Load Analysis and Design of a stand-alone Solar PV Power System for a Secondary School in Nigeria.

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Abstract

This paper presents the load analysis and design of stand-alone solar PV system for Uyo High School, Uyo, Akwa Ibom state in Nigeria. The solar potential of this location is 4.71 kWh/m^2 /day. The load analysis of the school was carried out in BEopt by varying the schedule to accommodate a building like a school. The system was designed for a load of 7.5 kW and the proposed system will satisfactorily meet the power needs of the school. The dynamic simulation was carried out in MATLAB/Simulink and the system performance was evaluated. A storage battery system was incorporated into the system to provide backup and ensure continued supply to load during bad weather and periods of poor solar insolation. The research indicates that the designed system can meet the power need of the school satisfactorily.

Keyword – BEopt, MATLAB/Simulink, solar PV, dynamic simulation, renewable energy.

I. INTRODUCTION

Energy has been one of the primary needs of man from time immemorial. The necessity to cook, keep one's self warm amongst others were some of the needs expressed by the caveman. The need for this same energy in the present day has reached unprecedented heights as this, directly and indirectly, measures the standard of living of any society and her level of industrialization [1]. Despite Nigeria's attempt in unbundling the monopoly of the nation's power company in 2005, which had hitherto been responsible for all the power supply chain management, vis-a-vis, generation, transmission and distribution, it has not yielded the kind of result that was anticipated as the power situation in the country has not improve significantly [2].

According to Udoakah and David [3], Nigeria can satisfactorily meet all its energy needs if all the renewable energy options were adequately utilized. Wole-Osho et al. in [4] also attest to the potential of Nigeria in sustainably meeting her energy needs as he enumerates the country's vast potentials in Hydro, wind, biomass and solar.

Nigeria is located between latitudes 4°N and 14°N and longitudes 2°E and 15°E with a total area of 923,768 km^2 [5]. Nigeria's proximity to the equator gives it a high potential for a full solar energy-driven economy all year round. The direct normal irradiance (DNI) ranges from 3.0 kWh/m^2/day (1095 kWh/m^2/yr.) in the south to 7.5 kWh/m^2/day (2737.5 kWh/m^2/yr.) in the north with average sunshine of 6.5 hours [6]. With this solar potential, one would expect the country to have made a significant investment in solar power generation to meet some of the energy challenges being faced in the country, but that is not the case. Presently, PV installation in Nigeria is still at its preliminary stages, with applications limited to street lighting, water pumping and small-scale household usage, its potential for large-scale electricity production in various locations especially northern Nigeria has been estimated with good annual yield [6]

The problem with Nigeria's power sector is not just in the generation; the transmission and distribution sectors are also in a terrible state [2]. There have been reported cases of power station generating below their capacity because the radial transmission system cannot accommodate the generated power [7]. The distribution lines are also old and in need of total overhauling. Since the cost implication of fixing these transmission and distribution networks is very high, the distribution companies have resorted to load shedding, and this has left the average customer in Nigeria having access to utility power for 4 to 5 hours in a day [7]. The other major challenge facing the consumers other than the unreliability of the grid is the problem of estimated billing by the distribution companies [8]. This has left the customers paying far more than the electricity they are consuming within the month. With the persistent power unavailability and estimated billing scheme, most power users have resorted to using diesel generators to power their homes and business premises. Besides the growing increase in the price of diesel, generating power this way is unsustainable and dangerous to the environment.

Most schools, both secondary and tertiary institutions, are also being affected by this unreliable power supply, and this has had an adverse effect on both teaching and learning in these schools.

With regards to literature, Okoye et al [7] carried out an assessment of the solar resource availability and designed a stand-alone PV system for three commercial cities in Nigeria; Kano, Onitsha, and Lagos. They concluded that the cost of electricity for the PV system is lower than that of the diesel generator that is widely being used for power supply. In another relevant work, Udoakah et al. in [9] designed a 1KVA solar power system with automatic change-over for the Electrical Engineering laboratory at the University of Uyo to help students carry out their laboratory work even when the university's supply is gone. This system was able to solve the problems experienced by students during their laboratory sessions. Elsewhere, Okoye and Solyali [1] considered the optimal sizing of a stand-alone solar power system and applied this model to residential buildings in Nigeria. They used an integer programming optimization method to determine the optimal number of each component needed for the system stressing that accurate sizing is critical to achieving excellent economic viability of any stand-alone solar PV system. On applying this model in residential homes in Bursari, a local government in Yobe state, in the North-Eastern part of Nigeria, they concluded that each household would save $361 in one year when compared to the diesel generator that is being used in the area. Dumkhana and Idoniboyeobu in [10] carried out a solar PV and battery analysis was on the faculty of Engineering building in Rivers state University of Science and Technology Port

