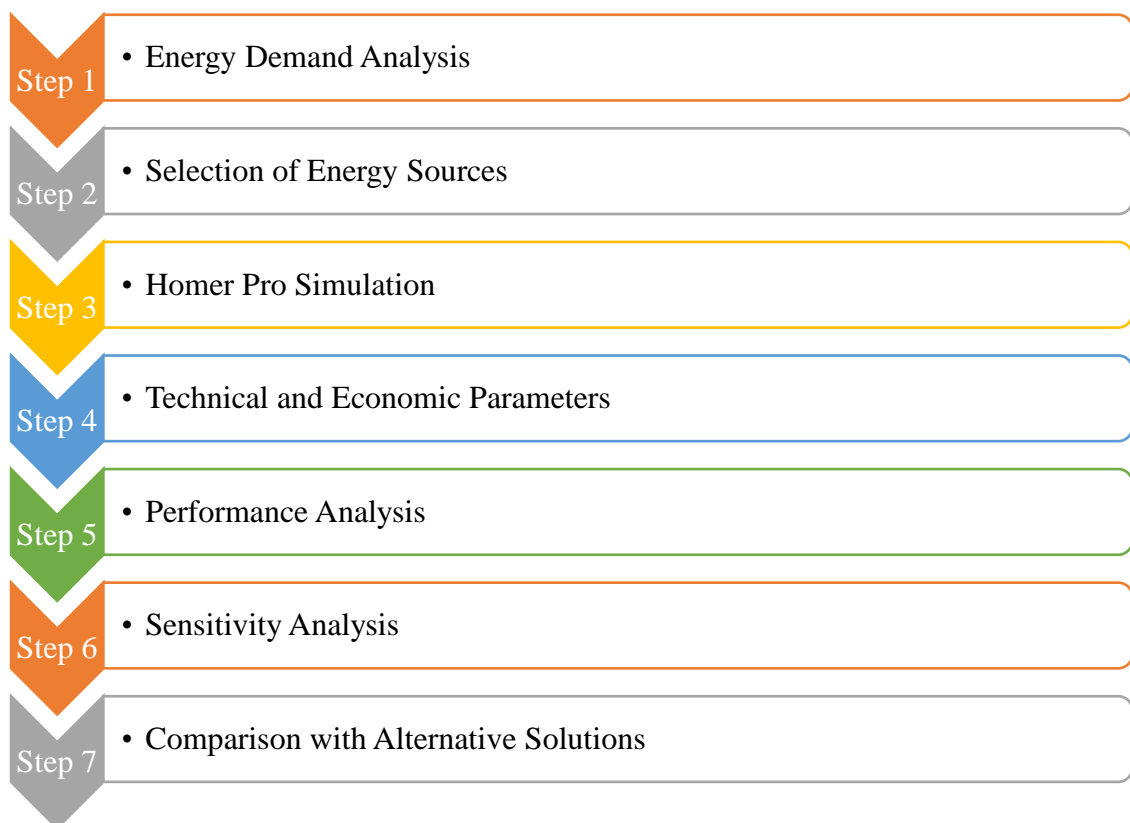


Figure 3.1 Flowchart on the theoretical model for Evaluating Hybrid Energy Supplies

3.2 Study Area

Wenchi Municipality is in the western part of the Bono Region. Wenchi Municipal is one of the largest of the 12 districts in the Bono Region and it is one of the Municipal capitals of the region. Wenchi lies between latitude 7°30' north and longitude 2°15' West and latitude 8°05' north and longitude 1°55' east. It shares borders with Sunyani Municipal to the south, Techiman Municipal to the west, Kintampo South District to the northwest and Tain District to the east. Wenchi covers a total land area of 1,145 square kilometres. Wenchi, the Municipal capital is 56 km to Sunyani and 29 km from Techiman which is possibly the commercial town (largest market) in the Region. Wenchi is approximately about 50 km east of the Ivory Coast border. The Wenchi landscape is mainly surging with mild slopes of less than 1% inclination. The land usually rises from 30 m above sea level to over 61m in the North West. Figure 3.2 shows the map of Wenchi municipal. The municipality has two major seasons, the rainy and the dry seasons with an average annual rainfall between 1,140 - 1,270 mm. In Wenchi, the average minimum temperature is 21.2°C and maximum, 30.9°C (GSS, 2014; mofa.gov.gh).

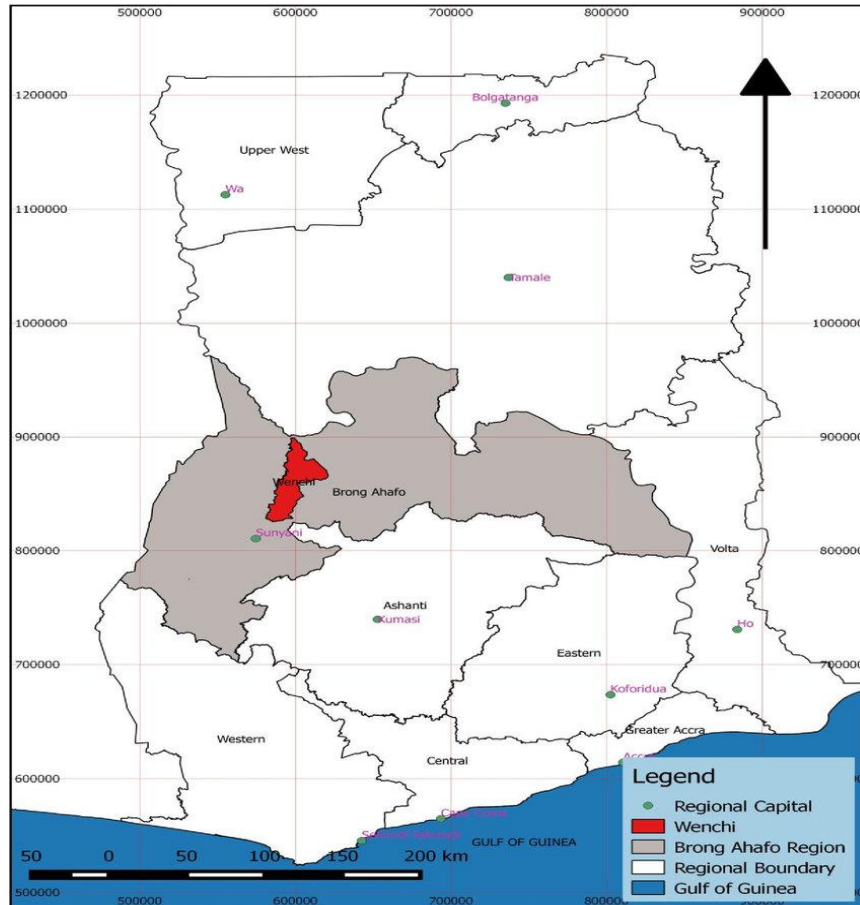


Figure 3.2 Map of Wenchi Municipal. Source: Wenchi Municipal Assembly

3.3 Wenchi Hospital Energy Profile

Hospitals are significant consumers of energy, and energy consumption patterns in hospitals vary based on several factors, such as the size of the hospital, the type of services provided, and the use of medical equipment. On average, hospitals consume between 50-150 kWh/m² of energy per year, which is significantly higher compared to other buildings.

The energy consumption in hospitals is primarily attributed to heating, cooling, lighting, and the use of medical equipment. The use of medical equipment, such as X-ray machines, MRI machines, and dialysis machines, is one of the main drivers of energy consumption in hospitals.

To determine the energy profile of Wenchi Methodist Hospital, a detailed analysis of its energy consumption patterns was assessed. This analysis included data on energy consumption from cooling, lighting, Fan, TV, Fridge, Iron, Washing Machine, Sterilizer, Air-condition, Computer, Cleaning Machine and medical equipment, as well as the usage patterns and operating hours of each. Monthly electric bill was also assessed and compared to standard.

3.4 Energy Sources

In general, hospitals in Ghana typically rely on a mix of energy sources, including grid electricity and diesel generator sets. The choice of energy source depends on several factors, such as the local energy infrastructure, the availability of grid electricity, and the cost of energy. Grid electricity is the primary source of energy for the hospital and is used to power the majority of the hospital's operations, including lighting, heating, cooling, and medical equipment. The grid electricity is supplied by the local utility company and is typically reliable and cost-effective.

However, hospitals also require a reliable backup power source in case of power outages or interruptions. In the case of Wenchi Methodist Hospital, diesel generator sets serve as the backup power source. These generator sets are typically used during power outages and provide the hospital with a reliable source of energy to ensure the continuity of essential services and patient care.

The use of diesel generator sets has its drawbacks, however, as they are less efficient and more expensive compared to grid electricity. In addition, diesel generator sets emit greenhouse gases and other pollutants, which can have negative environmental

impacts. To mitigate these impacts, hospitals can explore alternative energy sources, such as renewable energy sources, and implement energy efficiency measures to reduce their reliance on diesel generator sets.

3.5 Simulation Software for the Hybrid Power System

3.5.1 HOMER Software

HOMER is an optimization tool that is used to determine the best course of action (Moses & Shruthi, 2017; Pradhan et al., 2017) in many micro-power systems. For decentralized systems, system configuration is required. HOMER has been used to investigate issues of off-grid electrification in both developed and underdeveloped countries (Moses & Shruthi, 2017b). HOMER tool is used for the evaluation of hybrid renewable energy technology (RET) systems as well. HOMER contrasts a wide range of both hardware and software to improve the system's or frame plan's necessities and sensitivities. The review used in HOMER is based on the exclusive features of the object framework, in addition to the framework's life-cycle cost (LCC) (Olatomiwa et al., 2017).

Among all the software, HOMER Pro 3.14.2 was chosen, on the basis that, it is widely recognized as the leading software for hybrid energy system analysis and is used by many organizations and researchers around the world. This widespread use and recognition help to ensure the accuracy and reliability of the results produced by the software. HOMER Pro is also able to model a wide range of energy sources, including renewables, such as wind and solar, as well as conventional energy sources, such as diesel and natural gas. This comprehensive modelling capability makes it an ideal tool for analysing hybrid energy systems that combine multiple energy sources.

Homer pro uses Genetic Algorithm to handle non-linear and non-convex problems, and to search for global optima. The metaheuristic optimization techniques efficiently searched the vast design space of the hybrid system, considering different combinations of renewable energy sources, battery storage capacities, generator sizes, and other parameters. These algorithms aimed to minimize the total net present cost (NPC) and levelized cost of energy (LCOE) while ensuring a reliable power supply and reduced carbon emissions.

In conclusion, HOMER Pro is widely used for hybrid energy system modelling because of its user-friendly interface, advanced optimization algorithms, widespread recognition, comprehensive modelling capabilities, and integration with other tools.

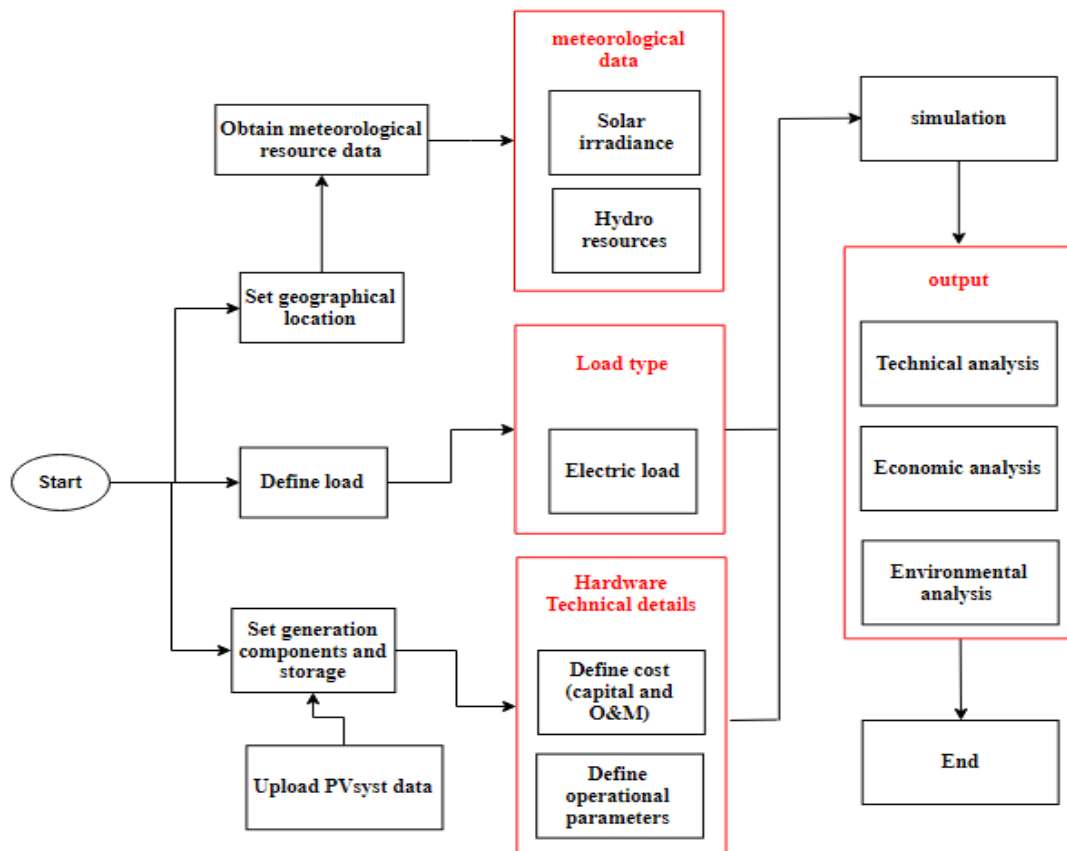


Figure 3.3 Flow chart for the simulation

Table 3.1 Key input parameters for HOMER simulation and optimization

| Parameters | Comments/Reference |
|--|---|
| Name and location of Study area | Wenchi hospital |
| Daily energy demand | Estimate from energy audit |
| Daily solar radiation, wind speed, temperature | Data from NASA database, using the latitude and longitude values of the study area |
| Components cost details (capital, replacement and operation & maintenance costs) | Market price from suppliers and installers in Ghana and from the international market |
| Components for lifetime | Typical manufacturer specification is considered |
| Inflation rate | Market rate in Ghana |
| Discount rate | Market rate in Ghana |
| Project lifespan | 20 – 25 years |
| Renewable energy fraction | Typical range (%): 0 – 100% Based on hybrid power system configuration |

3.5.2 HOMER Powering Health Tool

Homer Powering Health is a specific application of the HOMER tool that focuses on designing and optimizing renewable energy systems for healthcare facilities in developing countries. This tool was developed by the non-profit organization, Possible Health, in collaboration with NREL (HOMER, 2020a).

