Analysis and Design of a Hybrid Power Generation System for the Electrification of Health and Education Facilities in Sierra Leone

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I declare this content is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the University of Lisboa.

Resumo

O acesso à energia moderna é um motor fundamental para o desenvolvimento de comunidades e países inteiros. Este serviço traz grandes benefícios, com impacto na qualidade das instituições públicas, especialmente nos sectores da saúde e da educação. A utilização de sistemas híbridos de produção de energia fora da rede baseados na energia solar fotovoltaica e bancos de armazenamento de baterias está a ser cada vez mais utilizada para electrificar áreas remotas onde as extensões da rede não são viáveis de construir. A Serra Leoa é um dos países com a mais baixa taxa de acesso à electricidade do mundo, com apenas 26% da sua população a ter acesso a este serviço. O objectivo deste estudo é mapear a situação energética actual dos hospitais, centros de saúde e escolas secundárias da Serra Leoa e propor soluções padrão para a sua electrificação através da concepção de sistemas híbridos autónomos de produção de energia. O trabalho compreende o desenvolvimento de uma análise multicritério para seleccionar as instalações a utilizar como estudos de caso para a realização de auditorias energéticas, criando perfis de carga e estimativas das necessidades energéticas futuras. Com estes dados, foram criados vários projectos de sistemas de energia fora da rede para cada tipo de instituição e as suas sub-categorias. Finalmente, estes sistemas foram optimizados utilizando HOMER Pro, considerando o custo dos materiais, instalação, e operação e manutenção, a fim de recomendar vários projectos de sistemas híbridos de energia autónomos sustentáveis para electrificação rural de instituições públicas na Serra Leoa.

***Palavras-chave**: Electrificação rural; Solar PV; Simulação HOMER Pro; Off-grid; Sistema híbrido de geração de energia.*

Abstract

Access to modern energy is a key driver for the development of communities and whole countries. Major benefits come with this service, impacting the quality of public institutions, especially within the health and education sectors. The use of off-grid hybrid power generation systems based on solar PV and battery storage banks is being increasingly used to electrify remote areas where grid extensions are not feasible to construct. Sierra Leone is one of the countries with the lowest electricity access rate in the world with only 26% of its population having access to this service. The objective of this study is to map the current energy situation of hospitals, health centres, and secondary schools of Sierra Leone and propose standard solutions for their electrification by designing hybrid stand-alone power generation systems. The work comprises the development of a multi-criteria analysis to select the facilities to be used as case studies to perform energy audits, creating load profiles and estimations of future energy needs. With this data, several designs for off-grid power systems were created for each type of institution and its sub-categories. Finally, these systems were optimized using HOMER Pro, considering the cost of the materials, installation, and operation and maintenance in order to recommend various sustainable hybrid stand-alone power system designs for rural electrification of public institutions in Sierra Leone.

Keywords*: Rural electrification; Solar PV; HOMER Pro simulation; Off-grid; Hybrid power generation system.*

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List of Abbreviations

AC	Alternating Current
AG	Auto-sized Generator
ATS	Automatic Transfer Switch
BESS	Battery Energy Storage System
BG	Backup Genset
BMS	Battery Management System
CAPEX	Capital Expenditure
CEER	Council of European Energy Regulators

CFL	Compact Fluorescent Lamp
CHC	Community Health Centre
CHP	Community Health Pole
CHW	Community Health Worker
CLSG	Côte d’Ivoire - Liberia - Sierra Leone - Guinea
DC	Direct Current
DoD	Depth of Discharge
EDSA	Electricity Distribution and Supply Authority
EGTC	Electricity Generation and Transmission Company
EPC	Engineering Procurement and Construction
ER	Emergency Room
EWRC	Electricity and Water Regulatory Commission
GHI	Global Horizontal Irradiation
ICT	Information and Communication Technology
ICU	Intensive Care Unit
IPP	Independent Power Producer
JSS	Junior Secondary School
KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
MBSSE	Ministry of Basic and Secondary School Education
MCHP	Maternal and Child Health Post
MEWR	Ministry of Energy and Water Resources
MoHS	Ministry of Health and Sanitation

MPPT	Maximum Power Point Tracking
MTS	Manual Transfer System
NGO	Non-Governmental Organization
NOCT	Nominal Operating Cell Temperature
NPV	Net Present Value
NREAP	National Renewable Energy Action Plan
O&M	Operations & Maintenance
OPD	Outpatient Department
OPEX	Operational Expenditure
PPA	Power Purchase Agreement
PV	Photovoltaic
RE	Renewable Energy
RF	Renewable Fraction
SARA	Service Availability and Readiness Assessment
SAS	Stand-Alone System
SCBU	Special Care Baby Unit
SDG	Sustainable Development Goal
SHS	Solar Home System
SL	Sierra Leone
SLL	Sierra Leonean Leone
SoC	State of Charge
SRS	Solar Residential System
SSS	Senior Secondary School

TTA	Trama TecnoAmbiental
WAPP	West African Power Pool
WASSCE	West African Senior School Certificate Examination
WHO	World Health Organization

Chapter 1

Introduction

In 2020 the World Bank estimated that 9.5% of the global population does not have access to electricity. These are 770 million people lacking the service, with 571 million living in sub-Saharan Africa [1]. Most of them are settled in remote areas, living in poverty situations and earning extremely low incomes [2]. The unavailability of electricity impacts many sectors that are key for the development of a country such as gender equality, food security, health, education, livelihood, and reduction of poverty. It has been estimated that only 28% of health facilities have access to electricity in sub-Saharan Africa. Likewise, in 2016 just 49.3% and 57.1% of lower and upper secondary schools in the region had this service available [3].

Sierra Leone is one of the countries with the lowest electrification rates globally with only 26% of its total population having access to electricity [4]. The country's electricity generation comes mainly from the Bumbuna Dam hydropower plant which has a maximum capacity of 50MW, a quarter of the total installed capacity in the country. The grid infrastructure is extremely poor having just two transmission lines offering a highly unreliable electricity service. The Sierra Leone government have made efforts to increase electricity access with a focus on decentralized renewable energy off-grid solutions but still, the country has not been able to reach its electrification targets. Currently, there is a major nationwide renewable energy project aiming to electrify 125,000 households by installing 94 solar-powered microgrids. Nevertheless, there are no large projects or targets that focus on the electrification of public institutions such as hospitals, health centres, and schools even though more than half of these facilities in Sierra Leone do not have any type of power source.

1.1 Objectives

The goal of this work is to map the current energy situation of public infrastructure in Sierra Leone and to propose several standard solutions for their electrification by designing hybrid stand-alone power systems catered specifically to hospitals, health centres and secondary schools of the country. This study will comprise the assessment of the global energy access situation and Sierra Leone's energy profile, followed by the development of a multi-criteria analysis to select the sites to be used as case studies to perform energy audits, creating load profiles and estimations of future energy needs. With this data, several designs for off-grid power systems will be created for each type of institution and its sub-categories. Finally, these systems will be optimized considering the cost of the materials, installation and operation and maintenance in order to recommend various sustainable hybrid stand-alone power system designs for rural electrification of public institutions in Sierra Leone.

To guide the development of this work, several specific objectives were defined:

1. Understand the impact that modern energy access has on public institutions,
2. Understand the technical solutions available for rural electrification with renewable energies,
3. Understand the situation of the energy sector in Sierra Leone, focusing on
    a. The general situation and
    b. The public infrastructure situation
4. Select and study the energy demand of twenty-two representative social infrastructures in rural areas of Sierra Leone (two hospitals, ten health centres, and ten secondary schools),
5. Assess and select the key performance indicators (KPIs) for the power system of each case study,
6. Design a stand-alone hybrid (PV, battery storage, and diesel generator) power system to meet the demand of these facilities for an *Ideal* scenario,
7. Optimize the design of the power system to find the best solution for the given KPIs,
8. Analyse the main findings and define how this can be applied to other rural electrification projects in Sierra Leone

This thesis was done as part of a university internship with the company Trama TecnoAmbiental (TTA). My contribution to the project has been to analyse data and develop the criteria and methodology for the selection of the study cases to be used in the project. As well, I performed HOMER simulations and analysed results for several of the selected case studies.

1.2 Outline

In order to achieve the specified objectives, the thesis was organized into eight chapters which are summarized below.

Chapter 1: Introduction to the thematic of the thesis, followed by the goals and the structure of the study, finishing by describing its limitations.

Chapter 2: Overview of the global energy access situation, continuing by describing the benefits and challenges of the electrification of health and education. This is followed by a description of the different technologies used in rural electrification projects and finally explaining different business models employed to run these types of projects.

Chapter 3: General introduction to Sierra Leone’s demographics and geo-political division followed by their energy landscape, finishing with a description of the health and school sectors of the country.

Chapter 4: The methodology of the study is reported, including the criteria for the selection of case studies, the data collection, and the approach for the simulations.

Chapter 5: The results of the site selection and the detailed description of the case studies are described in this chapter.

Chapter 6: The design of the hybrid power generation systems is explained by showing the configuration and general assumptions for the HOMER simulations of each case study, including load profiles, components, and economics.

Chapter 7: In this chapter, the results of the simulations are shown and analysed in order to determine which hybrid power generation system configuration is more suitable for each of the case studies.

Chapter 8: The conclusions of the study are shown and recommendations for future work are proposed in this last chapter.

1.3 Limitations

As mentioned before, this thesis was developed as part of a university internship with the company TTA. The project described in this study was done for an International Agency which asked to keep its name confidential as well as the names and specific locations of the case studies. Moreover, some information was taken directly from TTA’s databases which are not publicly available. Finally, it is important to mention that several decisions regarding some design aspects and economic assumptions were made directly at the International Agency level.

Chapter 2

Energy Access and Public Institutions

Access to modern energy supply is one of the key tools to break the barrier to economic development in emerging economies. It is estimated that 770 million people live without power, most of them concentrated in Sub-Saharan Africa and South-Asia. At the same time, hundreds of millions more live with unreliable and expensive electricity. This population is usually either in remote areas, has very low incomes, or both, commonly residing in informal settlements with no permanent infrastructure [2].

The lack of energy affects a wide range of development indicators such as health, education, food security, gender equality, livelihood, and poverty reduction [2]. Acknowledging the problem, the UN acted and created a set of targets to tackle it within the Sustainable Development Goals (SDGs). SDG7 aims to “Ensure access to affordable, reliable, sustainable and modern energy for all” pointing out that energy is a critical aspect for people to be part of the global progress [5]. The Stockholm Environmental Institute made a study on the synergies that SDGs will have between them as they progress. The results showed that SDG7 will affect positively most SDGs, especially towards decent work and economic growth (SDG8), responsible consumption and production (SDG12), climate action (SDG13) as more renewable energy (RE) capacity is installed, and industry, innovation, and infrastructure development (SDG9). Nevertheless, it is expected to negatively affect the clean water and sanitation goal (SDG6) since new energy projects might affect significantly water ecosystems [6].

In 2010 only 83% of the global population had access to electricity, this percentage increased to 90% by 2019 [7] showing that efforts have been made towards electrification. However, the World Bank has stated that actions need to move faster if SDG7 is to be met by 2030. Solutions applying both grid and off-grid technologies are crucial to achieve universal electricity access but they must be supported by an enabling environment containing pertinent policies, institutions, strategic planning, regulations, and incentives [2].

2.1 Electrification of Public Institutions

The quality of public services is a key indicator of the quality of life of the population of a country as well as being linked to its economic development. Electricity access in these facilities, such as schools and health centres, plays a crucial role in their development and reliability. The Word Health Organization (WHO) estimates that only 28% of health facilities is sub-Saharan Africa have access to affordable and reliable power. Similarly, an assessment done by UNESCO found that only 49.3% and 57.1% of lower and upper secondary schools in sub-Saharan Africa had access to electricity in 2016 [3].

2.1.1 Education

It has been proven that electricity access greatly benefits education [3], [6], [8]. The lack of electricity in these facilities prevents them from providing services such as early-morning or night classes, introduce information and communication technologies (ICTs) into the classrooms and recruit and retain better-qualified teachers. Electrified schools have been related to better test scores and graduation rates. An example of this is shown in Figure 1 [3] in a study done in 56 economically developing countries. It can be seen that primary completion rates linearly increase as the energy access rate increases.

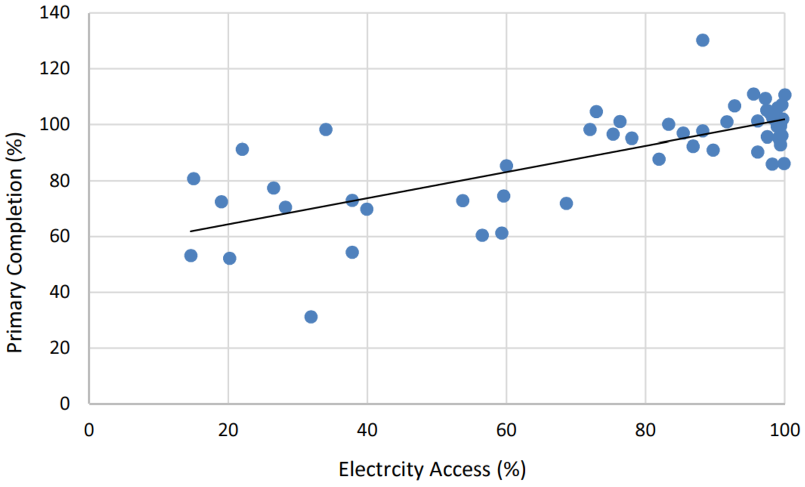


Figure 1: Population electrification rate and primary school completion rate, 2012

Moreover, in many cases, school electrification produces multiplier effects such as improved community sanitation, gender empowerment, and even reduced migration and strengthened the resilience of the community [3].

Even though there are major benefits that come with electricity access there are still millions of students without this service. This situation can mainly be attributed to the high up-front cost and limited financing that these types of projects entail. Even if the schools manage to finance the connection/installation that will provide electricity many would not have the means to afford the price of the service or the cost of maintenance.

2.1.2 Health

When health facilities lack access to adequate and reliable power, it jeopardizes the health of hundreds of millions of people, especially women and children who often carry the burden of inadequate primary health services [9]. Electricity access in a health facility is vital for the delivery of quality services. Lighting is one of the most basic amenities that make a great difference in this sector since it allows workers to conduct deliveries more safely, extend the operational hours of the facility and provide 24h emergency services. Thus, staff can see a greater number of patients in a day. Access to reliable electricity is also essential for the refrigeration of vaccines, blood banks and medicines as well as increasing the facility's retention of skilled health workers, especially in rural areas. By integrating e-health features (i.g., electronic health records, telemedicine, clinical decision-supported system, etc) a facility can improve diagnosis and triage through virtual services. Also, with internet and ICT the staff can better communicate in emergencies, operate and maintain the facility, and track patient records. Finally, with energy to power water pumps and water purifiers, sanitation and hygiene will improve, preventing infectious disease outbreaks.

Despite the many advantages, there are still tens of thousands of health centres that do not have access to electricity with an estimated 70% of medical devices in the global south not functioning and remaining unused with almost a third of equipment failure caused by power supply problems [9]. Many facilities in low- and middle-income countries are characterized by low energy demand and governments and utilities with tight budgets find it difficult to justify grid extensions to these areas where revenues are low and the cost of building and maintaining the infrastructure is high [9].

Chapter 3

Available Technology and Financial Approaches for Electrification

3.1 Applied Technologies

To electrify rural areas several technologies can be applied. The extension of the national electricity grid, the installation of stand-alone systems (SAS) and/or the development of microgrids are the main solutions available today in the market. For remote areas extending the main grid can be excessively expensive and, in some cases, even using off-grid systems can be financially challenging [2]. Thus, depending on the specifics of the project (e.g., geographical location, available renewable energy resources, energy demand, local policies, available budget, etc) one technology will be chosen to be the most suitable.

3.1.1 Electricity Grid Extension

Extending the electricity grid to rural areas can be extremely challenging due to a lack of sufficient power generation capacity, poor transmission and distribution infrastructure, high cost of supply to remote areas, or simply lack affordability for electricity services [2].

Often, rural areas are difficult to access and located far away from the main grid which normally has insufficient capacity in developing economies. In these locations, they have a relatively small energy demand and, since the size of the demand determines the cost per kWh of the grid extension, the public institutions and the deteriorated local utilities have low or no interest in investing in transmission lines to areas that do not cover the minimum consumption for the project to be economically viable [10].

As a result of expanding the grid, the electricity demand will probably increase [10]. Nevertheless, if there is no matching increase in energy generation capacity, increasing the number of electricity consumers will only deteriorate the quality of a service that is already highly flawed.

3.1.2 Stand-alone System (SAS)

Stand-alone systems (SASs) or electricity home systems are small power systems designed to provide energy to individual households or small buildings. The power generation is installed close to the load thus, there are no transmission and distribution costs. To further minimize costs, components can be reduced, and capacities can be kept low to primary serve small DC loads and communications. This type of system is a very suitable solution for dispersed rural communities, especially when implementing them with renewable energies, providing an installation that is relatively inexpensive and simple to maintain. There are several types of SAS, with some of them being presented in this section.

Solar Home System (SHS)

Solar home systems (SHSs) are normally composed of several independent components such as PV modules, charge controllers, batteries, and loads. These systems can reach a power output of up to 250 Wp while smaller systems, ranging from 1 W to 10 W power output, are called Pico PV systems and normally work with small DC loads such as lights and radios. For large SHSs, a DC/AC inverter is needed to be able to power AC voltage loads. This requires a good design and the use of optimized charging technology to avoid deep discharge of the batteries [10].

Solar Residential System (SRS)

The solar residential systems (SRSs) are larger than the SHSs, ranging from 500 W to 4,000 W power output. These installations usually deliver electricity to large individual infrastructures such as hotels, hospitals, or schools. Most SRSs are hybrid, combining two of more energy sources such as solar PV and diesel generators. They allow an extensive catalogue of loads compared with the previous systems.

Wind Home System (WHS)

Wind home systems (WHSs) are in a different range of investment costs and are meant to fulfil different electricity demand patterns than solar systems. They use small wind turbines (SWTs) which are characterized by having a diameter of less than 15 m and a power output below 50 kW. However, most SWTs are 7 m in diameter or less and the power output ranges between 1 kW and 10 kW. Commonly, they produce AC-voltage current that must be rectified to DC to store the energy in batteries and/or to connect them to the grid.

For SWTs to have an economically viable operation, average wind speeds of over 5 m/s will be suitable, producing around 300 kWh per surface area of the rotor annually. In many cases, the kWh produced by these systems is cheaper than those of PV. Nevertheless, the use of SWTs is normally just feasible for businesses that have the capacity to cover high investment costs and highly depends on the project type.

Small Hydropower Plant (SHP)

Hydropower is the most used renewable energy in the world, being a mature technology that has been used for over 70 years. A small hydropower plant (SHP) is characterized by having a capacity between 1 MW and 10 MW. They reach high efficiencies between 70% and 90%, having a low operation and maintenance cost and a lifespan of up to 100 years, showing an appealing energy payback ratio [10].

Commonly, the SHPs have little or no water storage capacity so they must be located at rivers with consistent and steady flow. This contributes to the environmental challenge that the construction of this type of project has since it presents an intrinsic interaction with its surrounding.

This technology is often the most inexpensive over its lifespan for rural electrification projects. However, it requires a high capital investment from which it is estimated that 75% will go to location and site preparation and 25% will be expended on equipment [10].

3.1.3 Microgrid

Microgrid refers to a small-scale distribution network which can provide electricity to local communities. This can be supplied by one or more power generation plants and usually operates as an isolated system with clearly defined geographical and electrical limits. However, this system can be interconnected with the main grid. They commonly use low AC voltage (220 V or 380 V) with centralized hybrid power production and a capacity ranging from 5 kW to 500 kW, implementing energy storage as well [10].

This technology provides a continuous and reliable electricity supply, allowing critical infrastructure, such as hospitals and schools, to better operate and help the development of the local economy.

3.2 Business Models for Electrification Projects

To be successful, a rural electrification project must include the development of the power generation infrastructure, the logistics for distribution, and the organisation for operating and selling the electricity along with a sustainable business model for the installation. However, many times the lack of organizational structures, poor policies of the country/region, inadequate regulations, the elevated initial capital investment, and the lack of willingness or availability to pay by the rural users makes the financial stability of the project crumble in a matter of months after the project starts running [10]. Thus, designing a financial plan specific to each project is a key aspect for the effective implementation of rural electrification projects.

The organization and ownership of the project, the financial structure, the type of customer and the type of technology are characteristics that will greatly impact the design of the business model for a specific installation.