Harcourt in the southern part of Nigeria, located on latitude 4.5°N and longitude 7.0°E. A 250KV solar PV system was analyzed using a PVSyst V5.5 software. The study considered the electrical load requirements for 8 hours a day, bearing in mind that, being an academic building, the significant demand for electricity will be within these 8 hours (8 am to 4 pm). He concluded that the PV system would reduce noise pollution as well as mitigate the harmful emissions that have resulted from the use of multiple diesel generators within the academic environment.

From the reviewed literature, there has not been any work that has explicitly considered any secondary school in the country for a complete off-grid PV system to power the loads. From the nature of most government-owned secondary schools, it will not make any economic sense for the schools to be connected to the grid as these schools, non-boarding ones, are only open for 6 hours (8 am to 2 pm) Mondays through Fridays. During these 6 hours that students are there for learning, the grid supply may not be available. This paper seeks to carry out a comprehensive load analysis and design a solar PV system that will take care of the entire electrical load in Uyo High School, Uyo, the capital city of Akwa Ibom State in the southern region of the country. The school is located on latitude 5° 1.3'N and longitude 7° 56.1'E.

II THERMAL MODELLING OF THE SCHOOL

Because of the unstable grid supply, getting the daily load profile of the school was difficult. Also, since the school is not in session all year round, the annual energy consumption cannot be explicitly determined. To solve these problems, the thermal modeling of the entire school was done in BEopt, taking into account the variations in the load during the entire day and the periods the school is not in session. Fig.1 shows the modeling of the school structure, and fig. 2 shows the annual energy as estimated in BEopt as 23801 kWh/yr for the six units of the school building.

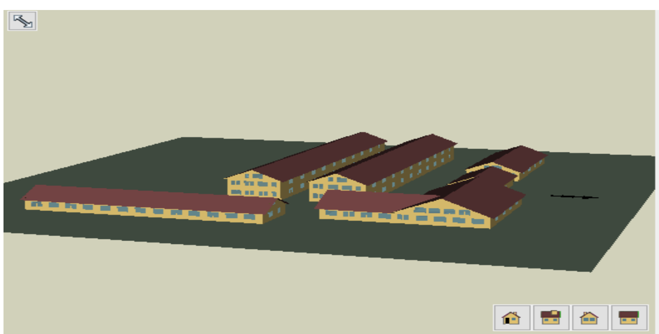

Fig. 1: Layout of the School building designed in BEopt.

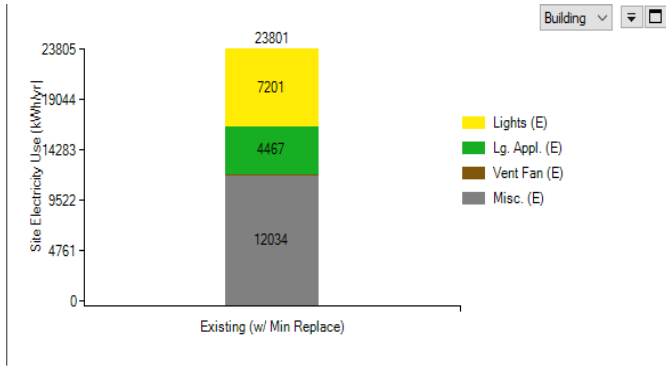

Fig. 2: Annual Electrical energy of the school, showing different loads.

There are six (6) separate buildings in the school which houses the principal staff offices, classrooms, library and teaching staff rooms. The primary load in the school, as can be seen in fig. 2, is lighting, large appliances, ventilation fans, and miscellaneous load. Since Nigeria is a temperate country, the classrooms are built in such a way that opposite walls are practically made up of windows to allow for natural sunlight and ventilation during school hours. The lighting energy is for perimeter lighting during the night and lighting in offices when required. The bulk of the energy is on miscellaneous. These are energy used by the plug-in loads. The large appliances are for the few air conditioners in the Computer laboratory. The active school session is for 6 hours (8 am – 2 pm) Mondays through Fridays. The peak load for the day is estimated at 8.83 kW, and the daily energy is 65.21 kWh/day.

