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Design and Modeling of a Standalone DC-Microgrid for Off-Grid Schools in Rural Areas of Developing Countries

Yohannes Biru Aemro [1,2,*], **Pedro Moura** [2] and **Aníbal T. de Almeida** [2]

[1] Energy for Sustainability Initiative, MIT-Portugal Program, University of Coimbra, 3030-290 Coimbra, Portugal
[2] Institute of Systems and Robotics, Department of Electrical and Computer Engineering, University of Coimbra, 3030-290 Coimbra, Portugal; pmoura@isr.uc.pt (P.M.); adealmeida@isr.uc.pt (A.T.d.A.)
* Correspondence: yohannes.aemro@isr.uc.pt

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Abstract: Energy access is critical for health, education and social welfare improvements. In countries like Ethiopia, with a low electrification rate and with the majority of the population located in rural areas, about 76% of primary schools do not have access to electricity. This limits the hours of classes and does not allow the use of basic or modern teaching resources. Off-grid solutions have emerged as potential cost-effective alternatives to electrify rural areas and schools, but the availability of off-grid appliances and the size of the system can lead to different solutions. Therefore, this study proposes a DC microgrid system to supply the electricity demand of a rural school located in Ethiopia, considering load estimation scenarios with standard and high-efficiency appliances. The simulation results show that the designed DC microgrid is a valid option to electrify the rural school under each load and generation scenarios. The system costs were also evaluated, and the high-efficiency appliances option has a 51% lower cost. The study also applies to other sub-Saharan countries in the region with very low energy access rates and abundant solar energy, thus giving a large contribution to achieve the United Nations Sustainable Development Education Goal 4 (SDG 4).

Keywords: energy access; DC microgrid; solar photovoltaic (PV); battery storage system; off-grid efficient appliances; school energy; UN2030 agenda for sustainable development

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1. Introduction

1.1. Motivation

The socio-economic development of any nation and its inhabitants depends on the availability of cost-effective energy supply systems to ensure the required demand [1]. However, the access to energy services in the developing world presents a low rate [2], which is aggravated by high transmission and distribution costs, weak infrastructure, poor operating and maintenance performance [3], high greenhouse gas emissions and its associated environmental and health impacts, as well as lack of capital [4]. The impact of these problems on the balance between energy supply and demand in developing countries is huge, leading to poor living standards and a lack of human development [5].

Currently, about 771 million people do not have access to electricity, with the majority of them located in rural and remote areas of developing countries [2]. Due to the remoteness and geographical location (usually far from the grid) of the rural and remote areas, connecting with the grid is expensive and difficult to achieve [6]. The huge investment needed to connect with the grid, as well as the economic condition of developing countries and their inhabitants makes the problem more challenging [7].

Therefore, alternative power systems such as microgrids are proposed by policymakers, researchers, governments and utility companies to supply the energy services demanded by the population sector located in rural and remote areas [8].

Many developing countries set plans for energy access and sustainable energy development [4], being one of the options the deployment of renewable energy resources into the grid ensuring a reduction of greenhouse gas (GHG) emissions, improving the power stability and reliability, and reducing operation and maintenance costs [9]. Therefore, electricity access has been improving mainly due to the deployment of distributed renewable energy resources [2] in locations without previous generation sources or access to the main grid [10]. However, there are still many people living without access to electricity in sub-Saharan African countries, South Asia and Latin America [11], which requires efficient systems to supply reliable and affordable energy services. On the other hand, due to the lack of electricity access, the level of services such as education, health, and clean water is much lower than in urban areas [12].

Worldwide, nearly 660 million children are enrolled in primary schools and about 188 million children (about one third) attend primary schools that do not have electricity access. Data suggests that in sub-Saharan Africa approximately 90% of children go to primary schools without electricity [13]. To address energy access problems in rural areas of developing countries, mini-grids/microgrids, and mainly DC microgrids are becoming one of the most efficient and reliable solutions [14] to solve the energy access problems in rural schools. Due to the absence of reactive power in DC distribution lines and the reduction of conversion steps, DC-microgrids can be more advantageous than AC-microgrids in terms of reduction of losses and voltage drops and can increase the capacity of the electrical lines. Additionally, the development of DC-based household and office appliances, as well as the fact that energy storage and renewable generation technologies are directly compatible with DC microgrids, facilitates the introduction of DC microgrids. Therefore, planning, implementation and operation can be simpler and cheaper with DC-microgrids than AC-microgrids [15–17]. The advantages of DC microgrids over AC microgrids are the main criteria to focus this study on DC-microgrids for rural school applications. Furthermore, the development of a draft standard for DC-microgrids for rural and remote electricity access applications from different perspectives including design, operation and maintenance, market needs, technical aspects and testing procedures [18]. This standard development will make DC microgrids more effective and efficient, as well as a widely accepted system for rural electrification and to electrify rural schools, health centers and other service centers than the conventional microgrid system.

In Ethiopia (the second-most populous country in sub-Saharan African), above 80% of the population is living in rural and remote areas [19] and 76% of the primary schools do not have access to electricity [20]. Access to electricity in schools is crucial to improve the quality of schools by providing electricity for electricity-dependent materials and equipment, by increasing teacher quantity and improving the quality of training [21]. On the other hand, electricity access increases teaching hours by allowing to have class in the early morning and late afternoon when the rooms do not have access to natural light [13]. It is also important to ensure make-up classes in places that do not have enough staff to cover the courses with the available teachers. For example, in Kenya, electricity access gives the possibility for teachers to give make-up classes in the early morning and late evenings for courses that are not covered in normal teaching hours due to lack of teachers [22].

Furthermore, electrifying schools is important to attract teaching staff in quantity and quality. In most rural areas, attracting quality teaching staff is a great concern due to electricity access in the school as well as in the surrounding. A study in Ghana presents that teacher's living condition including having electricity access in their house affects the morale and absenteeism of teachers [20]. In Tanzania, Mara region (a rural area), teachers housed in the school with no access to electricity even to charge their mobile phones, implying that the lack of qualified teachers is attributed to lack of energy services in remote locations [23]. Additionally, a microgrid deployed in a school can give multiple benefits to the nearby community. It can promote healthcare services, pump and purify water for drinking, sanitation, reducing rural/urban migration, prepare and preserve food and medical supplies, as well as air conditioning [24]. For instance, in Brazil and Kenya, electrification of schools, solve water and sanitation issues, which in turn may help to reduce absenteeism and even aid the wider community [25]. This paper presents and proposes the model, design, and simulation of a DC microgrid system using MATLAB/Simulink (developed by Mathworks, Massachusetts, United States) composed of solar energy and battery storage for a rural school located in Ethiopia, considering different generation and load scenarios by considering the use of standard and high-efficiency appliances.

1.2. Related Works

There are plenty of studies proposing microgrids for rural electrification applications in developing countries. For example, authors in [26] discussed the past and current practices to improve energy access, as well as promoting rural electrification using microgrids in China, India, The Philippines, Africa, and North America. On the other hand, as per [27], different kinds of microgrids such as AC, AC/DC or DC are studied for rural electrification applications. Authors in [28] presented the reliability, economic and environmental analysis of a microgrid composed of diesel generator, PV system, wind and battery.

In another study authors in Ref. [29] assessed the model and management of a smart microgrid model consisting of a solar photovoltaic array, battery energy storage and a diesel generator for rural electrification in Nigeria. On the other hand, DC microgrids are also studied for rural electrification applications. For instance, authors in Ref. [30] assessed a DC microgrid consisting of solar PV, wind power and a battery for rural communities in Ruksibhanjyang village, Mityal, Nepal. The study used Hybrid Optimization of Multiple Energy Resources (HOMER) developed by HOMER Energy LLC, Boulder, CO, USA and MATLAB-Simulink for the design and modeling of the proposed DC microgrid.

In Ref. [31] the authors also presented the design and model of DC microgrid consisting of solar PV and battery banks for residential buildings. The authors considered distributed and centralized DC microgrids to supply loads of the five houses with a centralized battery bank system. For the case of the distributed systems, the DC microgrid is designed to supply loads of the houses independently which is the houses have rooftop mounted solar PV and battery bank. In the case of the centralized system, the centralized battery bank system is responsible for the demand when there is a shortage of power generation and to store the power when there is surplus generation. The authors in Ref. [32,33] also presented the design and analysis of DC microgrids for rural electrification.