In many developing countries, healthcare facilities struggle with unreliable or non-existent electricity, which can have serious consequences for patient care. The Homer Powering Health tool aims to address this problem by helping to design renewable

energy systems that can provide reliable and affordable power to healthcare facilities (Islam et al., 2022b).

The tool takes into account the specific energy needs of healthcare facilities, such as lighting, medical equipment, and refrigeration for vaccines and medicines. It also considers the unique energy requirements of different healthcare facilities, such as hospitals, clinics, and labs.

The Homer Powering Health tool can be used to assess the feasibility and economic viability of different renewable energy system designs for healthcare facilities, and to compare the costs and benefits of different options. It can also be used to estimate the load demand for hospitals (District hospital and Rural hospital, Small Inpatient clinic and Rural dispensary) (HOMER, 2020b). (Islam et al., 2022b) applied the same method used in this work to determine the load demand for the Wenchi Methodist hospital.

3.6 Resource assessment at Wenchi

A resource assessment for Wenchi based on available renewable energy resources was conducted according to the potential for different renewable energy sources in the area, including solar and wind. This assessment considered factors such as the availability of the resource, the local climate, topography, and other relevant factors that determine the feasibility of each renewable energy source.

3.6.1 Solar radiation

Wenchi is located in a region that receives a high amount of solar radiation, making it a good location for solar energy production. A solar resource assessment involved

local climate data, such as average daily solar radiation levels, to determine the potential for solar energy production.

The average solar radiation data obtained from the National Renewable Energy Lab database for the selected area Wenchi Methodist hospital, is estimated to be 4.81 kWh/m²/day and average clearness index is 0.49. The details are clarified in Figure 3.4. It also observed that more solar irradiance can be expected from the month of January to May and November to December as well while a smaller amount of solar irradiance is to be anticipated from July to September

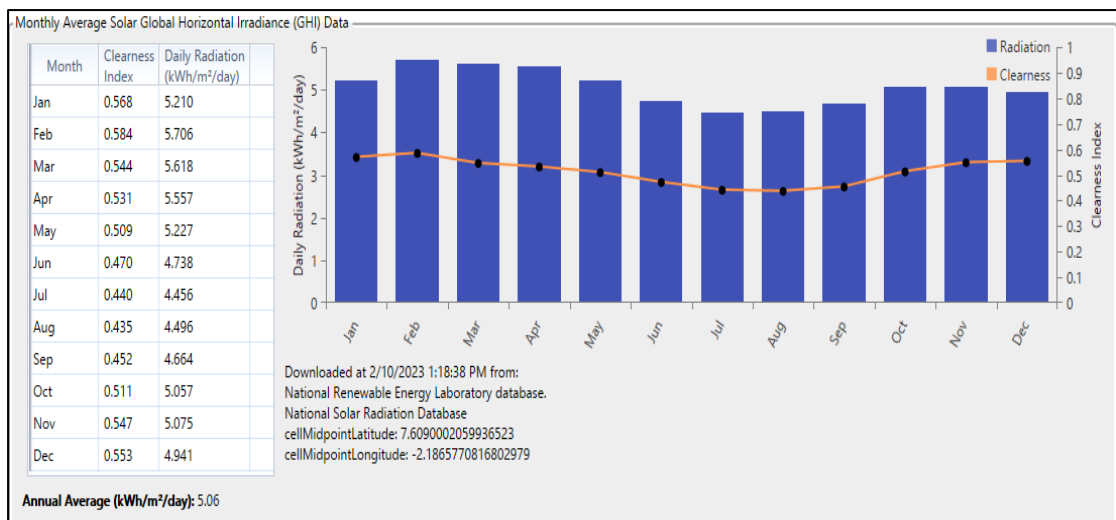


Figure 3.4 Monthly Average Solar Global Horizontal Irradiance (GHI)

3.6.2 Wind speed

The hourly wind speed data of the region (latitude 7°30' north and longitude 2°15' West and latitude 8°05' north and longitude 1°55' east.), is measured at the height of 70m by Anemometer. Annually wind speed distribution profile of the selected site is shown in Figure 3.5. According to wind speed data, the regional average wind speed is about 3.66m/s. Furthermore, it is clear that the highest and lowest wind speed values occur in March and October-November correspondingly.

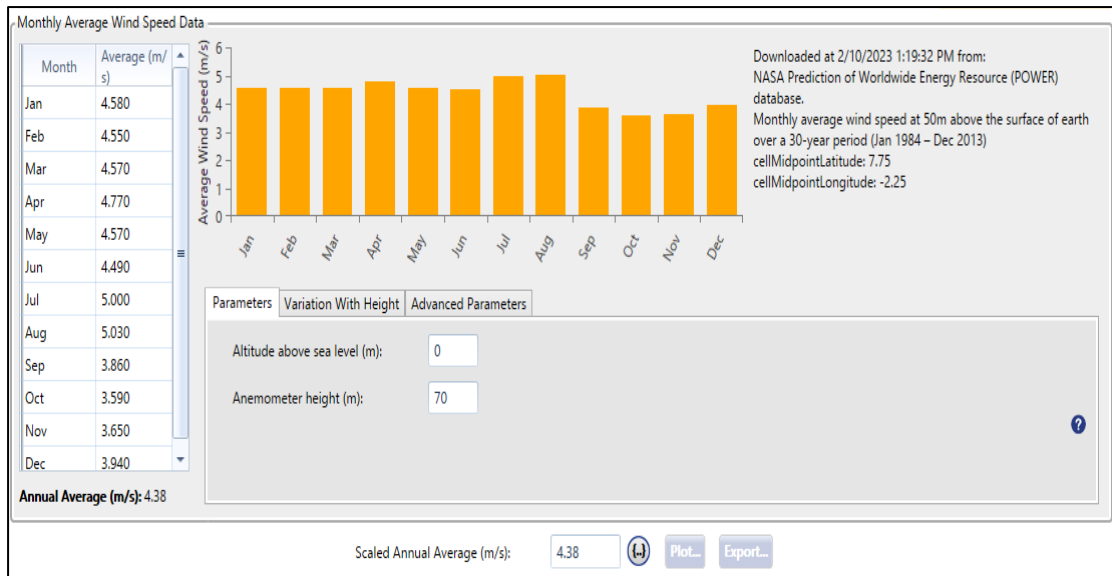


Figure 3.5 Monthly average wind speed data of site (HOMER Pro)

3.6.3 Estimation of Load Requirements

The microgrid system in question had already populated the dialog boxes of the HOMER Powering Health Tool with the required input data (HOMER, 2020b). This was done by the program automatically importing all geographic data, and utilizing its own search functionality to input the chosen location, which in this case was Wenchi. Additionally, the input load data was collected from various sources such as the vaccination unit, outpatient treatment unit, obstetric delivery unit, operating theatre, maternity ward, general wards, laboratories, operating room, administrative office, and mortuary. The total energy consumed by Wenchi Methodist Hospital was calculated by adding up the electricity loads used in different hospital wards. Both conventional mathematical methods were employed to estimate the load demand, and Table 3.2 represent the load requirements estimation.

Table 3.2 Estimation of the load requirement of hospital

| Equipment | Quantity | Average Power (W) | On time | Total Energy (kW·h/day) |
|---------------------------|-----------------|--------------------------|----------------|--------------------------------|
| Vaccine fridge (per 75l) | 4 | 30 | 24 | 2.9 |
| Exam lights (LED) | 11 | 10 | 4 | 0.44 |
| Sterilisation equipment | 2 | 500 | 1 | 1 |
| Suction | 5 | 50 | 1 | 0.3 |
| Water heater / Kettle | 1 | 1,000 | 0.1 | 0.1 |
| Lights / LED | 238 | 10 | 4 | 9.5 |
| Ceiling fan | 38 | 30 | 9 | 8.9 |
| TV / DVD | 5 | 75 | 2 | 0.8 |
| Incubator | 2 | 300 | 24 | 14.4 |
| Sterilisation equipment | 1 | 500 | 1 | 0.5 |
| Centrifuge (large) | 2 | 100 | 1 | 0.2 |
| Microscopes | 4 | 20 | 1 | 0.1 |
| Laboratory Incubator | 1 | 100 | 24 | 2.4 |
| Water bath | 2 | 300 | 24 | 14.4 |
| CD4 Machine (HIV) | 1 | 100 | 8 | 0.8 |
| Refrigerator (blood) | 5 | 42 | 24 | 5 |
| Hematology analyser | 1 | 60 | 24 | 1.4 |
| Blood chemical | 5 | 75 | 1 | 0.4 |
| PCR Machine | 2 | 200 | 6 | 2.4 |
| Computer desktop | 30 | 70 | 8 | 16.8 |
| Computer laptop | 10 | 45 | 8 | 3.6 |
| Printer | 10 | 10 | 8 | 0.8 |
| Refrigerator (domestic) | 5 | 42 | 24 | 5 |
| Air Conditioner (Inv.) | 5 | 450 | 16.8 | 37.8 |
| Surgery spot lights (LED) | 2 | 150 | 6 | 1.8 |
| Ventilator | 2 | 150 | 6 | 1.8 |
| Anaesthetic machine | 2 | 100 | 6 | 1.2 |
| Suction machine | 11 | 180 | 1 | 1.9 |
| Pulse Oximeter | 5 | 5 | 8 | 0.2 |
| X-Ray machine | 1 | 600 | 2 | 1.2 |
| Portable X-ray | 2 | 150 | 9 | 2.6 |
| Ultrasound | 1 | 200 | 4 | 0.8 |
| Exhaust fan | 10 | 40 | 24 | 9.6 |
| Ventilator | 10 | 150 | 24 | 36 |
| Patient monitor | 10 | 100 | 24 | 24 |
| Infusion pump | 10 | 50 | 24 | 12 |
| Defibrillator | 2 | 10 | 24 | 0.5 |
| Refrigeration | 3 | 650 | 24 | 31.2 |
| Pump | 4 | 120 | 6 | 2.9 |
| Geysers | 0.15 | 6,344 | 6 | 5.7 |
| | | | | 295.44 |

3.7 Design Specification

Figure 3.6 presents the synoptic description of the stand-alone hybrid renewable system to be sized. The proposed system considered based on available resources at the Wenchi hospital is made up of two renewable power generators (wind turbine and solar PV), converter and a diesel generator as a back-up power source, a battery and grid. Solar PV and wind turbine are connected to the direct current (DC) bus via appropriate inverters or converters to the load. In contrast, load and the diesel generator are connected to the alternative current (AC) bus. In the proposed system, the inverter functions to power the hospital directly and redirect any excess DC energy to the national grid. To monitor the amount of electricity generated and sell any surplus to the national grid, a net meter is employed. The integration of the battery bank in this system helps to minimize the generator capacity. Furthermore, in the event of a grid failure or insufficient solar power, a diesel generator serves as a backup power source to supply electricity to the health facility.