III SIZING AND OPTIMIZATION OF SYSTEM.

The system sizing and optimization was done with HOMER pro [11]. The average annual solar irradiance for the location is 4.71 kWh/m^2/day. The plot is shown in fig. 3. HOMER simulated over 700 combinations of different solutions for the system. An optimized system was chosen by HOMER based on some parameters, which include net present cost (NPC), cost of energy (COE), excess energy generated, initial and operating cost, and battery autonomy. The optimized solution proposed by HOMER pro consists of 42.2 kW Canadian solar superpower CSK6-295MS panel each 295 W, 60 pieces 12V 205 Ah [12] Trojan lead acid battery, 360 V DC bus voltage hence, and battery autonomy of 40.6 hours to provide backup for periods of bad weather and cloudy days.

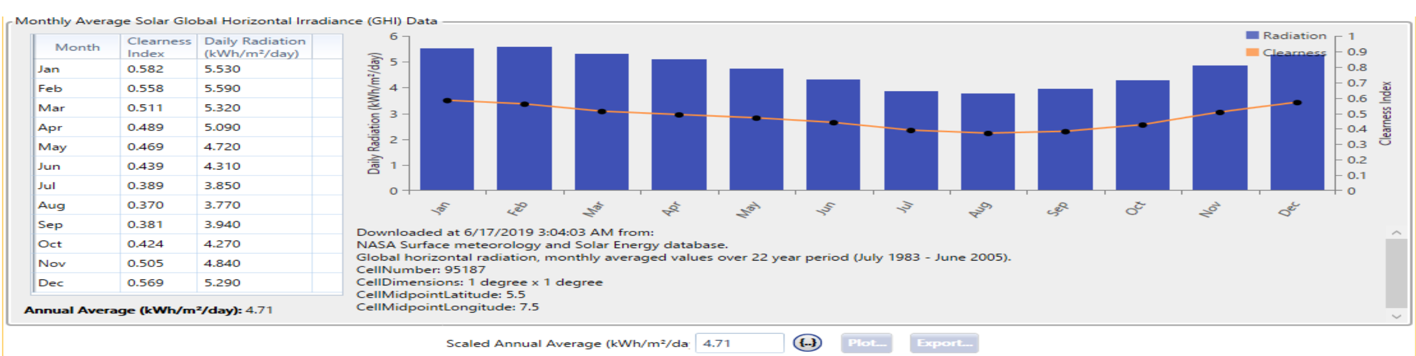

Fig. 3: Annual average solar energy potential of the selected school.

The optimized power converter size for the system is 9.78 kW, with a system peak load of 8.83 kW. Though the efficiency of CSK6-295MS panel is 18.02%, it made more economic sense when compared to some monocrystalline PV types that have an efficiency of 20% [13]. The battery storage is charged up during high solar insolation. Fig. 4 shows the load profile for the school, and fig. 5 shows the optimized result for the school. The net present cost (NPC) of the system is $98,471, with a Levelized cost of Energy of $0.320 per kWh. The bulk of these costs is accrued due to battery storage. If reliability is not the priority of the system, the storage capacity can be reduced to lower the cost of the system.

The electrical load for the school is primarily an AC load that is considerably constant every day. The system is 100% renewable and from the optimized result, can meet the energy demand of the school. The percentage of unmet electric load in a year is 0.0839%, which translates into 20 kWh/yr.

The optimized schematic of the system in HOMER pro is shown in fig. 6.

