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

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Abstract—**Access to modern electricity 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.

I. INTRODUCTION

In 2020 the World Bank estimated that 9.5% of the global population does not have access to modern electricity. These are 770 million people lacking the service, with 571 million living in sub-Saharan Africa [1]. Only 28% of health facilities in this region have access to electricity. Likewise, in 2016 just 49.3% and 57.1% of lower and upper secondary schools had this service available [2]. Following the same trend, in Sierra Leone, only 26% of the population has access to electricity with more than half of education and health facilities not having any type of power source.

The goal of this study is to create standard solutions for the electrification of hospitals, health centres, and secondary schools in Sierra Leone by designing hybrid stand-alone power systems catered specifically to these facilities. To achieve this, several facilities were audited in order to collect information about their energy needs to then be used as inputs for the power generation system simulations in HOMER.

II. ENERGY ACCESS AND PUBLIC INSTITUTIONS

The lack of energy affects a wide range of development indicators such as health, education, food security, gender equality, livelihood, and poverty reduction [3]. 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 [4]. In 2019, 90% of the global population had access to electricity, a 7% increase since 2010 [5] 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 achieving universal electricity access, but they must be supported by an enabling environment containing pertinent policies, institutions, strategic planning, regulations, and incentives [3].

A. *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 World Health Organization (WHO) estimates that only 28% of health facilities in 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 [2].

1) *Education:* The lack of electricity in schools prevents them from providing services such as early-morning or night classes, the introduction of information and communication technologies (ICTs) into the classrooms and the recruitment and retention of better-qualified teachers. Several studies have even related electrified schools o better test scores and graduation rates [2], [6], [7]. 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) *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 [8]. Lighting allows workers to conduct deliveries more safely, extend the operational hours of the facility and provide 24h emergency services. 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 and improving sanitation, especially in rural areas. It also allows the integration of e-health[1] and ICT, improving staff performance and the operation of the facility. Despite the many advantages, there are still tens of thousands of health centres that do not have access to electricity. These facilities are characterized by low energy demand so 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 [8].

III. AVAILABLE TECHNOLOGY AND FINANCIAL APPROACHES FOR ELECTRIFICATION

A. *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 [3]. 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.

B. *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 [9]. 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 need to be considered when designing the business model for a specific installation.

IV. SIERRA LEONE ENERGY PROFILE

Sierra Leone is located in the northwest 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 [10]. The country is divided into fourteen districts as shown in the map below. 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.

Figure 1 Map of Sierra Leone

A. *Energy Landscape*

It was estimated that the country had a rural electrification rate of only 4.8% in 2020 [10]. 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 [11].

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. From the electricity generated, 219 GWh (71%) comes from hydropower, 80 GWh (26%) is produced with oil, 6 GWh (2%) is from solar with only 4 GWh (1%) coming from bioenergy. According to Sierra Leone's Ministry of Energy and Water Resources (MEWR), approximately 1,460-1,800 kWh/m^2 of solar radiation can be expected annually in the country [12]. Similarly, there is a large potential of 2 GW for hydropower and 2.7 GWh for biomass according to the German Federal Ministry for Economic Affairs and Energy.

B. *Health Sector*

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[1] *healthcare practices supported by electronic processes such as electronic health records, telemedicine, clinical decision-supported system, etc.*

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 [13].

The health facilities in the country are divided into the following categories, also called *tiers*, depending on the services provided.

Primary Health Facilities - Peripheral Health Units (PHUs)

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; Offers maternal care, routine deliveries, immediate postnatal, and neonatal care; Routine vaccination, treatment of childhood illnesses and malnutrition; Basic first aid; Community outreach services.
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

4) *Regional Hospital:* Reginal headquarters, affiliate with Regional Hub; Comprehensive emergency obstetric and neonatal care; Speciality and referral services; Additional diagnostic imaging services; Treatment of cancers and rare diseases.
5) *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 all the facilities, 84% have sanitation amenities, 57% have an improved water source, and only 23% have a power source, this being mainly diesel generators [14]. The health facility density is only 1.8 per 10,000 population which is below the national target of 2. On the other hand, the shortage of beds is even more severe, having less than 15 beds per 10,000 population as a national average when WHO recommendation is 25.

C. *Education Sector*

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 [15].