Furthermore, in Ref. [34] the school electricity need was assessed and the design requirements for an AC/DC hybrid system and AC microgrid composed of a solar PV and battery storage system for a microgrid in a rural area of Malawi were presented. These literature case-studies indicate that microgrids with several renewable energy sources are studied widely for rural electrification applications. However, there are still questions that should be addressed on the selection of off-grid systems and options for rural school applications due to the diversity of off-grid technologies and systems, as well as the variability of renewable energy sources and variety of commercially available appliances. Furthermore, this study addresses the large impact of high-efficient DC appliances on the system's overall feasibility and performance, as well as on the sizing of off-grid solutions, which is a limitation in other previous studies.

1.3. Contribution

Due to the reliability of available renewable energy sources throughout the year and the commercial availability of different appliances, there are still ambiguities on off-grid system preferences, as well as on the selection of appliances with different efficiency levels for diverse applications, as well as on the system sizing. On the other hand, there is also limited literature on the electrification of off-grid schools. To address this knowledge gap and contribute to the literature in the area of the energy supply system of off-grid schools, this paper proposes the design and modeling of a DC-microgrid for off-grid schools' application, based on different load estimation and generation scenarios. The main objective of this paper is to design and model a standalone DC microgrid composed of a solar PV system, system controller and battery storage system using MATLAB/Simulink for rural off-grid energy-efficient school applications. In many studies [35,36] of off-grid solutions for rural energy access HOMER and other mathematical models are used as design and optimization tools. In this study, MATLAB/Simulink is used due to its higher flexibility compared with HOMER. It has the advantage of to easily modify the system and optimization rules depending on the analysis outputs and optimizations needs, whereas in HOMER it is not possible to change the design and the model except the inputs such as load demand and energy sources, as well as optimal cost for each energy sources. On the other hand, the chosen modeling and optimization tool for this study allows the assessment of data, development of algorithms, build and deployed models. Furthermore, it has also the potential to integrate the system with the grid with some modification of the layout or expand the system to electrify the community by increasing the PV size and the battery storage system size.

A case study for a rural primary school in Ethiopia is considered and one main innovation of the study is the consideration of high-efficiency DC appliances and comparing them with the standard efficiency appliances, the associated load estimations, as well as considering the variability of renewable generation. The load estimation scenarios are based on standard efficiency (appliances widely available in the market) and high-efficient appliances (emerging off-grid appliances with high efficiency compared with the standard appliances available in the market) necessary for the school. The appliances are categorized as high and standard efficiency based on the data platform for off-grid appliances developed by the Efficiency for Access Coalition [37], which compared the efficiency of different appliances by grouping the standard efficient appliances as a baseline, which are widely available in the market, and the emerging off-grid appliances with efficiency, quality, durability improvements as high-efficiency appliances. For instance, for table fans, the high-efficiency group has efficiency up to four times the volume of air per minute per Watt of input power compared to the standard efficiency fans [38,39]. Whereas the generation scenarios consider the maximum and minimum solar generation months in the year, which is very critical for the sizing of the proposed off-grid system. Moreover, the efficiency of appliances and variability of generation is vital to the system sizing, in order to avoid oversizing the proposed DC microgrid, with the consequent higher system cost (solar PV, battery and controllers). On the other hand, oversizing also requires larger areas for installation and implementation of the system, which could be a problem in areas where space is limited. Therefore, analyzing the impact of appliances with different efficiency levels is one important aspect that should be addressed in the design and development of off-grid systems which is one of the many objectives of this study. Furthermore, by assessing the cost of the appliances and the overall system cost, the study aims to present the economic feasibility of the proposed off-grid system for rural school applications in developing countries.

1.4. Background Data and Load Estimation

1.4.1. School Data

Gomenege Primary School is a government-owned primary school located in Tachi-Gayint Worda, Amhara Region, Ethiopia with coordinates 11°38′20.4″ N 38°25′13.5″ E. Figure 1 presents the rural primary school with primary school children's in the class attending courses and Gomenege primary school location on the map. The school has more than 450 students, from grade 1 up to 8 with two shifts, one from 8 h to 13 h and the other from 13 h to 18 h. Sometimes, there are also classes from 18 h to 20 h. The school has 8 classrooms, one director's office, two staff offices, and one office for security. There is a great interest to perform the teaching-learning process through electronic media such as TVs, radio and basic computer skills classes and computer-aided course deliveries. Therefore, to improve the education system based on the global standard of primary schools, a DC microgrid system is proposed.

(**a**) (**b**)

Figure 1. Rural primary school with primary school students in the classroom located in Ethiopia: (**a**) Rural primary school in Ethiopia; (**b**) Gomenege Primary School location.

1.4.2. Load Estimation

Load estimation is a crucial part of designing any kind of power system. In particular, it is important for off-grid distributed renewable energy systems, such as DC microgrids, due to the intermittency of renewable energy resources. On the other hand, the type of used appliances also determines the required load, and therefore the microgrid sizing and associated costs. For this study, the load was estimated using two scenarios, a first scenario using standard appliances and a second using high-efficiency appliances.

The common loads in most primary schools are lighting, computers, wireless internet, printers, photocopy machines, radio, table fans and ceiling fans (in hot seasons of the year), and mobile chargers. Table 1 presents the load estimation of the school considering appliances with standard efficiency and Table 2 presents the load estimation of the school considering high efficient appliances, as compared to the appliances listed in Table 1.

The load estimation was done taking into account three computers in each of the staff offices and one computer in the director's office, two lighting lamps in each classroom, one printer and one copy machine in the director's office, three lamps in the compound of the school outside the classrooms, one lamp in each director and security office, four table fans in each office (director, staff, and security), one ceiling fan for each class. Based on the classroom and office sizes, the type of lamps with its power capacity was selected, for instance, the size of classrooms is much larger than the size of offices requiring lamps with higher power capacity. In the case of mobile charging, radio receiver and GSM wireless telecommunication the same power capacity is considered for each appliance in both scenarios. The ceiling and table fans were selected from a recent report by Global LEAP Awards [40].

Table 1. Energy consumption of the school considering appliances with standard efficiency [41–45].

Appliances/Services		**Specification**	**Power (W)**	**Average Use Time (h/day)**	**Energy Consumption (Wh/day)**
Lighting/CFL Lamps	Classrooms	11 W × 16	176	3	528
	Staff office	9 W × 4	36	10	360
	Director office	9 W × 1	9	10	90
	Security office	9 W × 1	9	8	72
	Outside	11 W × 3	33	8	264
Computers		200 W × 7	1400	10	14,000
Printer		360 W ×1	360	1	360
Photocopy		1000 W ×1	1000	2	2000
Fan	Ceiling fan	35 W × 8	280	3	840
	Table Fan	30 W × 4	120	3	360
Radio receiver		5 W × 1	5	3	15
Mobile Charging		3 W × 4	12	4	48
GSM wireless Tel		2 W × 4	8	8	64
Total Power consumption			3448		19,000

Table 2. Energy consumption of the school considering high efficient appliances as compared to appliances with standard efficiency [41–44].

Appliances/Services		**Specification**	**Power (W)**	**Average Use Time per Day (h/day)**	**Energy Consumption (Wh/day)**
Lighting/LED Lamps	Classrooms	5 W × 16	80	3	240
	Staff office	3 W × 4	12	10	120
	Director office	3 W × 1	3	10	30
	Security office	3 W × 1	3	8	24
	Outside	5 W × 3	15	8	120
Computers		100 W × 7	700	10	7000
Printer		150 W ×1	150	1	150
Photocopy		250 W × 1	250	2	500
Fan	Ceiling fan	25 W × 8	200	3	600
	Table Fan	12 W × 4	48	3	144
Radio receiver		5 W × 1	5	3	15
Mobile Charging		3 W × 4	12	4	48
GSM wireless Tel		2 W × 4	8	8	64
Total Power consumption			1486		9055

Figure 2 presents the considered power consumption of the school over 24 h, based on the load estimations in Tables 1 and 2. The loads are distributed based on the hours of the day when the appliances are used, which is for computers from 8 h to 18 h, for classroom lighting from 18 h to 21 h (in case there are some classes given at night), and for other services such as photocopy, printer the load is distributed from 11 h to 17 h. The load follows the same profile for every working day over the year when the school is working, and it is changing every hour depending on the working time of the appliances as presented in Figure 2. The presented load profiles are aligned with the typical primary school consumption pattern in rural and remote locations of Ethiopia over a day. As presented in the above tables, the estimated power over one day in the school gives a total energy consumption of 19 kWh for appliances with standard efficiency and 9 kWh for high-efficiency appliances. The estimation of energy consumption using less efficient appliances is more than double when compared to the supper efficient appliances scenarios. The peak loads are 2.47 kW for standard efficiency appliances and 1 kW for high-efficient appliances.