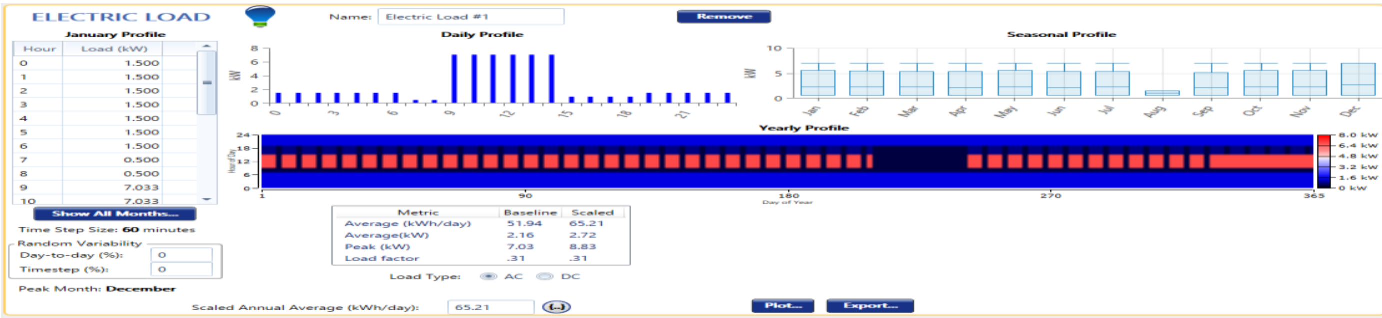

Fig. 4: Daily, Monthly and Annual load profile for the school from HOMER pro

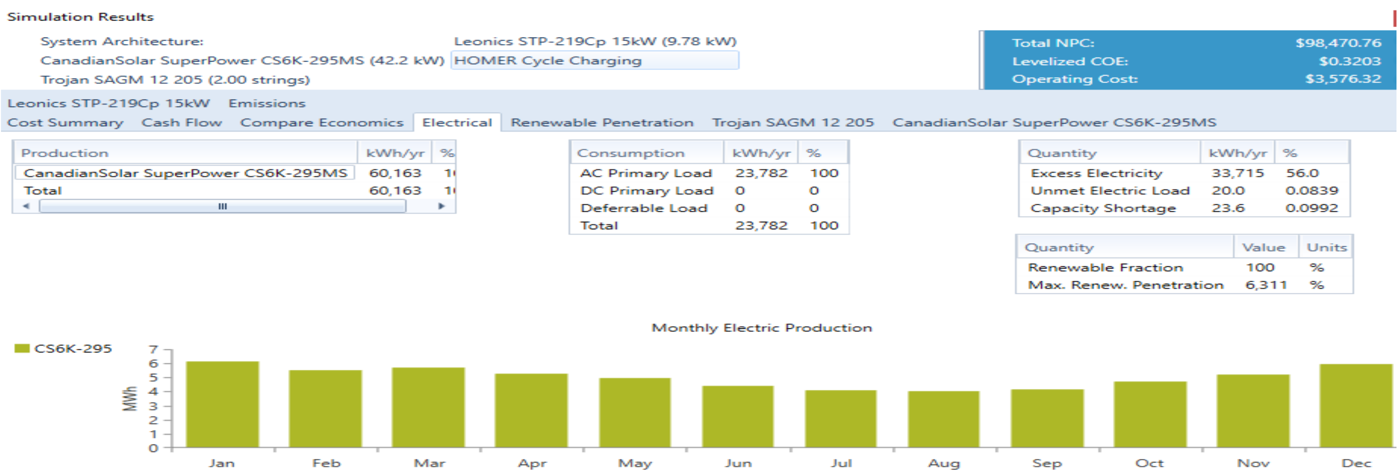

Fig.5: HOMER pro Optimized result for the school.

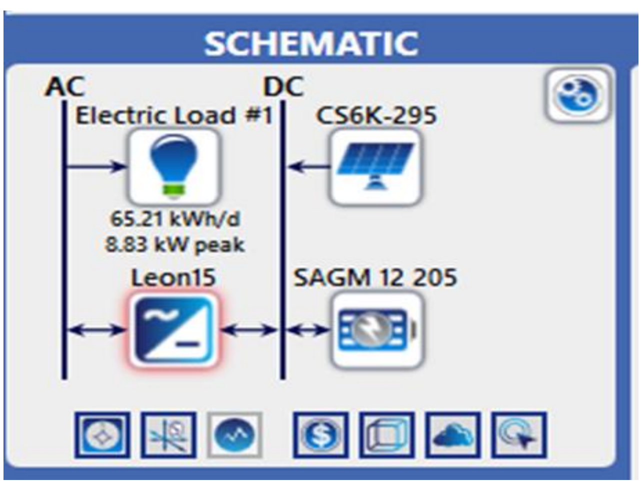

Fig. 6: Structure of the system showing the subblocks in HOMER pro.

IV PROPOSED SYSTEM DESIGN

The proposed system is made up of a roof-mounted solar PV, DC-DC boost converter, MPPT controller, battery bank, DC-AC converter, AC voltage controller, and electric load.