3.2.1 Project Organization and Ownership

Commonly, the investment, the construction, and the operations of a rural electrification project have different owners and responsible [11]. Public utilities and private companies share a similar challenge when investing in the rural electrification sector since projects are normally developed in non-profitable areas with high initial capital requirements. On the other hand, NGOs get donors to fund the installations in these areas but, the long-term financial sustainability of the project can struggle due to the customer's low willingness or ability to pay the electricity tariffs. Differently, community cooperatives can own and operate a power generation system in a co-ownership arrangement. Since owners are also customers, they can have tailor-made tariffs and create jobs in the local community. Nevertheless, they often need a long time for preparation due to the lack of technical skills and can produce social conflicts within the community regarding payments, benefits, and tariffs. These ownership models can be combined in order to decrease the shortcomings of each other and exploit their advantages. Still, this would require a stable partnership between the actors since it involves complex agreements to ensure the sustainability of the project.

3.2.2 Financial Structure

For a rural electrification project to be feasible, it must have a sustainable financial structure, allowing it to get means for the design, installation, maintenance, and operations throughout its lifetime, accommodating the needs of the local community. To achieve this, tariffs and subsidies are used.

Tariff

When designing electricity tariffs, it is important to balance sustainability with affordability. The tariff should cover at least the running costs of the power generation plant to secure proper operation. As well, it should recover the cost imposed on the system by customers and, ideally, it should include the replacement of the system once the lifetime is over. In cases where the initial capital is heavily subsidies, the calculations of the tariff should focus on affordability and the willingness to pay of the customer. However, most of the time affordability needs to be carefully weighed against sustainability so the project does not fail [11].

Subsidies

Many rural electrification projects need subsidies to be installed due to their initial capital-intensive nature. This financial support is an effective tool to overcome market imperfections and create incentives for private investors to enter a high-risk market such as this one. It is of significant importance that the design of the subsidies is done carefully to avoid market distortion and that they are targeted to the people they want to aid. For rural electrification, one of the goals would be to strengthen the buying power of the people living in these communities and this could be done through subsidized electricity rates.

As with any other investment, subsidies should be minimized as much as possible to ensure financial sustainability. Therefore, they should mainly be given as investment-based and connection-based subsidies to be able to show the actual cost of electricity and avoid inefficient use of the service [11].

Chapter 4

Sierra Leone Profile

Sierra Leone is located in the north-west of Africa, having frontiers with Liberia and Guinea and an extensive cost of the Atlantic Ocean. It has an area of 71,740 km^2 and a population of 7.977 million of which 57% reside in rural areas, the majority living in poverty [4].

The country is divided into fourteen districts as shown in the map below. The Eastern region contains the districts of Kailahun, Kenema and Kono. The Western region is composed of the Western Rural and Western Urban districts. The districts of Bo, Bonthe, Moyamba and Punjehun are part of the Southern region and finally, the Northern region houses the remaining districts of Bombali, Koinadugu, Tonkolili, Port Loko and Kambia. The capital Freetown is located in the Western Urban district, on the northern coast and is the most densely populated city of the country, followed by Kenema in the Kenema district and Port Loko in the Port Loko district.

Ministère des Affaires étrangères et du Développement international, direction des Archives (pôle géographique) © Septembre 2015

Figure 2: Sierra Leone map

4.1 Energy Landscape

Sierra Leone has one of the lowest electricity access rates in the world with an electrification rate of only 26% of its total population. In rural areas the situation is more severe, estimating a rural electrification rate of 4.8% in 2020 [4]. Similarly, around 80% of the population still uses traditional biomass for cooking such as firewood or charcoal while kerosene lamps, battery lamps and candles are still the main sources of lighting [12].

The Electricity Distribution and Supply Authority (EDSA) holds the monopoly as the single electricity seller to consumers and the single buyer from independent power producers (IPPs) in Sierra Leone. The country has a total installed capacity of 200 MW out of which more than 90% is REs. There are several small power generation facilities, the biggest one being the Bumbuna Dam hydropower plant with a 50 MW peak capacity during the rainy season. Figure 3 [13] presents the electricity generation of the country by source showing that 219 GWh (71%) comes from hydropower, 80 GWh (26%) is produced with oil, 6 GWh (2%) from solar and the remaining 4 GWh (1%) coming from bioenergy.

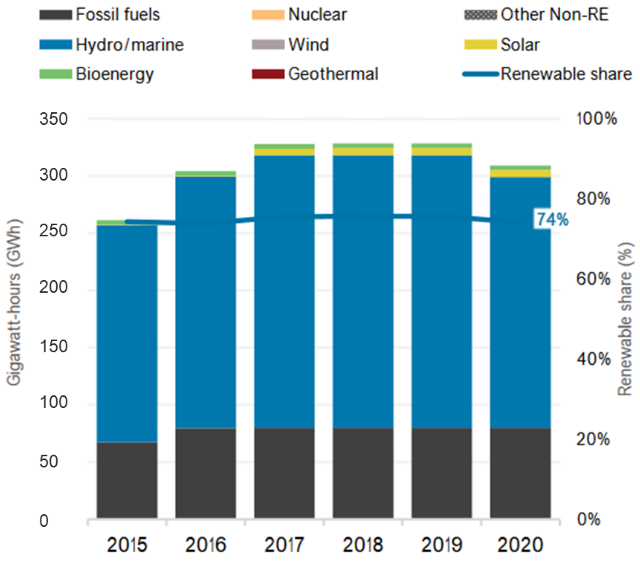


Figure 3: Sierra Leone's electricity generation by source

Sierra Leone owns just a few electricity transmission lines from the main grid. The primary transmission line is 161 kV which extends 220 km from Bumbuna Dam to Freetown. This line also connects Makeni and Lunsar towns. There is a smaller 33 kV line from Bo to Kenema which is powered by the Dodo hydropower plant. In 2021, the Côte d'Ivoire - Liberia - Sierra Leone - Guinea (CLSG) electricity interconnection line of the West African Power Pool (WAPP) was inaugurated in the country with an approximate 530 km, 225 kV power line which is now serving the districts of Punjehun, Kenema, Kono, Tonkolili, Koinadugu, Bombali, and Kambia.

The grid electricity tariffs are highly subsidized by the government being around 0.102 $/kWh for households and 0.136 $/kWh for businesses [14]. The electricity supply of the country is highly characterized by its unreliability, with connected customers experiencing frequent outages.

4.1.1 Renewable Energy Potential

Sierra Leone is a country with many natural resources that could be used for power production in order to electrify the country with local renewable energy.

Solar Energy

In Figure 4 the distribution of the global horizontal irradiation along Sierra Leone can be seen. According to Sierra Leone's Ministry of Energy and Water Resources (MEWR), approximately 1,460-1,800 kWh/m^2 of solar irradiation can be expected annually in the country [15]. A more optimistic study undertaken by the Joint Research Centre of the European Commission portrays Sierra Leone's solar potential to be as high as 2,200 kWh/m^2.

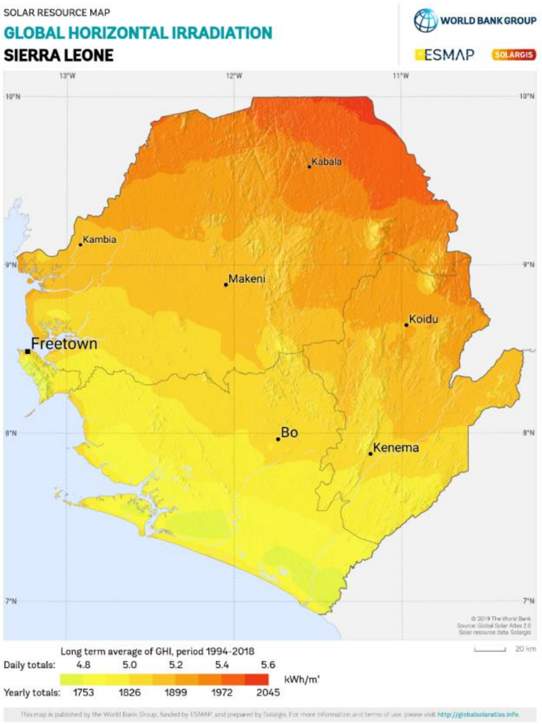


Figure 4: Sierra Leone global horizontal irradiation

Hydropower Energy

Hydropower is already the main source of electricity in the country, producing 71% of its electricity. Sierra Leone has several rivers that could be exploited for electricity as there is a potential of 2 GW for hydropower according to the German Federal Ministry for Economic Affairs and Energy. Similarly, studies from the 2009 National Energy Policy and Strategic Plan of Sierra Leone identified 27 potential hydropower sites with a total capacity of 1,513 MW. Another study supporting these estimations is the World Small Hydropower Development Report by UNIDO [16] which estimates hydropower potentials of 1,200 MW. Although there are numerous resources, most water streams suffer from water flow variations between the dry and wet seasons for which the feasibility of a new plant needs to be studied carefully accounting for this factor.

Biomass Energy

The country’s energy consumption is dominated by biomass both for cooking and lighting. There is a potential of 2.7 GWh for the use of biomass according to the German Federal Ministry for Economic Affairs and Energy. Nevertheless, this potential is not being currently exploited as biomass only contributes to 1% of the electricity produced in the country.

Wind Energy

Sierra Leone has an average wind velocity between 3-5 m/s with some areas of the country reaching 12 m/s [15]. Due to the availability of low wind speed turbines, there is a strong potential for their use, especially in rural areas.

4.1.2 National Targets, Policies, and Regulatory Framework

The Sierra Leone (SL) government has taken action to expand the energy sector through several legislative reforms in order to restructure the sector. In 2011, the National Electricity Act was implemented which split the National Power Authority into the Electricity Generation and Transmission Company (EGTC) and EDSA, enabling the development of IPPs projects in the country. In the same year, the Electricity and Water Regulatory Commission (EWRC) was established, focusing mainly on the regulatory aspects of set tariffs for consumers and between the EGTC and IPPs [17].

As well, in the SL National Energy Strategic Plan of 2009, the objective of setting up a Rural Electrification Scheme was set. It is aimed to develop strategies to increase access to modern energy for poverty reduction in off-grid and provide incentives for the setting of small-scale decentralized solar power supplies in order to meet basic needs of lightning, refrigeration, media, and communication technology in rural areas. This scheme was set to start in 2012 and will be finished by 2025 relying on government funds in cooperation with local councils and funds from donors and other agencies for its implementation [18].

The National Renewable Energy Action Plan (NREAP) [19] was released in 2015 where off-grid RE targets for the country were established as

- 44% and 92% of the population served with electricity by 2020 and 2030, respectively.
- 30% and 55% of the population connected to the grid by 2020 and 2030, respectively.
- 11% and 27% of the rural population served by RE and hybrid microgrids by 2020 and 2030, respectively.
- 3% and 10% of the rural population served with SAS by 2020 and 2030, respectively.
- 25 and 65 RE/hybrid microgrids by 2020 and 2030, respectively.

Currently, some of the 2020 targets have not been met with only 26% of the population having access to electricity and the national grid reaching just a few cities (i.e., approx. 920,000 people). On the other hand, there are some major off-grid projects which have helped to reach the targets for SAS and the number of microgrids within the country as well as being in line to achieve the same targets by 2030.

Nevertheless, to reach the overall objective of electrification many actions regarding incentives, quality standards, and overall regulations need to be implemented to reach 92% of electrification rate by 2030.

4.1.3 Rural Electrification Initiatives

Lately, the overall off-grid electricity market has grown, especially in African countries where access to electricity is still extremely inadequate. In Sierra Leone there are several rural electrification projects and initiatives based on RE technologies, most of them being from external organizations/donors working along with the local government.

The SL Government established a Rural Electricity Board and a Rural Electricity Fund to promote and make electrification widely available in all regions and a Renewable Energy Empowerment Project to develop a knowledge base of existing renewable energy policies.

The CLSG interconnector project under the West African Power Pool program, aims to provide an increased supply of electricity to these countries to meet the growing demand and will create an incentive for hydropower potentials that exist in Sierra Leone. In 2021, this transmission line was inaugurated in SL, connecting eight districts to an electricity source.

Currently, the biggest RE project in the country is called Rural Renewable Energy Project (RREP) which aims to electrify 125,000 households by 2022. It is being financed by the Foreign, Commonwealth & Development Office (FCDO) and will install 94 solar-powered microgrids and 3 SAS at health centres across the country, providing 4 MW of RE capacity. As well, the project involves technical assistance and institutional support to the government and the private sector with monitoring and evaluation of the installed systems [20].

4.1.4 Challenges of the Energy Sector

The SL energy sector is facing many challenges regarding finance, enabling environment, infrastructure, availability and accuracy of data as well as population awareness.

Currently, the enabling legal framework for the SL energy sector is ill-defined with no clear regulation of private participation in electricity generation, no microgrid licencing and concessions, no standardized power purchase agreements (PPAs), and no rural electrification agency [21]. As well, there is a need for a less bureaucratic process of receiving tax/duty waivers for private companies importing certified solar products.

In the financial aspect, there is a lack of private investment and economic incentives. There is also a need for microfinance for solar businesses and a fully conditioning mobile money platform in order to facilitate the pay-as-you-go modality for electricity bill payments.

One key enabler for energy access is the infrastructure. The national transmission and distribution infrastructure needs to be improved since most parts of the country have no access to the grid, many distribution lines have been damaged, old and deteriorated equipment is still in use, and there are major power losses in the generation, transmission and distribution (i.e., almost 40% transmission losses). In addition, the generation does not cover the demand, and there is poor energy efficiency overall. These, along with the fact that the service standards of EDSA are inadequate, have forced households and industries to rely on diesel generators for electricity and inefficient/traditional cook stoves.

Finally, the major challenge that SL and many African countries experience is the lack of accurate data and lack of awareness. The absence of detailed research and data collection in the energy sector makes it difficult for private companies to invest in the country. Similarly, little awareness of quality standards, improved cookstoves, environmental benefits, and recycling of old batteries is necessary in order to facilitate the development and sustainability of electrification projects in the country.

4.2 Health Sector

Access to healthcare in Sierra Leone is mostly constrained by geographical barriers, extremely high expenses that are paid out-of-pocket, lack of skilled medical staff, and poor quality service [22].

In Sierra Leone, the health facilities are divided into the following categories, also called *tiers*, depending on the services provided.

- Primary Health Facilities – Peripheral Health Units (PHUs)
  0. **Community Health Worker (CHW)**
     - Works at a community level – it is not a health facility
     - Integrates community case management, nutritional screening, and distribution of family planning commodities
     - Promotes maternal care, hygiene, sanitation, and referral of severe cases
     - Social mobilization for outreach services and mass campaigns
     - Links with community governance and ownership structures.
  1. **Maternal and Child Health Post (MCHP)**
     - Closest health facility to the community
     - Should ideally serve a population of 500 to 5,000 within a 5 km radius of the facility
     - Maternal care, routine deliveries, immediate postnatal, and neonatal care
     - Routine vaccination, treatment of childhood illnesses and malnutrition
     - Basic first aid
     - Community outreach services
     - Surveillance for pandemic-prone diseases
     - MCH aides are qualified to dispense free health care drugs and other basic medicines.
  2. **Community Health Post (CHP)**
     - Health facilities of small towns
     - Serve a population of 5,000 to 10,000 or more within an 8 km radius of the facility
     - Attend to some pregnancy complications and complicated deliveries (may have a midwife on staff)

    - Treatment of some severe childhood illnesses
    - Surveillance for epidemic-prone diseases
  3. **Community Health Centre (CHC)**
    - Health facility at the chiefdom level
    - Serves a population of 10,000 to 30,000 or more within a 15 km radius of the facility
    - Basic emergency obstetric and neonatal care
    - Treatment of some severe childhood illnesses
    - Laboratory and pharmacy services
    - Screening and referral of some non-communicable diseases
    - Surveillance and treatment of some epidemic-prone diseases.
- Secondary Health Facilities
  1. **Regional Hospital**
    - Reginal headquarters, affiliated with Regional Hub
    - Comprehensive emergency obstetric and neonatal care
    - Speciality and referral services
    - Additional diagnostic imaging services
    - Treatment of cancers and rare diseases.
  2. **District Hospital**
    - Comprehensive emergency obstetric and neonatal care
    - Treatment of severe childhood illnesses including severe acute malnutrition with complications
    - Diagnosis and treatment of severe malaria
    - Clinical management of chronic diseases
    - Laboratory and pharmacy services, diagnostic imaging, blood services, and surgery
    - Surveillance, detection, and treatment of epidemic-prone diseases
    - Emergency triage.

The country counts with a network of 1,286 public and private health facilities, including 54 hospitals, 224 CHCs, 328 CHPs, 629 MCHPs, and 49 Clinics. Out of these, 200 are located in urban areas and 1,202 are owned by the Government. In the 2017 SARA Plus Report for Sierra Leone [23], which measured the quality and availability of health services and equipment, it was estimated that 84% of all health facilities had sanitation amenities, 57% had an improved water source, but only 23% had a power source, this being mainly diesel generators.

The figure below shows the availability of health facilities by district with respect to 10,000 population. Moyamba is the district with the highest concentration of health facilities with 3.4, being above the national target of 2 and the national average of 1.8. On the other hand, the Western Urban district has the lowest with only 0.6 facilities per 10,000 people. This might seem low but Figure 5 [23] only shows the number of facilities per district without considering the type of health services provided, or the size and capacity of the health centre. In order to measure the level of physical access to inpatient services by district, a graph with the number of beds per 10,000 population can be seen in Figure 6 [23]. All districts are below the recommended density of 25 inpatient beds per 10,000 people with the Western

Rural district having the lowest and Bo district having the highest density but still not reaching the recommended levels. Following this trend, the national average is extremely low, not even reaching 15 beds per every 10,000 inhabitants.

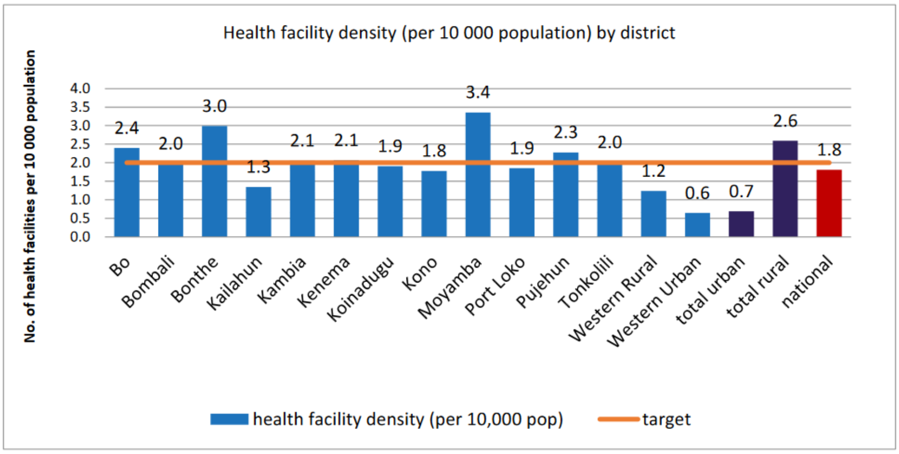


Figure 5: Sierra Leone health facility density (per 10,000 population) by district

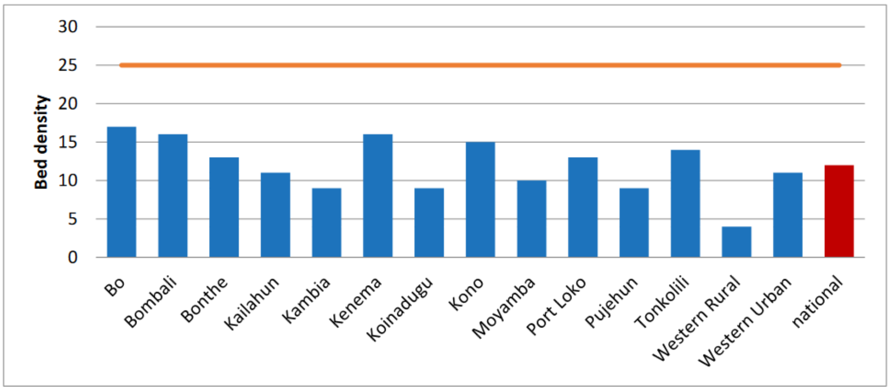


Figure 6: Sierra Leone bed density (per 10,000 population) of health facilities per district

4.3 Education Sector

Sierra Leone is experiencing a rapid increase in population with a growth rate of 2.2% each year [24]. This puts direct pressure on the educational system since the country has, and will have, a youthful population. Currently, 80% of the population is aged 35 and below and more than half of them are eligible for education. Since 2011, enrolment has increased across all educational levels mainly due to the implementation of the Free Quality School Education programme. With this rise in enrolment, additional challenges for the system have developed with the average class size increasing by almost 40% in some educational levels. Additionally, almost 30% of schools are working with a “not approved” status, which means that the government is not giving financial or institutional support to those facilities which can affect the quality of education [25].