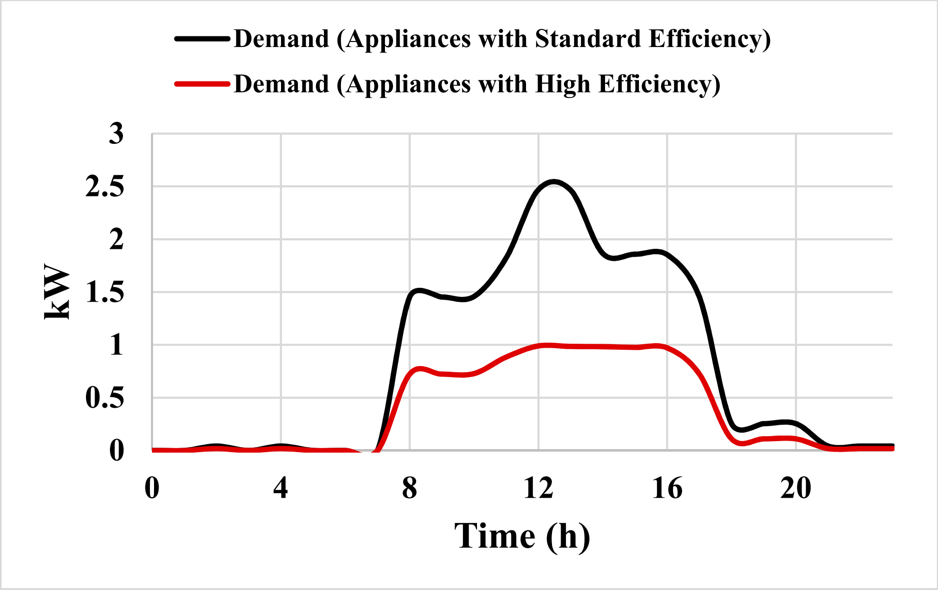


Figure 2. Daily Load Profile of the school with high and standard efficient appliances.

1.5. Paper Organization

The remainder of the paper is organized as follows: In Section 2, the details about microgrids and the classification of microgrids are presented. Moreover, the differences between AC and DC microgrids and the comparative advantages of one over the other are presented. In Section 3, the design and model of the proposed DC Microgrid are presented, including the PV generation potential of the school site, the PV sizing, the battery sizing, as well as the modeling of the proposed DC microgrid using MATLAB/Simulink. Section 4 presents the results and discussion of the proposed DC microgrid model in terms of validation of the model, simulation and costs. Finally, in Section 5 the summary and conclusions of the work are presented.

2. Microgrids

In the last couple of decades, a major shift has been observed in power systems due to the change in generation and transmission systems. The need of improving power quality, optimizing the operation and maintenance cost, increasing energy access in places where the power grid far away, environmental and social sustainability, are some of the main reasons behind these changes. The increasing penetration of renewable energy sources along with the depletion of fossil fuels and its associated environmental issues and investment costs, are among the factors for the observed power system changes [46]. However, with the randomness and intermittence of renewable sources, like wind and solar power, it is necessary to integrate different renewable sources for their better utilization and to have continuous energy supply. With this regard, microgrids can have a key role to achieve these goals and accommodate the changes required in the current power system, as well as to supply energy locally for people located in rural and remote locations of developing countries [17].

A microgrid is a power system composed of distributed generation, loads, energy storage and control systems that can function as an isolated system or connected with the main grid. It is important to achieve more operational flexibility compared with conventional power systems. Microgrids can then provide solutions for commercial, industrial, and residential consumers in order to achieve objectives such as lower greenhouse gas (GHG) emissions; lower stress on the transmission and distribution system and ensure local, reliable, and affordable energy security for urban and rural communities [47–50]. Figure 3 presents a schematic diagram of a microgrid that consists of different components including distributed renewable generation, diesel generator, energy storage, loads, connection to utility grid and control systems. Based on the compatibility among different components and operating voltage microgrids can be classified as AC and DC [51].

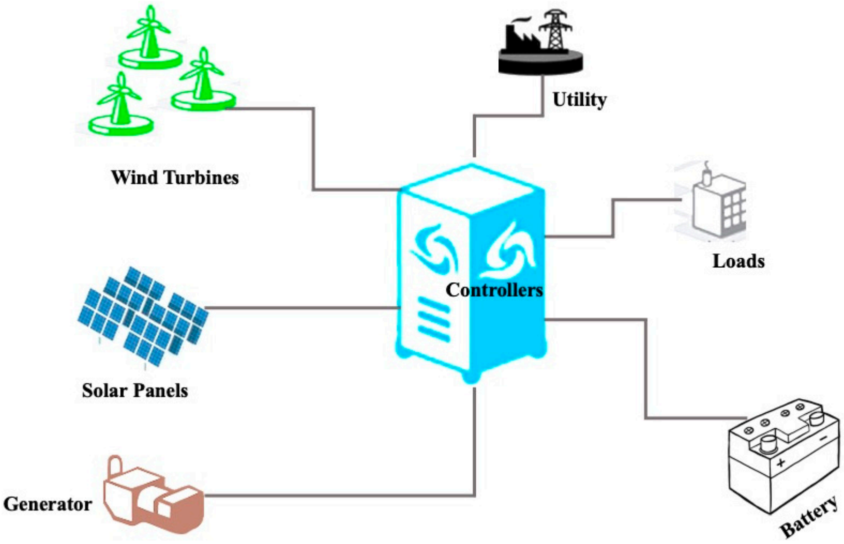


Figure 3. Schematic of a microgrid connected with Utility grid.

2.1. AC Microgrid

Figure 4 presents a typical AC microgrid for rural electrification, consisting of wind turbines, photovoltaic systems, battery storage and loads (AC and DC loads). As shown in the figure, an AC bus is created and all sources with variable frequency and variable voltage are connected to the AC bus through AC/AC and DC/AC converters. The DC/AC inverters are necessary to convert the outputs of DC sources, such as battery storage and photovoltaic systems for any type of AC microgrids, whereas the sources with AC output is connected with AC/AC converters. Furthermore, AC to DC converters are installed to supply DC loads. Therefore, due to the use of different power electronics devices and conversions of power outputs from AC to DC or DC to AC, AC microgrids present higher losses.

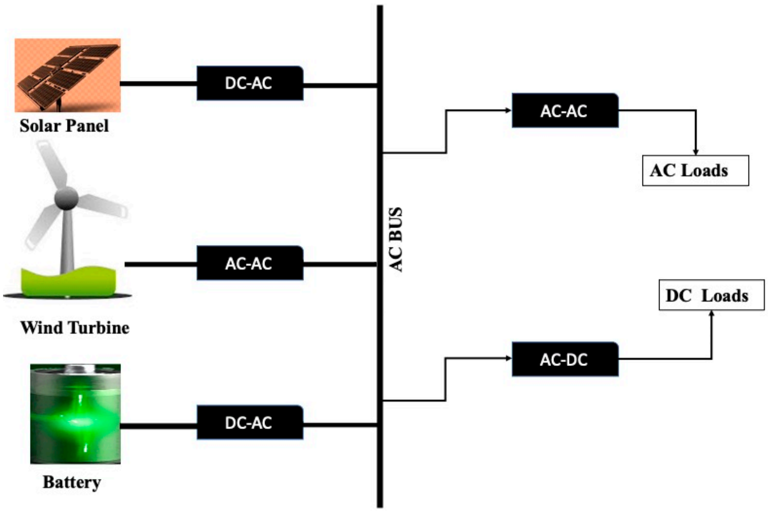


Figure 4. Typical off-grid AC microgrid.

On the other hand, due to the variable nature of the different distributed power sources and the necessity of many power electronic devices, as well as the magnitude of power availability from different sources at different periods, a smart load controlling and management system is needed [52–54]. With this regard, AC microgrids are compatible with the existing power system infrastructure, as a result, extensive research has been made on understanding and improving their performance However, the controlling and management system is still complex, inefficient and expensive compared with the emerging DC microgrids due to the need to controlling reactive power flows, synchronization, power quality, and frequency regulation [55].