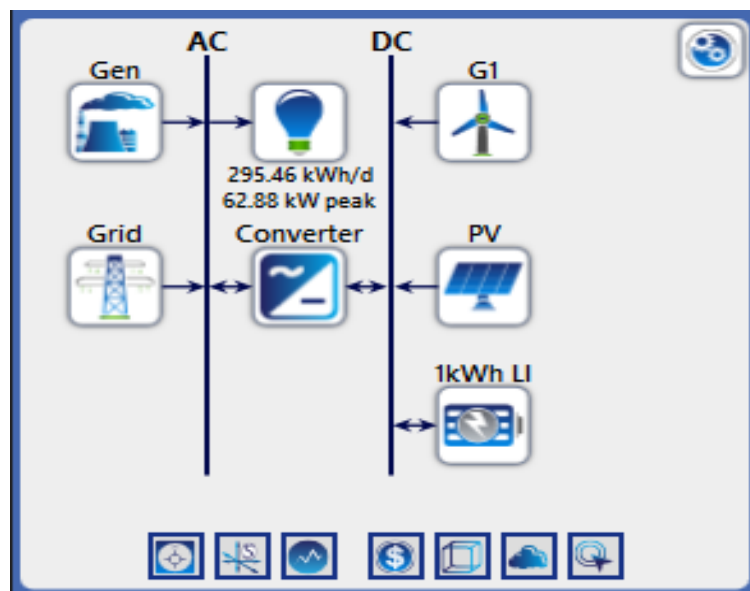


Figure 3.6 Schematic diagram of the propose Hybrid energy System

3.8 Technical and economic parameters for the components used in the hybrid system.

Various components were used in achieving the objectives of the study. The components used are wind turbine, solar PV, diesel generator, converter, and the grid.

3.8.1 Solar PV

Total PV capacity will be determined by the Homer Optimizer. The type of solar PV used is abbreviated Generic Flat plat PV with a rated capacity of 1kW. Solar PV has a derating factor of 80%. Table 3.3 shows the detailing in terms of its parameter

Table 3.3 HOMER input for PV component

| Description | Value |
|---------------------|----------------------|
| Panel type | Generic Flat plat PV |
| Abbreviation | PV |
| Rated capacity (kw) | 1 kW |
| Derating factors | 80% |
| Capital cost | \$ 875 |
| Replacement cost | 771.30 \$/year |
| O&M cost | 0.01 \$/year |

Solar PV electrical output

Homer Pro modeling software uses a set of equations to predict the electrical output of generation sources. Equation 3.1 is used to determine the PV module's electrical output for the model (Thoresen & Skogheim, 2021):

$$P_{output} = Y_{pv} f_{pv} \left(\frac{G_T}{G_{T,STC}} \right) \left(1 + a_p (T_c - T_{c,STC}) \right) \quad (3.1)$$

From the equation,

Y_{PV} is the power output of the PV panel (kW), f_{PV} is the derating factor (%), G_T and $G_{T,STC}$ are the solar radiation and solar radiation under STC (kW/m^2), respectively, a_p is the Temperature coefficient of power, T_c , and $T_{c,STC}$ are the temperature of the PV cell and temperature of the PV cell under STC respectively.

One crucial performance measure for assessing the effectiveness of a PV system connected to the grid is the capacitor factor (Mensah et al., 2019). The final energy generated by a solar PV installation over a certain period divided by the output of energy that would have been created had the system been operated at total capacity for the whole time is known as the capacity factor. The yearly capacity factor, for instance, is provided by equation 3.2.

$$C_f = \frac{E_{AC(a)}}{P_{PV-rated} \times A_h} \quad (3.2)$$

Where A_h is the total anticipated number of operating hours in a given time, usually considered to be a year ($A_h = 8760$ h for a typical year with 365 days), and $E_{AC(a)}$ is the total annual energy generated (kWh).

3.8.3 Diesel Generator

Homer auto-sizing diesel Generator (DG) is selected for the study in other to meet the required load demand in the absence of grid and solar availability. Table 3.4 provide all the details on the DG. In HOMER, the lifetime of generators is specified in terms of operating hours. The number of years that a generator will last is therefore an output variable, which HOMER calculates according to the following equation:

$$R_{gen} = \frac{R_{gen,h}}{N_{gen}}$$

where: $R_{gen,h}$ = Generator lifetime [hr], N_{gen} = the number of hours the generator operates during one year [hr/yr].

Table 3.4 HOMER input for Diesel Generator component

| Description | Value |
|----------------------|------------------|
| Name | Auto size Genset |
| Fuel | Diesel |
| Fuel curve intercept | 3.07 L / hr |
| Fuel curve slope | 0.236 L/hr /kW |
| Fuel price | \$1.3 |
| Minimum Load Ratio | 25% |
| Lifetime (hours) | 15,000.00 |
| Capital cost | \$589 |
| Replacement cost | \$500 |
| O&M cost | 0.01\$/hr |

3.8.4 Converter

To enable a seamless flow of electricity between the DC and AC bus and integrate the hybrid system, the converter/inverter component was installed. This component ensures an efficient electrical transfer within the system. An auto sizing system converter is used for simulation purposes. It has a lifetime of 15years and parallel with AC generator. Table 3.5 shows the technical parameter the converter used.

Table 3.5 HOMER input for Converter component

| Description | Value |
|----------------------|--------------|
| Capacity | 1kW |
| Inverter efficiency | 95% |
| Rectifier efficiency | 95% |
| Rectifier capacity | 100% |
| Lifetime (years) | 15 |
| Capital cost | \$608 |
| Replacement cost | \$608 |

3.8.5 Battery

A battery bank in a hybrid energy system refers to a set of batteries that are used to store excess energy generated from renewable energy sources such as solar or wind power. The battery bank acts as an energy storage system, allowing the stored energy to be used later when renewable energy sources are not available or are generating less power. Net metering applies and net generation is calculated annually, HOMER calculates the total annual energy charge using the following equation:

$$C_{grid,energy} = \sum_i^{rates} \left\{ \begin{array}{ll} E_{netgridpurchases,i} \cdot c_{power,i} & \text{if } E_{netgridpurchases,i} \geq 0 \\ E_{netgridpurchases,i} \cdot c_{sellback,i} & \text{if } E_{netgridpurchases,i} < 0 \end{array} \right\}$$

where: $E_{netgridpurchases,i}$ = the annual net grid purchases (grid purchases minus grid sales) during the time that rate i applies [kWh], $c_{power,i}$ = the grid power price for rate i [\$/kWh], $c_{sellback,i}$ = the sellback rate for rate i [\$/kWh]

The software allows for the optimization of the battery bank size and configuration, based on the energy demand, the renewable energy sources available, and the system's cost constraints. A summary description of the battery component used for the modelling is shown in Table 3.6

Table 3.6 HOMER input for Battery component

| Description | Value |
|-------------------------|--------------|
| Nominal Voltage: | 48 V |
| Nominal Capacity | 1 kWh |
| Maximum Charge Rate | 167 A |
| Maximum Discharge Rate | 500 A |
| Depth of Discharge: 80% | 100% |
| Capital Cost | \$400/kWh |
| Replacement Cost | \$350/kWh |
| O&M Cost | \$0.0 |

3.8.6 Wind Turbine

Wind turbine is modelled as a renewable energy component that generates electricity from wind power. The electricity generated is based on the wind speed and other factors, such as the turbulence intensity and air density. To simulate the operation of a wind turbine in HOMER Pro, the software used the wind resource data for Wenchi. This data is imported from the National Renewable Energy Laboratory (NREL) wind data tool. A summary description of the wind turbine component used for the modelling is shown in Table 3.7

Table 3.7 HOMER input for wind turbine component

| Description | Value |
|--------------------|--------------|
| Rated capacity | 1 kW |
| Hub Height | 17 m |
| Lifetime | 20 years |
| Capital Cost | \$7000 |
| Replacement Cost | \$7000 |
| O&M Cost | \$70 |

Wind Turbine electrical output

HOMER calculates the power output of the wind turbine in each time step using a three-step process. First, HOMER calculates the wind speed at the hub height of the wind turbine, then how much power the wind turbine produces at that wind speed at standard air density. Finally, HOMER adjusts that power output value for the actual air density.

Calculating Hub Height Wind Speed

In each time step, HOMER calculates the wind speed at the hub height of the wind turbine using the inputs you specify in the Wind Resource page and the Wind Shear entry.

If you choose to apply the logarithmic law, HOMER calculates the hub height wind speed using the following equation:

$$U_{hub} = U_{anem} \cdot \frac{\ln(z_{hub} / z_0)}{\ln(z_{anem} / z_0)}$$

where:

U_{hub} = the wind speed at the hub height of the wind turbine [m/s]

U_{anem} = the wind speed at anemometer height [m/s]

z_{hub} = the hub height of the wind turbine [m]

z_{anem} = the anemometer height [m]

z_0 = the surface roughness length [m]

$\ln(..)$ = the natural logarithm

3.9 Metaheuristic Optimization Techniques

The user sets the objective of the optimization, which typically involves minimizing or maximizing a certain parameter. In the context of hybrid energy systems, the objective is to minimize the total net present cost (NPC), levelized cost of energy (LCOE), while ensuring a reliable energy supply. HOMER Pro allows the user to define a set of design variables that influence the configuration of the hybrid energy system. These variables include the sizing of renewable energy sources (e.g., solar PV, wind turbines), battery storage capacity, generator size, and other relevant parameters. The software also considers any constraints imposed on the system

design. These constraints could include the maximum capacity of renewable energy sources, the minimum or maximum battery storage capacity, or any other limitations on the system's components.

To initiate the GA process, HOMER Pro generates an initial population of potential solutions. Each solution represents a unique configuration of the hybrid energy system, defined by the values of the design variables. A fitness function is defined based on the objective of the optimization. It evaluates how well each solution performs in achieving the objective. For example, the fitness function could assess the NPC, LCOE, or carbon emissions associated with a particular system configuration. The GA in HOMER Pro performs three main genetic operations to evolve the population of solutions over generations:

- 1. Selection:** Solutions are selected for reproduction based on their fitness. Better-performing solutions have a higher probability of being selected.
- 2. Crossover:** Selected solutions undergo crossover, where parts of two or more solutions are combined to create new offspring solutions. This mimics the process of genetic recombination in natural evolution.
- 3. Mutation:** A small percentage of the offspring undergo random changes (mutations) in their design variables. This introduces diversity into the population.

Evaluation and Iteration: After the genetic operations, the fitness of the new offspring solutions is evaluated using the fitness function. The best-performing solutions are retained, and the process continues through multiple generations (iterations).

Termination Criteria: The GA process continues until a termination criterion is met. Common termination criteria include reaching a specified number of generations, achieving a certain level of convergence, or exceeding a defined computation time.

Optimal Solution: Once the GA process is complete, HOMER Pro identifies the best-performing solution in the final population. This solution represents the optimal design configuration that fulfills the specified objective and constraints.

3.10 Economic analysis

The economic analysis provides a rigorous analysis of the project's costs and benefits and helps to determine whether the project would be profitable. Economic analysis is often used when evaluating proposed power plants and wind and solar farms. However, economic analysis does not replace other environmental review forms, such as site and impact assessments. Instead, the economic analysis provides additional information

3.10.1 The net present cost (NPC)

Net Present Cost (NPC) can be a significant factor in a project's success. While cost is essential, it is not the only consideration for running a successful project. NPC of an energy project is the total of all the individual costs incurred in the execution of the project throughout the project, reflected with the cost being discounted to present value. Homer Pro uses the discount factor to account for the time value of money, not inflation. Instead of accounting for inflation, Homer Pro employs the discount factor to reflect the temporal worth of money. Inflation is factored out of the study by substituting the actual discount rate for the nominal discount rate. Home Pro

calculates the NPC as given in equation 3.7 by adding the discounted cash flows for each year of the project's lifecycle (Thoresen & Skogheim, 2021).

$$C_{NPC} = \frac{C_{a,total}}{CRF(i,n)} \quad (3.7)$$

Where;

C_{NPC} = Total net present cost

$C_{a, total}$ = total cost of the individual parts of the system.

$CRF (i,n)$ = Capital recovery factor

3.10.2 Levelized Cost of Energy (LCOE)

The LCOE is an essential consideration for investors and consumers when evaluating the economics of a particular energy source or technology. For example, the cost of electricity generated by a power plant divided by the energy produced is known as the LCOE. The cost-effectiveness of various hybrid renewable energy systems technologies is evaluated and compared using this metric (Come Zebra et al., 2021).

The formula for LCOE is expressed in equation 3.8 (Thoresen & Skogheim, 2021):

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \quad (3.8)$$

Where;

$C_{ann,tot}$ = total annualized cost of the system (\$/yr)

E_{served} = total electrical load served (kWh/yr)

3.11 Sensitivity Analysis:

Sensitivity analysis is a powerful tool for assessing the impact of input parameter variations on the output of a model. In this thesis, a sensitivity analysis was conducted to investigate the impact of solar PV price, diesel fuel price, inflation rate, and

discount rate on the techno-economic analysis of the hybrid energy system for Wenchi Methodist hospitals in the Bono Region of Ghana.