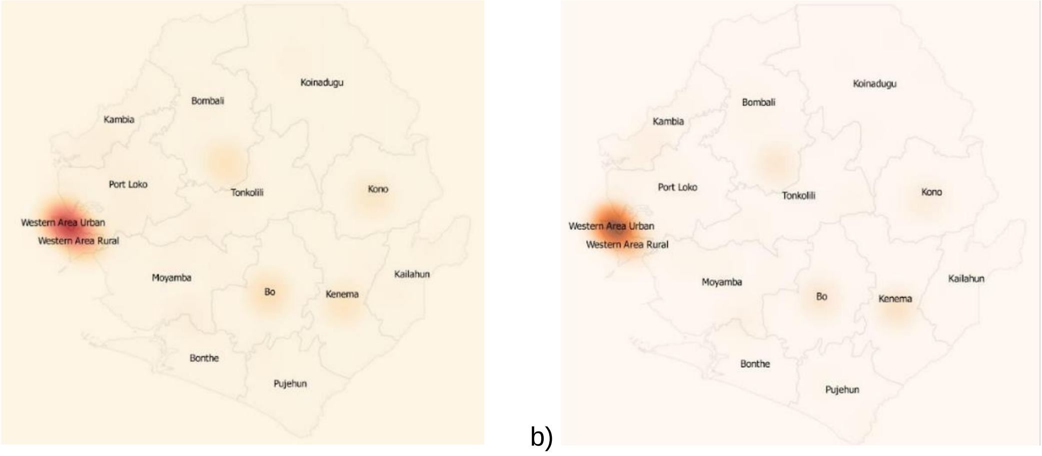
The country’s education system is segmented as follows:

- Pre – School: first cycle of basic education, starting at the age of three and lasting three years
- Primary School: second cycle of basic education, staring at the age of six and lasting six years
- Junior Secondary School (JSS): third cycle of basic education, starting at the age of twelve and lasting three years
- Senior Secondary School (SSS): fourth and last cycle of basic education starting at the age of fifteen and lasting three years
- Tertiary Education: higher education studied after finishing secondary school

The 2020 Sierra Leone school Census [25] registered 11,168 schools from which 14.5% (1,600) were JSS and 6% (658) were SSS. It was estimated that around 2.7 million learners were enrolled across the first four levels of education with the majority being enrolled in primary school. Out of the total students, 50.6% were girls and 49.4% were boys.

Most schools are owned by missions of religious organizations, having 64.3% of pupils, the community schools accounted for 10.4% of pupils, while students enrolled in private schools were only 7.1%. Students enrolled in government schools accounted for 18.1% of the total enrolment.

The distribution density for secondary schools, JSS and SSS, can be seen in Figure 7 [25]. The Western Urban district has the greatest concentration of both JSS and SSS, followed by the Western Rural and Tonkolili districts. With the same trend, the Western Urban district has the highest number of pupils with 15.4%, then the Western Rural with 7.5% and Tonkolili district with 7.1%. In comparison, due to its small population, the Bonthe district was the lowest with only 0.2% of the total students nationwide.



a) b)

Figure 7: Sierra Leone heat map for: a) JSS and b) SSS

In terms of infrastructure, the Census found that 64% of JSS and 45% of SSS have no source of electricity. From those facilities that do have electricity, the most common source is the national grid, followed by generators working with diesel/gasoline, and solar energy. On the other hand, 22% of JSS and 32% of SSS do not have a water source. For the schools with access to water, the most used are boreholes, followed by wells and piped systems with a few facilities relying on rivers and other sources.

Chapter 5

Selection and Description of the Case Studies

After studying the education and health sector of Sierra Leone it was necessary to select the sites that would be audited within the project. Ten secondary schools and ten PHUs that represented the current situation of the country were to be chosen. The selection of the two hospitals that were audited was not part of the scope of this project.

To create the selection criteria, data about the trends of each type of facility was collected from several public country reports and two databases provided by the Ministry of Health and Sanitation (MoHS) and the Ministry of Basic and Secondary School Education (MBSSE).

5.1.1 PHUs Criteria

A database listing all the health facilities of the country was provided by the Sierra Leone MoHS. This list contains the region, district, chiefdom, facility name, facility tier, facility ownership, and council to where the facility belongs, which are only basic characteristics of the sites. Since the information for the PHUs is not centralized at the ministry level, detailed data such as electrification status and water supply are not available for the individual facilities. These records can only be found through the District Medical Officer of each district nevertheless, in some cases, this data is non-existent in the record. Thus, the criterion for the selection was straightforward. The sites needed to be in different districts and nine of them needed to be owned by the MoHS with only one being private following the ownership trends. Since the MCHPs offer fewer services and are smaller overall, it was assumed that their energy consumption will be less than the other tiers. Hence, out of the ten facilities to be selected, four should be CHCs, the other four should be CHPs, and two need to be MCHPs. This criterion is summarized in the table below.

Table 1: Criteria for selection of PHUs

Criteria	Characteristic	Number of PHUs (out of 10)
PHU Tier	CHC	4
	CHP	4
	MCHP	2
District	Located in different districts	10

5.1.2 Secondary Schools Criteria

The list of schools given by the MBSSE included several characteristics of all the recorded schools in the 2020 Sierra Leone School Census. For each education facility, this list contains region, district, council, chiefdom, section, town, school type, school name, number of male and female teachers, number of male and female pupils, total pupils, approval status, electricity and water source, internet connection, ownership, shift status, and accessibility. The first step for the site selection was to choose the criteria that had the most significance in order to reduce the number of options. This was selected to be the approval status of the secondary schools. Therefore, a graph with the approval status of the secondary schools, seen in the figure below, was analysed. It was found that 75% of schools are approved followed by 13% that are not and 8% that applied for approval. It was important that the selected schools were supported by the Government and followed the legal education system of the country. Thus, it was decided that only approved schools were to be considered for the study and, as they represent the majority, this would still be a representative sample.

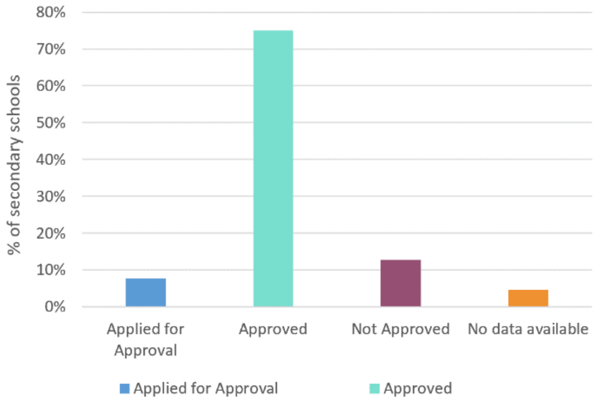


Figure 8: Approval status of secondary schools

After applying this filter, the list was reduced to 2,164 secondary schools. The next criterion to be analysed was the genders served by the schools. Even though this parameter is not known to affect the electricity consumption of schools, this was considered important in order to prevent the project from favouring one gender over another. As seen in Figure 9, 94% of the facilities offer co-ed/mixed education, meaning they teach girls and boys. Hence, as this is the major trend, it was decided that all considered schools should be co-ed in order to have a representative list. By applying this filter, the list was reduced to 2,040 secondary schools.

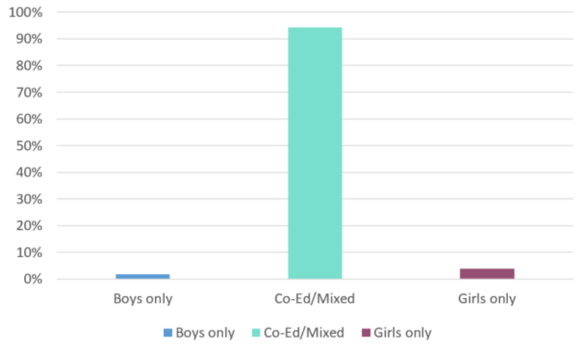


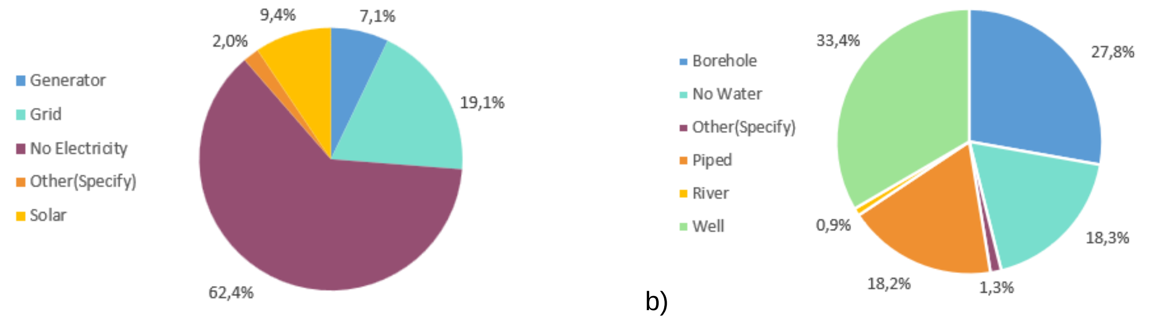
Figure 9: Genders served in approved secondary schools

To further develop the criteria, it was first necessary to select a feature from which the secondary schools could be separated into defined groups. This was chosen to be the size of the schools based on the number of students that they have since these data significantly affects the energy consumption of a facility. It was established that three sizes were to be defined: small, medium, and large. This was done to analyse which sizes of schools were predominant within the country. In total, the 2,040 approved/co-ed/secondary schools have 829,797 students of which one-third is 276,595 students. By analysing the database, it was found that 206 schools teach one-third of the total number of students, these facilities being characterized by having enrolled more than 860 students each. On the other hand, 488 schools, teaching between 400 and 860 students, educate another third of the total pupils. Lastly, the final third of the total students are schooled within 1,346 facilities that have less than 400 students enrolled. Thus, with this analysis, the size categories were split as seen in Table 2 below.

Table 2: Characterization of secondary schools by size

Size Category	# Students per School	Number of Schools
Large	> 860	206
Medium	400 < # students < 860	488
Small	< 400	1,346

After specifying the main categories for secondary schools based on the number of students, other trends of the schools were analysed. In Figure 10 the electricity and water source tendencies for the filtered secondary schools can be seen. The majority, 62.4%, of the facilities do not have any type of electricity source, followed by 19.1% having a connection to the grid and 9.4% having some sort of solar power. On the other hand, Figure 10.b shows that most schools have wells as water sources, followed by 27.8% which have boreholes, and 18.3% which have no access to any type of water source.

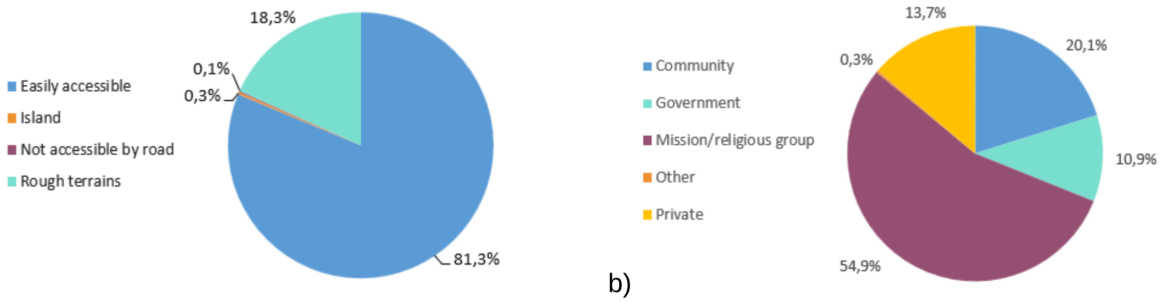


a) b)

Figure 10: Infrastructure of approved and co-ed secondary schools; a) Electricity source, b) Water source

The accessibility of a facility is a crucial factor when choosing locations to implement electrification projects since the transport of materials can count as a big percentage of the investment. In Figure 11.a it can be seen that most of the secondary schools are easily accessible, meaning that they can be accessed by common roads. On the other hand, 18.3%of schools have rough terrains to reach them, and a small percentage are on islands or are not accessible by road.

In the next figure, the ownership distribution of the facilities can be seen. More than half of the schools are owned by mission or religious groups with the other half being split between communities, government, and private ownership.



a) b)

Figure 11: Approved and co-ed secondary schools; a) Accessibility, b) Ownership

Lastly, the shift status of the facilities was studied. This characteristic is extremely relevant for energy consumption since it dictates how many hours a facility works. For single-shift schools, there is only one class period, normally in the morning. Differently, for double-shift schools, a facility is used for two teaching periods, one in the morning and one in the afternoon. In Figure 12 it can be seen that 90% of schools are single shift and only 10% of schools are double shift.

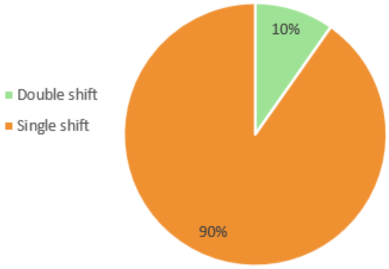


Figure 12: Shift status for approved and co-ed secondary schools

The general trends for the schools' characteristics, discussed above, were considered and the criteria for the school selection were established. To get a representative sample of secondary schools, each selected facility had to be in a different district. Since this project aims to electrify facilities with RE, it was decided that schools with no source of electricity and with generator sets (gensets) were the only ones to be considered. In Figure 10.a it can be seen that 62.4% of the secondary schools in the country do not have electricity and 7.1% use gensets so, 69.5% of the facilities would be studied for this analysis. Therefore, following this trend, 10% (one) of the selected schools should have gensets as an electricity source and 90% (nine) of schools should have no electricity. Moreover, the split for water source type was also done following the country's trend as seen in Figure 10.b. Thus, 30% (three) of the facilities needed to have wells and the other 30% (three) needed to have boreholes as water sources, with 20% (two) having piped systems and the other 20% (two) having no water. Similarly, the ownership, the shift status, and the accessibility were also split according to the percentages shown in their respective pie charts. All secondary schools need to be co-ed and approved by the government. Out of the ten selected secondary schools, three need to be Large, three need to be Medium, and four need to be Small. With these criteria, a selection process was done in order to create a list of ten secondary schools which represented the current situation of the country. Table 3 summarizes the criteria for the selection of schools.

Table 3: Criteria for selection of secondary schools

Criteria	**Characteristic**	**Number of schools (out of 10)**
Size of School	Large	3
	Medium	3
	Small	4
District	Located in different districts	10
Electricity Supply	No electricity	9
	Genset	1
Water Supply	Borehole	3
	Piped	2
	Well	3
	No water	2

Criteria	Characteristic	Number of schools (out of 10)
Owner	Mission/ religious group	5
	Community	3
	Government	1
	Private	1
Accessibility	Easily accessible	9
	Rough terrains	1
Shift Status	Single shift	9
	Double shift	1
Student Accommodation	With accommodation	1
	Without accommodation	9
Students Gender	Mixed/ Co-Ed	10
Approval Status	Approved	10

5.2 Data collection

After selecting the sites, energy audits had to be performed in each facility in order to collect data about their energy needs and problems, their electric equipment, their infrastructure, and their power sources. To do so, a survey was developed based on previous templates of TTA and following the guideline of USAID [26]. The result was a list of around 14 questions, varying depending on if the facility was a hospital, a school, or a PHU (see Appendix 7). The data was collected by visiting the sites and interviewing the administration, members of staff, and the site's technicians.

To assess how well-equipped the facilities were, a database provided by TTA was used. *The Basic Electrical Equipment List* (see Appendix 1 to Appendix 6) provides information on the basic electrical equipment needed in hospitals, PHUs and schools along with their common power ratings and usage schedules. This list was developed by TTA based on their experience, interviews with experts and publicly available guidelines such as [27], [28] and [29].

5.2.1 Description of the Case Studies

The qualitative and quantitative data gathered for each of the visited sites is presented below. This information is focused on the current electricity availability and the future needs of the facilities.

Hospitals

Two hospitals in Sierra Leone were analysed in this project, each showing quite different energy situations which can represent the two realities of hospitals in the country.

Hospital 1 - Western Area

Hospital 1 is composed of two hospitals that are next to each other, Hospital A and Hospital B. The administration and the finances of each facility are independent but, they share a grid connection, a transformer, and the main switchboard from which the circuits branched to each hospital. Thus, for the energy analysis, these will be considered as one big facility, Hospital 1.

Each of the hospitals has a staff of around 300 people, Hospital A having 197 beds and Hospital B 135 beds, assisting 2,119 and 300 patients per month, respectively. They both provide in-patient services and lack staff quarters. The two facilities extend through an area of 15,000 m^2 which includes 8 buildings comprising several medical departments.

Hospital 1 is connected to the EDSA grid which, as discussed in Chapter 3, is highly unreliable. Through the performed energy audit, it was estimated the powered received from the grid does not present problems with voltage dips or frequency. Nevertheless, there is a power interruption almost daily, normally lasting 2-6 hours, and several shorter interruptions throughout the day although there is no clear pattern on the frequency of these blackouts since they can occur multiple times per week or per day. These energy shortages have never lasted a full day. However, during the dry season, they tend to go on for longer periods since the electricity comes from a hydropower plant. The power that the hospital receives from the grid does not experience problems with voltage dips or frequency.

The transformer that feeds the hospital is shared with the local community, being undersized for these loads and, since the hospitals' loads cannot be prioritised, this causes blackouts. Hospital A counts with a new 100 kVA diesel generator which is connected to its critical loads and is only used when the grid supply is down, consuming around 50 L/day of diesel which was stated, by the facility administration, to be sufficient for the facility's electrical needs. On the other hand, Hospital B suffers from fuel shortages, forcing them to constantly shut down critical buildings during grid power interruptions. They have a 16 kVA genset to power some of the wards and a 27 kVA genset to power the outpatient theatre. Currently, Hospital B owns a PV and battery energy storage system (BESS) that powers the blood bank and several PV panels that are non-operational. Similarly, Hospital A has thirty PV panels in good condition that are not being used.

The water is supplied in both facilities by Goma Valley, the national water company of Sierra Leone. Each facility counts with a water tank. The water is considered drinkable by the people although there is mistrust about this among the hospital's personnel.

There is an O&M department which is shared between the two facilities. They have a team that is responsible for the O&M of electrical infrastructure, gensets, and energy efficiency actions as well as the implementation of preventative maintenance.

During the site visit, the loads of the facility were measured with a power data logger, calculating an average load of 2,566.7 kWh/day and a peak load of 100.0 kWp. The recorded load profile shape was kept but the magnitude of the loads was increased by 30% to account for the growth in consumption that will be experienced as a product of the availability of a new reliable energy source which will cover the current energy shortages. The outcome of this estimation can be seen in Figure 13 as the Ideal load profile for Hospital 1. The graph identifies two different profiles: weekday and weekend. The weekday shows a pronounced peak between 14:00 and 15:00 while at the weekend there is a subtle peak around 11:00. The loads stay remarkably similar during the night-time in both cases.

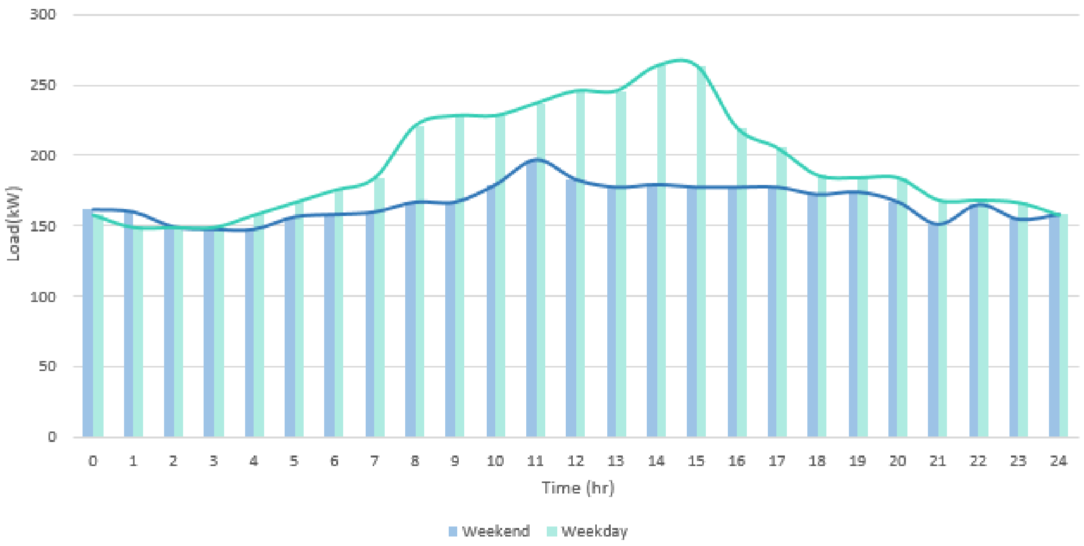


Figure 13: Ideal load profile of Hospital 1

Hospital 2 - Northern Area

Hospital 2 is owned by the Sierra Leone Government, and it serves an entire district. The hospital counts with 174 beds and a staff of 600 people. They treat approximately 140 outpatients per day and 70 to 75 in-patients per month. The facility has twenty-two departments, including the emergency room (ER), surgery, and laboratory, spread over 25 buildings in an area of 80,000 m^2.