2.2. DC Microgrid

The conventional power systems were designed to run based on high voltage AC transmission lines and low voltage distribution lines to households, service building and business centers which use different kinds of AC based loads like lamps, appliances, AC motors and other AC equipment. DC power systems have been used in industrial power distribution systems, telecommunication infrastructures and point-to-point transmissions over long distances or via sea cables and for interconnecting AC grids with different frequencies. Nowadays, the use of DC based electronic devices such as computers and other Information Communication technology (ICT) loads, LED lights, variable speed fans and compressor refrigerators, as well as the increasing penetration of DC power sources including photovoltaic, wind turbines, fuel cells and others, is increasing more than ever. However, if the system still sticks with the conventional power grid and use an AC off-grid system, all these advanced DC devices require conversion of the available AC power into DC for use, and the majority of these conversion stages typically use inefficient rectifiers and inverters. Moreover, the power from DC based renewable generation units must be converted into AC to tie with the traditional AC electric network, to be converted later to DC for many end uses. Therefore, the need and use of DC microgrids is very much useful to avoid such losses and to simplify the control and management units [46,56]. For off-grid applications, since the generation sources are DC and the most loads, such as the loads in the considered primary school, can be in DC. the feasibility of DC microgrids is much more efficient when compared with the AC microgrids. Moreover, the problem of harmonics due to power electronic converter is not present due to DC nature of output power [57]. Figure 5 presents a typical off-grid DC microgrid composed of a battery, solar panel and DC loads with charge and load controlling unit.

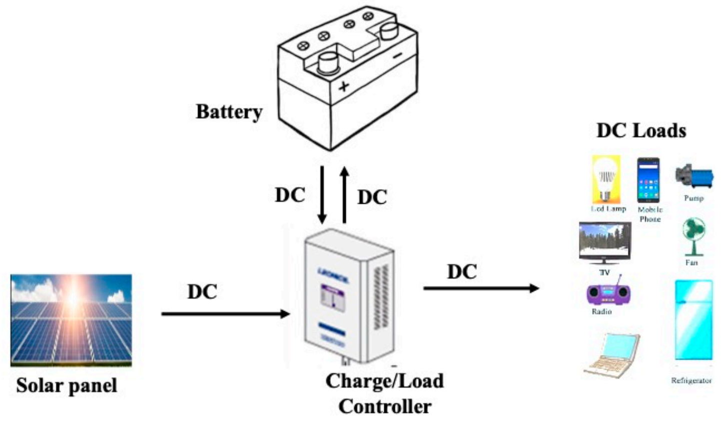


Figure 5. Typical schematic of off-grid DC microgrid.

Compared with AC microgrids, DC microgrids have several advantages: (1) higher efficiency and reduced losses due to the reduction of multiple converters used for DC loads; (2) elimination of synchronizing generators requirements, with rotary generating units, allowing to operate at their own optimum speed; (3) easier integration of various DC distributed renewable energy resources, such as energy storage, solar PV, small wind turbines and fuel cells, to the common DC bus with simplified interfaces; (4) more efficient supply of an increasing number of high efficiency DC loads, like LED lights, fans, computers, TVs, refrigeration; and (5) providing higher safety level and easier primary control. Therefore, in terms of high reliability, easy operation and maintenance, smaller size, high efficiency, lower design and operating cost, modularity and fault tolerance, DC microgrids in the low-medium power range (below 100 kW) are the best option for off-grid applications compared with AC microgrids [58–60].

In spite of such advantages, the protection and standardization of DC microgrids were a challenge for a long time [46]. However, recently a draft standard for DC Microgrids for Rural and Remote Electricity Access Applications was developed by the "IEEE P2030.10™ for DC Microgrids for Rural and Remote Electricity Access Applications Working Group." The standard covers and presents the design, operations and maintenance of a DC microgrid for rural and remote applications. Furthermore, the standard defines requirements for providing low voltage DC and AC power to off-grid loads [18]. This standard is a breakthrough in the DC microgrid topic enabling further research and advancing the application to electrify rural and remote areas in developing countries, including sub-Saharan Africa. Furthermore, many countries with a low level of electricity access in sub-Saharan Africa, are installing microgrids in rural areas to improve electricity access. This is due to the cost-effectiveness of microgrids and to increase the utilization of locally available renewable energy resources. On the other hand, expanding the existing grid is too expensive and is not reliable from economic, social and technical aspects, because many of the rural areas are located far away from the grid. Minigrid market trends shows that about 5544 minigrids are installed in Sub-Saharan Africa, but still, the cost of the minigrids and lack of policies and regulations are some of the challenges to scale up, promote and realize their potential and increase electricity access in rural and remote areas [16]. This indicates that there is a need for cost optimization and efficiency improvement in microgrids and the customers, as well as the government body at every level, should select the most cost-effective and efficient system to overcome the challenges in microgrids, as well as to achieve energy access for all plans. Based on the findings in the literature and the advancement of DC based electronic devices, as well as the standardization of DC microgrids, DC microgrids could be the best preferable solutions to electrify rural schools, health centers, refugee camps and households. Therefore, the study proposes a DC microgrid for a rural primary school in a developing country and presents its design and model, as well as the findings from a technical and economical point of view.

3. Design and Model of DC Microgrid

The proposed DC-microgrid is composed of solar photovoltaic (PV) panels, a control system and a battery storage system. The main purpose of this research work is to design, model and simulate the DC-microgrid that serves Gomenege Primary School. Such a model can then be used for other primary schools located in rural areas of Ethiopia and other countries in Sub-Saharan Africa which do not have access to electricity. The renewable energy potential analysis, the mathematical model of the solar PV, the mathematical model of the battery storage system and the system model and design of the proposed DC microgrid are presented in the following subsections of the work.

3.1. PV Power System

Solar PV is selected as the main energy source for the proposed system because of availability, technical and economic aspects. Compared with wind energy (which is about 3 m/s measured at 10 m height above ground) [61], solar energy availability (with average solar radiation of 6.09 kWh/m^2/day) at the school location and the lower capital cost makes it the best option. However other sources can be used as input considering the necessary modification. If the source is DC-based the proposed system will work with no need for modification or addition of other components. If the source is AC based, it may need additional power electronics components to convert AC to DC. The solar energy potential of the location and the clearness index is presented in Figure 6, being such data generated from the nearby location of the school site from the National Renewable Energy Laboratory (NREL) using PVwatts calculator [62]. The average daily solar radiation profile of the school site generated at 10° tilt angle is presented in Figure 6.The used tilt angle value is the optimum angle to ensure maximum possible annual PV generation for the school site considering the latitude of the site i.e., 11.4°. As shown in Figure 6 the minimum daily solar radiation is 4.96 kWh/m^2/day in August and the maximum is 6.84 kWh/m^2/day in March. The annual daily average solar radiation of the school site (6.09 kWh/m^2/day) is higher than the annual national daily average solar radiation of Ethiopia which is about 5.5 kWh/m^2/day [63]. On the other hand, schools have activities from mid-September to mid-June, and therefore the lowest solar radiation is in July and August will not have an impact on the power generation to supply the school demand. Furthermore, from September to June the daily radiation variation in each month is very low, which implies that solar photovoltaic energy is the ideal source to supply the power demand of the school.

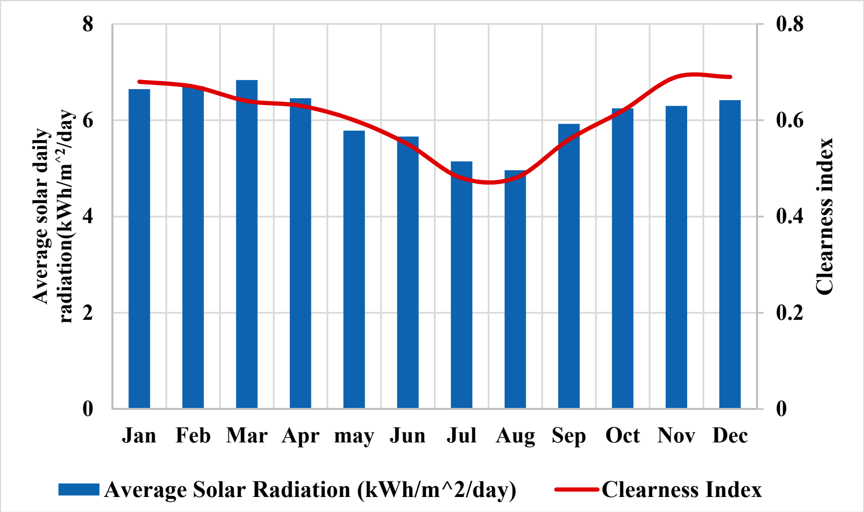


Figure 6. Average daily solar radiation of the school site in each month in 2018.

Due to the variability of solar radiation, the study considers maximum and minimum average solar irradiation days. The days are selected based on the daily average solar radiation in relation to the average daily solar radiation of the month, i.e., the days with solar radiation values closer to the daily average solar radiation. Figure 7 presents the solar irradiation profile for the selected days, which are 9 March and 22 June of the year are the ones that have maximum and minimum solar radiation days close to the average daily radiation of the year. The study considered for the generation and the battery sizing three days of full autonomy (which corresponds to more than three days with thick clouds, which usually does not happen).