The key input parameters considered in this analysis were solar PV price, diesel fuel price, inflation rate, and discount rate. To assess the impact of these parameters, each of them were varied by multiplying their original values by a factor of 2 and 0.5 as shown in Table 3.8

Table 3.8 Sensitivity analysis variables

| Variable | Original value | 2x multiplier | 0.5x multiplier |
|-------------------|-----------------------|----------------------|------------------------|
| Solar PV price | \$875/kW | \$1,750/kW | \$437.5/kW |
| Diesel fuel price | \$1.3/L | \$2.6/L | \$0.65/L |
| Discount rate | 5% | 10% | 2.5% |

3.12 Scenarios for Simulation

In the simulation of the hybrid energy system for Wenchi Methodist Hospital, different scenarios were considered to assess the system's performance under various conditions. The scenarios were designed to test the system's resilience and efficiency while exploring different combinations of renewable energy sources and grid integration. The following scenarios were evaluated:

Base Case Scenario: In this scenario, the hybrid energy system includes a combination of solar PV and wind turbine as the primary renewable energy sources, along with a diesel generator as backup and grid connection for net metering. The system's sizing and optimization were based on the hospital's historical energy consumption data and local solar and wind resource availability.

Solar PV Dominant Scenario: This scenario focuses on maximizing the utilization of solar PV as the primary renewable energy source, reducing the dependency on the wind turbine and diesel generator. The solar PV capacity is increased while keeping other components the same as in the base case scenario.

Wind Turbine Dominant Scenario: In this scenario, the wind turbine is emphasized as the primary renewable energy source, reducing the reliance on solar PV and the diesel generator. The wind turbine capacity is increased while keeping other components the same as in the base case scenario.

Grid Independence Scenario: This scenario aims to achieve a high degree of grid independence by maximizing the use of renewable energy sources and minimizing the reliance on the grid and diesel generator. The hybrid system is optimized to prioritize renewable energy generation, and the grid is used only as a backup source when renewable generation is insufficient.

3.12.1 Testing Methods

The simulation of the hybrid energy system was carried out using the HOMER Pro software, which employs advanced optimization algorithms to find the most cost-effective system configuration for each scenario. HOMER Pro's simulation capabilities allowed for the modelling of different renewable energy technologies, load profiles, and system configurations, ensuring a comprehensive evaluation of the system's performance.

3.12.2 Assumptions

Several key assumptions were made during the simulation to standardize the testing and enable meaningful comparisons between the scenarios:

Energy Demand: The energy demand profile used for simulation was based on historical data of Wenchi Methodist Hospital's energy consumption, including monthly and hourly variations.

Solar and Wind Resource Data: Solar radiation and wind speed data used in the simulation were obtained from reliable sources like the National Renewable Energy Lab (NREL) database, ensuring accurate representation of the local renewable resource potential.

Battery Efficiency: The battery efficiency was assumed to be constant during charge and discharge cycles, and any losses during energy storage and retrieval were not considered.

Grid Connection: The grid was assumed to be reliable, with net metering available for selling excess electricity to the grid and purchasing when needed.

Component Costs: The capital costs, replacement costs, and operation & maintenance costs for each component were based on market prices at the time of the simulation.

3.12.3 Output Parameters for Comparison

To compare the different scenarios and evaluate their effectiveness, the following output parameters were analyzed:

Net Present Cost (NPC): The total cost of the hybrid energy system over its lifetime, discounted to present value to assess the financial viability of each scenario.

Levelized Cost of Energy (LCOE): The cost of producing one unit of electricity (kWh) from the hybrid system, calculated by dividing the total annualized cost by the total electrical load served.

Renewable Fraction: The percentage of energy demand met by renewable energy sources in each scenario, reflecting the system's sustainability and environmental impact.

Capacity Factor: The capacity factor of the solar PV and wind turbine, indicating the efficiency of the renewable energy sources in converting available resources into electricity.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

This chapter presents the results and discussions of the work undertaken. It includes optimization results for the selected hybrid power system of the Wenchi Methodist Hospital facility.

4.1 Simulation Results

The Homer Pro simulation tool was utilized to generate a list of system configurations for the healthcare centre's hybrid system, consisting of solar panel, wind turbine, a converter, a generator, and a grid connection. Simulations provided numerous possible combinations utilizing metaheuristic optimization techniques (Genetic Algorithm), which can technically meet the demand based on the available resources.

Genetic Algorithm is a widely used and versatile metaheuristic optimization algorithm inspired by the process of natural selection. It employs a population of potential solutions that undergo evolutionary operations, including selection, crossover, and mutation, to iteratively improve the solution's fitness. The GA implementation in Homer Pro efficiently explored a vast design space of the hybrid energy system, considering various combinations of renewable energy sources, battery storage capacities, generator sizes, and other relevant parameters. It aimed to minimize the total net present cost (NPC) and levelized cost of energy (LCOE) while ensuring a reliable and uninterrupted power supply for Wenchi Methodist Hospital.

Optimization process of HOMER PRO that simplifies the design process based on identifying least-cost electrical power system was adopted. Therefore this study only considered the best optimal system with the lowest net present cost and levelized cost of energy.

By means of the resources and components available at the site, the simulation results determined the optimal setup to be a 115 kW photovoltaic system connected to a 500 kW grid line, a 37.5 kW converter, and a 70 kW generator, represented in Figure 4.2. This hybrid system makes use of a net meter to measure the electricity shared with the national grid. The design parameters of the hybrid energy were informed by the simulation outcomes, with the initial capital cost, net present cost, and levelized cost of energy estimated to be \$171,325, \$156,358, and \$0.0679 respectively, as displayed in the sky-blue frame Figure 4.1.

| Architecture | | | | | | | | Cost | | | | System | |
|--------------|----|----------|-------------|-----------|----------------|-----------|---------------|------------------------|------------|--------------|-------------------|--------|--|
| PV (kW) | G1 | Gen (kW) | 1kWh LI (#) | Grid (kW) | Converter (kW) | NPC (\$) | LCOE (\$/kWh) | Operating cost (\$/yr) | CAPEX (\$) | Ren Frac (%) | Total Fuel (L/yr) | | |
| 115 | | 70.0 | 987 | 500 | 37.5 | \$156,358 | \$0.0679 | \$10.44 | \$156,175 | 96.7 | 343 | | |
| 115 | 1 | 70.0 | 1,004 | 500 | 36.3 | \$164,726 | \$0.0718 | \$142.04 | \$162,236 | 96.3 | 345 | | |
| 114 | | 70.0 | 1,103 | | 62.9 | \$184,270 | \$0.0975 | \$768.93 | \$170,792 | 98.1 | 576 | | |
| 113 | 1 | 70.0 | 1,100 | | 63.2 | \$193,851 | \$0.103 | \$934.78 | \$177,466 | 98.1 | 583 | | |
| 98.2 | | 70.0 | | 500 | 39.7 | \$359,152 | \$0.124 | \$12,317 | \$143,255 | 62.5 | 7,762 | | |
| 96.8 | 1 | 70.0 | | 500 | 40.8 | \$366,727 | \$0.126 | \$12,382 | \$149,702 | 62.9 | 7,747 | | |
| | | 70.0 | 151 | | 56.1 | \$970,721 | \$0.514 | \$51,440 | \$69,097 | 0 | 35,194 | | |
| | 1 | 70.0 | 150 | | 56.2 | \$972,862 | \$0.515 | \$51,157 | \$76,191 | 0 | 34,911 | | |
| | | 70.0 | 1,080 | 500 | 55.9 | \$1.03M | \$0.545 | \$54,797 | \$69,005 | 0 | 32,093 | | |
| | 2 | 70.0 | 958 | 500 | 54.6 | \$1.04M | \$0.550 | \$54,661 | \$82,187 | 0 | 31,246 | | |
| | | 70.0 | | 500 | | \$1.19M | \$0.631 | \$66,092 | \$35,000 | 0 | 17,966 | | |
| | 2 | 70.0 | | 500 | 0.495 | \$1.20M | \$0.634 | \$65,710 | \$49,301 | 0 | 17,709 | | |
| 296 | | 70.0 | | | 37.6 | \$1.60M | \$0.846 | \$73,477 | \$311,535 | 3.13 | 42,109 | | |

Figure 4.1 Different configurations of hybrid energy systems from Homer Pro

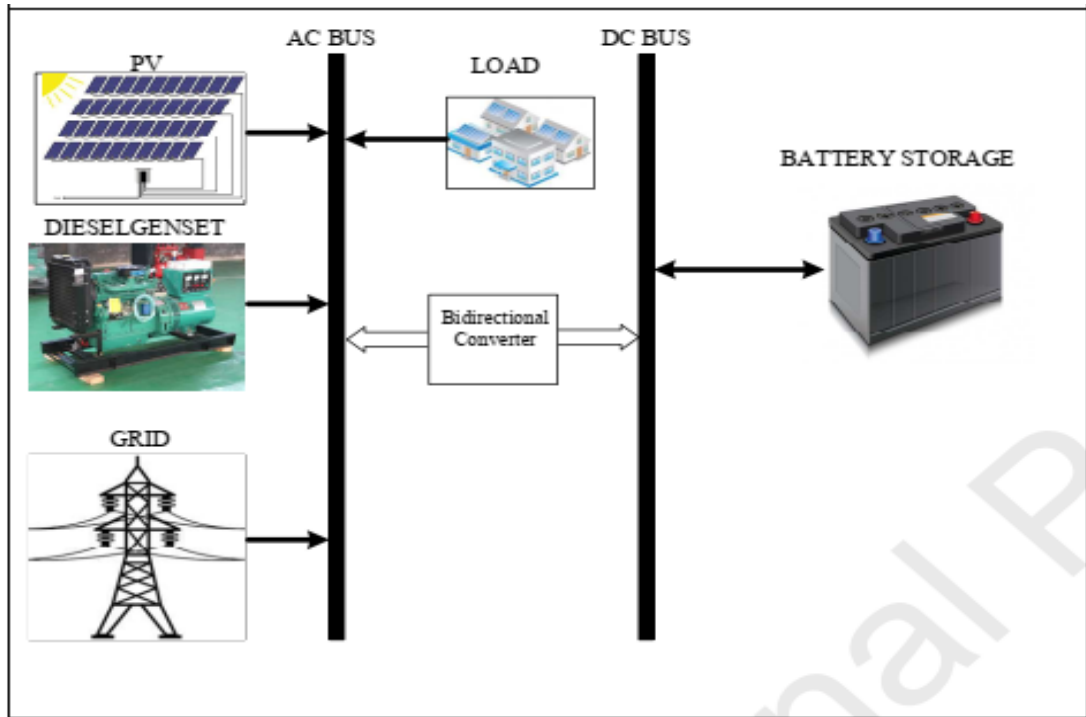


Figure 4.2 Best optimal hybrid energy system configuration for the hospital

4.2 Load Assessment

Wenchi Methodist Hospital is a healthcare facility located in the Wenchi municipality of Ghana. The hospital provides medical services to the local community and serves as a centre for medical care and treatment. As with most healthcare facilities, Wenchi Methodist Hospital consumes a significant amount of energy.

The electrical load data are obtained from the hospital by accessing the monthly electricity bill over a year. This energy is used for a variety of purposes, including lighting, heating, ventilation, air conditioning, and powering medical equipment. It offers 24-hour emergency care and general ward services, as well as 8-hour outpatient services, operations, and diagnostic services. Adequate lighting is provided for security reasons, especially during night-time. The various wings of the hospital, such as offices, outpatient units, and operating theatres, are operational from 8 AM to 5

PM, consuming the largest amount of electricity during these hours as shown in

Figure 4.3

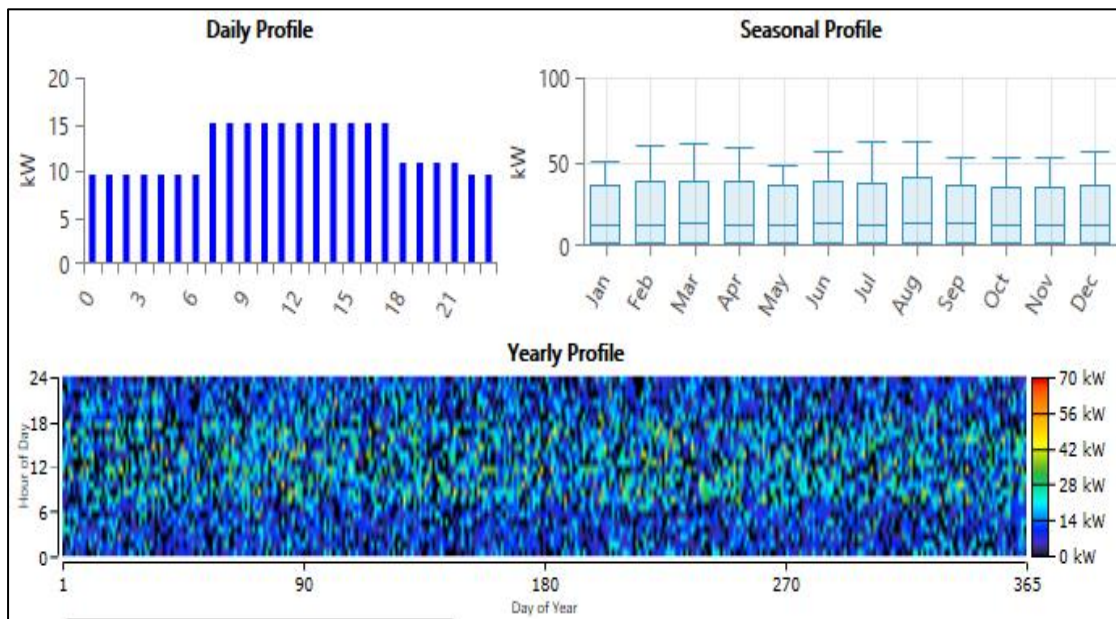


Figure 4.3 The daily, seasonal, and yearly load profile of the Wenchi Hospital

The load demands vary from January to December according to the monthly electricity demand. The figure displays the maximum load demand in July and the minimum in May. The proposed hybrid energy system for the hospital was designed to meet daily load and peak demands of 295.46kWh/day and 62.88 kW respectively, and as a result, it is expected to produce excess renewable energy throughout the day, as shown in Figure 4.3.