The facility is completely off-grid, relying on gensets and a small PV and BESS for their energy supply. The management of the hospital aspires to have 70% of its power provided by RE generation and storage. The WAPP transmission line passes near the hospital and could potentially supply power, but there are inconclusive discussions about the possibility of connection. The facility owns six gensets of which two are 13 kVA, each supplying half of the hospital, one is 10 kVA supplying the special care baby unit (SCBU), a working 45 kVA, and two 60 kVA and 50 kVA generators that are used to supply the whole hospital but are currently broken and need repairs. Aside from the gensets, there is a partially functioning 12 kW PV system with a 57 kWh lead-acid battery system installed in 2016. Four of the panels are broken, decreasing the working capacity to 11 kW. The RE generation serves three of the departments. The solar generation cannot be used at the same time as the gensets.

Currently, Hospital 2 uses 75 L/day of diesel, almost half of what it used to get before the diesel price increase in April 2022. Before this, they could power their critical loads with 150 L/day of fuel paid with financial aid provided by the Government and an NGO.

Two boreholes are connected to a generator to pump water to the tanks during the night to supply water to the hospital, but it does not fulfil the entire demand. There used to be a solar water pump but is broken. The water is not potable, but they have purification sites where the water goes to an open pool and people filter their water to drink.

The hospital has expansion plans for the ER, the x-ray unit, and the infectious disease unit, aiming to start this year. They are also planning to build an oxygen plant where they can bottle compressed oxygen and sell it to the surrounding regions. Therefore, part of the hospital is piped with compressed oxygen. This new plant will come with its own 100 kVA genset although the hospital's superintendent is advocating for solar energy as well.

One full-time technician manages the operation and maintenance of the whole hospital. The technician would be able to perform routine O&M on a PV and battery system, but they are not specialized in RE generators and any problems such as a charge imbalance or any communication issues would be better solved by RE-specialized technicians.

Measurements of the loads could not be performed for Hospital 2, but it was projected that the facility currently has a peak load of 133.3 kWp based on interviews with the technician of the facility. To estimate the current energy consumption the 75 L/day of diesel used were converted to electrical energy by knowing that there are around 38 MJ/L of diesel and that this can be approximated to 10 kWh [30]. From the data collected it was found that the gensets in Hospital 2 have an average conversion efficiency of 25% thus, an average electricity consumption of 187.5 kWh/day was calculated. On the other hand, it was found during the visit that the hospital would need twice the electricity they are getting now to be able to operate in ideal conditions and power all their appliances.

The load profile was built using scaled values based on load data from a Sierra Leone hospital, HOMER's Powering Health Tool [31], and the interviews with the Hospital's administration and staff. It is important to notice that a scaled version of the load profile of Hospital 1 would not have been representative of the situation in Hospital 2. This is because Hospital 2 is considerably smaller than Hospital 1, it does not serve as many patients, and it is not connected to the grid, making the load profile highly different from each other. Most of the country's hospitals have similar characteristics to those f Hospital 2 with no grid connection and low patient traffic during the night-time and weekends. This behaviour translates into a load profile like the one seen in the figure below which shows scaled values based on the peak load (i.e., the peak load is 100%). The consumption pattern was estimated to be *Ideal*, meaning that these would be the load profile if the hospital had access to all the electricity they require for its optimal operation.

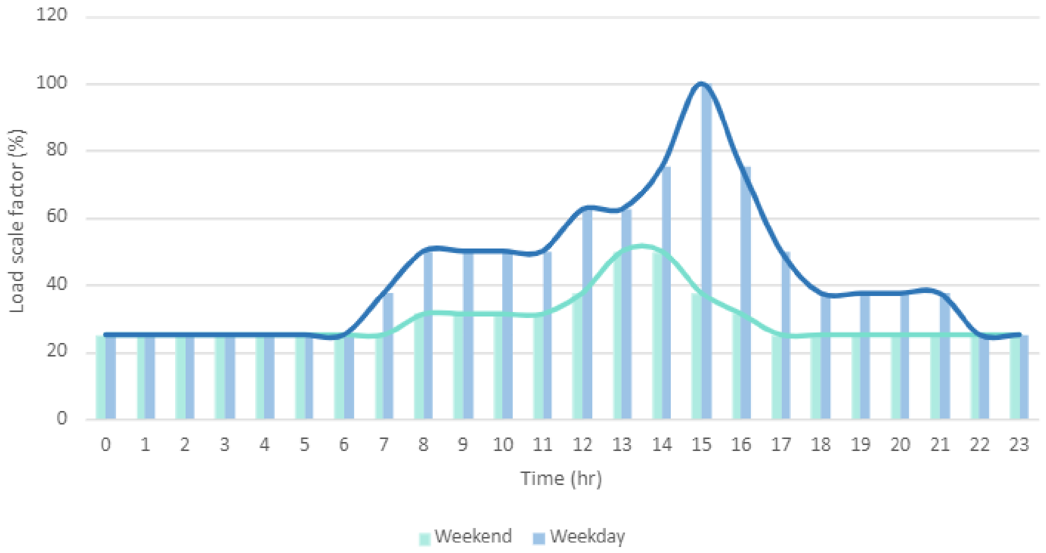


Figure 14: Ideal load profile for Hospital 2

Peripheral Health Units

Following the criteria developed in section 5.1.1, ten PHUs were chosen, all in different districts. The selected sites were subject to an energy audit in order to gather data about their energy status. Before this was done, the only available data was the type of facility and its location. After comparing these with the acquired information during the site visit, it was found that, even though the PHUs have tiers and specific recommended services that they should offer, the establishments often provide additional services to fulfil the local demand due to a shortage of health facilities in the region. Nevertheless, all visited facilities were underequipped based on TTA's *Basic Electrical Equipment List*. A summary of some of the key data collected during the PHUs' energy audits is shown in

Table 4.

For each of the tiers, there is no clear pattern in the number of beds since some MCHPs have the same amount of beds as one of the CHCs and one of the CHPs. On the other hand, it can be seen that CHCs and MCHPs have a greater number of patients per month than that of CHPs as they have also a higher number of employees. Most of the facilities have some type of electricity source but are not connected to the national grid, EDSA. Thus, they use solar lanterns and small solar kits to power LEDs during the night which are especially important during night deliveries. Only one of the audited facilities has a genset as a power supply and only two have a small PV with BESS. Differently, PHU 1, PHU 7 and PHU 5 were connected to microgrids which provided electricity for a few hours each day. Several PHUs have broken energy generation systems and water pumps and have no access to technicians or budget to repair them. The sites showing no water supply rely on the local community wells/boreholes and must collect it and transport it manually while other facilities must resource to other water sources during the dry season.

Table 4: Characteristics of visited PHUs

PHU Name	**District**	**Facility Type**	**Beds**	**Patients/ month**	**Staff**		**Electricity Source**[a]					**Water supply**		
					#	Staff quarters	Grid	Genset	PV	Micro Grid	Solar kit/lights	Borehole	Well	Pump[b]
1	Punjehun	CHC	6	900	11	✓	✗	✗	✓	✗	✓	✗	✓	✓
2	Western Area Rural	CHC	12	750	26	✗	✗	✗	✓	✗	✗	✓	✗	✓
3	Kambia	CHC	4	750	7	✓	✗	✗	✗	✓	✗	✗	✓	✓
4	Kenema	CHC	12	750	11	✓	✗	✗	✗	✗	✓	✗	✗	✗
5	Bo	CHC	8	417	12	✓	✗	✗	✗	✓	✗	✗	✗	✗
6	Moyamba	CHP	6	120	4	✗	✗	✗	✗	✗	✓	✗	✗	✗
7	Bonthe	CHP	4	200	3	✗	✗	✓	✗	✗	✗	✗	✓	✓
8	Bombali	CHP	2	450	8	✗	✗	✗	✗	✗	✓	✓	✗	✓
9	Tonkolili	MCHP	4	680	6	✗	✗	✗	✗	✗	✓	✗	✗	✗
10	Kono	MCHP	4	750	9	✗	✓[c]	✗	✗	✗	✓	✗	✗	✗

[a] *Only considers the current working electricity sources. Does not account for damaged equipment.*
[b] *Considers hand pumps and submersible pumps, powered by fuel or solar energy.*
[c] *Facility is grid-connected but does not have electricity*

Two scenarios were created for the load profiles of PHUs as can be seen in Figure 15**¡Error! No se encuentra el origen de la referencia.** and Figure 16. The Current scenario is based on the electrical equipment list and usage schedules that each PHU provided, showing the current loads for each of the tiers. It was estimated that CHCs, CHPs, and MCHPs have an average load of 6.07 kWh/day, 1.73 kWh/day, and 1.54 kWh/day, respectively. As well, their peak loads were found to be 0.57 kWp, 0.22 kWp, and 0.064 kWp, respectively. As all visited facilities were underequipped, an *Ideal* scenario was created based on the *Basic Electrical Equipment List* for PHUs (see Appendix 1 and Appendix 2), showing the loads that would be expected if the sites had access to all the equipment and the electricity they required. It can be seen that the Current load profiles vary depending on the tier of the facility, with the CHC having the highest consumption and the MCHP having the lowest. On the other hand, the Ideal load profiles have the same shape for all PHUs, with the magnitude of the load scaled up or down depending on the tier. Having as a base case the Ideal load profile for MCHP, it was calculated that Ideal CHPs would require 1.2 times more energy and Ideal CHCs would need 2.3 times more energy compared to MCHPs.

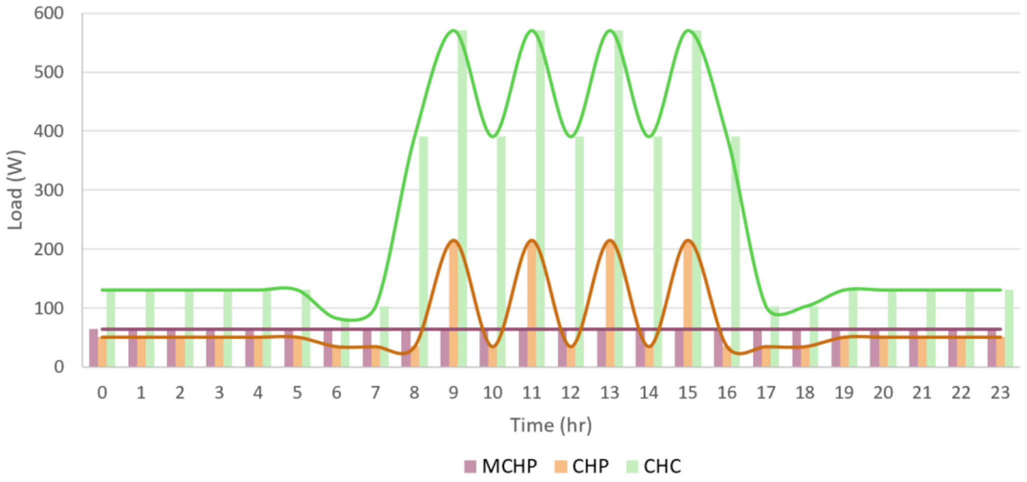


Figure 15: Current load profile of all PHU tiers

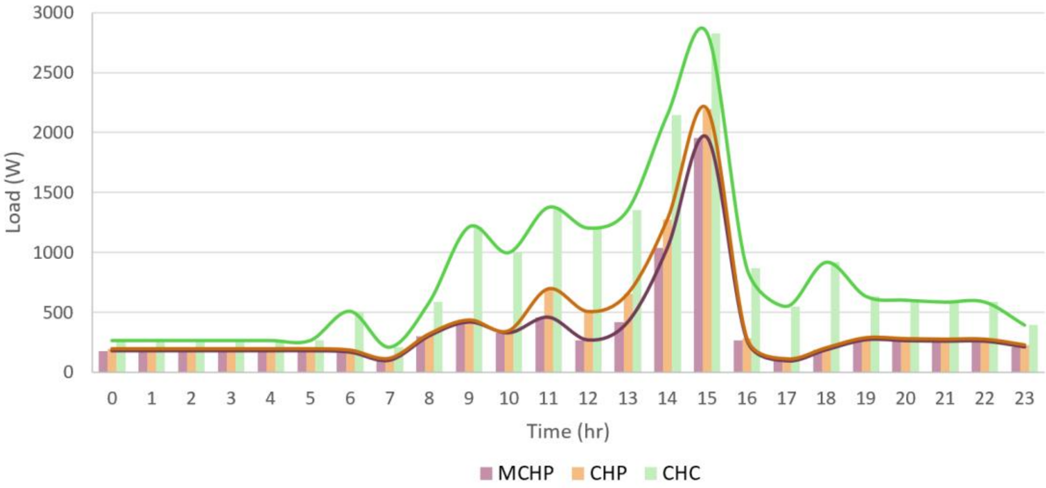


Figure 16: Ideal Load profile for all PHU tiers

Schools

Based on the criteria created in section 5.1.2, ten approved/co-ed/ secondary schools were chosen to be located in different districts. A summary of the key data collected during the schools' energy audits can be seen in Table 5. This information did not completely match the database given by the MBSSE. All visited schools reported a larger number of students than the database, with eight of the ten schools being in the Large category and none of them fitting in the Small category. All sites have some type of electricity source, especially for lighting, with five of them having an unreliable grid connection which was not reported in the database. Six facilities have broken water pumps and power generation equipment. As well, all schools have some type of water source that, again, does not match the database. Based on these findings, it was estimated that around half of the official data differs from the actual situation of the facilities. Thus, the data collected from the site visits will be the one considered for the rest of the analysis.

From the interviews with the schools' administrators, it was found that the monthly subsidy per student that should be provided by the Government is not keeping up with the growth of the student population and payments are usually late. The administrators report that the subsidy is inadequate to properly run a school. All the visited facilities teach both junior and senior secondary education and most of them have plans for expansion which include computer labs and/or student accommodations. Moreover, from these visits and interviews with local experts in school electrification, it was found that the most impactful loads for secondary schools are computer labs, student accommodations, and West African Senior School Certificate Examination (WASSCE) centres where students perform in their third year of SSS the examination for selection to tertiary institutions and certification.

Table 5: Characteristics of visited secondary schools

School Name	**District**	**Educational Level**	**Classrooms**	**Students**		**Staff**		**Electricity Source[b]**					**Water supply**		
				#	Housing [a]	#	Staff quarters	Grid	Gen-set	PV	Micro grid	Solar kit/lights	Bore-hole	Well	Pump[c]
1	Kenema	SSS	27	2048	✕	32	✕	✓	✓	✕	✕	✓	✕	✓	✓
2	Bonthe	Junior & Senior	19	2058	✕	51	✓	✕	✓	✕	✓	✕	✓	✕	✓
3	Bo	Junior & Senior	22	2075	✕	52	✕	✓	✓	✕	✕	✕	✓	✕	✕
4	Western Area Rural	Junior & Senior	12	1030	✕	43	✕	✓	✕	✕	✕	✕	✕	✓	✕
5	Bombali	Junior & Senior	15	1565	✕	55	✕	✕	✓	✕	✕	✓	✕	✕	✕
6	Tonkolili	Junior & Senior	27	1450	✕	39	✓	✓	✕	✕	✕	✕	✓	✕	✓
7	Kambia	Junior & Senior	19	1051	✓	53	✓	✕	✕	✕	✓	✕	✓	✕	✓
8	Moyamba	Junior & Senior	12	417	✕	21	✓	✕	✓	✕	✕	✕	✓	✕	✓
9	Kono	Junior & Senior	10	1020	✕	26	✕	✓	✕	✕	✕	✕	✓	✕	✓
10	Port Loko	JSS	24	637	✓	45	✓	✕	✓	✕	✕	✓	✕	✓	✓

[a] Some schools offer in-site accommodation for the students, also known as boarding schools.
[b] Only considers the current working electricity sources. Does not account for damaged equipment.
[c] Considers hand pumps and submersible pumps, powered by fuel or solar energy.

The data collected from the visited secondary schools showed that they had virtually no loads or they were considerably small with electricity being used for a few hours per day to power water pumps, lights, and fans, estimating an average load of 5.2 kWh/day and a peak load of 4 kWp for large schools, with no loads when the facilities were closed. Thus, the load profiles created for the schools were only based on the *Ideal* loads that the facilities would have if they had all the equipment listed in the *Basic Electrical Equipment List* for schools (see Appendix 3 to Appendix 6) and a reliable electricity source. Therefore, the load profiles for all schools have the same shape, only varying in load magnitude depending on the size of the facility. Having as a base case the loads for a Small school (i.e., scale factor 1), the loads for a Medium school were estimated to be 1.8 times greater and the loads for a Large school to be 2.6

times higher than those of the base case. For this reason, only the Large school load profile was used for this study since this can just be scaled down to extrapolate the results.

The shift status of the school was also an important factor to consider when estimating the load profile. Since double-shift schools open for around three and a half hours more than single-shift schools it was important to create load profiles which fit both schedules. Single-shift schools normally work from 8:00 to 14:00 while double-shift work from 8:00 to 17:30. Thus, it was estimated that double-shift schools will have 60% of the total single-shift loads during their afternoon operations. This can be seen in Figure 17.

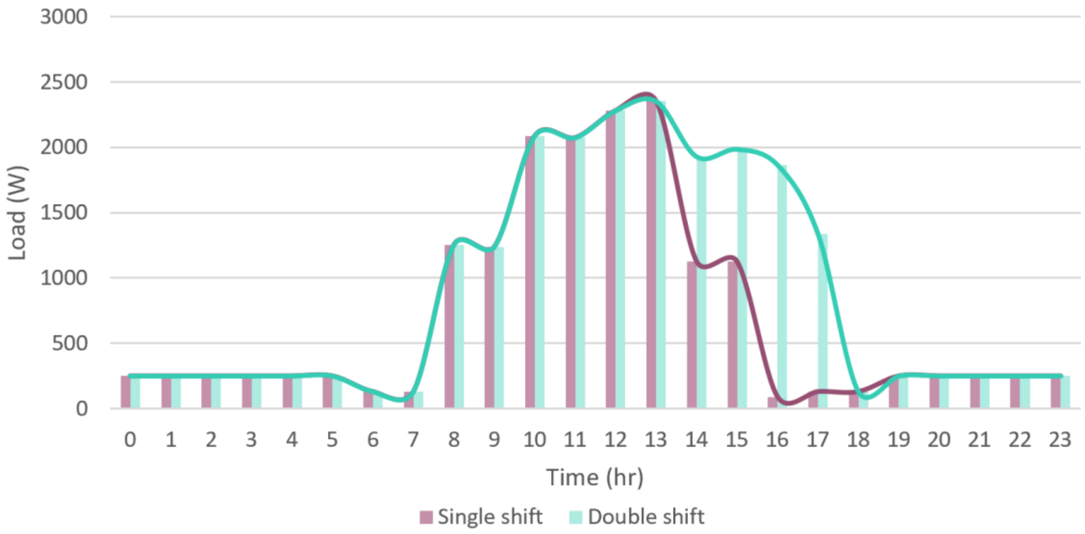


Figure 17: Ideal load profile for a Large secondary school

Before, the impact on the energy requirements of schools offering the services of student dorms, computer labs, and WASSCE centres was discussed. Thus, since many of the interviewed schools had expansion plans for computer labs and student dorms, these loads were calculated in order to give an accurate load profile. On the other hand, since WASSCE centres are only active for two months every year, August and September, when the students are on holiday, and none of the visited schools was a WASSCE centre, this load was not considered for this study. The resultant profile can be seen in Figure 18 ***¡Error! No se encuentra el origen de la referencia.***for a Large/single shift school. The computer lab was assumed to have 30 desktops and the student accommodation was estimated to house 100 students distributed in 10 dorms and 2 staff members with individual quarters considering the equipment to be that listed in the *Basic Electrical Equipment List* for schools.