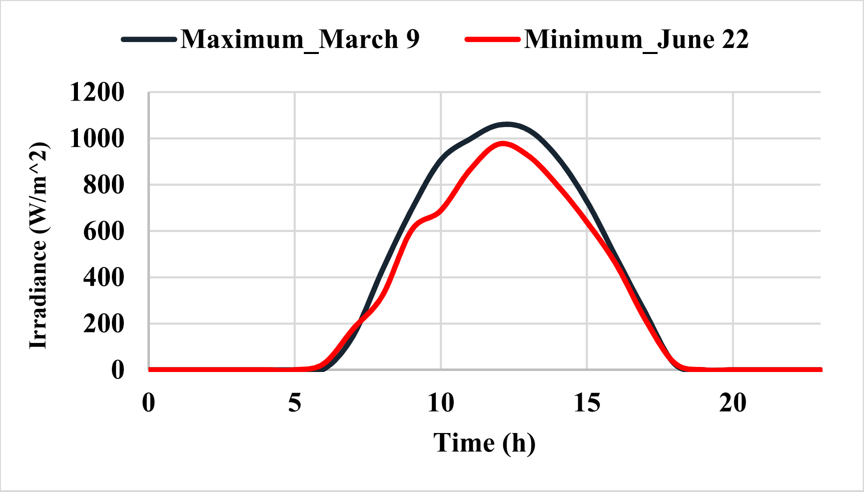


Figure 7. Solar irradiance of maximum and minimum irradiance days.

The total output power of the PV system at time t can be expressed by Equation (1) [64]. Where N_{pv} is the number of PV panels, A_{pv} is the area of the PV module (m^2), I_{pv} is the solar irradiation incident on the PV system (kWh/m^2), η_{pv} is the efficiency of the PV system and $P_{pv}(t)$ is the total power generated by the PV system:

$$P_{pv}(t) = N_{pv} \times A_{pv} \times I_{pv} \times \eta_{pv} \quad (1)$$

The PV system capacity is determined by considering the variation of the solar radiation during the day, the estimated load for both scenarios and the overall system efficiency. There are losses due to charging and discharging of the battery, Joule losses in the cable, but since the proposed system is a DC microgrid which is more efficient than the conventional microgrids, a 90% overall system efficiency is considered [65]. On the other hand, inserting and testing different capacity values of the PV in PVwatts calculator were considered until the anticipated PV generation profile (which able to supply the demand) resulted in assuming the tilt angle of the location, the nearby location of the site and systems losses. Based on the given conditions, the PV systems were sized at 3.7 kWp and 1.8 kWp for the load estimation using appliances with standard and high-efficiency appliances, respectively.

Considering the resulted PV capacity, the generated energy for the maximum generation scenario for both load estimation cases is 23.66 kWh (standard efficiency) and 11.21 kWh (high efficiency). Whereas for the minimum generation scenario the generated energy for standard and high-efficiency load estimation cases are 19.59 kWh and 9.53 kWh, respectively. The generated energy is higher than the estimated energy demand for the school load which is 19 kWh (standard efficiency) and 9.1 kWh (high efficiency). This implies that the sized PV system can supply the school energy demand and losses for a full day even without the need for stored energy. Figure 8 presents the demand and PV generation (maximum and minimum) profile for each load estimation scenario over 24 h.

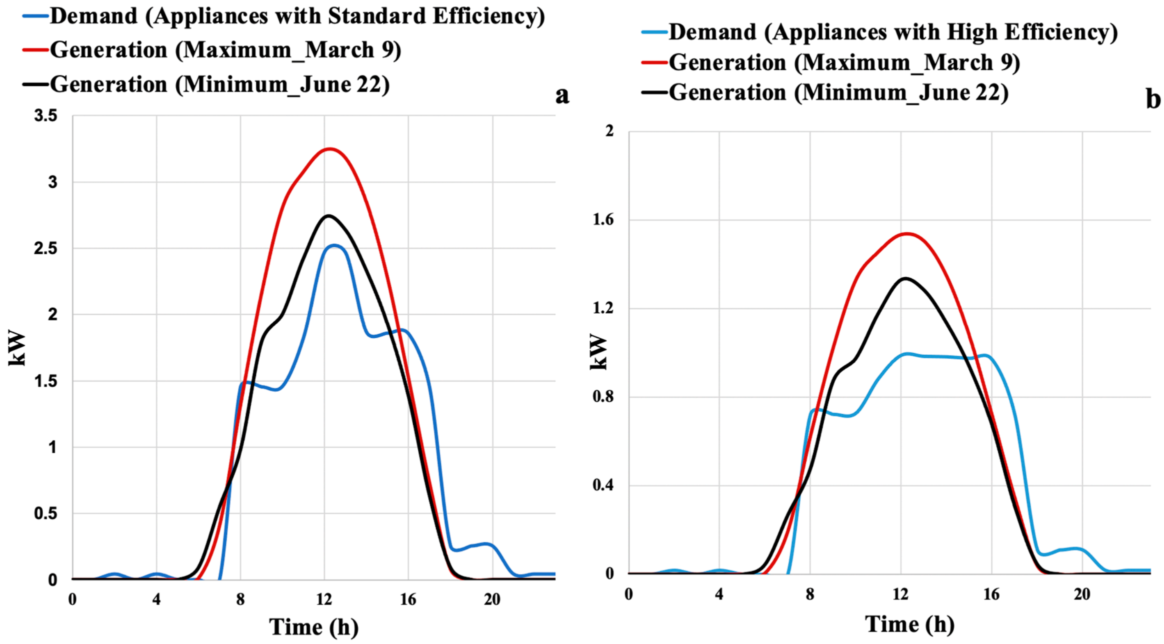


Figure 8. Demand and generation under different load estimation scenarios: (**a**) demand and generation (maximum and minimum) for standard efficiency; (**b**) demand and generation (maximum and minimum) for high efficiency.

3.2. Battery Storage System

Since renewable energy resources are intermittent, a battery storage system is necessary to compensate for the periods with low or no generation of solar energy. The battery storage system is utilized together with solar PV systems to reduce the uncertainty that is associated with the local availability of renewable energy sources [66]. During the period of lack of enough generation and at the peak periods the stored energy in the battery system can be utilized to supply the required power [6]. The battery storage system will level out the impacts of power fluctuation of the available renewable energy sources where the microgrids power systems are installed and it will enhance its reliability and stability. The efficiency and performance of the battery depend on ambient temperature, state of charge, voltage effects, rate of charging and discharging. These factors also determine the lifespan of the battery. On the other hand, the impact of these factors depends on the type of battery used. In this study lithium-ion batteries are used considering its lifetime cost, high-efficiency advantages over other types of batteries.

As per Ref. [6], the battery should not be overcharged to be durable, because overcharging will affect the efficiency and the lifespan of the battery. Similarly, the battery must not be over-discharged because over-discharging will reduce the lifetime of the battery. The maximum State of Charge (SoC) of the battery should be set to its nominal capacity, which is a basic requirement for the durability of the battery. Besides this, the minimum SoC of the battery should not be less than 20%, being the SoC of the battery bank at a given time t expressed by Equation (2) [67]:

$$SOC\ (t) = \ SOC(t-1) + \frac{P_i\ (t)\ \times\ \Delta t}{1000 \times C_b} \tag{2}$$

where $P_i\ (t)$ is the power flow towards the battery, Δt is the simulation time and C_b is the nominal capacity of the battery.

The battery bank usually operates between the maximum and minimum capacity of the battery, which means it is limited within the maximum and minimum allowable capacity. Mathematically it can be represented by Equations (3) and (4) [6]:

$$SoC^{min} = (1 - DoD)SoC^{max} \tag{3}$$

$$SoC^{min}\ \leq SoC(t) \leq SoC^{max} \tag{4}$$

where SoC^{min} is the minimum allowable capacity of the battery, SoC^{max} is the maximum allowable capacity of the battery, and DoD is the depth of charge of the battery. The sizing of the battery bank can be calculated using Equation (5) [53]:

$$C_{BB} = \frac{E_d\ \times\ T_{out}}{B_{eff}\ \times\ Do.D} \tag{5}$$

where C_{BB} is the size of the battery bank in Wh (Watt-hours), E_d is the daily energy demand, T_{out} is days of autonomy which is days which can supply the load using the battery in case some faults occur in the PV panel for maintenance and/or rainy/cloudy days), B_{eff} the battery efficiency (the ratio of the energy out from the battery to the energy supply to the battery by the system) and DoD is the depth of discharge.