The country's education system is segmented as follows:

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

In 2020 there were 11,168 registered schools of 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 [15]. In terms of infrastructure, 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.

V. SELECTION AND DESCRIPTION OF THE CASE STUDIES

A. *Case Study Selection Criteria*

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.

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[1] *healthcare practices supported by electronic processes such as electronic health records, telemedicine, clinical decision-supported system, etc.*

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).

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 a s electrification status and water supply are not available for the individual facilities. 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. 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

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[2], and accessibility. Since more information was available, an in-depth study of the general trends of secondary schools was done in order to create criteria that would allow the selection of a representative sample for the study. First, several filters were applied such as all the selected schools must be "Approved", all must teach boys and girls (i.e., Co-ed), and all must be located in different districts. After this, the size of the schools was defined based on the number of students. Finally, other characteristics such as type of electricity supply, ownership and water supply were distributed among the ten sites that needed to be selected following the trends of the country. The resultant selection criteria were summarized in the table 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

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
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

B. *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 [16]. The result was a list of around 14 questions, varying depending on if the facility was a hospital, a school, or a PHU.

To assess how well-equipped the facilities were, a database provided by TTA was used. *The Basic Electrical Equipment List* 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 based on TTA’s experience, interviews with experts and publicly available guidelines such as [17], [18] and [19].

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.

1) *Hospital 1- Western Area:* This site is composed of two hospitals that are next to each other, Hospital A and Hospital B, within an area of 15,000 m^2. Between the two facilities, they assist more than 2,400 patients per month, having around 300 beds. 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 is connected to the EDSA grid which is highly unreliable. It was estimated there is a blackout almost daily, normally lasting 2-6 hours, and several shorter interruptions throughout the day. 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 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. 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 2 as the *Ideal* load profile for Hospital 1.

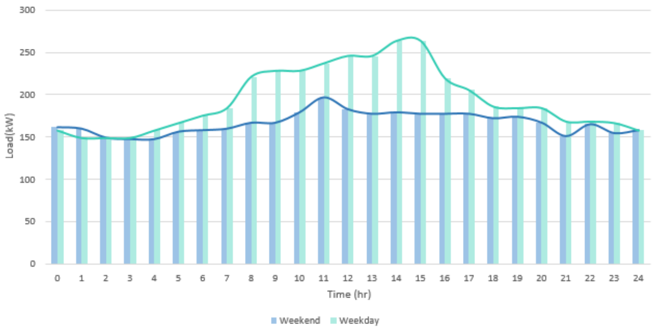

Figure 2: Ideal load profile of Hospital 1

2) *Hospital 2 – Northern Area*: The facility treats approximately 140 outpatients per day and 70 to 75 in-patients per month having a bed capacity of 174. The facility spreads over an 80,000 m^2 area with its electricity system being completely off-grid. Its electricity supply consists of 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. Currently, the facility 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 the critical loads with 150 L/day of fuel paid with financial aid provided by the Government and an NGO. 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. The load profile seen below was built using scaled values based on load data from a Sierra Leone hospital, HOMER’s Powering Health Tool [20], and the interviews with the Hospital’s administration and staff. 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.

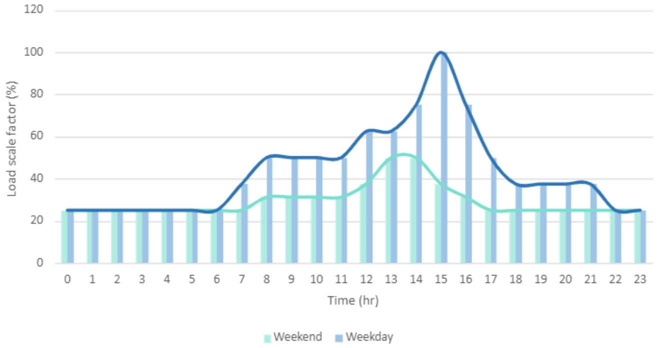

Figure 3: Ideal load profile for Hospital 2

3) *Peripheral Health Units (PHUs):* Ten PHUs were chosen to be audited. 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*. 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, three PHUs were connected to microgrids which provided electricity for a few hours each day. Several PHUs have broken energy generation systems and water pumps having no access to technicians or budget to repair them. Five of the sites show no water supply as they rely on the local community wells/boreholes and must collect the water and transport it manually while other facilities must resource to other water sources during the dry season.