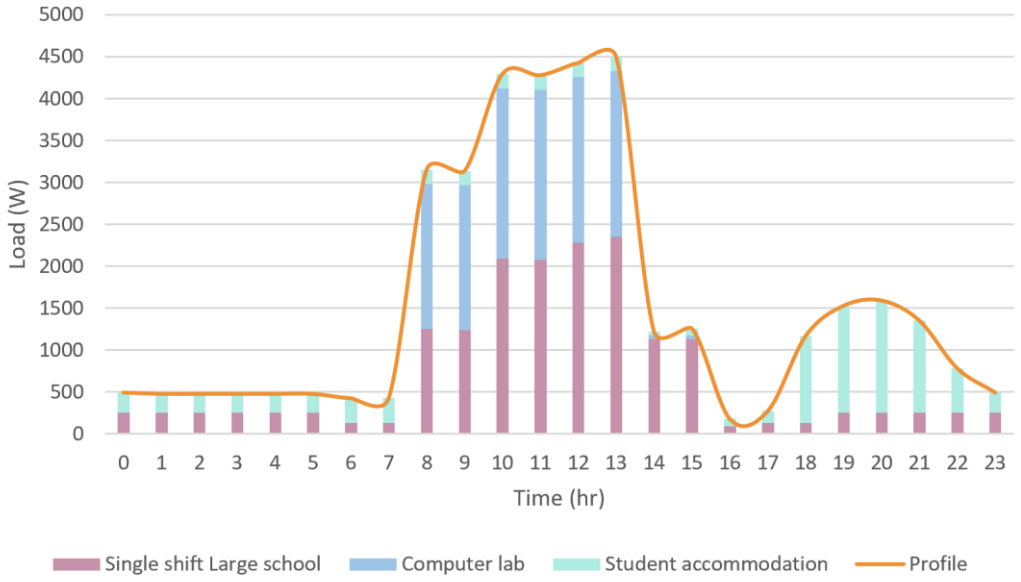


Figure 18: Ideal load profile for a Large single shift school with a computer lab and student accommodation

Chapter 6

Design and Simulation of the Energy Systems

The general configuration used for the hybrid power generation system can be seen in Figure 19. The design consists of an AC load and a diesel genset connected to the AC bus, with a solar PV array and a battery storage bank connected to the DC bus. Linking the DC and AC bus there is a bi-directional battery inverter that charges the batteries either from the PV array or from the grid. For one of the case studies, Hospital 1, the grid is present, which will be connected to the AC bus and the battery inverter will also be capable of charging the batteries with electricity from the grid. The system is aimed to rely as much as possible on the RE generation and the battery storage bank while only using the diesel genset as a backup source of energy. This way, the system would be less susceptible to fluctuations in the costs of diesel and would help decrease greenhouse gas emissions.

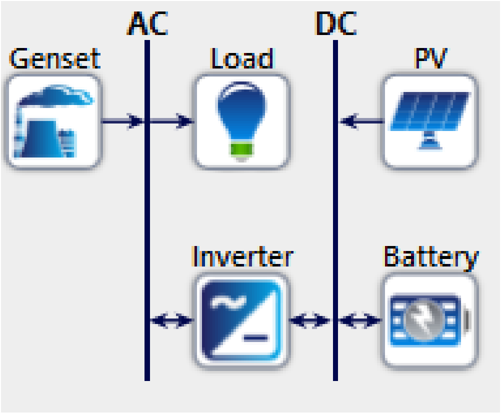


Figure 19: General configuration for the hybrid power generation systems

The electrical systems for four different load profiles corresponding to the study cases were simulated using HOMER (Hybrid Optimization of Multiple Energy Resources) Pro software, created by the National Renewable Energy Laboratory (NREL) and HOMER Energy, to optimize the system size. This tool is used to design distributed generation systems, both on- and off-grid, in a simplified way allowing the evaluation of many possible system configurations through their optimization and sensitivity analysis algorithms. HOMER simulates the operation of a system by making energy balance calculations at each time step of the year. For each time step, the software compares the electrical and/or thermal demand in that time step to the energy that the system can supply in that time step and calculates the flow of energy to and from each component of the system. For systems that include batteries or fuel-powered generators, HOMER also decides at each time step how to operate the generators and whether to charge or discharge the batteries. The tool performs these calculations for each system configuration that the user wants to consider, and it determines if it is feasible and estimates the cost of installing and operating the systems over the lifetime of the project. After this, HOMER takes the simulated systems and sorts and filters them according to the criteria defined by the user, displaying a list of configurations arranged by net present cost (NPC). The software also allows the user to define sensitivity variables as inputs, repeating the optimization process for each specified sensitivity variable [32].

HOMER optimization output is based on the least expensive system calculated through the system's NPC. The NPC of a component (e.g., PV array, battery, genset, etc) is the present value of all the costs of installing, O&M, and replacement of the component over the project lifetime, minus the present value of all the revenues it earns over the project lifetime. The software calculates the NPC for each component and the whole system, considering the salvage cost of the components and the energy sold to the grid as revenues. To perform the NPC calculation HOMER creates a cash flow for the project and, to account for the time value of money, it multiplies the nominal costs by the discount factor which is calculated as follows

$$f_d = \frac{1}{(1+i)^N} \qquad\qquad i = \frac{i'-f}{1+f} \tag{1}$$

where

f_d is the discount factor

N is the number of years

i is the real discount rate [%]

i' is the nominal discount rate (i.e., the rate at which the capital can be borrowed)

f is the expected inflation rate.

To set-up the HOMER simulation, a source of energy, a power generation system, and a power consumer need to be defined. For the simulations of the case studies, load profiles were defined, the natural resources (e.g., solar radiation) of each location were specified, and the characteristics of the components of the hybrid renewable energy system were defined. All the components' costs presented in this chapter include the installation expenses and, along with the costs of operations and maintenance, the values were taken from a costs database developed by TTA specifically for Sierra Leone.

6.1 Load Profile

The load profiles for the case studies were created based on measurements done on-site, electrical equipment used, and estimation found in the literature, as presented in Section 5.2.1.

HOMER uses scaled load data for calculations. This is done by multiplying each of the baseline data values by a common factor that results in an annual average value equal to the value that the user specified as the scaled annual average in kWh/day. The scaled data keeps the shape and statistical characteristics of the baseline data but can differ in magnitude. When the annual average value of the baseline is equal to the scaled one their load data is identical.

As the input load profile for this project is average power by hour, HOMER allows the user to create two types of random variability to make the load more realistic, it can be day-to-day and/or timestep. If a 20% of day-to-day variability is set, HOMER will change each day's load profile by a random amount, so the load retains the same shape for each day but is scaled upward or downward. On the other hand, the timestep-to-timestep variability changes the shape of the load profile without affecting its size. If these two are combined a realistic-looking load profile can be created as HOMER multiplies the value of each time step over a year by a perturbation factor defined as

$$\zeta = 1 + \varphi_d + \varphi_{ts} \tag{2}$$

where

φ_d is the daily perturbation value

φ_{ts} is the time step perturbation factor

HOMER randomly draws the daily perturbation factor once per day from a normal distribution with a mean zero and a standard deviation equal to the daily variability percentage entered by the user. Similarly, the software randomly draws the time step perturbation value every time step from a normal distribution with a mean of zero and a standard deviation equal to the timestep variability input value. An example of a load profile without random variability and with both types of random variability applied can be seen in Figure 20 below.

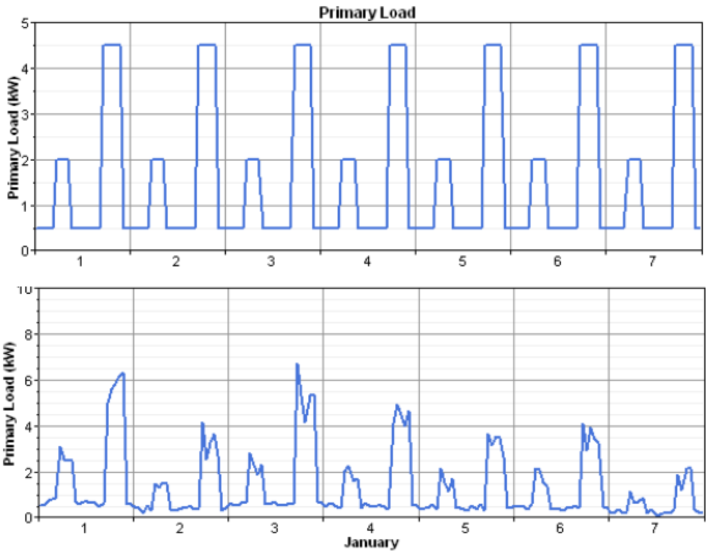


Figure 20: Load profile, without and with random variability

Simulated Load Profiles Configuration

The load profiles used for the simulations were the ones presented in section 5.2.1. To represent the PHUs the loads for the *Ideal* CHC were used in order to account for future load growth. Similarly, the loads for the *Ideal* Large/single school with a computer lab and student accommodation were employed for the simulations. A summary of the main characteristics of the load profiles used in the HOMER simulations of each case study can be found in Table 6.

Table 6: Characteristics of the case studies' Ideal load profiles used for HOMER simulations

Case Study	Average Load [kWh/day]	Peak Load [kWp]	Description
Hospital 1	3,257.1	263.2	Ideal load profile for Hospital 1
Hospital 2	375	70.5	Ideal load profile for Hospital 2
PHU	19.2	3.5	Ideal load profile- Scaled for a CHC
School	37.4	6.4	Ideal load profile - Scaled for a single shift Large school with a computer lab and student housing

Even though the *Current* scenario of the case studies will not be simulated, a table summarizing the main aspects of the documented load profiles is shown below. Since many of the site's administrators said in the interviews that the electricity they received was enough to cover their critical loads, this assumption was also made for this study, understanding as critical loads all the energy required from electrical equipment that keeps the basic services of the facility operating.

Table 7: Characteristics of the case studies' Current load profiles

Case Study	Average Load [kWh/day]	Peak Load [kWp]	Description
Hospital 1	2,566.7	100.0	Current measured loads for Hospital 1.
Hospital 2	187.5	133.3	Current load estimations from diesel consumptions and the use of their PV system.
PHU	6.1	1.2	Current load estimations from diesel consumption of audited CHCs. It includes lights, fans, phone chargers, and a water pump.
School	5.2	4.0	Current load estimations from diesel consumption of audited single-shift Large schools. It includes lights, fans, phone chargers, and a water pump.

6.2 Resources

In HOMER, a “Resource” refers to the environmental conditions of the selected location that will act as inputs or affect the performance of the selected power generation technology. Solar resources such as irradiation and temperature as well as wind speed, fuel specifications, and biomass specifications are some of the options HOMER offers. For this analysis, only the solar global irradiation and the monthly average temperature were used as they affect the performance of the PV system. In Figure 21 and Figure 22 below Hospital 1 resources of solar direct irradiation and average daily temperature are shown as an example of the data HOMER uses in order to calculate the production of the PV installation. The temperature and solar irradiation values were extracted from NASA Surface Meteorology and Solar Energy database.

The baseline data is a time series representing the average temperature for each time step of the year. HOMER displays the monthly averages and synthesizes hourly data from these monthly averages. The software downloads the monthly average values based on the latitude and longitude of the project location. After there are values in the monthly table HOMER builds a set of temperature values for each hour of the year, assuming a constant temperature throughout the month and writes a time series where the temperature in each month is constant at the average value. This is a simplifying assumption but for more precise representation time-series data can be imported.

HOMER uses these temperatures to calculate the PV cell temperature in each timestep by applying the following equation

$$T_c = T_a + G_T\left(\frac{\tau\alpha}{U_L}\right) \tag{3}$$

$$\frac{\tau\alpha}{U_L} = \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \tag{4}$$

where

T_c is the temperature of the cell

T_a is the ambient temperature [K]

G_T is the solar irradiance [kW/m^2]

τ is the solar transmittance of any cover over the PV array [%]

α is the solar absorptance of the PV array [%]

U_L is the coefficient of heat transfer to the surroundings [kW/m^2°C]

$NOCT$ refers to the Nominal Operating Cell Temperature [°C]

The NOCT is defined as the cell temperature that results at incident radiation of 0.8 kW/m^2, an ambient temperature of 20°C, and no-load operation. HOMER assumes $\tau\alpha$ has a value of 0.9.

For the solar global horizontal irradiation (GHI) with the location of the project site, the user downloads a data set as a baseline of one-year time series representing the average global solar radiation on the horizontal surface for each time step of the year. To do this HOMER synthetizes hourly data from the downloaded monthly averages using its algorithm based on the work of V.A. Graham [33].

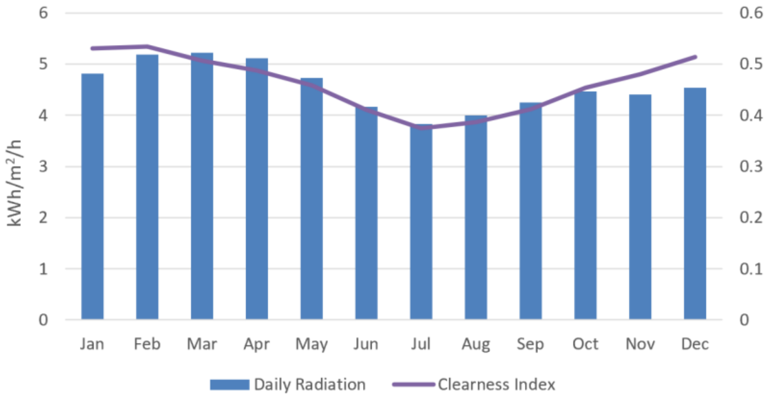


Figure 21: Solar Irradiation of Hospital 1

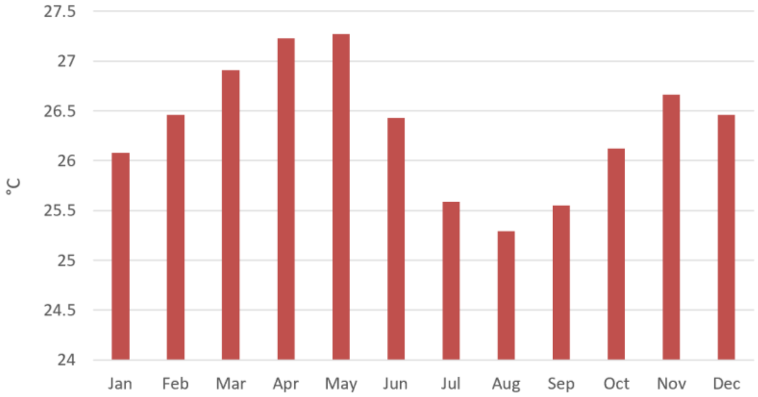


Figure 22: Average daily temperature of Hospital 1

The incident radiation on the PV array determines the production of electricity. This radiation is not normally horizontal thus, in each step HOMER must calculate the global solar radiation incident on the surface of the PV array using the solar GHI resource. Some of the angles to be used in the calculation can be seen in Figure 23 and are explained below.

- Latitude, φ: the angular location north or south of the equator, north positive; −90° ≤ φ ≤ 90°.
- Declination, δ: the angular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive; −23.45° ≤ δ ≤ 23.45°.
- Slope, β: the angle between the plane of the surface in question and the horizontal; 0° ≤ β ≤ 180°. (β > 90° means that the surface has a downward-facing component.)
- Surface azimuth angle, γ: the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive; −180° ≤ γ ≤ 180°.
- Hour angle, ω: the angular displacement of the sun east or west of the local meridian due to

rotation of the earth on its axis at 15° per hour; morning negative, afternoon positive.

- Angle of incidence, θ: the angle between the beam radiation on a surface and the normal to that surface.
- Zenith angle, θz: the angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface.
- Solar altitude angle, αs: the angle between the horizontal and the line to the sun, that is, the complement of the zenith angle.
- Solar azimuth angle, γs: the angular displacement from south of the projection of beam radiation on the horizontal plane. Displacements east of south are negative and west of south are positive.

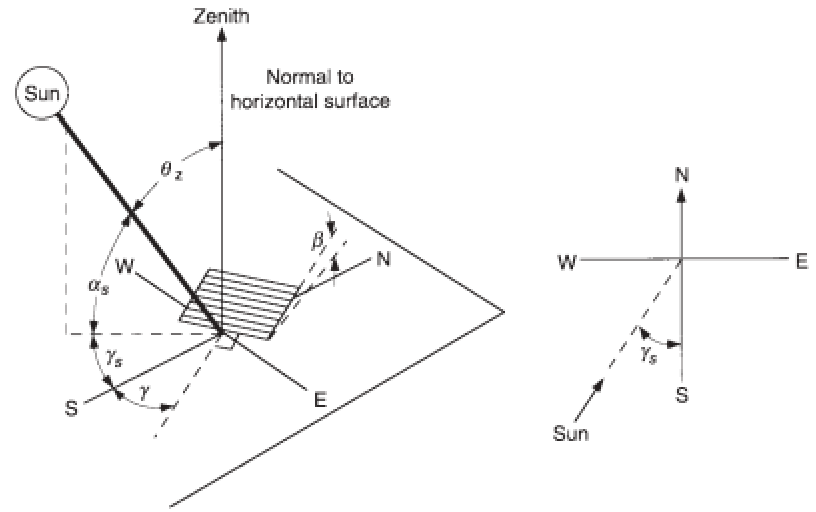


Figure 23: Solar angles

The orientation of the PV array can be defined by the azimuth γ and the slope β. The latitude, the time of year, and the time of day are also factors relevant to the geometry of the system. The time of year affects the solar declination which HOMER calculates as

$$\delta = 23.45^\circ \sin\left(360^\circ \frac{284+n}{365}\right) \tag{5}$$

where n is the day of the year (a number between 1 and 365).

The time of the day affects the location of the sun, which can be described by an hour angle which HOMER calculates as

$$\omega = (t_s - 12hr)15^\circ/hr \tag{6}$$

where t_s is the solar time in hours. This value is 12 hr at noon and 13.5 hr one hour later. The equation is based on the fact that the sun moves across the sky at 15°/hr.

HOMER assumes that all time-dependent data, such as radiation data and electric load data, are specified not in solar time, but in local standard time, also called civil time. It calculates solar time from civil time by applying

$$t_s = t_c + \frac{\lambda}{15°/hr} - Z_c + E \tag{7}$$

where

t_c is the civil time in hours corresponding to the midpoint of the time step [hr]

λ is the longitude [°]

Z_c is the time zone east of GMT [hr]

E is the equation of time [hr]

The equation of time accounts for the effects of obliquity (the tilt of the earth's axis of rotation relative to the plane of the ecliptic) and the eccentricity of the earth's orbit). HOMER calculates the equation of time as

$$E = 3.82(0.000075 + 0.001868 cosB - 0.032077 sinB - 0.014615 cos2B - 0.04089 sin2B) \tag{8}$$

Where B is defined by

$$B = 360° \frac{(n-1)}{365}$$

The angle between the sun's beam radiation and the normal surface, the angle of incidence, is calculated using the following equation

$$cos\theta = sin\delta sin\vartheta cos\beta - sin\delta cos\vartheta sin\beta cos\gamma + cos\delta cos\vartheta cos\beta cos\omega + cos\delta sin\vartheta sin\beta cos\gamma cos\omega + cos\delta sin\beta sin\gamma sin\omega \tag{9}$$

The zenith angle can be then calculated by applying the equation below

$$cos\theta z = \cos\vartheta\cos\delta\cos\omega + \sin\vartheta\sin\delta \tag{10}$$

HOMER assumes the output of the sun is constant in time when referring to the amount of radiation arriving at the top of the atmosphere over a particular point on the earth's surface. Nevertheless, the amount of radiation striking the top of the earth's atmosphere varies over the year because the distance between the sun and the earth varies over the year due to the eccentricity of the earth's orbit. The amount of solar radiation striking a surface normal to the sun's rays at the top of the earth's atmosphere known as extraterrestrial normal radiation is defined as

$$G_{on} = G_{sc}\left(1 + 0.033 cos \frac{360n}{365}\right) \tag{11}$$

where

G_{on} is the extraterrestrial normal radiation [kW/m^2]

G_{sc} is the solar constant [1.367 kW/m^2]

With this, the extraterrestrial horizontal radiation can be calculated as follows

$$G_o = G_{on} cos\theta z \tag{12}$$

Since HOMER works based on time steps, equation 10 is integrated over one timestep to define the average extraterrestrial horizontal radiation over the time step. The equation below gives the amount of solar radiation striking a horizontal surface at the top of the atmosphere at any time

$$\overline{G_o} = \frac{12}{\pi} G_{on} \left[cos\vartheta cos\delta (sin\omega_2 - sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180°} sin\vartheta sin\delta \right] \tag{13}$$

where

ω_1 is the hour angle at the beginning of the time step [°]

ω_2 is the hour angle at the end of the time step [°]

The solar resource data provides the average amount of solar radiation striking a horizontal surface at the surface of the earth in every time step. With this value and the one calculated in the earlier equation, the clearness index can be found by

$$k_T = \frac{\overline{G}}{\overline{G_o}} \tag{14}$$

where $\overline{G}$ is the global horizontal radiation on the earth's surface averaged over the time step [kW/m^2]

Global solar radiation has two components, beam radiation, and diffused radiation. It is especially important to identify these when calculating the amount of radiation striking on an inclined surface because the orientation of the surface will have a stronger effect on the beam radiation since this comes from one specific direction, casting a shadow

$$\overline{G} = \overline{G}_b + \overline{G}_d \tag{15}$$

where

$\overline{G}_b$ is the beam radiation [kW/m^2]

$\overline{G}_d$ is the diffused radiation [kW/m^2]

Thus, since the solar resource is the global solar irradiation, HOMER calculates these two components by using the approach of Erbs which relates the clearness index with the diffuse fraction as seen in the equation below

$$\frac{\overline{G}_d}{\overline{G}} = \begin{cases} 1.0 - 0.09k_T & for\ k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388{k_T}^2 - 16.638{k_T}^3 + 12.336{k_T}^4 & for\ 0.22 < k_T \leq 0.80 \\ 0.165 & for\ k_T > 0.80 \end{cases} \tag{16}$$

To calculate the global irradiation striking the PV array HOMER applies the HDKR model, which assumes that there are three components to the diffuse solar radiation: an isotropic component that comes from all parts of the sky equally, a circumsolar component that emanates from the direction of the sun, and a horizon brightening component that emanates from the horizon. The model implements three key ratios shown in the equations below

$$R_b = \frac{cos\theta}{cos\theta z} \qquad A_i = \frac{\overline{G_b}}{\overline{G_o}} \qquad f = \frac{\overline{G_b}}{\overline{G}} \tag{17}$$

where

R_b is the ratio of beam radiation on the tilted surface to the beam radiation on the horizontal surface

A_i is the anisotropy index, which is a measure of the atmospheric transmittance of beam radiation. This term is used to estimate the amount of circumsolar diffuse radiation

f is the factor used to integrate horizon brightening since more diffuse radiation comes from the horizon than from the rest of the sky. This term is related to cloudiness.