For the sizing of the battery storage system, the daily energy demand for the estimated load is 19 kWh for appliances with standard efficiency and 9.1 kWh for appliances with high efficiency. The considered days of full autonomy were 3 days (in case some faults occur in the PV panel for maintenance and/or several rainy/very cloudy days). For the assumption, the average daily radiation in June was considered, since it has minimum daily radiation as compared to the other months (Figure 3) in the period when classes are given. For the battery and system controller, it was considered an efficiency of 90% and a depth of discharge of 80% [68]. As a result, the battery is sized to 80 kWh and 38 kWh for appliances with standard and high efficiency, respectively.

3.3. System Modeling and Design Using MATLAB/Simulink

Figure 9 presents a typical schematic design of DC microgrid containing a solar panel and battery storage system. It also contains the solar charger and load controllers/DC-DC converter, which controls the voltage coming from the solar panel and the battery as well as going to the battery to charge it and to the load. Compared with the conventional AC microgrids, DC microgrids have a simplified schematic design since they do not require many power electronics like inverters to convert the DC current to AC current or vice-versa. Moreover, the absence of much power electronics in the system makes the system more efficient by avoiding power losses and more reliable. Furthermore, it has the potential to be integrated with the grid with the addition of power electronics to link with it. Additionally, the application range is not only specified for schools rather it can be used for large community energy needs and other service centers including health centers and refugee camps.

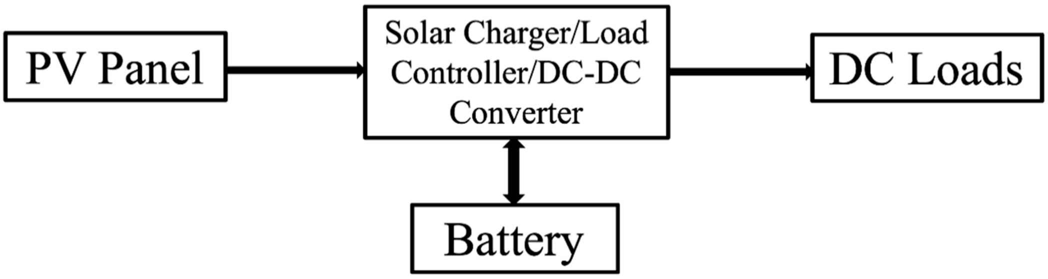
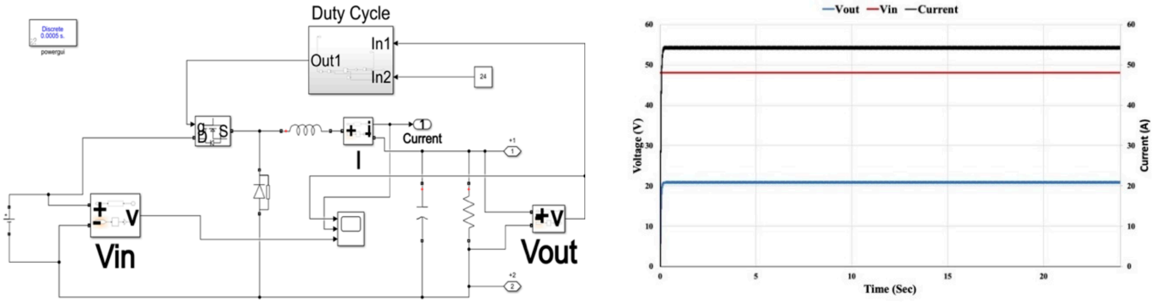


Figure 9. Schematic design of DC Microgrid composed of Solar PV, System Controller and Battery.

The proposed DC microgrid includes a PV system, DC-DC converter, and a battery and was modeled using MATLAB/Simulink. The DC-DC converters are used in conjunction with the PV system and the battery to control the power flow, as well as stabilize the voltage and generate maximum power. The type of DC-DC converter used in this system is a DC-DC buck converter, which reduces the input voltage since the voltage of most of the appliances and the battery is about 24 V and it is necessary to control the voltage coming from the PV system. Figure 10 presents the DC-DC buck converter modeled in MATLAB/Simulink and the simulation output of the converter. The simulation output indicates that the designed DC-DC buck convertor controls and reduces the input voltage from 48 V (assuming that the nominal voltage of the PV system is 48 Volts) to about 22 V, implying that the selected appliances are working in the range of 12–24 V.



(**a**) DC-DC Buck Converter Design in MATLAB/Simulink

(**b**) Simulation output

Figure 10. Design and simulation output of DC-DC buck converter design in MATLAB/Simulink: (**a**) DC-DC buck converter design; (**b**) simulation output.

Figure 11 presents the design of the proposed DC microgrid system with the PV system, battery and DC-DC buck converter which is connected with the loads. The battery controlling strategy which is encircled by red is also presented. The loads are connected with the supply system in a distributed mood over 24 h. The PV system is connected with the DC-DC buck convertor and the DC-DC buck converter is also connected with the battery and with the loads.

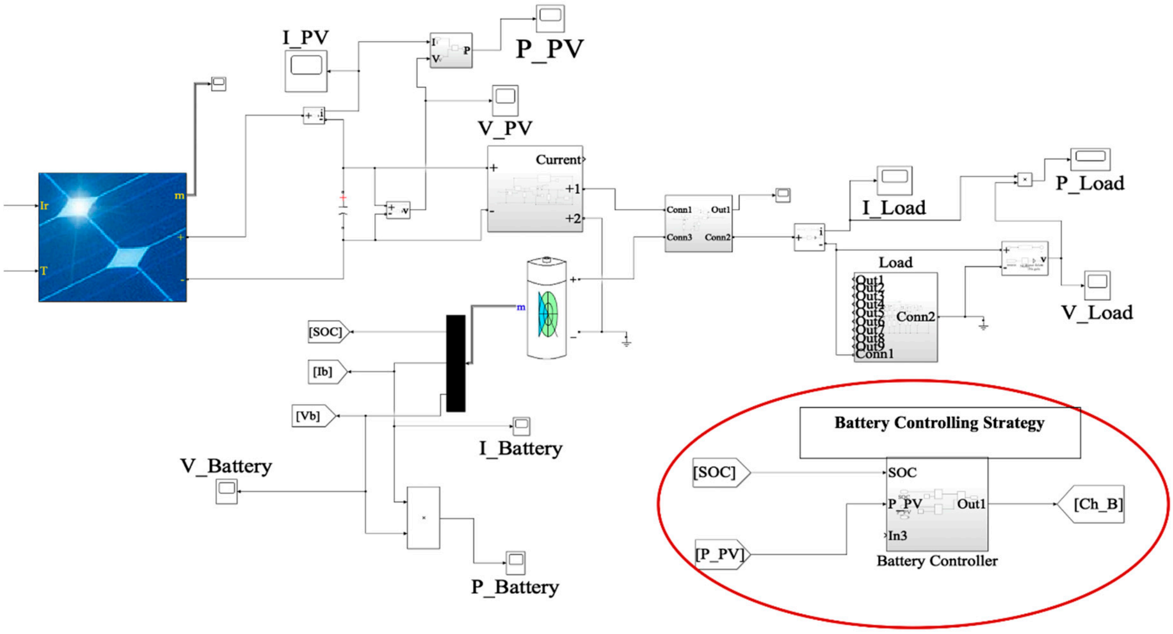


Figure 11. DC microgrid design using MATLAB/Simulink.

Figure 12 indicates the charge controller strategy in the developed DC microgrid (Figure 8). Most batteries are designed to operate in the state of charge range of 20–90%. Therefore, the strategy in the controller will check if the batteries are in the range of 20–90%. Besides that, the battery controller is depending on the power generation and load demand. If the power generated is higher than the required load power and the battery is at a low *SoC* below 90% the battery will be charged. However, if the load power is higher than the generated power load shedding should be taken into consideration to protect the safety of the battery. Similarly, if the generated power is greater than the power load and *SoC* is in the range of 20% to 90% the battery will be charged unless the battery should be discharged. The other scenario is if the *SoC* is higher than 90% up to a maximum of 100%, as well as if the DC microgrid generates power more than the required demand the current will be sent to a dump load (in the system controller) to avoid overcharging and prevent DC bus voltage increasing unless the battery will be discharged to supply power to the load.