A SOLAR PANEL

Canadian solar CS6X 295W solar panel is used to simulate the system, and the configuration is 15 series-connected module per string and 10 parallel string to achieve the system power of (15*10*295W) 44.25 kW. A DC bus voltage of 360V is adopted for the system to reduce the cost of the copper conductor needed to carry a larger current for a lower voltage.

B DC – DC BOOST CONVERTER

The DC-DC boost converter is to regulate the DC voltage that is coming out from the solar panels and output a fixed 360V needed to charge the battery bank and serve as the input to the DC-AC converter (inverter). The circuit diagram for the boost converter is shown in fig. 7. The output voltage and current of the inverter are related to the input voltage and current by (1) and (2). It can be observed from the equations that both current and voltage is dependent on k, the duty cycle. The output voltage can be managed by fixing the duty cycle.

$$V_{OUT} = \frac{V_{IN}}{(1-k)} \quad (1)$$

$$I_{OUT} = (1 - k)\, I_{IN} \quad (2)$$

V_{OUT} and I_{OUT} is the output voltage and current respectively from the converter.
V_{IN} and I_{IN} is the input voltage and current respectively to the converter.
k is the duty cycle of the converter.

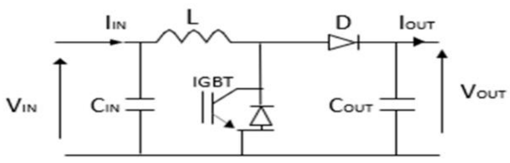

Fig. 7 DC-DC boost converter Circuit diagram

C MAXIMUM POWER POINT TRACKING

The MPPT was applied to the boost converter following the PV system to maintain the power production of the PV system even in the event of variation in the environmental conditions. The tracking scheme used for the system is the perturbation and observation MPPT tracking Scheme. This MPPT system makes use of the output voltage and current from the PV system as input pulses to drive the pulse generator to control the boost converter duty cycle. This, in turn, then acts as feedback to control the voltage from the PV and eliminated ripples, thereby keeping the voltage value stable.

D BATTERY STORAGE SYSTEM

Trojan SAGM 12V 205 Ah was proposed in the HOMER sizing. The battery will provide autonomy of 40.6 hours. The parameters of the battery are as shown below:

Nominal Voltage: 12V
Nominal Capacity: 2.63 kWh
Maximum Capacity: 219 Ah
Maximum Charge Current: 41A
Maximum Discharge Current: 300A

The storage system is made up of 60 units of the battery, and the configuration is explained below;

The number of parallel strings:

$$N_p = \frac{Total\ Battery\ Size}{Rating\ of\ Battery} = \frac{438}{219} = 2\ parallel\ banks$$

The number of batteries in series:

$$N_S = \frac{DC\ Bus\ Voltage}{Battery\ Nominal\ Voltage} = \frac{360}{12} = 30\ batteries$$

E DC – AC CONVERTER WITH CONTROL

The voltage source inverter in this system is to convert the fixed DC Voltage into a single-phase AC voltage with variable magnitude and fixed frequency of 50Hz. The inverter design employed for this project is a full bridge, single-phase IGBT-based inverter [14]. It consists of four transistors, two of which are turned on per time for the positive cycle while the other two acts on the reverse cycle. The switches/gates are controlled by controlling the pulse rate. However, the inverter output voltage is easily affected by variations in the line and other system parameters. Therefore, the inverter output must be properly controlled to maintain a constant value [15]. For this project, the voltage control scheme was incorporated to maintain a steady DC voltage input to the inverter. The boost converter voltage is sensed and compared with a pre-set reference value; any error is then fed into the PI controller for correction. The output from the PI controller is then multiplied by a sinusoidal value to convert it to AC. This AC waveform is compared with a triangular waveform to generate a pulse for controlling inverter gates. Fig.8 shows the implemented control scheme for the single-phase inverter used in this system in block diagram form. [14,15]

F LOAD

The load for the system is a purely resistive load. This is informed by the fact that the facility is a school, and the demand is resistive in nature.