4.3 Techno-Economic Evaluation

The techno-economic feasibilities of the hybrid system have been performed using the HOMER Pro and PVSyst simulation programs. The following sections demonstrate the technical and economic assessments of the hybrid energy system.

4.3.1 Evaluation of the Solar Panel Performances

The central component of the proposed hybrid energy system is the flat plate photovoltaic (PV) modules. As previously mentioned, the hybrid energy system is designed to meet peak demand, with the majority of its energy generated by the solar panels. Figure 4.4 shows the simulation of the photovoltaic power output using the HOMER Pro tool. The estimated size of the photovoltaic system was determined to be 115 kW. The average output was found to be 18.6 kW, with an annual production of 163,138 kWh or 163.14 MWh. The system operated for 4,352 hours each year. The maximum hourly output was recorded at 111 kW, with a PV penetration rate of 151% into the grid. The simulation of the PV output demonstrated its potential for investment, highlighting its capability to deliver returns.

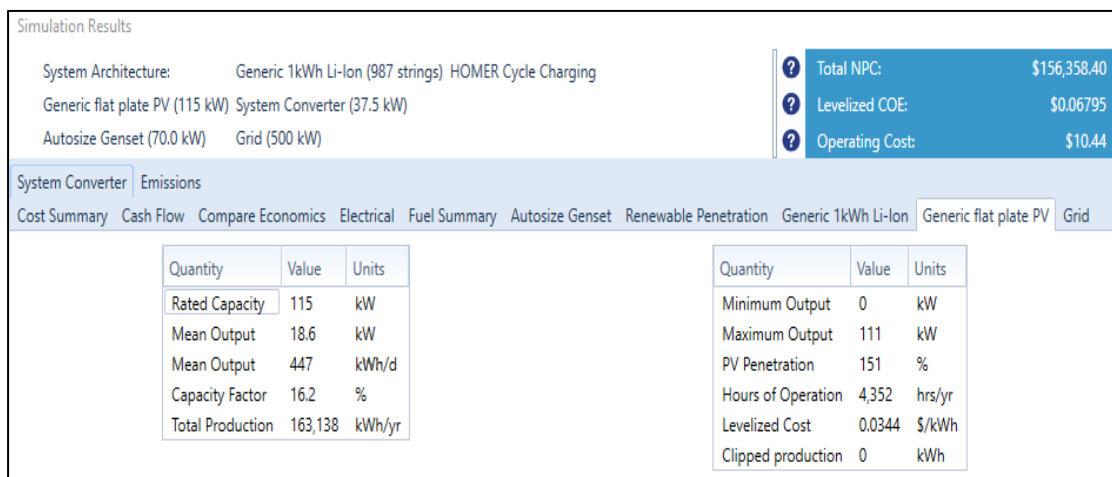


Figure 4.4 Generic flat-plate PV modules output from Homer Pro

4.3.2 Evaluation of the System Converter Performance

The proposed design features an inverter, which acts as the device for converting DC to AC power. The HOMER Pro software determined that the capacity required for the converter was 37.5 kW, with an average output of 14.7 kW. Figure 4.5 provides details on the annual inverter output and rectifier output. It has been observed that the inverter operates for 7,522 hours in a year. As a result, the inverter received a total of

135,571 kWh in DC electricity, converting it into 128,792 kWh of AC electricity for the hospital's power needs. However, due to inversion loss factor, 6,779 kWh of the power was lost.

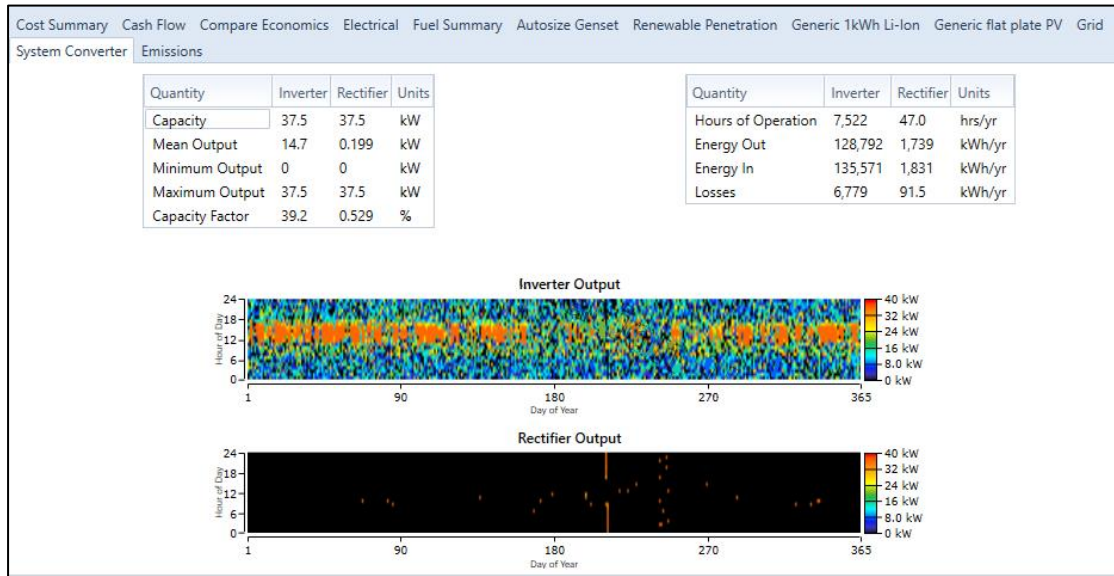


Figure 4.5 System converter output from Homer Pro

4.3.3 Evaluation of the Auto-Size Genset Performance

The diesel generator plays a critical role in providing uninterrupted power supply to the Wenchi Methodist Hospital. When the grid supply or photovoltaic energy is not available, the generator acts as the sole source of power. Figure 4.6 shows the performance of the generator, as simulated by the HOMER Pro tool. As seen from the figure, the generator's contribution to the power supply is minimal, with only three hours of operation in a year. The generator has a mean output of 50.1 kW, produces 1,152 kWh of electricity annually, and consumes 343 litres of fuel. Due to the component's operational hour of 23 hours per year, the hybrid system releases minimal greenhouse gases. The hospital's utilization of 97.4% green electricity,

coupled with its ability to sell surplus power to the grid, results in both economic and ecological advantages.

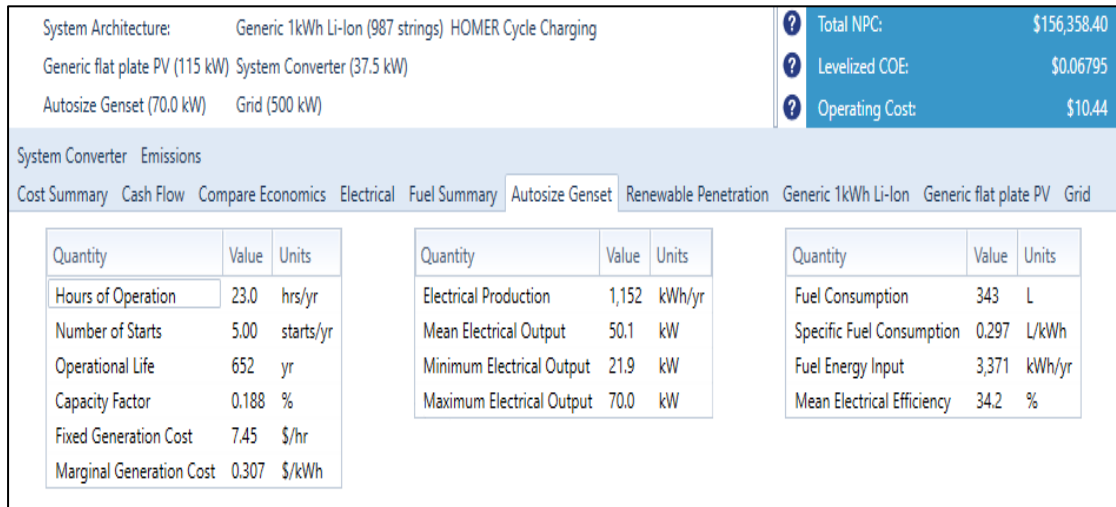


Figure 4.6 Generator output power by Homer Pro simulation

4.3.4 Evaluation of the Grid Performance

The primary source of electrical supply in the hybrid system is the national grid, which serves as a backup during times when solar energy is not sufficient. Typically, the excess energy generated by the photovoltaic panels during daylight hours is fed back into the grid using a net meter, and when sunlight is not available or is not sufficient to meet the hospital's energy needs, electricity is drawn from the grid.

According to the simulation results displayed in Figure 4.7, the hybrid energy system provides 23.44 MWh of electricity to the grid annually. This simulation includes the scenarios where energy is both purchased and sold to the grid. The grid functions as a storage device and is the main supplier of energy in this hybrid system. The simulation shows that the hospital will only need to purchase 3.17 MWh of electricity each year, while having the potential to sell 23.44 MWh. This highlights the ability of the proposed hybrid energy system to effectively power the hospital, even with the potential for expansion or increased demand for medical services.

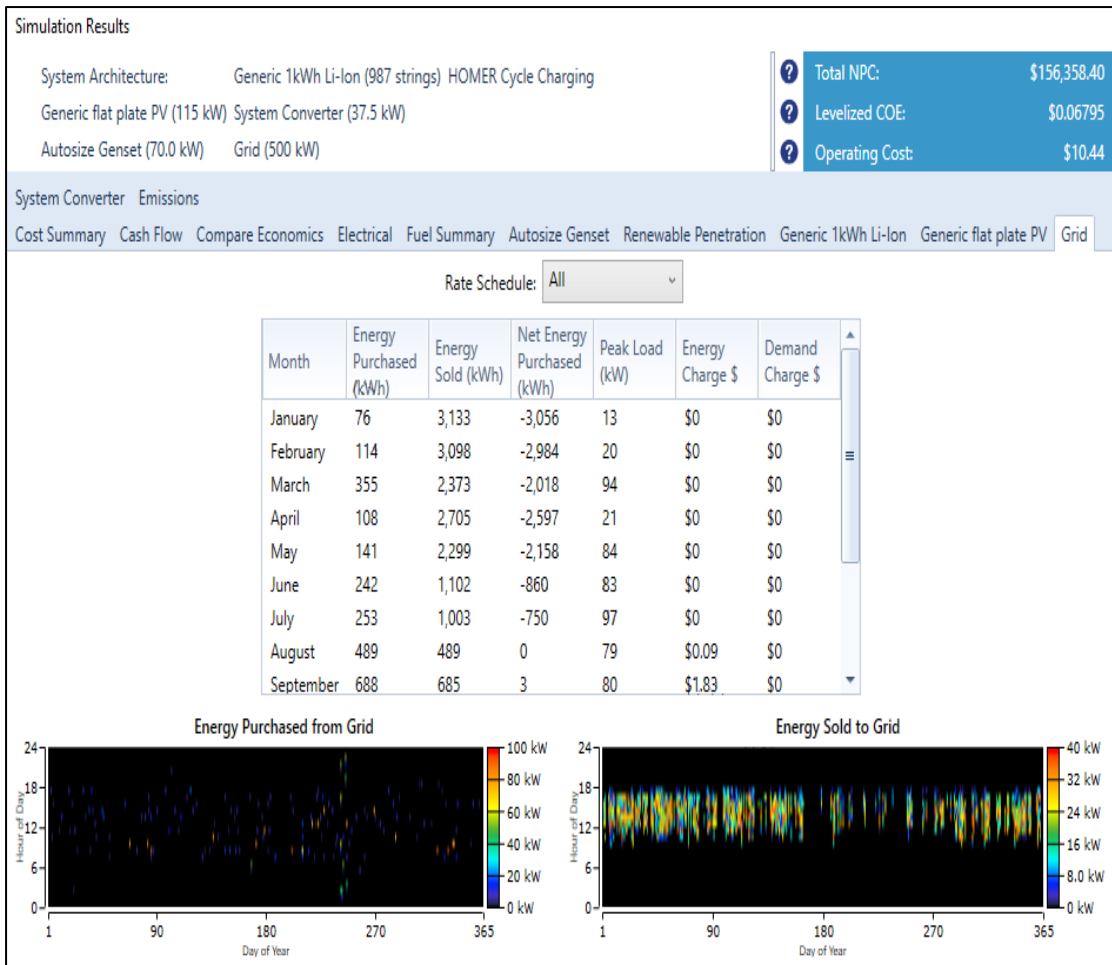


Figure 4.7 The scenario of the electric power purchased from and sell to the grid

4.3.5 Evaluation of the Electrical Performance

The electrical output performance of the micro grid system is a key factor in the technical assessment.