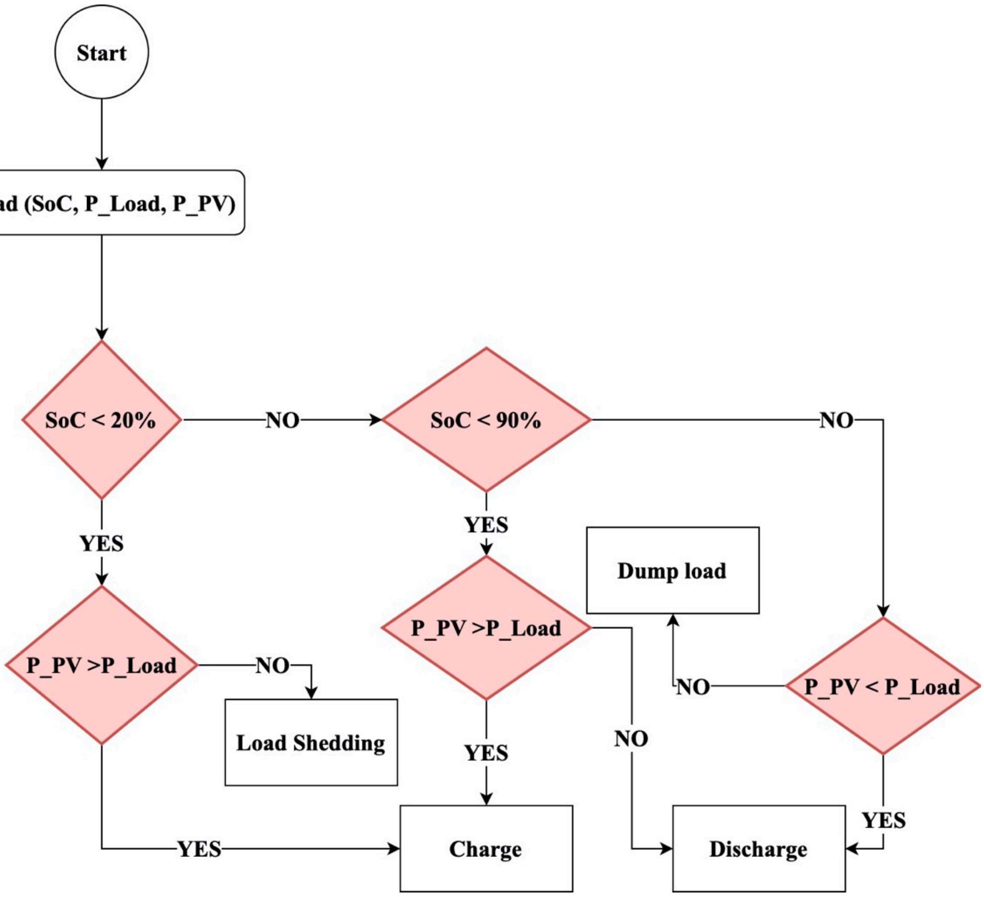


Figure 12. Battery controlling strategy.

4. Results

4.1. Validation of MATLAB/Simulink Model

The designed MATLAB/Simulink model was simulated for each load estimation and generation scenarios. The objective of this simulation was to validate whether the designed DC-microgrid is reliable or not. Figure 13 presents the voltage and current simulation outputs for standard efficiency appliances. The voltage curves indicate that it gives an output of around 24 V with about 2 V variation for the load and the battery which is the expected value provided that the appliances and battery voltages are set at 24 V for the design. Furthermore, the load current simulation result shows the same profile as the load profile and when there is less or no PV generation, i.e., from late afternoon to sunrise and early mornings, the battery supplies the load. On the other hand, it presents high variation due to the load is distributed as presented in the load profile curve (Figure 2) and the loads are connected in parallel. As the load increases the current increases and as the load decreases the current is also decreasing. The variations between the loads, battery and PV voltages would be different and higher if the selected microgrid was AC microgrid. In other words, the losses would be higher, since it requires power electronic devices to ensure AC to DC power conversion, implying that the resulted voltage and current simulation outputs would be different from the presented ones if the assumptions were the same. Therefore, the results demonstrate that the designed DC Microgrid is suitable to supply the school demand under the presented load and generation variabilities. Moreover, it demonstrated the validation of the designed DC-microgrid under the given conditions to be used as a system for the school.

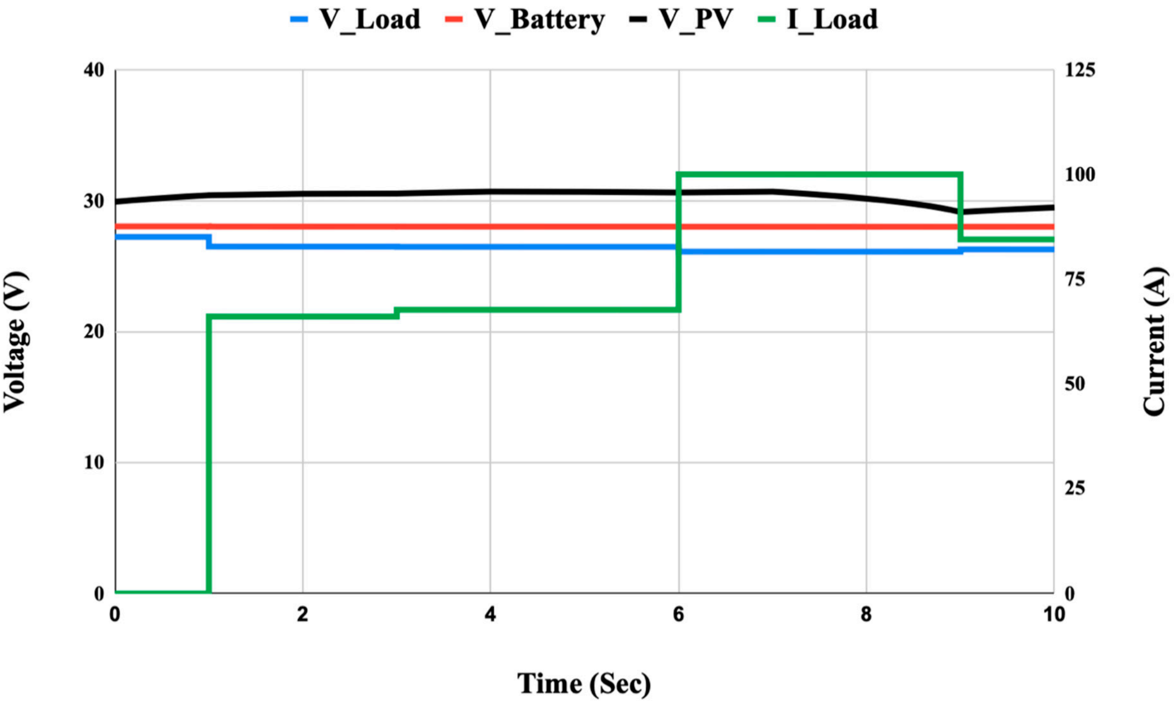
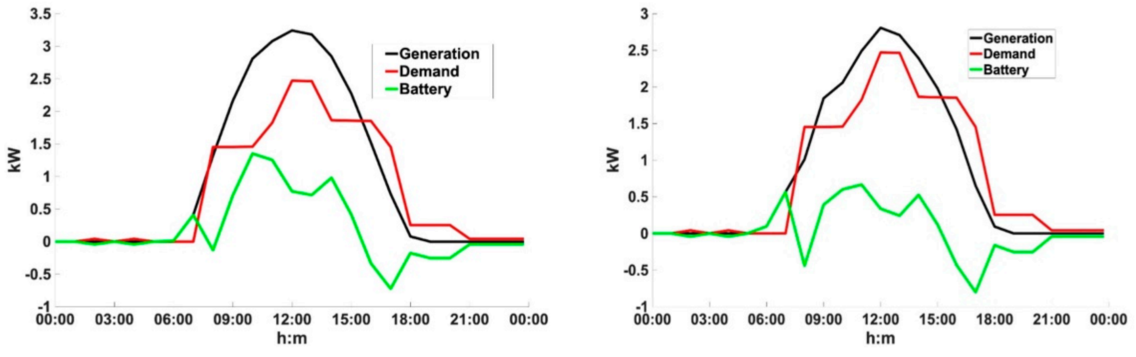


Figure 13. Voltage and current simulation outputs for load under standard efficiency appliances.