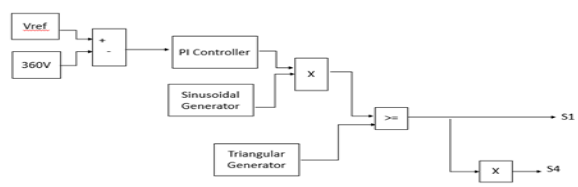

Fig. 8: Voltage Controller block for inverter

V DYNAMIC SIMULATION RESULTS

The system was simulated in MATLAB/Simulink software to determine the overall system behavior and dynamics to change in irradiance, temperature, load, and general harmonics of the system. The simulation result is shown in fig. 9-12

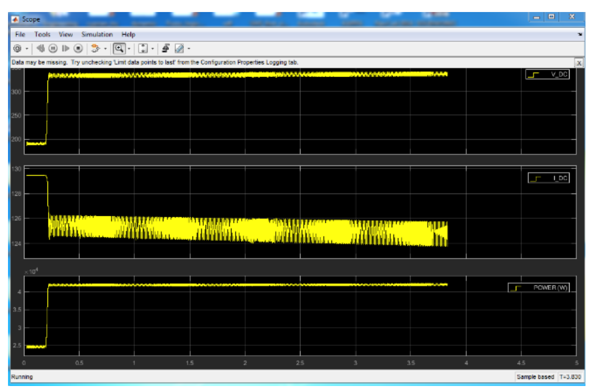

Fig.9: Voltage, Current and Power output from the Solar PV

The output current varies between 124 – 126A output current, and the power output is about 45 kW. The output voltage from the MPPT is seen in fig.10 with a more stable output of 360 V

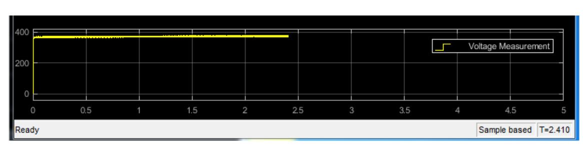

Fig. 10: Output voltage from the MPPT.

The output for the storage battery is shown in fig.11 with an initial state of charge set at 70%.

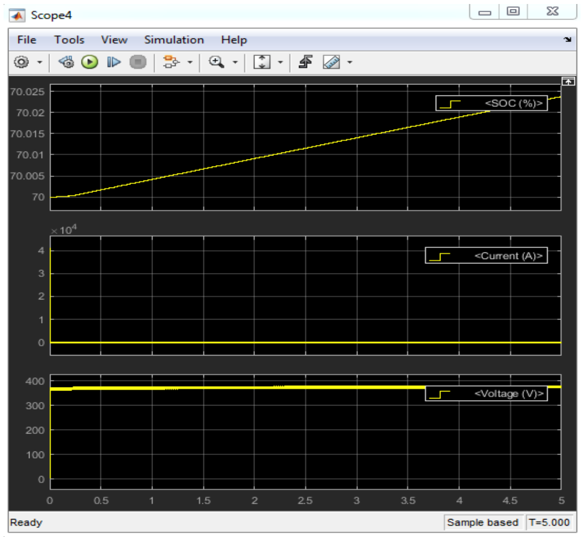

Fig.11: SOC, Current, and Voltage of the battery.

The discharge current is zero because the battery is in the charging state. The output RMS voltage from the inverter is shown in fig.12. This power is fed into the distribution box and distributed to the load.

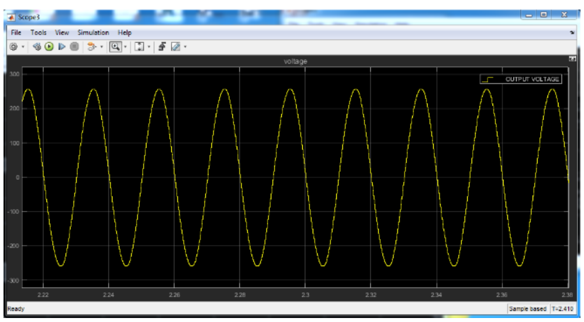

Fig. 12: Output voltage from the inverter.

VI CONCLUSION

For a country like Nigeria that is currently having issues with power issues, a distributed power system is highly needed to take the pressure off the existing national grid. For a public school like the one in the project, the power is in a very bad state, and the proposed stand-alone solar PV system will mitigate these power issues. This will deliver power in a timely manner and reliably. The system was simulated on a MATLAB/Simulink, and the dynamic behavior was studied. This showed acceptable output, and the simulated result met the load requirement for the school. If implemented, the power of Uyo High school can be met satisfactorily.

VII ACKNOWLEDGMENT

The authors would like to thank the School of Graduate Studies, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, for providing the enabling environment for carrying out this research.

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