Approximations of the current electricity consumption of the PHUs were done based on the electrical equipment list and usage schedules that each facility provided. 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 TTA's *Basic Electrical Equipment List* for PHUs showing the loads that would be expected if the sites had access to all the equipment and the electricity they required. This *Ideal* load profile can be seen in the figure below.

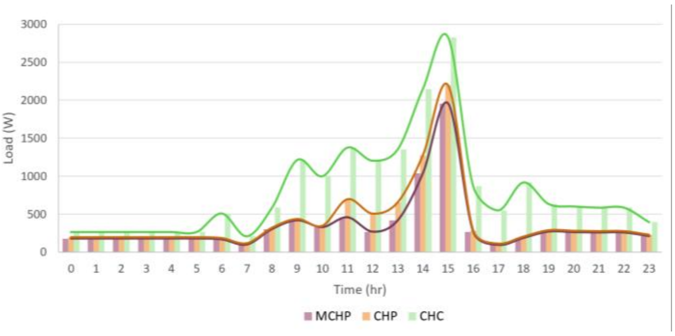

Figure 4: Ideal Load profile for all PHU tiers

4) *Secondary Schools:* Ten approved/co-ed/ secondary schools were chosen to be audited in order to collect data about their energy needs. The information found during the visits 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.

The data collected from the visited secondary schools showed that they had virtually no loads or they were considerably low 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. 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 TTA's *Basic Electrical Equipment List* for schools 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. To account for the high impact that computer labs and student dorms have on the energy requirements of a school, these loads were calculated separately and added to the load profile as seen in the figure below.

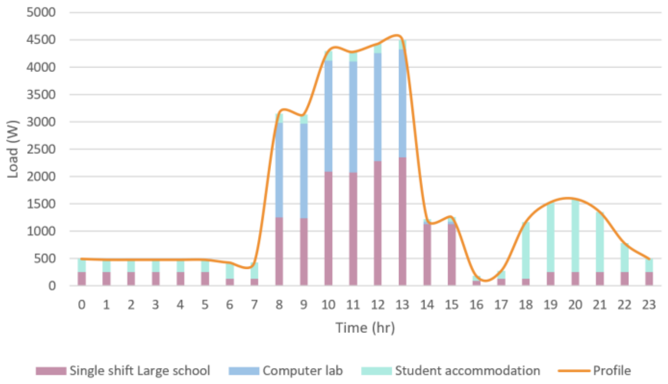

Figure 5: Ideal load profile for a Large single shift school with a computer lab and student accommodation

VI. DESIGN AND SIMULATION OF THE ENERGY SYSTEMS

The general configuration used for the hybrid power generation system can be seen in the figure below. 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 on 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 the fluctuations in the costs of diesel and would help decrease greenhouse gas emissions.

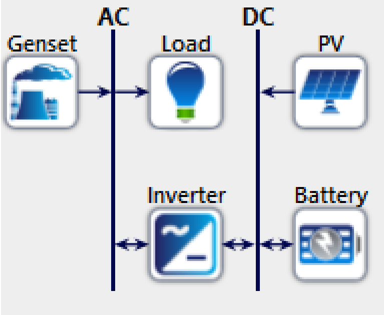

Figure 6 General configuration for the hybrid power generation systems

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 optimization output is based on the least expensive system calculated through the system's net present cost (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.

A. Load Profile

The load profiles used for the simulations were the ones presented in Chapter V. 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.

B. 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 of each of the sites in Sierra Leone were used as they affect the performance of the PV system.

C. Hybrid Power Generation System

1) *Grid*: the Sierra Leone national grid was simulated using the Schedule rates mode[3] offered by HOMER. The unreliability of the grid was also simulated by adding random power interruptions throughout the day.
2) *Solar PV Module*: 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 was set to the optimal angle for the specific location according to the Global Solar Atlas website.
3) *Diesel Generator*: two simulations for each of the case studies were done using two different approaches for the size of the 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 this project 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.