4.2. Simulation

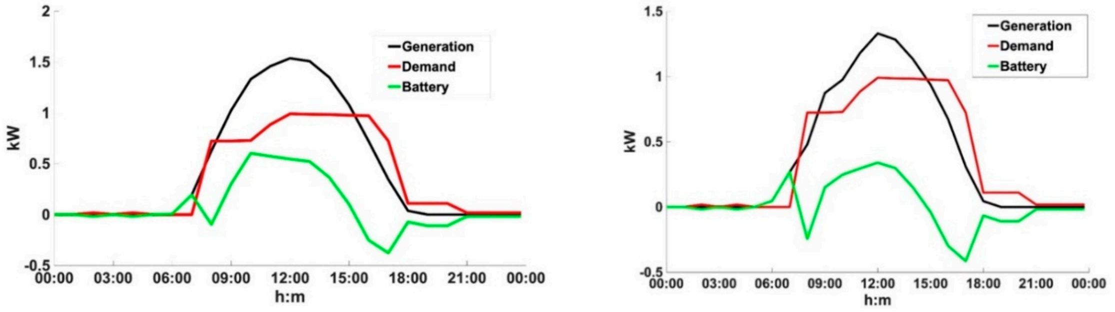
The simulation was done considering the minimum and maximum generation days for 24 h in order to evaluate the power flows of the PV system, demand and the battery. The anticipated results are when there is a much higher generation than the load demand, the PV system will supply the load and will charge the battery provided that if the battery needs to be charged. Whereas, when there is a lower generation the battery will discharge and supply power to the load. This implies that the sum of the demand and the battery power and losses will be equal to the generation.

Figures 14 and 15 present the power flows of the load, PV system and the battery for the standard and high-efficiency appliances under maximum generation and minimum generation scenarios, respectively. The simulation output shows that the model gives the anticipated result in both load estimation scenarios which is when there is enough generation to supply the demand the load gets power from the PV system and the battery charges as well as when there is less generation to supply the demand the battery supplies power to the load.



(**a**) Under maximum Generation (**b**) Under minimum Generation

Figure 14. Power flow for generation, demand and battery under Standard efficiency in the case of maximum and minimum generation: (**a**) under maximum generation; (**b**) under minimum generation.



(**a**) Under maximum Generation (**b**) Under minimum Generation

Figure 15. Power flow for generation, demand and battery under high efficiency in the case of maximum and minimum generation: (**a**) under maximum generation; (**b**) under minimum generation.

Table 3 presents the generated, consumed and stored energy for both load estimation and generation scenarios. It shows that the generated energy is enough to supply the demand and also the surplus generation is stored in the battery. For instance, under the maximum generation scenario and standard efficiency load estimation, the generated energy is 23.66 kWh, and the consumed energy is 19 kWh. The stored energy which is the initial energy in the battery (50% of the battery capacity for each load scenario) plus the total energy entering the battery is 46.61 kWh. Considering a 10% loss in the periods of charging and discharging of the battery, as well as system losses, the total stored energy at the end of the day is 41.95 kWh.

Table 3. Generated, consumed and stored energy for both generation and load estimation scenarios.

Generation Scenario	**Standard Efficiency**		
	Generated Energy (kWh)	**Consumed Energy (kWh)**	**Δ Stored Energy (kWh)**
Maximum	23.66	19	1.95
Minimum	19.69	19	−0.89
High Efficiency			
Maximum	11.21	9.1	0.89
Minimum	9.53	9.1	−0.32

Although the power flow profile is the same, the charging and discharging of the battery depends on the generation. In each generation scenario the battery initial capacity is the same meaning under the same load and different generation days the used initial capacity of the battery is the same based on the sizing of the battery made in Section 3. For both load estimation scenarios under maximum and minimum generation scenarios the battery charging and discharging rate are different. For instance, as shown in Figures 11 and 12, the power supplied to the load from the battery for the standard efficiency load scenario at 8:00 h is −0.13 kW for the maximum generation scenario and −0.44 kW for the minimum generation scenario. At the peak demand, which is 2.47 kW, power entering into the battery is 0.77 kW (maximum generation) and 0.34 kW (minimum generation). This implies that the battery is charging at a low rate at a lower generation level as compared to charging at a higher generation meaning the load gets more power from the battery. The discharging is also the same, at the maximum generation scenario the battery is discharging at a lower rate and at the minimum generation scenario, it discharges at a faster rate.

The result demonstrates that in both generation and load estimation scenarios the sizing of the battery and the PV system is able to supply the load in periods of low generation for the considered days of autonomy. However, the low stored energy results for each scenario indicates that in case of bad weather conditions, such as continuous rain and cloudy weather, different sizing of the battery and PV system may be necessary, depending on worst-case conditions (e.g., the maximum number of days with very small solar radiation).

Comparing it with AC microgrids which require more components, the results obtained in this study are different. Because of the required inverters, there will be additional power losses that lead to a different PV and battery sizing to balance the supply and the demand. This implies that, if the same generation and load estimation scenarios are considered and the system is supposed to be an AC microgrid, the sizing of the battery and the PV system could not supply the load especially in periods of low or no generation for the considered days of autonomy. Therefore, the results presented in Table 1, could be much lower if the same PV and battery sizing are considered. Studies shows that DC microgrids are 6–8% more efficient than AC microgrids [69], implying that to supply the load estimated in this study, a PV generation higher than the presented generation by 6–8% is required. On the other hand, for lower load demands like the system investigated in this study, DC microgrids are more suited from different perspectives including efficiency, power balance, power quality and cost [16].

4.3. Cost Analysis

According to IRENA and BNEF, the average cost of a PV system in Africa ranges from US $1.2 to US $4.9/W [70] and the average cost of lithium-ion batteries is about US $350/kWh [71]. Considering the fall of the PV cost in the last couple of years US $1.2/W is used in this study. The cost of the system controller is estimated to be US $1000. Based on the given cost scenarios the estimated total system cost required for the load estimation based on standard efficiency is US $33,440 and for the load estimation using high-efficiency appliances is US $16,460. The estimated system cost of the proposed DC microgrid under standard efficiency appliances is higher than the cost of the system under high efficient appliances by 103.2%. Even if, the cost of high-efficiency appliances is higher (10–40%) than standard efficiency appliances [72], using high-efficiency appliances is still very cost-effective as compared to the cost of the system designed using standard efficiency appliances. Besides, the costs could be much higher with both scenarios if the proposed microgrid was AC microgrids due to the need for additional investment for inverters and other necessary power electronics

5. Conclusions

The main objective of this paper was to design and model a DC-microgrid system composed of a solar PV system, system controller and battery storage system for a primary school in the rural sub-Saharan region, using Ethiopia as a case study. For the design of the DC-microgrid two load estimation and two scenarios of generation profiles were considered. The first scenario was the estimation of daily load based on standard efficiency appliances and the second scenario was the estimation of the daily load based on emerging high-efficiency appliances, which is one of the novel aspects of this study. On the other hand, the average maximum generation and average minimum generation days were considered to assess the system performance in both scenarios.

Taking into account the estimated loads for both cases and generation scenarios the PV and the battery were sized at 3.7 kWp and 80 kWh, and 1.8 kWp and 38 kWh for standard efficiency and high-efficiency appliances, respectively. The proposed DC microgrid was designed and simulated for both load and generation scenarios using MATLAB/Simulink. The simulation results show that the proposed and designed DC-microgrid can supply the required demand with the support of a battery storage system under both standard and high-efficiency appliances in both generation options under the presented conditions. The stored energy in each load and generation scenarios at the end of the day was enough to supply the demand for two days. Severe weather conditions with several days without sunshine are very uncommon in Ethiopia during school months. A small additional investment (increasing the solar PV capacity by 50%) can be used to make the system more robust in relation to longer periods of reduced solar radiation. On the other hand, the system cost was assessed, and the result indicates that the system with standard efficiency appliances more than doubles the cost with the option with high-efficiency appliances, proving the high impact of the selected appliances on the cost-effectiveness of the solution.

This is a major result to promote the large-scale electrification of off-grid schools. The implementation of the study outcome will have a significant impact on promoting education, increase quality education, to attract teachers in rural areas which is a challenge in many areas due to lack of energy access and increasing the number of children attending schools. If there is electricity in the nearby primary school, families could send their children (that increases the number of children attending classes) to get mutual benefit including to charge their mobile phone and lighting appliances which avoid long travels to charge the mobile phone, as well as to save money that could be paid for charging. Apart from promoting such benefits, school electrification has a fundamental impact on the level of awareness of the community, raising self-confidence, increase income-generation opportunities and empowering women by increasing the number of girls attending the schools and increasing the number of girls promoting to secondary and higher education. The study also applies to other sub-Saharan countries in the region with very low energy access rates and abundant solar energy, thus giving a large contribution to achieve the United Nations Sustainable Development Education Goal 4 (SDG 4).

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