Figure 4.8

| Production | | | Consumption | | | Quantity | | |
|-----------------------|----------------|------------|-----------------|----------------|------------|---------------------|--------|------|
| | kWh/yr | % | | kWh/yr | % | | kWh/yr | % |
| Generic flat plate PV | 163,138 | 97.4 | AC Primary Load | 107,842 | 82.1 | Excess Electricity | 22,889 | 13.7 |
| Autosize Genset | 1,152 | 0.688 | DC Primary Load | 0 | 0 | Unmet Electric Load | 0 | 0 |
| Grid Purchases | 3,169 | 1.89 | Deferrable Load | 0 | 0 | Capacity Shortage | 0 | 0 |
| Total | 167,460 | 100 | Grid Sales | 23,442 | 17.9 | | | |
| | | | Total | 131,283 | 100 | | | |

| Quantity | Value | Units |
|-------------------------|--------|-------|
| Renewable Fraction | 96.7 | % |
| Max. Renew. Penetration | 70,541 | % |

displays the simulation results of the electrical output power of the hybrid system as determined by the HOMER Pro. The results show that 97.4% of the total output is generated by solar panels. In contrast, the generator and grid line only contribute 2.58% of the power production, with annual outputs of 0.688 kW and 3,169 kW

respectively. Out of the total 167,460 kWh of electricity produced, 107,842 kWh is consumed by the AC load, while an excess of 23,44 kWh can be sold to the grid. The DC power generated is 163,138 kWh, but due to various factors, 31,855 kWh of electricity is lost, leading to an estimated 131,283 kWh of AC electricity. Of this AC electric power, 82.1% or 107.84 MWh is consumed by the Wenchi Methodist Hospital, while the remaining 17.9% can be sold to the grid.

| Production | | | Consumption | | | Quantity | | |
|-----------------------|---------|-------|-----------------|---------|------|---------------------|--------|------|
| | kWh/yr | % | | kWh/yr | % | | kWh/yr | % |
| Generic flat plate PV | 163,138 | 97.4 | AC Primary Load | 107,842 | 82.1 | Excess Electricity | 22,889 | 13.7 |
| Autosize Genset | 1,152 | 0.688 | DC Primary Load | 0 | 0 | Unmet Electric Load | 0 | 0 |
| Grid Purchases | 3,169 | 1.89 | Deferrable Load | 0 | 0 | Capacity Shortage | 0 | 0 |
| Total | 167,460 | 100 | Grid Sales | 23,442 | 17.9 | | | |
| | | | Total | 131,283 | 100 | | | |

| Quantity | Value | Units |
|-------------------------|--------|-------|
| Renewable Fraction | 96.7 | % |
| Max. Renew. Penetration | 70,541 | % |

Figure 4.8 Annual electric power production of the hybrid system

4.3.6 Capacity shortage (CS) and Renewable Fraction (RF) for selected scenarios

Figure 4.9 shows a schemes based on the hybrid system’s capacity shortages (CS) and renewable fractions (RF). The renewable fraction is the difference between the force/energy generated by a renewable vitality source and the total power pulled from the system (Kumari et al., 2017). HOMER helps identify the renewable part for each extraordinary reproduced configuration after a recreation has been executed and completed for a specific setup. The maximum renewable fraction (RF) in the proposed setup/power system or architecture is expected to be in the range of 0 to 100% (Olatomiwa et al., 2015). Renewable fraction is mostly expected to be as high as possible under the circumstances without drastically affecting the net present cost (NPC). This shows or explains the way the setup or the hybrid makes the most extreme utilization of the power yield coming from the renewable source.

The results from the simulation reveals that, the optimal hybrid power system had high renewable fraction (RF) of 96.7% with capacity shortage of 0%. Capacity shortage fraction, is the total capacity shortage divided by the total annual electric load.

| Quantity | kWh/yr | % |
|---------------------|--------|------|
| Excess Electricity | 22,889 | 13.7 |
| Unmet Electric Load | 0 | 0 |
| Capacity Shortage | 0 | 0 |

| Quantity | Value | Units |
|-------------------------|--------|-------|
| Renewable Fraction | 96.7 | % |
| Max. Renew. Penetration | 70,541 | % |

Figure 4.9 Renewable penetration performance

4.5 Financial Analysis

The success of a renewable energy system is contingent on various financial considerations such as investment cost, interest rate, and internal rate of return. In the case of the chosen hospital, there is no requirement for supplementary investment in grid connectivity since it is already connected. However, during the installation of the photovoltaic panels, the expansion of the hybrid energy system will be necessary due to the net-metering mechanism and commissioning process. The investor for this project will be either the state-run hospital authority or another organization like the Department of Public Health.

Since the solar panels and inverter are not manufactured in Ghana, they will need to be imported and constitute the primary components of the system. The estimated cost for these components was determined by verifying the prices indicated on the manufacturer's website. Other components required for the system can be obtained from the local market at regular prices, which includes VAT and TAX. The initial cost of the system will account for the components, integration, and commissioning.

The capital cost, or initial investment cost, for the system was estimated to be US\$ 156,175.41. Regular maintenance is necessary to ensure the system operates properly and the estimated operation and maintenance cost (OPEX) was calculated to be US\$ 10.44. The interest rate levied on the investor or authority could differ depending on the subsidy and scheme utilized, but the financial evaluation of the hybrid system revealed a return on investment of 12.8% and an internal rate of return of 7.3%. The internal rate of return represents the annual profit made on the initial investment of US\$ 156,358. The cost of energy (COE) for the hybrid energy system was determined to be 0.0679\$/kWh, which is lower and cost effective compared to the cost of energy from the grid (0.10\$/kWh). The simple payback period for the hybrid system was calculated to be 9 years, but the discounted payback period, which takes into account the time value of money, was estimated to be 8.5 years. This means it will take 9 years to recover the initial investment.

4.6 Sensitivity Analysis:

4.6.1 Solar PV

The sensitivity analysis shows that the solar PV price has a significant impact on the techno-economic analysis of the hybrid energy system. As the solar PV price increases, the levelized cost of electricity (LCOE) also increases. For instance, when the solar PV price is doubled to \$1,750/kW, the LCOE increases from 0.0679\$/kWh to \$0.113/kWh, which is an increase of 66.4%. On the other hand, when the solar PV price is halved to \$437.5/kW, the LCOE decreases to \$0.0464/kWh, which is a decrease of 31.60% as illustrated in Figure 4.10. This indicates that the hybrid energy system becomes more economically viable when the solar PV price decreases.

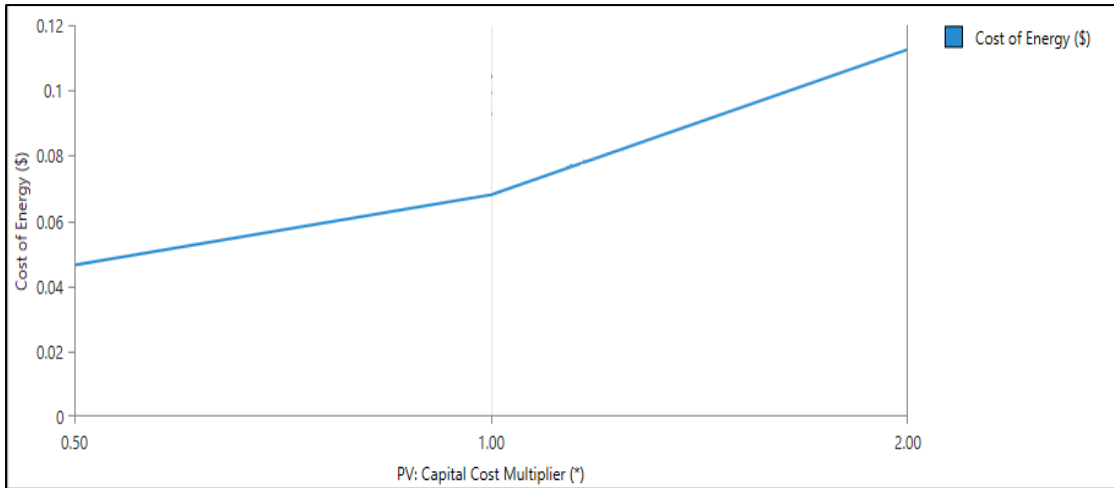


Figure 4.10 Sensitivity analysis changing PV capital cost

4.6.2 Diesel Fuel Price

The sensitivity analysis also shows that the diesel fuel price has a significant impact on the techno-economic analysis of the hybrid energy system. As the diesel fuel price increases, the LCOE also increases. For instance, when the diesel fuel price is doubled to \$2.6/L, the LCOE increases from 0.0679\$/kWh to \$0.0692/kWh, which is an increase of 1.9%. On the other hand, when the diesel fuel price is halved to \$0.65/L, the LCOE decreases to \$0.0667/kWh, which is a decrease of 3.82% as illustrated in Figure 4.11. This indicates that the hybrid energy system becomes more economically viable when the diesel fuel price decreases.

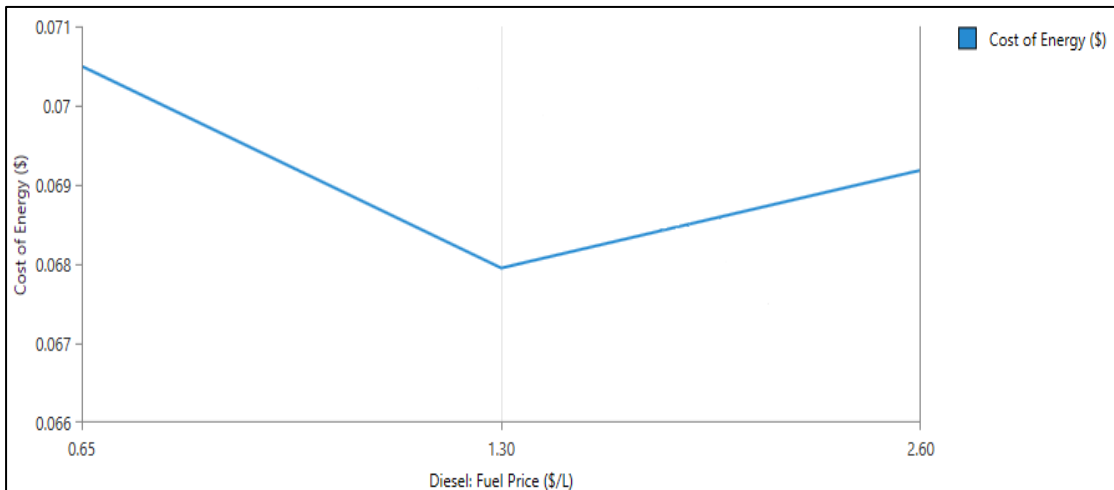


Figure 4.11 Sensitivity analysis changing Diesel fuel price

4.6.3 Discount Rate

The sensitivity analysis also shows that the discount rate has a significant impact on the techno-economic analysis of the hybrid energy system. As the discount rate increases, the LCOE also increases. For instance, when the discount rate is doubled to 10%, the LCOE increases from 0.0679\$/kWh to \$0.115/kWh, which is an increase of 69.4%. On the other hand, when the discount rate is halved to 2.5%, the LCOE decreases to \$0.047/kWh, which is a decrease of 30.7% as illustrated in Figure 4.12. This indicates that the hybrid energy system becomes more economically viable when the discount rate decreases.