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 fuel. The battery model used for all simulations was the Generic Li-ion model offered in HOMER's library.
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. For the sizing of this component, a security factor of 30% over the value of the peak load was added to prevent overloading and consequently, failure of this component.
6) *System Controller*: HOMER offers the "Load Following" strategy for controlling the simulated power generation system. This consist of, 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. This strategy was chosen to be able to prioritise and maximize the use of RE. The controller intalled cost was 360 $ and has a lifetime of 25 years.

D. Economics

In the three tables presented below the general economic parameters used for the simulations are shown as well as the specific costs for each of the used components. All these values were taken from TTA's cost database developed specifically for Sierra Leone.

Table 4 Inputs for general economic parameters

Economic parameter	Input
Nominal (annual) discount rate [%]	12
Expected inflation rate [%]	5
Project Lifetime [yr]	15
Fuel cost [$/L]	1.64

Table 5 Inputs for fixed costs

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

Table 6 Inputs for components costs

Model	PV	Genset	Li-ion Battery	Battery Inverter
CAPEX [$/kW]	830	250	450 $/kWh	790
Replacement [$/kW]	830	250	360 $/kWh	790
O&M	7.5 $/kWh	0.03 $/hr	2.0 $/kWh	-
Lifetime [yr]	20	15	$10_{\text{3,000 throughput}}$	15

E. 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 Chapter II 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 installation 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 project. 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.

VII. RESULTS AND ANALYSIS

A. 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 HOMER optimizer gives results based on the less expensive option, meaning the system with the lowest NPC and LCOE.

Table 7 HOMER optimization results for all sites

Case Study		Hospital 1		Hospital 2		School		PHU	
Simulation Design		(AG)	(BG	(AG)	(BG)	(AG)	(BG)	(AG)	(BG)
Configuration	Average load [kWh/day]	3,257.1		375		37.4		19.2	
	Peal 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	149.0	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

	Battery Nominal Capacity [kWh]	24	872	208	200	16	40	8	16
	Converter [kW]	350	350	95	95	10	10	5	5
Economics	NPC [$]	2,778,386	3,021,958	584,983	575,528	54,392	61,323	34,917	36,397
	LCOE [$/kWh]	**0.25**	**0.27**	**0.46**	**0.45**	**0.43**	**0.48**	**0.54**	**0.56**
	CAPEX [$]	1,019,750	1,654,738	499,493	484,142	37,583	47,372	22,268	25,630
	Fuel cost [$/yr]	**42,293.02**	**8,384.01**	**5,565.10**	**9,298.20**	**732.80**	**154.00**	**424.14**	**140.15**
	O&M [$/yr]	**151,494.90**	**135,591.70**	**2,655.43**	**2,632.25**	**1,063.57**	**1,021.10**	**928.52**	**903.09**
Performance	Renewable Fraction [%]	41.0	52.3	93.9	93.2	92.7	98.2	91.7	96.7
	Total fuel [L/yr]	25,788.4	5,112.2	3,393.4	3,675.2	446.8	93.8	258.6	85.5
	Excess electricity [%]	17.6	33.1	44.6	42.3	46.7	44.0	41.8	42.2
	Genset use [hrs]	837	343	461	689	530	200	603	469
	Battery Autonomy at average load [hr]	**0.17**	**6.10**	**12.65**	**12.20**	**9.76**	**24.40**	**9.52**	**19.03**
	Grid Purchased energy [kWh]	613,950.70	550,535.20	-	-	-	-	-	-

B. *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.

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 281.6 L/yr more than the AG configuration but the O&M cost is still slightly less. The excess electricity production of the BG design is 42.3% which is 2.3% less than that of AG which shows that the BG configuration performs marginally more efficiently even though its component has lower capacities. The battery autonomy is just 0.45hr 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 rainy 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 buying fuel to run the genset at its minimum capacity. Therefore, if the hospital applies load shedding techniques during the rainy 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 size better aligned with the demand.

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.

1) *Battery Considerations*: previously, 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 [21]. This was done to prevent HOMER from oversizing the battery system due to only a few days of the year when the PV electricity generation is low. The system performance of the BG design of School showed 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.

   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 these 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. Thus, 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. 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. 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 can be seen in Table 8. 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 8 Hospital 2 simulation comparison; with li-ion and with lead acid BESS

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
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

VIII. CONCLUSION

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 demand, 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, the results of the simulations conducted to prove that li-ion batteries would perform better than lead acid batteries for the off-grid application of this project 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 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.

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