With these three terms, the HDKR model can be used to calculate the global radiation incident on the PV array as follows

$$\overline{G}_T = \left(\overline{G_b} + \overline{G_d}Ai\right)R_b + \overline{G_d}(1- Ai)\left(\frac{1+cps\beta}{2}\right)\left[1 + fsin^3\left(\frac{\beta}{2}\right)\right] + \overline{G}\rho_g\left(\frac{1-cos\beta}{2}\right) \tag{18}$$

where ρ_g is the ground reflectance, albedo [%].

6.3 Hybrid Power Generation System Components

The hybrid power generation system design for each case study consists of a PV array, a battery storage bank, an inverter and a diesel generator. The technical specifications and assumptions made for each of these components in the HOMER simulations are explained in detail below. As well, the installation cost and O&M cost of the components are given based on TTA’s cost database which was specifically estimated for Sierra Leone.

6.3.1 Grid

A grid can be added to the hybrid system in HOMER. The software allows the user to define the grid within four different modes. The first is the Simple rates mode which lets the user specify a constant power price, sell-back price, and scale capacity. The second is the Real-time rates which allow the definitions of prices on an hourly basis. The third is the Schedule-rates mode which permits different prices of electricity at each time of day and month of the year. Finally, the grid extension mode compares the cost of grid extension with the cost of each stand-alone system configuration in the model.

A feature offered by HOMER is the possibility to define the reliability of the grid within the Real-time rates and Schedule-rates modes. This option allows modelling an unreliable grid by adding blackouts which can be scheduled by time of day and month or by generating random power interruptions throughout the year. These interruptions are modelled as one or more timesteps in which no electricity can be purchased from or sold to the grid. To create random blackouts, inputs for the failure frequency and duration are needed. HOMER then generated each power interruption by selecting a pseudo-random time step from the year-long simulation period to later choose the duration of the outage by selecting a pseudo-random number from a normal distribution specified by the input of the mean average duration of the outage and the time variability of the duration. The tool generates distinct, non-overlapping power interruptions equal to the input for the frequency of the outages [32].

Simulated Grid Configuration

The inputs used to simulate the grid of Sierra Leone were recorded in the table below. These values were taken from the energy audits and interviews done during the field visit.

Table 8: Inputs for simulation of Sierra Leone's electricity grid

Parameter	Input
Mode	Schedule rates
Electricity price [$/kW]	0.229
Grid Sales	Not allowed
Mean outage frequency [1/yr]	365
Mean repair time [h]	1
Repair time variability* [%]	500
CO2 emissions [g/kWh]	187.2

**The standard deviation of a grid failure duration, expressed as a percentage of the mean.*

6.3.2 Solar PV Module

HOMER software allows the user to specify whether the PV array will produce DC or AC power. If the electrical bus is set to AC, HOMER accounts for a built-in inverter within the PV that can be configured. For this project, all simulations were done with an AC electrical bus for simplicity.

HOMER applies several of the previously discussed terms in order to calculate the electrical output power of the PV array. This is determined by the following equation

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \left[1 + \alpha_p \left(T_c - T_{c,STC} \right) \right] \tag{19}$$

where

Y_{PV} is the rated capacity of the PV array, meaning its power output under standard test conditions [kW]

f_{PV} is the PV derating factor [%]

$\overline{G}_{T,STC}$ is the incident radiation at standard test conditions [1 kW/m2]

α_p is the temperature coefficient of power [%/°C]

T_c is the PV cell temperature in the current time step [°C]

$T_{c,STC}$ is the PV cell temperature under standard test conditions [25°C]

Simulated PV

The PV panel model used was the HOMER's Generic model which has an efficiency of 13% and an operating temperature of 47 °C. The derating factor was set to 90% and the tilt angle β was set to the optimal angle for the specific location according to the Global Solar Atlas website. For the sizing of the PV array, the HOMER optimizer option was used. The summary of the used PV model can be seen in the table below.

Table 9: Inputs for simulated solar PV panel

Model	**Generic flat plate PV panel**
Capacity per module [W]	900
Efficiency [%]	13
CAPEX [$/kW]	830
Replacement [$/kW]	830
O&M [$/yr]	7.5
Lifetime [yr]	20
Derating factor [%]	90

6.3.3 Diesel Generator

The diesel generator used for the simulations was the Generic Model that HOMER provides. The software creates a fuel curve in order to show the amount of fuel the generator consumes to produce electricity. The figure below shows the fuel curve of a 50kW generic genset created by HOMER. It can be seen that HOMER assumes a straight line. Even though this might not accurately represent certain types of generators such as variable-speed diesel, for constant-speed internal combustion gensets this approximation is valid.

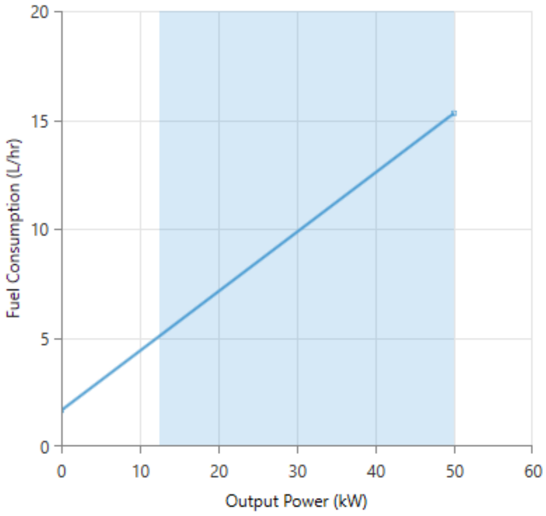


Figure 24: Genset fuel curve

HOMER uses the fuel curve intercept coefficient in order to calculate the fuel consumption rate of the genset. This term can be defined as the no-load fuel consumption of the genset divided by the rated capacity. In other words, the y-intercept of the fuel consumption line divided by the genset size

$$F_0 = \frac{y{-}intercept}{Y_{gen}} \tag{20}$$

where

F_0 is the generator fuel curve intercept coefficient [L/hr/kW$_{\text{rated}}$]

$y - intercept$ is the y-intercept of the fuel curve [L/hr]

Y_{gen} is the rated capacity of the genset [kW]

When the genset is running in a particular time step, HOMER calculates the fuel consumption rate for that time step by applying the following equation

$$F = F_0 Y_{gen} + F_1 P_{gen} \tag{21}$$

where

F is the fuel consumption rate [L/hr]

F_1 is the genset fuel curve slope [L/hr/kW$_{\text{output}}$]

$P_{gen}$is the output power of the genset in this time step [kW]

HOMER calculates the electrical efficiency of the genset and gives an efficiency plot like the one seen below.

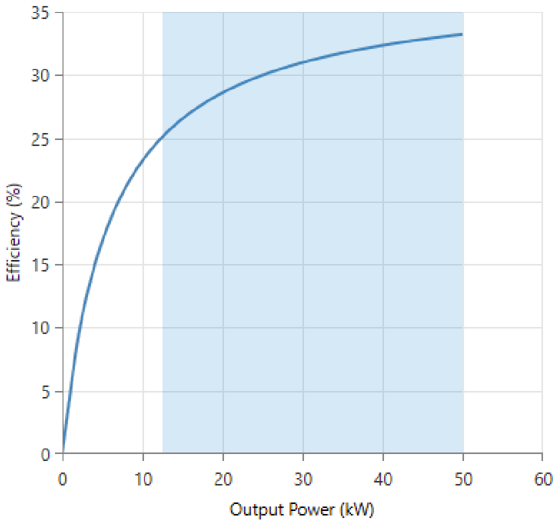


Figure 25: Genset electrical efficiency curve

This rate between the electrical output of the genset and the chemical energy of the input fuel is defined by the following equation

$$\eta_{gen} = \frac{3.6P_{gen}}{\dot{m}_{fuel}LHV_{fuel}} \tag{22}$$

where

P_{gen} is the electrical output of the genset [kW] and the 3.6 factor comes from the conversion from kWh to MJ (1kW h=3.6MJ)

$\dot{m}_{fuel}$ is the mass flow rate of the fuel [kg/hr]

LHV_{fuel} is the low heating value of the fuel [MJ/kg]

The mass flow rate is related to the genset fuel consumption rate with this relationship being defined differently depending on the units of the fuel. In this case, since diesel is being used, the units are litres, and the relation is as follows

$$\dot{m}_{fuel} = \dot{m}_{fuel}\left(\frac{F}{1000}\right) \tag{23}$$

Where ρ_{fuel} is the density of the fuel [kg/m^3].

Simulated Genset

HOMER give the option to select “Auto-size Genset” as the diesel generator model for the simulation. By using this, HOMER calculates the genset size that would be able to supply the whole demand, at any time, without the need for other energy sources. This genset size is then used for all the simulated systems that include a genset. Since the genset for these power generation systems is wanted mainly as a backup the Auto-size Genset model might oversize the genset for the required application, increasing the fuel consumption of the facility. Thus, another design was simulated with a generator sized only to cover the critical loads of each site. These loads were assumed to be the loads that they can currently cover since most of the sites stated this during interviews so, the backup generators were sized to match the current peak load of the case studies. The table below summarizes the input used for the Auto-size Genset (AG) model and the Backup Genset (BG) model.

Table 10: Inputs for simulated genset

Model	Auto-size Genset	Backup Genset
CAPEX [$/kW]	250	250
Replacement [$/kW]	250	250
O&M [$/operation hr]	0.03	0.03
Fuel price [$/L]	1.64	1.64
Lifetime [hrs]	15.0	15.0
Size [kVA]	~ Ideal Peak Load	~ Current Peak Load

6.3.4 Battery Storage

Due to the off-grid nature of most of the sites, battery storage is needed in order to have a reliable RE power generation system with low dependency on diesel gensets.

The autonomy of the battery storage is defined as the ratio of the battery size to the electric load. HOMER calculates this value by applying the following equation

$$A_{batt} = \left(\frac{N_{batt} V_{nom} Q_{nom} \left({}^{1-SOC_{min}}/_{100} \right) (24hr/d)}{L_{prim,ave} (1000Wh/kWh)} \right) \tag{24}$$

where

$\mathrm{N_{batt}}$ is the number of batteries in the storage system

$\mathrm{V_{nom}}$ is the nominal voltage of a single battery [V]

$\mathrm{Q_{nom}}$ is the nominal capacity of a single battery [Ah]

$\mathrm{SOC_{min}}$ is the minimum state of charge of the storage system [%]

$\mathrm{L_{prim,ave}}$ is the average primary load [kWh/d]

Another important feature of a battery is its lifetime. Two factors can determine the end of life of the battery, it can reach its expected lifetime, or it can reach its use limit. The throughput defines the use limit of a battery as it is the amount of energy that cycles through the battery in one year which compares the energy level of the storage bank measured after charging losses and before charging losses. HOMER allows setting if the battery's lifetime is limited by the time, throughput or by whichever happens first. The software uses the following equation to calculate the battery life

$$R_{batt} = \begin{cases} \frac{N_{batt} Q_{lifetime}}{Q_{thrpt}} & if\ limited\ by\ throughput \\ R_{batt,f} & if\ limited\ by\ time \\ min\left(\frac{N_{batt} Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right) & if\ limited\ by\ throughput\ and\ time \end{cases} \tag{25}$$

Simulated Battery

The battery model used for all simulations was the Generic Li-ion model offered in HOMER's library. The sizing of the component was calculated using the HOMER optimizer option. The specifications for this model were summarized in the table below.

Table 11: Inputs for simulation of the battery model

Model	**Generic Li-ion**
Nominal Capacity [kWh]	8
Nominal voltage [V]	48
Roundtrip efficiency [%]	90
CAPEX [$/kWh]	450
Replacement [$/kWh]	360
O&M [$/kWh]	2.0
Lifetime [yr]	10
Throughput [kWh]	3,000
Initial state of charge [%]	100
Min state of charge [%]	5

6.3.5 Battery Inverter

In the simulations for this project, the batteries are connected to the DC bus while the loads are AC. Thus, a battery inverter is required. HOMER calculates the energy output from the batteries using the following equation

$$E_{batt,out} = \frac{E1_{batt} - E_{load}}{\eta_{inv} \eta_{batt}} \tag{26}$$

where

$\mathrm{E}_{\mathrm{batt,out}}$ is the energy output of the battery [kWh AC]

$\mathrm{E1}_{\mathrm{batt}}$ is the initial energy stored in the battery [kWh]

E_{load} is the energy consumed by the load [kWh]

η_{inv} is the inverter efficiency [%]

η_{batt} is the battery efficiency [%]

Simulated Battery Inverter

An inverter-rectifier was simulated with the parameters shown in the table below. For the sizing of this component, a security factor of 30% was added to prevent the overloading and consequently, its failure.

Table 12: Inputs for simulation of converter

Model	**Generic Inverter-Rectifier**
Capacity [kW]	1.3*Peak Load
CAPEX [$/kW]	790
Replacement [$/kW]	790
O&M [$/yr]	0
Lifetime [yr]	15
Efficiency [%]	95

6.3.6 System Controller

HOMER offers two strategies for controlling the simulated power generation system. The first is called Cycle Charging strategy consisting of, whenever the genset needs to operate to serve the primary load, it operates at full power output and the surplus electrical production goes towards the lower priority objectives such as charging the storage bank. The Load Following strategy works in such a way that whenever the genset operates, it produces only enough power to meet the primary load while lower priority objectives such as charging the storage bank are left to the RE power sources. Thus, since the power generation system design for this project aims to have the gensets mainly as backups when renewable energy is not sufficient, the Load Following strategy for the control of the system was chosen in order to prioritise and maximize the use of RE. The controller costs 360 $ and has a lifetime of 25 years.

6.4 Economics

During simulations, HOMER calculates the levelized cost of energy (LCOE) for each system configuration. This parameter measures the lifetime cost of the power generation system (i.e., including the CAPEX, the fuel price, and O&M costs) over the total energy served to the load that was produced from the power generation system. Therefore, the LCOE is linked with the NPC of the system so HOMER's optimization results will be the system with the lowest NPC that will also be the one with the lowest LCOE. HOMER calculates LCOE by implementing the following equations

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \tag{27}$$

$$C_{ann,tot} = CRF(i, R_{proj})C_{NPC,tot} \tag{28}$$

$$CRF(i, N) = \frac{i(1+i)^N}{(i+1)^N - 1} \tag{29}$$

where

$C_{ann,tot}$ is the total annualized cost [$/kWh] described as the annualized value of the total net present cost

E_{served} is the total electricity load served [kWh/yr]

i is the annual real discount rate [%]

R_{proj} is the project lifetime [years]

$C_{NPC,tot}$ is the total net present cost [$]

$CRF(\,)$ is a function returning the capital recovery factor which is a ratio used to calculate the net present value of an annuity (a series of equal annual cash flows)

N is the number of years.

The economic inputs and assumptions done for all simulations can be seen in the tables below. For the School and PHU fixed cost for O&M was added in order to consider the payment for a technician that will take care of the maintenance of the RE system. Since Hospital 1 and Hospital 2 had already technicians, this fixed cost was not added. In addition to the main generation components, a fixed capital expenditure (CAPEX) was added for all simulations since this considers the re-wiring of the facilities and the construction of a powerhouse where the inverter, batteries and control system will be kept. Due to the difference in area, this last fixed cost considerably varies between the case studies.

Table 13: Inputs for general economic parameters

Economic parameter	Input
Nominal (annual) discount rate [%]	12
Expected inflation rate [%]	5
Project Lifetime [yr]	15

Table 14: Inputs for fixed cost

Case Study	Fixed CAPEX [$]	Fixed O&M cost [$/yr]
Hospital 1	$213,900	0
Hospital 2	$182,700	0
School	$5,000	$780.00
PHU	$6,000	$780.00

6.5 Key Performance Indicators (KPIs)

To adequately measure the results of the simulations and be able to compare them quantitatively, was required to establish a list of key performance indicators (KPIs). This selection was done considering the current situation of the studied facilities as well as their needs regarding electricity. The challenges for electrification projects of public institutions were discussed in section 2.1 showing that the coverage for O&M costs as well as the long-term financial sustainability of the project were major issues. The LCOE is one of the most significant markers for many power-generation projects since it indicates the minimum price at which electricity should be sold for a project to break even and cover all costs of production. Thus, the O&M cost of the system, the cost of fuel as well as the LCOE, were considered to have the highest weight for the design selection. Along with these, the autonomy of the battery storage system was also part of the criteria since the aim is for the system to be as reliable as possible with the minimum requirement of fossil fuels. The CAPEX of the system was considered as a secondary criterion since this input normally comes from donations/subsidies and does not entail a great concern for the sustainability of the system. Another secondary criterion was the excess electricity production. While many off-grid systems are oversized to cover future demand growth, a system that produces more than 50% extra electricity would be considered excessive and unnecessary for this project whose lifetime is 15 years. Thus, the KPIs were established to be LCOE, O&M cost, annual fuel cost, battery autonomy, and excess electricity produced by the system.

Chapter 7

Results & Analysis

7.1 Optimization Results

For each site, two simulations were performed with two different sizes of genset. The “Auto Gen”, or AG, simulation refers to the simulation done using the auto-size genset model that HOMER offers, and the “Backup Gen”, or BG, refers to the simulation done using a smaller generator sized just to cover the critical loads of the sites. The PV array and the battery storage bank capacity were set to be calculated by HOMER optimizer thus, these values adjusted as the genset size changed. HOMER’s optimization results for both simulations were recorded for each of the case studies in the table below. It is important to notice that, as mentioned in the previous chapter, HOMER optimizer gives results based on the less expensive option, meaning the system with the lowest NPC and LCOE.

Table 15: HOMER optimization results for all sites

Case Study		**Hospital 1**		**Hospital 2**		**School**		**PHU**	
Simulation Design		Auto Gen (AG)	Backup Gen (BG)	Auto Gen (AG)	Backup Gen (BG)	Auto Gen (AG)	Backup Gen (BG)	Auto Gen (AG)	Backup Gen (BG)
Configuration	Average load [kWh/day]	3,257.1		375		37.4		19.2	
	Peak Load [kW]	263.2		70.5		6.4		3.5	
	Existing PV [kW]	-	-	11	11	-	-	-	-
	Grid Connection	Yes	Yes	No	No	No	No	No	No
	New PV [kW]	543.0	899.5	156.7	133.3	18.5	18.2	9.0	9.3
	Genset [kW]	270.0	100.0	71.0	50.0	7.1	4.0	3.6	1.5

Case Study		**Hospital 1**		**Hospital 2**		**School**		**PHU**	
Simulation Design		Auto Gen (AG)	Backup Gen (BG)	Auto Gen (AG)	Backup Gen (BG)	Auto Gen (AG)	Backup Gen (BG)	Auto Gen (AG)	Backup Gen (BG)
Configuration	Battery Nominal Capacity [kWh]	24.0	872.0	208.0	192.0	16.0	40.0	8.0	16.0
	Converter [kW]	350	350	95	95	10	10	5	5
Economics	NPC [$]	2,778,386	3,021,958	584,983	553,684	54,392	61,323	34,917	36,397
	LCOE [$/kWh]	**0.25**	**0.27**	**0.46**	**0.44**	**0.43**	**0.48**	**0.54**	**0.56**
	CAPEX [$]	1,019,750	1,654,738	499,493	455,365	37,583	47,372	22,268	25,630
	Fuel cost [$/yr]	**42,293.02**	**8,384.01**	**5,565.10**	**7,726.51**	**732.80**	**154.00**	**424.14**	**140.15**
	O&M [$/yr]	**151,494.90**	**135,591.70**	**2,655.43**	**1,492.488**	**1,063.57**	**1,021.10**	**928.52**	**903.09**
Performance	Renewable Fraction [%]	41.0	52.3	93.9	91.3	92.7	98.2	91.7	96.7
	Total fuel [L/yr]	25,788.4	5,112.2	3,393.4	4,711.3	446.8	93.8	258.6	85.5
	Excess electricity [%]	17.6	33.1	44.6	37.1	46.7	44.0	41.8	42.2
	Genset use [hrs]	837	343	461	885	530	200	603	469
	Battery Autonomy at average load [hr]	**0.17**	**6.10**	**12.65**	**11.67**	**9.76**	**24.40**	**9.52**	**19.03**
	Grid Purchased energy [kWh]	613,950.70	550,535.20	-	-	-	-	-	-

7.2 Analysis of the Results

The simulation results for the two designs, AG and BG, followed similar trends for all of the case studies. Overall, all backup gensets had considerably lower capacity than that of the auto-sized genset. This was expected since the auto-size genset should have the capacity to cover all loads by itself at any given moment. As well, all the BG designs presented a lower O&M cost than that of the AG designs mainly due to the decrease in genset capacity and, in some cases, the reduced capacity of other components of the system.