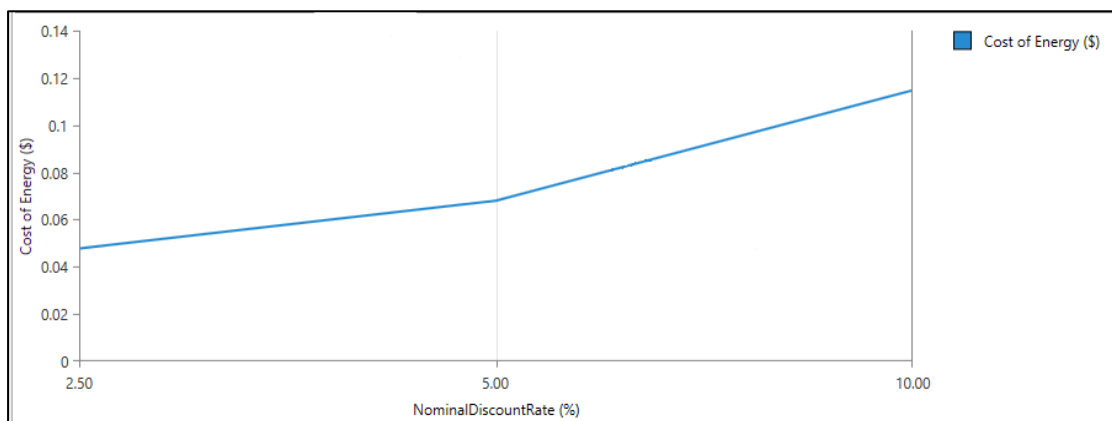


Figure 4.12 Sensitivity analysis changing Discount rate

4.6.4 Summary

The sensitivity analysis shows that only the solar PV price and discount rate have a significant impact on the techno-economic analysis of the hybrid energy system. The change in diesel fuel prices had a small impact on the hybrid system since the generator set only contributes less than 1% to the total energy production. The results indicate that the hybrid energy system becomes more economically viable when the solar PV price and when the discount rate decreases. Therefore, policymakers and

investors should consider these factors when making decisions on the deployment of hybrid energy systems in hospitals in Ghana.

4.7.3 Impact on Wenchi Methodist Hospital

The Wenchi Methodist Hospital is a crucial part of the healthcare system for rural settlements and low-income urban populations. Each day, it is visited by a large number of patients, with over 700 people using its outdoor treatment facilities and over 50 being admitted to the hospital. In order to provide the necessary medical care, a reliable source of power is crucial. Unfortunately, many sub-district hospitals in Bono region, including the Wenchi Methodist Hospital, face power shortages and high cost of electricity, especially during the day when demand is at its highest. To address this issue, implementing a hybrid energy system is proposed as a long-term solution.

While photovoltaic technology is seen as a reliable source of sustainable energy, its high initial investment can be a challenge, particularly in developing countries where financial constraints and high land prices exist. The hybrid energy system offers a more cost-effective solution by utilizing available rooftop space and additional equipment like battery banks and charge controllers. The present techno-economic evaluation provides important information for hospital authorities in making informed decisions about investing in the hybrid energy system. The simulation results indicate that the hybrid energy system is a feasible and practical solution for providing a steady power supply to rural healthcare centres. Additionally, the system is cost-effective, environmentally friendly, and technically sound, making it a more

sustainable and better alternative for ensuring uninterrupted medical services to rural populations.

4.7 Summary

The main objective of this research was to conduct a techno-economic analysis of hybrid energy systems for hospitals, with a specific focus on Wenchi Methodist Hospital in Ghana. The study aimed to assess the energy consumption patterns and sources at Wenchi Methodist Hospital, evaluate the feasibility of implementing a hybrid energy system, and conduct a cost-benefit analysis of the proposed system.

4.7.1 Summary of findings

Objective 1: Develop a theoretical model for evaluating hybrid energy supplies

The theoretical model successfully outlined a systematic approach to analyse and optimize the hybrid energy supplies for Wenchi Methodist Hospital. By integrating solar photovoltaic panels, wind turbines, battery storage, and a diesel generator, the proposed system aims to provide a sustainable and reliable power supply while minimizing dependency on fossil fuels and grid electricity. The Homer Pro simulation software was utilized to model and optimize the hybrid system configuration, considering factors such as solar irradiance, wind speed, equipment specifications, and costs.

Objective 2: Assessing Energy Consumption Patterns and Sources

The study analysed the energy consumption patterns at Wenchi Methodist Hospital, revealing a significant demand for reliable and uninterrupted power supply to support medical services. The hospital relies heavily on grid-connected electricity, which is subject to frequent outages, leading to disruptions in patient care and potential harm to

patients. The analysis highlighted the need for a sustainable and dependable energy solution to address the hospital's energy challenges.

Objective 4: Evaluating the Feasibility of Implementing a Hybrid Energy System

Through the utilization of the Homer Pro simulation tool, the study explored various hybrid energy system configurations that could meet the hospital's energy demands. The optimization process identified the most cost-effective and sustainable setup, consisting of a 115 kW photovoltaic system connected to a 500 kW grid line, a 37.5 kW converter, and a 70 kW generator. The simulation results demonstrated that the proposed hybrid system could handle peak load demands and provide excess renewable energy for potential sale to the grid.

Objective 5: Conducting a Cost-Benefit Analysis of the Hybrid Energy System

The techno-economic evaluation revealed promising results for the hybrid energy system. The initial capital cost of US\$ 156,175.41 was estimated for the system, with an operation and maintenance cost of US\$ 10.44. The return on investment (ROI) was calculated to be 12.8%, and the internal rate of return (IRR) was determined to be 7.3%, indicating favourable financial prospects. The levelized cost of energy (LCOE) for the hybrid system was 0.0679\$/kWh, which was lower and more cost-effective compared to the grid electricity cost of 0.10\$/kWh. The simple payback period was projected to be 9 years, and the discounted payback period was estimated at 8.5 years.

4.7.2 Discussion of Findings

The findings of this study align with existing literature on the importance of reliable and sustainable energy supply in healthcare facilities. Hospitals, especially in rural

and low-income areas, often face challenges with inadequate power supply, leading to compromised medical services and patient care. Implementing hybrid energy systems, as demonstrated in this study, offers a viable solution to address these challenges (Abu-Taha & Shaheen, 2019; Zizoui et al., 2022).

The theoretical model's use of techno-economic analysis, including metrics such as levelized cost of energy (LCOE), net present cost (NPC), payback period (PB), and rate of investment (ROI), resonates with the methodologies applied in previous studies. Such economic evaluations play a crucial role in determining the viability and profitability of implementing hybrid energy systems in healthcare centres (Alsagri et al., 2021; Islam et al., 2022a; Usman et al., 2018; Zizoui et al., 2022).

The simulation results indicate that the proposed hybrid energy system for Wenchi Methodist Hospital is technically feasible and economically viable. The integration of solar photovoltaic panels, converter, and generator in the hybrid setup allows for optimal utilization of renewable energy sources while ensuring a reliable power supply. The excess energy generated can be sold to the grid, providing potential revenue for the hospital and contributing to the national power grid (Usman et al., 2018).

Comparing the cost of the hybrid energy system to the current situation of relying solely on grid electricity reveals several benefits. While the initial capital cost of the hybrid system may seem higher, the long-term cost savings through reduced energy bills and potential revenue from selling surplus energy to the grid outweigh the upfront investment. Additionally, the hybrid system offers energy independence and resilience, mitigating the impact of power outages and fuel price fluctuations (Achirgbenda et al., 2020; Olatomiwa & Mekhilef, 2015).

The successful implementation of the hybrid energy system at Wenchi Methodist Hospital can have both short-term and long-term benefits. In the short term, the hospital will experience improved energy reliability, leading to enhanced patient care and medical services. The ability to generate and sell renewable energy can generate additional income for the hospital, which can be reinvested in healthcare facilities and services.

In the long term, the adoption of sustainable energy practices can position Wenchi Methodist Hospital as a model for other healthcare facilities in the region. Demonstrating the feasibility and benefits of hybrid energy systems can encourage other hospitals and healthcare institutions to follow suit, leading to a broader transition to sustainable energy sources in the healthcare sector. This, in turn, can contribute to reducing carbon emissions and advancing Ghana's efforts towards meeting its renewable energy targets.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The provision of reliable and sustainable energy sources in hospitals is a critical issue in many countries, including Ghana. Despite the increasing demand for constant power supply, the energy needs of hospitals are often not met by the traditional grid-

connected electricity, which is unreliable and prone to power outages. This can result in significant harm to patients and disrupt the provision of healthcare services. In this thesis, a techno-economic analysis of hybrid energy systems for hospitals was conducted with a focus on Wenchi Methodist Hospital in Ghana.

The research objectives were to assess the energy consumption patterns and sources at Wenchi Methodist Hospital, evaluate the feasibility of implementing a hybrid energy system in Wenchi Methodist Hospital, and conduct a cost-benefit analysis of the hybrid energy system. The research questions that guided the study were centered on the current energy consumption pattern in hospitals and how it compares with the energy consumption trends in the healthcare sector, the potential for implementing hybrid energy systems in hospitals, and the capital costs, operating costs, payback period, and life cycle cost of implementing hybrid energy systems in hospitals.

The results of this study indicate that the implementation of a hybrid energy system consisting of a 115 kW photovoltaic system connected to a 500 kW grid line, a 37.5 kW converter, and a 70 kW generator is the most cost-effective and sustainable option for Wenchi Methodist Hospital. The simulation results also demonstrated that the proposed hybrid energy system is capable of handling the peak load demands of the hospital, which occur during the operational hours of the various hospital wings.

The study's findings are of significant importance to policymakers, healthcare administrators, and energy stakeholders. The recommendations of this study will help healthcare administrators to make informed decisions about investing in hybrid energy systems and promote sustainable energy practices in the healthcare sector. The results of this study will also inform the development of energy policies and

regulations to promote the adoption of sustainable energy systems in hospitals in Ghana and other countries.

In conclusion, this study demonstrated the feasibility and potential benefits of implementing hybrid energy systems in hospitals. The findings provide valuable insights into the technical and economic feasibility of hybrid energy systems and promote the use of sustainable energy sources in the healthcare sector

5.2 Recommendation

Although the results satisfy the project's objectives, further research should be conducted to investigate the feasibility of implementing hybrid energy systems in other healthcare facilities in Ghana and other countries to provide a more comprehensive understanding of the potential benefits of sustainable energy systems in the healthcare sector.

Future research should focus on conducting long-term performance monitoring and analysis. This will involve collecting data on energy production, consumption, and cost savings over an extended period, such as several years. By analyzing the system's performance over time, researchers can assess its efficiency, identify any potential issues or areas for improvement, and validate the cost-benefit analysis conducted in this study.

Future research should also explore the incorporation of emerging technologies and innovations in hybrid energy systems for hospitals. Advancements in solar panel efficiency, energy storage solutions, and smart grid technologies can significantly enhance the performance and economic viability of such systems.

In addition to the technical and economic evaluations conducted in this study, future research should encompass a comprehensive socio-economic and environmental impact assessment of hybrid energy systems in hospitals

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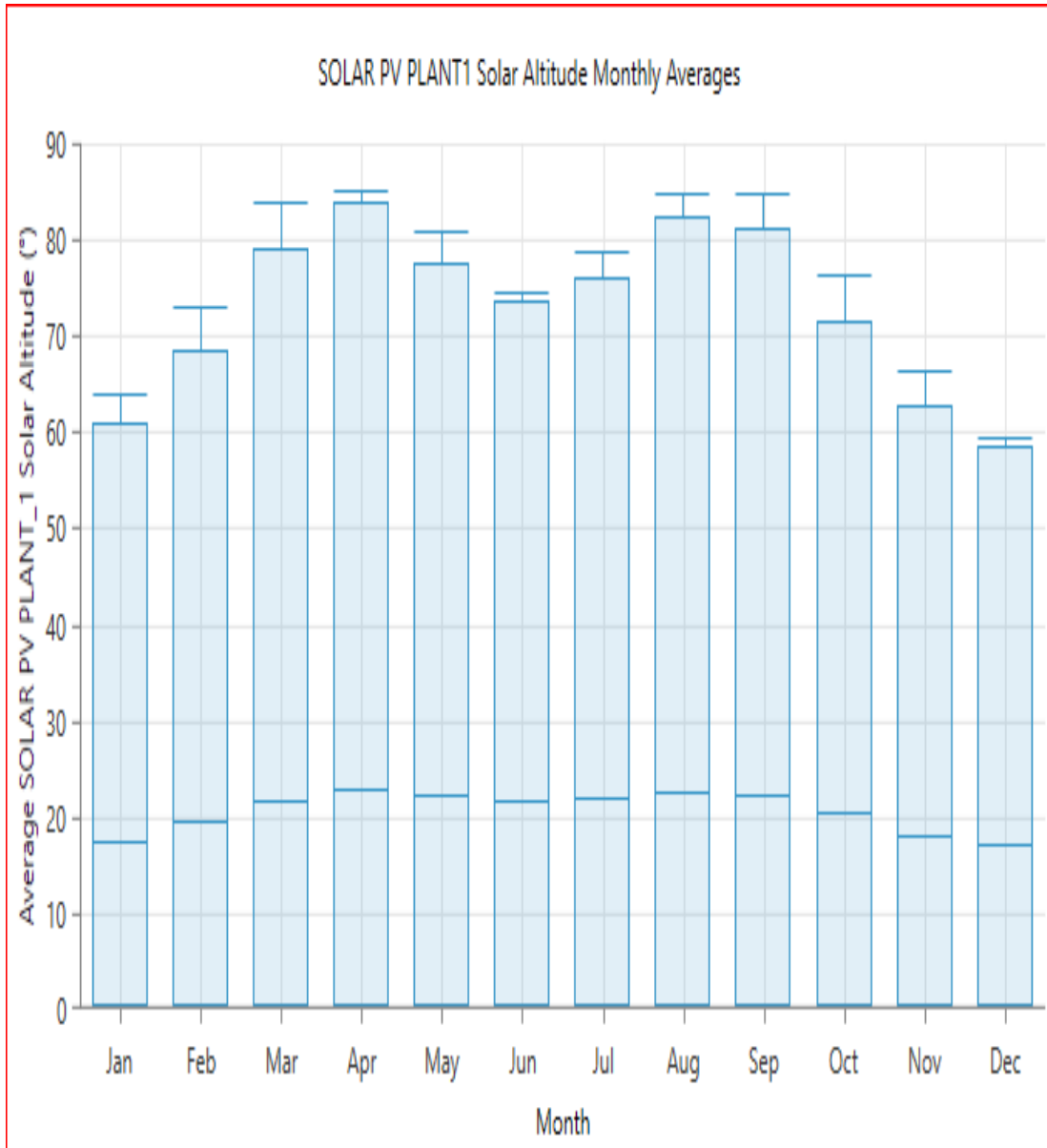
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APPENDICES

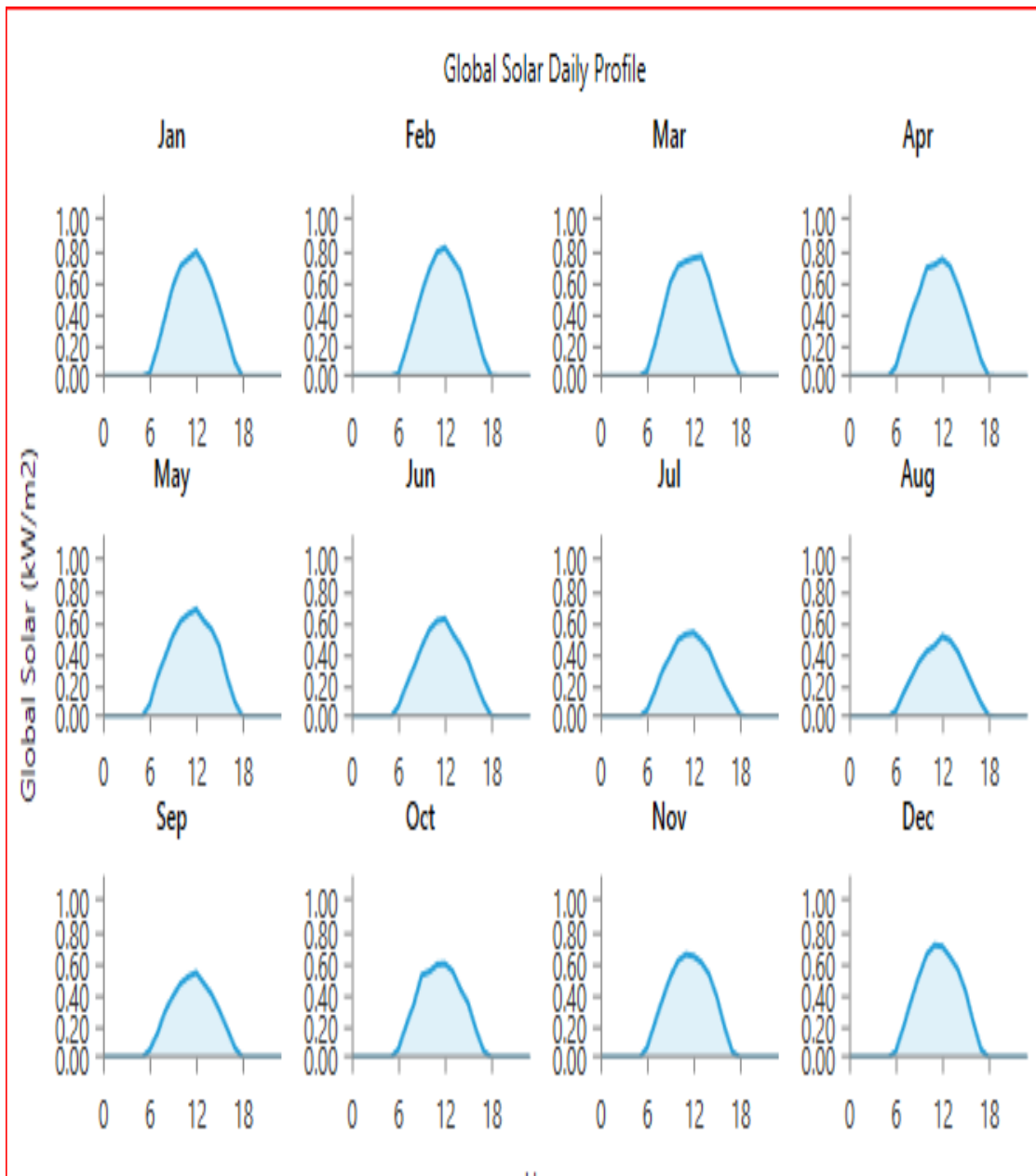
APPENDIX 1:

Solar PV plant, solar altitude monthly averages



APPENDIX 2

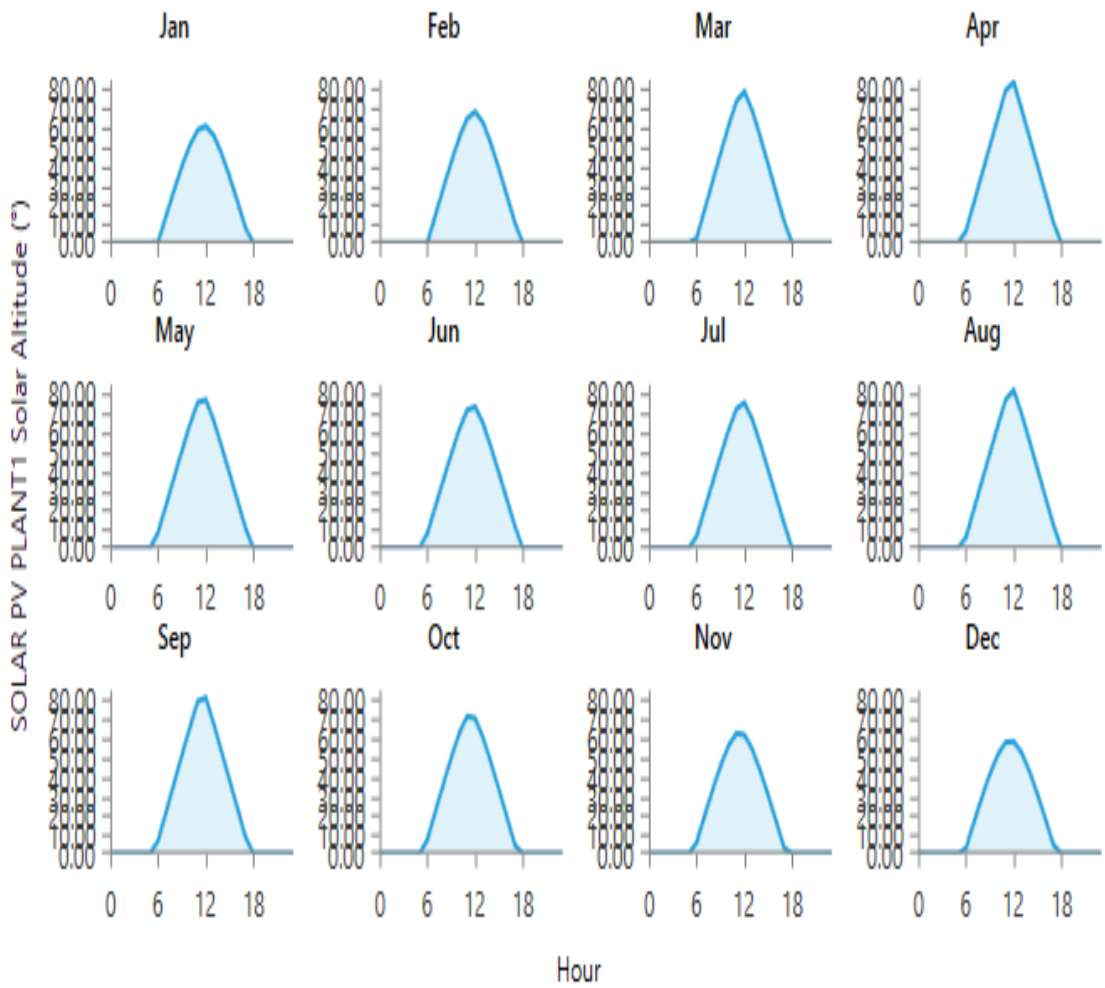
Global solar daily profile



APPENDIX 3

Solar plant altitude data

SOLAR PV PLANT1 Solar Altitude Daily Profile



APPENDIX 4

Categorized optimization results

| export... | | Export All... | | Sensitivity Cases | | | | | | | | | | Compare Economics | | Column Choics | |
|--|--|----------------------|-----------------|-------------------|--------------|--------------|--------------|----------|----------|----------|------------------------|----------------------|--------------|-------------------|-------|------------------|--|
| Left Click on a sensitivity case to see its Optimization Results. | | | | | | | | | | | | | | | | | |
| Export... | | Optimization Results | | | | | | | | | | Categorized | | Ove | | | |
| Left Double Click on a particular system to see its detailed Simulation Results. | | | | | | | | | | | | | | | | | |
| Architecture | | | | | | | | | | Cost | | | System | | 500kW | | |
| | | SM500 (kW) | SM500-MPPT (kW) | WF33 | 500kW_E (kW) | 500kW_D (kW) | Leon900 (kW) | Dispatch | NPC (\$) | COE (\$) | Operating cost (\$/yr) | Initial capital (\$) | Ren Frac (%) | Total Fuel (L/yr) | Hours | Production (kWh) | |
| | | 155 | 500 | 26 | 500 | | 110 | CC | \$1.76M | \$0.127 | \$268,479 | \$79,250 | 14.6 | 902,276 | 8,080 | 1,894,780 | |
| | | | | 26 | 500 | | | CC | \$1.77M | \$0.128 | \$275,201 | \$48,869 | 8.56 | 963,122 | 8,091 | 2,022,556 | |
| | | | | | 500 | | | CC | \$1.91M | \$0.138 | \$301,774 | \$16,603 | 0 | 1,067,302 | 8,760 | 2,241,334 | |
| | | 32.0 | 500 | | 500 | | 6.08 | CC | \$1.91M | \$0.138 | \$301,175 | \$22,048 | 0 | 1,059,333 | 8,760 | 2,224,600 | |
| | | 619 | 500 | 24 | 500 | 500 | 292 | CC | \$2.86M | \$0.204 | \$428,723 | \$176,973 | 22.7 | 810,122 | 8,060 | 1,645,874 | |
| | | | | 32 | 500 | 500 | | CC | \$3.01M | \$0.215 | \$469,731 | \$72,917 | 8.82 | 954,682 | 8,042 | 1,937,997 | |
| | | 773 | 500 | | 500 | 500 | 324 | CC | \$3.07M | \$0.219 | \$463,306 | \$173,552 | 17.3 | 865,918 | 8,725 | 1,758,646 | |
| | | | | | 500 | 500 | | CC | \$3.31M | \$0.236 | \$523,277 | \$33,205 | 0 | 1,062,117 | 8,760 | 2,154,708 | |
| | | 1,665 | 500 | 88 | 500 | | 475 | CC | \$18.3M | \$1.31 | \$2.85M | \$417,014 | 29.4 | 437,802 | | | |
| | | 2,048 | 500 | | 500 | | 487 | CC | \$20.0M | \$1.44 | \$3.14M | \$369,988 | 22.5 | 481,461 | | | |
| | | | | 90 | 500 | | | CC | \$21.5M | \$1.56 | \$3.42M | \$128,293 | 10.3 | 539,413 | | | |
| | | | | | 500 | | | CC | \$24.1M | \$1.75 | \$3.85M | \$16,603 | 0 | 608,206 | | | |