It can be seen that the renewable fraction (RF) of Hospital 1 is considerably smaller compared to the other sites. This is because it has the grid as part of its energy supply and the hybrid power generation system was not aimed to replace the grid, but to improve the reliability of the hospital's energy system. Hospital 1 also has the lowest LCOE among the case studies which can be attributed to its load profile. The load factor of a system refers to the ratio between the average load and the peak load, the higher this value is the more efficiently the energy is being distributed throughout the day. For Hospital 1, the daily peak load happens between 14:00 and 15:00, with a load factor of 0.52 thus, the power generation system can better supply electricity as it is produced. On the other hand, the PHU has a steep peak in its load profile at 15:00 with a load factor of 0.23. This shows that the load distribution through the daylight has sharp changes, leading to the need for higher energy storage and genset use and therefore, higher energy prices.

Due to the magnitude of the hybrid power generation system, Hospital 1 presents the highest cost among all the case studies. The differences between the system configuration for the AG and BG designs are considerable, increasing both the capacity of the PV and BESS as the genset size decreases by more than half. The CAPEX for the BG design is 62% higher than that of the AG design. Nevertheless, the O&M is 16,000 $/yr lower and the LCOE only increases by 0.01 $/kWh. At the same time, due to the increase in battery and PV capacity, the genset use drops considerably in BG, decreasing the cost of fuel by almost 44,000 $/yr and the battery autonomy increasing by nearly 6 hrs. The production of excess electricity increases in the BG system by 16% but it is still within the limits established by the KPIs and the possibility to sell this energy back to the grid could be explored.

A comparable scenario of that of Hospital 1 can be seen for PHU. The PV size does not significantly change between both designs, but it does for the battery capacity. These changes have similar economic and performance outputs as that of the previous case study with an increase in CAPEX, a decrease in O&M, a small increase in LCOE, a considerable decrease in fuel consumption, and a spike in battery autonomy for the BG design. Since PHU is not connected to the grid, the autonomy of the battery is even more pertinent for the system to be reliable without the constant need for the genset.

For the case of School, the PV capacity is slightly smaller for the BG design than that of the AG design while the battery capacity increases by 24 kWh. It can be noticed that with the BG configuration the system performs more efficiently since the excess production of electricity decreases by almost 3% and the fuel consumption drops from 447 L/yr in AG to 94 L/yr in BG design. Due to the increase in battery capacity, the CAPEX of BG design is about 10,000 $ higher than that of AG. Nevertheless, its O&M cost is still lower.

Differently, the BG design for Hospital 2 has lower PV and battery capacity than that of the AG design. These characteristics led the system for the BG design to consume 1,318 L/yr more than the AG configuration but the O&M cost is still 1,000 $/yr less. The excess electricity production of the BG design is 37% which is 7.4% less than that of AG which shows that the BG configuration performs more efficiently even though its component has lower capacities. The battery autonomy is just 1hr less and the LCOE is slightly lower for the BG than that for the AG design. It is clear that this hospital presents a distinct behaviour of the two scenarios compared to the other sites since, as the genset size decreases the capacity of the PV and BESS also decreases. This peculiarity can be attributed to the load profile and the seasonal radiation profile of Hospital 2. The site shows a steep peak in its load profile, having a load factor of 0.22. In the middle of the rain season (i.e., June to August) the radiation in the area is the lowest of the year which creates the need to rely completely on the genset for a few days along these months. Since the HOMER simulation was set to not allow unmet load, HOMER oversize the genset just to be able to meet these peaks in those specific days. Parallelly, HOMER standards show that gensets can work at a minimum of 25% of their rated capacity thus, since the genset is oversized, HOMER decides that is more economic to increase the PV and BESS capacity than running the genset at its minimum capacity over the project lifetime. Therefore, if the hospital applies load shedding techniques during the rain season to avoid the steep peak, the load profile will change and HOMER Auto-size generator will be smaller, leading to a more efficient use of this component regarding its capacity resulting in a PV and BESS capacity sizing better aligned with the demand.

To illustrate the difference in performance, the figure below shows the working hybrid power generation system for School during a few weeks between July and August, the rainy season in Sierra Leone. During this time the electricity production of the PV system is the lowest of the year thus, the genset and the battery storage system work at their full capacity. Here, a higher use of the genset can be seen for the AG design in figure A as well as the batteries having more deep discharges which affect the longevity of the component. On the other hand, the BG system shows a lower use of the genset, relying more on the battery storage bank when solar energy is not available.

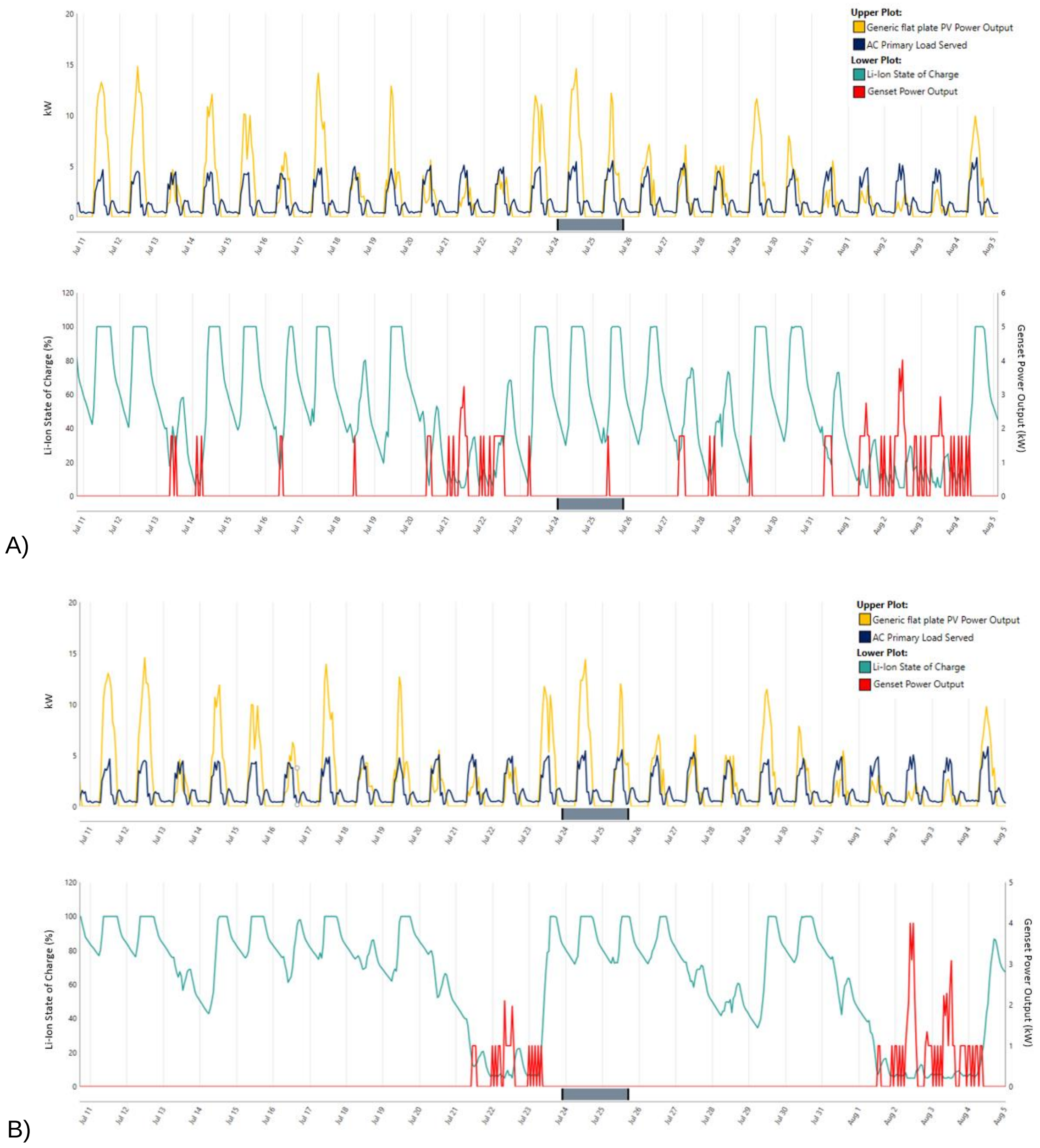


Figure 26: School hybrid power generation system performance for A) AG design and B) BG design

After analysing all KPIs, the most suitable design regarding performance and economics for all facilities was the one implementing the backup diesel generator which showed, in most cases, lower O&M costs, lower fuel consumption, higher utilization of the REs, and an almost negligible increase in LCOE.

7.2.1 Battery considerations

In section 6.3.4 the parameters used for the modelling of the battery storage bank were established. The minimum state of charge (SoC) of the battery was set to 5% which can seem low since normally this is around 20% for li-ion batteries [34]. This was done in order to prevent HOMER from oversizing the battery system due to only a few days of the year when the PV electricity generation is low. In the figure below the frequency of the SoC of the battery system during the year can be seen for the BG design of School. In the heat map, it is shown that in just a few days of the year the battery SoC drops below 20% most of the time being between 60% and 90%. More specifically, the histogram shows that the battery is less than 3% of the year in a SoC of 5% and most of the time, 25% of the year, has a SoC of 100%, rarely dropping to less than 40% SoC. A similar situation is experienced by the rest of the systems where the batteries rarely drop below 20% SoC during the year.

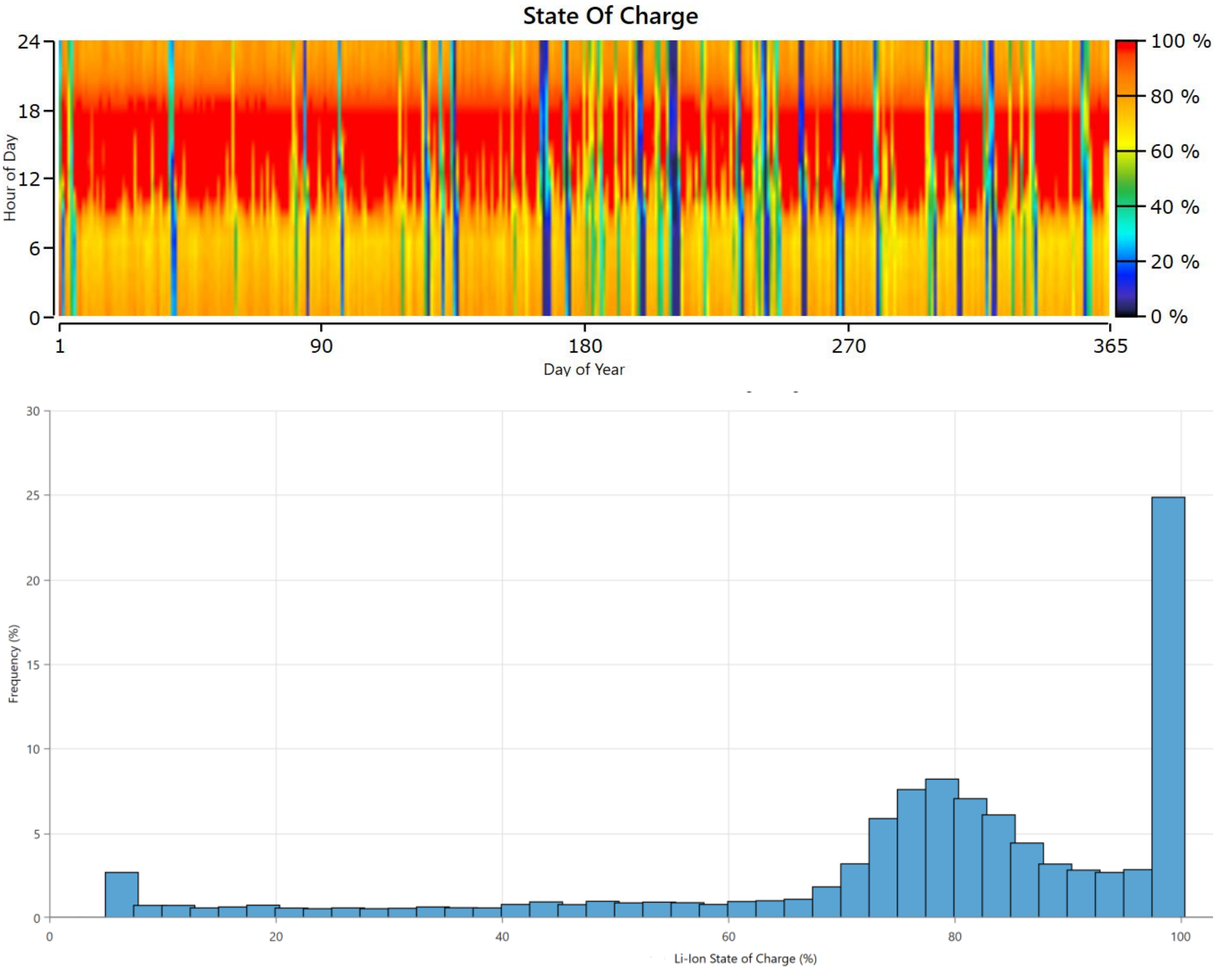


Figure 27: Battery storage bank frequency of SoC

The previous simulations were done using a lithium-ion generic battery model since the systems were designed for public institutions where the investment capital of electrification projects is normally covered by subsidies/donations but there is no assurance that capital would be available for replacement cost thus, it was desired to extend the life of this component as much as possible. Nevertheless, it was considered pertinent to explore if lead acid batteries will be economically and technologically more viable for this project.

Comparing the general characteristics of li-ion and lead acid batteries, li-ion are commonly known to have higher energy density, longer cycling lifetime, a higher depth of discharge (DoD) capability, and need lower maintenance than common lead acid batteries. However, lead acid storage is a mature and robust technology, with a lower capital investment and is widely used for remote PV installations [35]. Studies such as [34] and [36] compared these two technologies in an off-grid setting, both concluding that economically, a PV off-grid system with lead acid batteries was more suitable. Nevertheless, they pointed out the many technical advantages that li-ion batteries have.

It was mentioned that a low maintenance cost for the power generation system is critical for its sustainability. Similarly, replacement costs play a crucial role, especially for batteries. When a battery is replaced, there are other costs, apart from the CAPEX of the new component, that need to be considered such as the cost of disposal of the damaged batteries. In one of the visited sites, they have more than 5,000 kg of lead acid batteries that need to be disposed of, but there are no recycling/disposal centres in the district and the facility does not have the budget to pay for someone to transport them to Freetown where there are companies/technicians that upcycle the batteries for other purposes. Lead acid batteries have shorter lifespans than that of li-ion batteries thus, they need to be replaced more frequently so it is important to consider the disposal options and costs during the design phase.

In order to prove which of the two technologies will be more suitable for the application of this project, a simulation was done with two real battery models using the power generation components and load profile of the BG design for Hospital 2. The li-ion battery used was CEGASA eBrick 280 which has a lifetime of 15 years/45,669 kWh throughput and a cost of 400 $/kWh with a replacement cost of 400 $/kWh. On the other hand, the Sunlight OPzV 185 model was used for the lead acid BESS which has a lifetime of 6 years/7,987 kWh throughput and a cost of 248 $/kWh with a replacement cost of 248 kWh. All costs consider the installation expenses and were taken from TTA’s cost database. Both batteries were sized to give the same autonomy as the optimized results for the BG design of Hospital 2. The simulation results were recorded in Table 16 below. Similar to the findings from the previously mentioned studies, the economics for the design implementing lead acid BESS are better, with an NPC almost 10,000 $ lower and a CAPEX of 46,207 $ less. Nevertheless, the O&M cost for the design using li-ion BESS is around 200 $/yr cheaper. As expected, the technical performance of the li-ion is superior. The genset is used 240 hours less and the batteries only need to be replaced once during the lifetime of the project when implementing li-ion technology while the Sunlight BESS would need to be changed twice over the same period. Thus, depending on the site’s location, the disposal cost can be extremely high which could considerably increase the NPC of the system using lead acid.

Table 16: Hospital 2 simulation comparison; with li-ion and with lead acid battery system

Battery type	**Li-ion, CEGASA eBrick 280**	**Lead acid, Sunlight OPzV 185**
Nominal Battery Capacity [kWh]	188	221
NPC [$]	530,147.0	520,171.0
LCOE [$/kWh]	0.416	0.409
CAPEX [$]	443,790	397,553
O&M [$/yr]	1,135.0	1,347.0

Battery type	**Li-ion, CEGASA eBrick 280**	**Lead acid, Sunlight OPzV 185**
Fuel Cost [$/yr]	7,995.0	10,002.0
Renewable Fraction [%]	91.0	88.7
Total Fuel [L/yr]	4,875	6,111
Excess Electricity [%]	37.2	37.5
Genset use [hr]	916	1,156
Battery Autonomy (hr)	11.4	11.3
Annual Battery Throughput [kWh/yr]	51,634	49,668
Usable Nominal Battery Capacity with average use [kWh]	179	177
Number of replacements during the project's lifetime	1	2

Even though the economics for the lead-acid BESS are better, li-ion BESS technology is recommended for the application of this project due to its longer lifetime, lower O&M, and its better performance. It is important to notice that this suggestion is done under the assumption that there are qualified local technicians to offer maintenance to the li-ion BESS and based on the fact that there are no safe ways for the disposal of large BESS at the districts where the projects are proposed.

Chapter 8

Conclusion

In this study, the analysis of the health and education facilities of Sierra Leone was presented along with the design proposal of four hybrid power generation systems aimed to show the technical and financing resources needed to electrify these facilities. As mentioned in Chapter 2, electricity plays a key role in the development of a country, helping to improve the health, education, gender equality, food security, and livelihood of the population. Sierra Leone has one of the lowest electricity access rates in the world with only 26% of its total population having this service available. The country has a poor grid infrastructure which creates a highly unreliable power supply with users experiencing constant power cuts. Only 23% of the health facilities in the country have access to an electricity source, mostly using diesel generators. Similarly, just 46% and 55% of junior and senior secondary schools have electricity, the main source being the national grid followed by diesel generators.

To create a realistic picture of the situation of the health and education facilities of Sierra Leone, ten health centres, ten secondary schools, and two hospitals were audited in order to collect information about their energy demand and needs. A methodology was created for the selection of the ten schools and ten health centres based on the general trends of the sectors found in national census reports and databases provided by the MoHS and the MBSSE. The sites were selected and audited through surveys and interviews with administrators and staff members of the facilities. The description and load profiles of the two hospitals (Hospital 1 and Hospital 2) were developed in Chapter 5. In the same section, an overall description as well as load profiles for the ten schools and ten health centres were created. These profiles represented the *Ideal* electricity consumption of each of the facilities which were estimated based on TTA's *Basic Electrical Equipment List* for schools and PHUs and literature. In Chapter 6 the general configuration for the simulations of a hybrid power generation system was explained, showing that the system will be comprised of a PV array, a battery storage bank, a bi-directional battery inverter, and a diesel generator. The technical and economic specifications and the assumptions made for all of these components were also defined in this section. Two different simulations were done for each of the four load profiles. One of them implemented the auto-size genset model (AG) of HOMER and the other one used a genset sized only as backup (BG). Before analysing the results, a list of KPIs was established to be LCOE, O&M cost, annual fuel cost, battery autonomy, and excess electricity produced by the system.

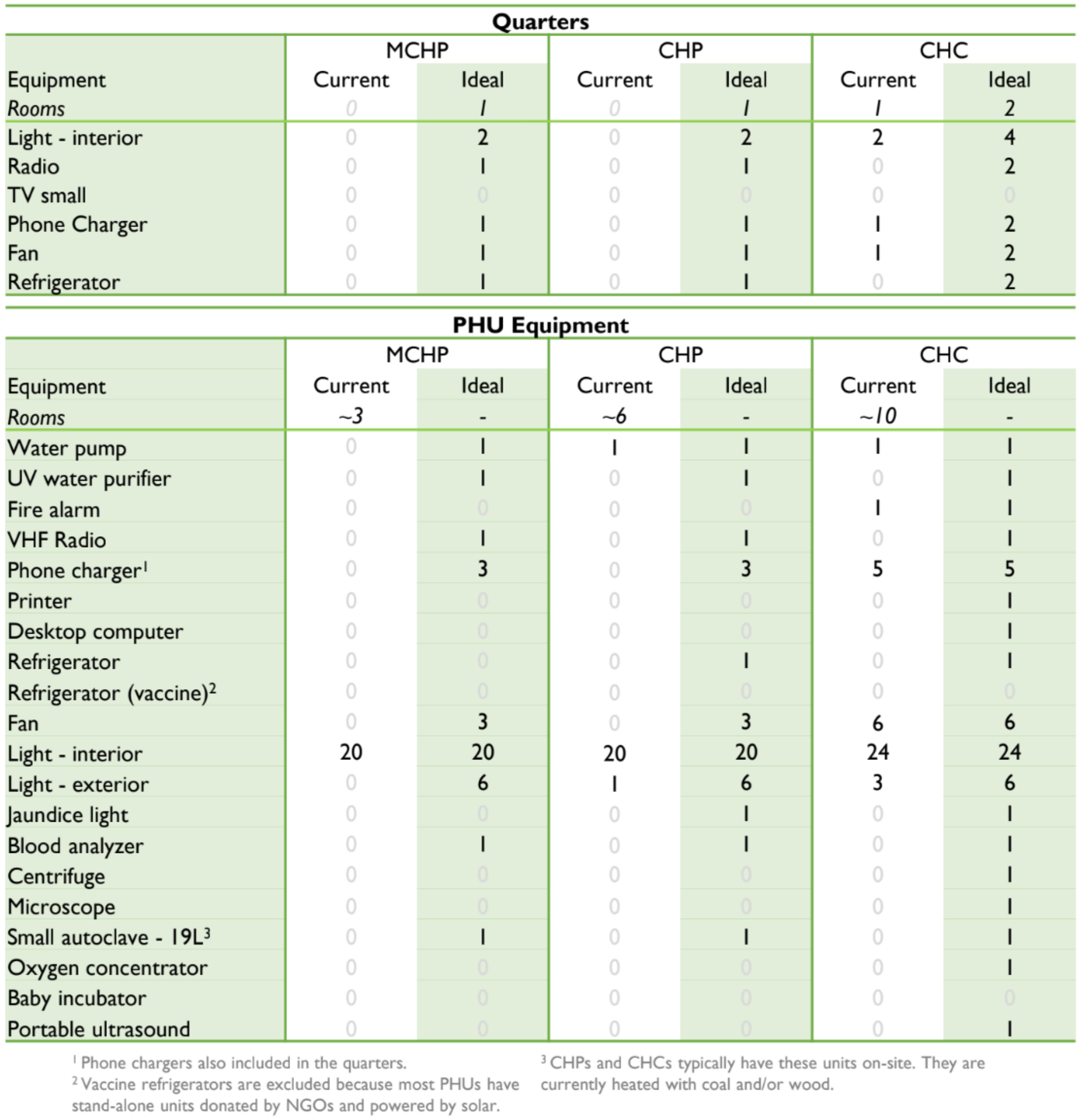
The results showed that for all of the sites the BG design was the most suitable, having the lowest O&M and the highest renewable fraction with only a slight increase in the LCOE that did not even reach a cent of a dollar. For all of the sites except Hospital 2, the cost of fuel was considerably lower for the BG design mainly due to the increase in battery autonomy and PV capacity. On the other hand, the AG design of Hospital 2 had a lower cost of fuel and a slightly higher battery autonomy. Nevertheless, the BG design was still the option that better fit the KPIs for Hospital 2. Currently, the visited facilities can barely power their critical loads but by implementing the BG design they will be able to fulfil 100% of their ideal electricity consumption, being able to power all the equipment they need to provide quality services. Even though in the scenario where all the case studies had access to all the diesel required to power their ideal electricity consumption, by installing the BG design Hospital 1, Hospital 2, School, and PHU would save up to 84%, 92%, 97%, and 96% only in annual fuel costs, respectively.

In addition to this, an analysis was conducted to prove that li-ion batteries would perform better for the off-grid application of this project. The configuration of the BG design for Hospital 2 was used as a base system and two real-life battery models (i.e., one of li-ion and one of lead acid) were used to simulate the system. The results showed that lead acid batteries are less capital-intensive with lower NPC and LCOE. Nevertheless, the lead acid BESS would need to be replaced twice over the lifetime of the project. In contrast, the system with li-ion batteries showed higher technical performance, only needing replacement once and showing a lower O&M and fuel cost. Since the safe disposal of batteries can be very costly and difficult in remote areas of Sierra Leone, it was concluded that the superior technical performance of systems with li-ion batteries such as their lower fuel consumption and higher renewable fraction would make them more suitable. This was recommended under the assumption that there are qualified technicians to perform the maintenance of the storage system and the fact that there are no safe solutions for the disposal of batteries in the districts where the projects are being proposed.

It is recommended for future work to consider subsidies within the economic calculations in order to show how these affect the LCOE of the systems. As well, an analysis of delivery models and tariffs for power generation systems aimed to electrify public infrastructure would give a better understanding of the effect that these projects can have on the economic and social development of a community. Furthermore, exploring the possibility of having these public institutions as energy centres from where a microgrid for the surrounding community can be developed could show opportunities to implement similar solutions with greater impact.

Appendix

Appendix 1: Basic Electrical Equipment List for PHUs



Quarters

	MCHP		CHP		CHC	
Equipment	Current	Ideal	Current	Ideal	Current	Ideal
Rooms	*0*	*1*	*0*	*1*	*1*	*2*
Light - interior	0	2	0	2	2	4
Radio	0	1	0	1	0	2
TV small	0	0	0	0	0	0
Phone Charger	0	1	0	1	1	2
Fan	0	1	0	1	1	2
Refrigerator	0	1	0	1	0	2

PHU Equipment

	MCHP		CHP		CHC	
Equipment	Current	Ideal	Current	Ideal	Current	Ideal
Rooms	*~3*	-	*~6*	-	*~10*	-
Water pump	0	1	1	1	1	1
UV water purifier	0	1	0	1	0	1
Fire alarm	0	0	0	0	1	1
VHF Radio	0	1	0	1	0	1
Phone charger[1]	0	3	0	3	5	5
Printer	0	0	0	0	0	1
Desktop computer	0	0	0	0	0	1
Refrigerator	0	0	0	1	0	1
Refrigerator (vaccine)[2]	0	0	0	0	0	0
Fan	0	3	0	3	6	6
Light - interior	20	20	20	20	24	24
Light - exterior	0	6	1	6	3	6
Jaundice light	0	0	0	1	0	1
Blood analyzer	0	1	0	1	0	1
Centrifuge	0	0	0	0	0	1
Microscope	0	0	0	0	0	1
Small autoclave - 19L[3]	0	1	0	1	0	1
Oxygen concentrator	0	0	0	0	0	1
Baby incubator	0	0	0	0	0	0
Portable ultrasound	0	0	0	0	0	1

[1] Phone chargers also included in the quarters.

[2] Vaccine refrigerators are excluded because most PHUs have stand-alone units donated by NGOs and powered by solar.

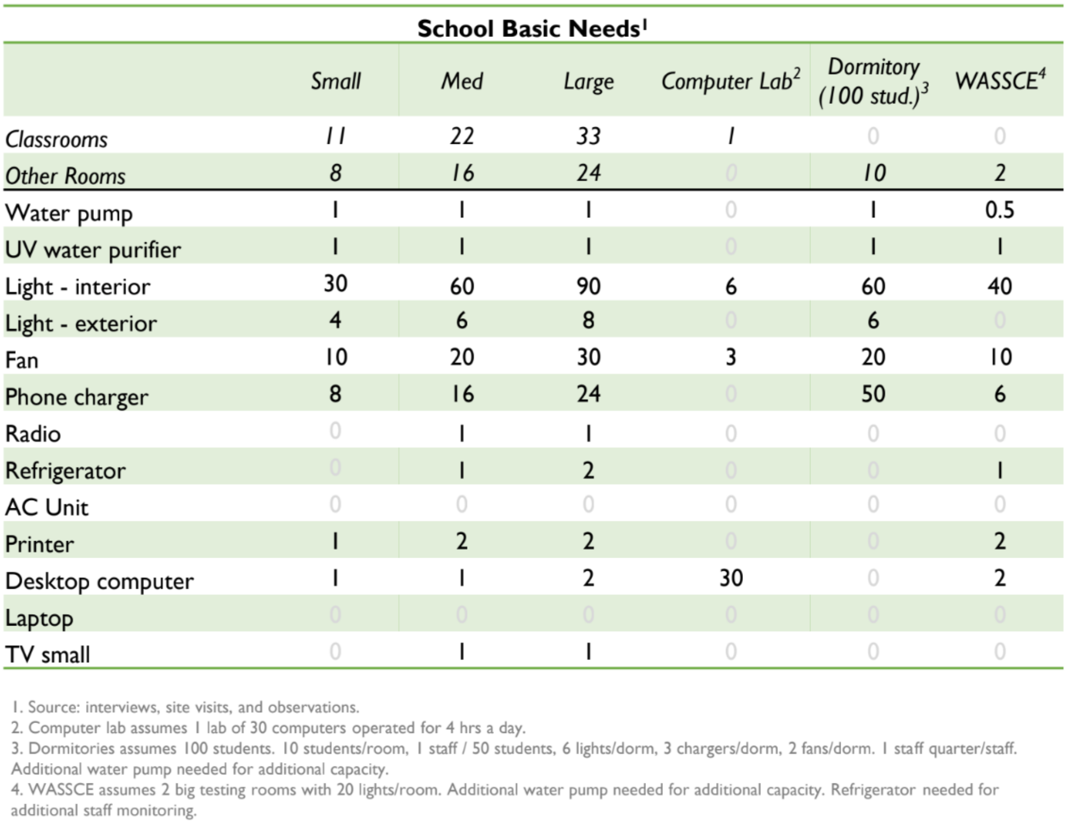
[3] CHPs and CHCs typically have these units on-site. They are currently heated with coal and/or wood.

Appendix 2: Basic Electrical Equipment List for PHUs - Usage Schedule

Time	1 hr	2 hr	3 hr	4 hr	5 hr	6 hr	7 hr	8 hr	9 hr	10 hr	11 hr	12 hr	13 hr	14 hr	15 hr	16 hr	17 hr	18 hr	19 hr	20 hr	21 hr	22 hr	23 hr	24 hr
Water pump										1.00		1.00		1.00		1.00								
UV water purifier											1.00		1.00		1.00		1.00							
Fire alarm	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
VHF Radio									1.00		1.00				1.00									
Phone charger								0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80					
Printer															0.50	0.50								
Desktop computer													0.50	0.50	0.50									
Refrigerator	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Refrigerator (vacccine)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Fan									0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60							
Light - interior	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Light - exterior	0.80	0.80	0.80	0.80	0.80	0.80														0.80	0.80	0.80	0.80	0.80
Jaundice light												0.50	0.50	0.50	0.50	0.50								
Blood analyzer									0.50		0.50	0.50				0.50								
Centrifuge										0.50					0.50									
Microscope										1.00	1.00	1.00	1.00	1.00	1.00									
Small autoclave - 19L															0.50	1.00								
Oxygen concentrator										0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75					
Baby incubator	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Portable ultrasound									1.00			1.00												

Time	1 hr	2 hr	3 hr	4 hr	5 hr	6 hr	7 hr	8 hr	9 hr	10 hr	11 hr	12 hr	13 hr	14 hr	15 hr	16 hr	17 hr	18 hr	19 hr	20 hr	21 hr	22 hr	23 hr	24 hr
Light - interior - quarter																			1.00	1.00	1.00	1.00	1.00	1.00
Radio - quarter							0.50	0.50	0.50										0.80	0.80				
TV small - quarter																				0.80	0.80	0.80	0.80	
Phone charger - quarter																			0.80	0.80	0.80			
Fan - quarter							1.00												0.60	0.60	0.60	0.60	0.60	
Refrigerator - quarter	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

Appendix 3: Basic Electrical Equipment List for Schools

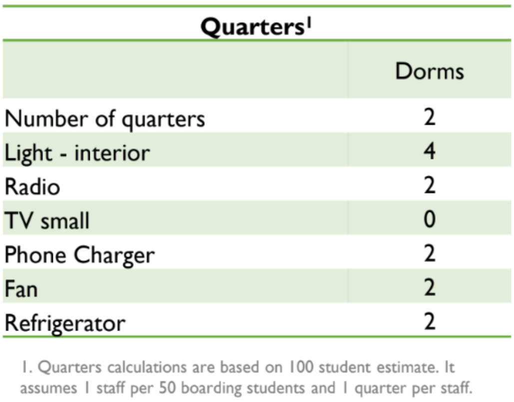


School Basic Needs[1]

	Small	*Med*	*Large*	*Computer Lab*[2]	*Dormitory (100 stud.)*[3]	*WASSCE*[4]
Classrooms	*11*	*22*	*33*	*1*	0	0
Other Rooms	*8*	*16*	*24*	0	*10*	2
Water pump	1	1	1	0	1	0.5
UV water purifier	1	1	1	0	1	1
Light - interior	30	60	90	6	60	40
Light - exterior	4	6	8	0	6	0
Fan	10	20	30	3	20	10
Phone charger	8	16	24	0	50	6
Radio	0	1	1	0	0	0
Refrigerator	0	1	2	0	0	1
AC Unit	0	0	0	0	0	0
Printer	1	2	2	0	0	2
Desktop computer	1	1	2	30	0	2
Laptop	0	0	0	0	0	0
TV small	0	1	1	0	0	0

1. Source: interviews, site visits, and observations.
2. Computer lab assumes 1 lab of 30 computers operated for 4 hrs a day.
3. Dormitories assumes 100 students. 10 students/room, 1 staff / 50 students, 6 lights/dorm, 3 chargers/dorm, 2 fans/dorm. 1 staff quarter/staff. Additional water pump needed for additional capacity.
4. WASSCE assumes 2 big testing rooms with 20 lights/room. Additional water pump needed for additional capacity. Refrigerator needed for additional staff monitoring.

Appendix 4: Basic Electrical Equipment List for Schools' Student Dorms



Quarters[1]

	Dorms
Number of quarters	2
Light - interior	4
Radio	2
TV small	0
Phone Charger	2
Fan	2
Refrigerator	2

1. Quarters calculations are based on 100 student estimate. It assumes 1 staff per 50 boarding students and 1 quarter per staff.

Appendix 5:Basic Electrical Equipment List for Schools- Usage Schedule

School Equipment - 1 shift

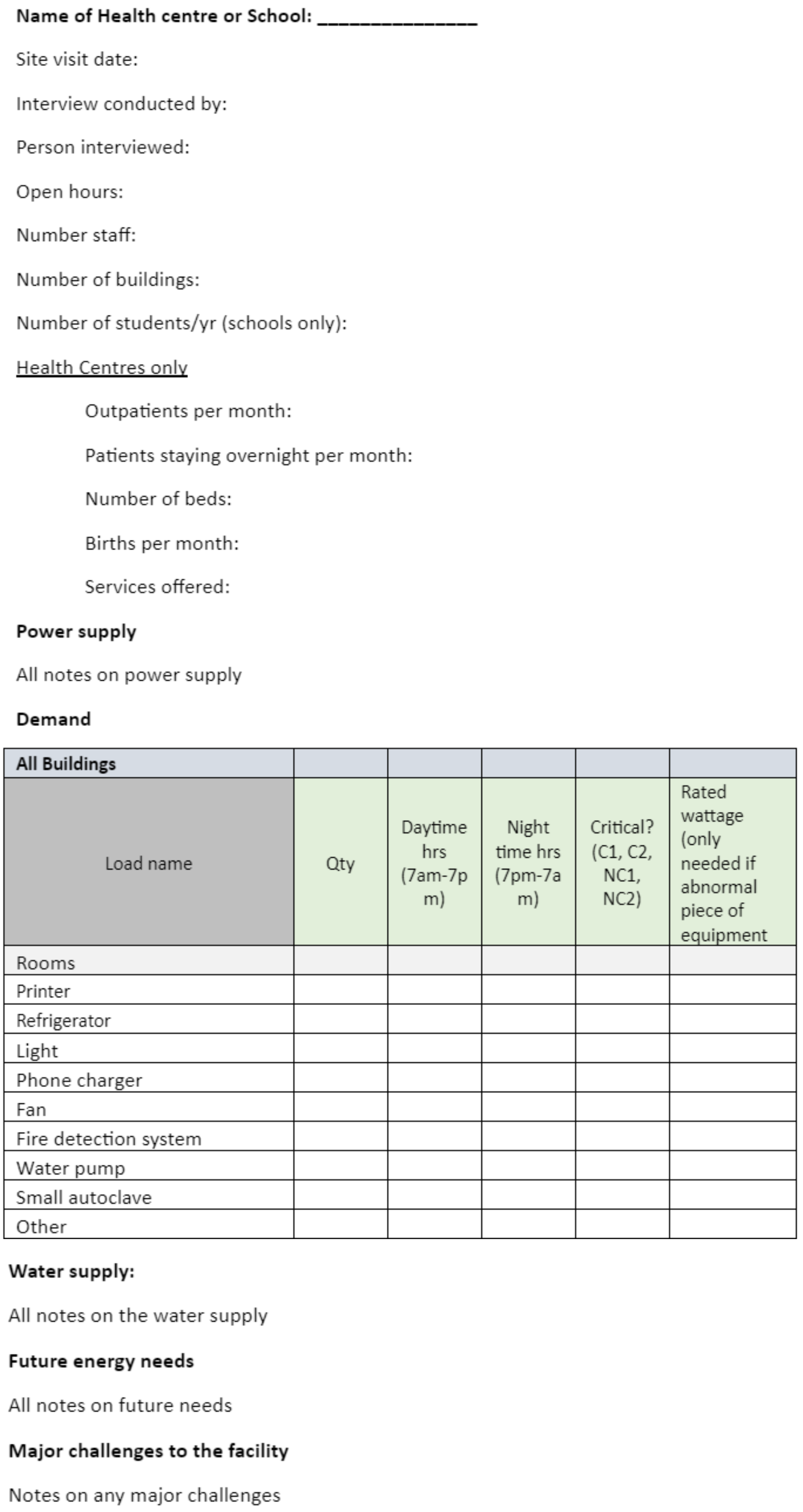
	Daytime (8am-2pm) 6 hrs	Nightime (2pm-8am) 18 hrs	Total Hrs
Water pump	2	0	2
UV water purifier	2	0	2
Light - interior	2	1	3
Light - exterior	0	12	12
Fire alarm	3	9	12
Phone charger	3	0	3
Radio	2	0	2
Refrigerator	3	9	12
AC Unit	3	2	5
Printer	1.5	1	2.5
Desktop computer	4	2	6
Laptop	3	3	6
TV small	3	2	5
Desktop computer - lab	4	0	4
Fan	2	0	2

Appendix 6: Basic Electrical Equipment List for Schools' Dorms - Usage Schedule

Quarters

	Daytime (8am-2pm) 6 hrs	Nightime (2pm-8am) 18 hrs	Total Hrs
Light - interior - quarter	0	6	6
Radio - quarter	0	3	3
TV small - quarter	0	3	3
Phone charger - quarter	0	2.5	2.5
Fan - quarter	0	4	4
Refrigerator - quarter	3	9	12

Appendix 7: Energy audit survey questions



Name of Health centre or School: _______________

Site visit date:

Interview conducted by:

Person interviewed:

Open hours:

Number staff:

Number of buildings:

Number of students/yr (schools only):

<u>Health Centres only</u>

Outpatients per month:

Patients staying overnight per month:

Number of beds:

Births per month:

Services offered:

Power supply

All notes on power supply

Demand

All Buildings					
Load name	Qty	Daytime hrs (7am-7pm)	Night time hrs (7pm-7am)	Critical? (C1, C2, NC1, NC2)	Rated wattage (only needed if abnormal piece of equipment
Rooms					
Printer					
Refrigerator					
Light					
Phone charger					
Fan					
Fire detection system					
Water pump					
Small autoclave					
Other					

Water supply:

All notes on the water supply

Future energy needs

All notes on future needs

Major challenges to the facility

Notes on any major challenges

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