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Characterization and Sizing of a Standalone Solar Photovoltaic (PV) System as an Instructional Resource for Power System Students

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Abstract— Installation of small scale standalone solar photovoltaic plants are ideally suited for educational institutions, as they can be more useful in the training of students and supply of energy to a portion or the entire institution. The comprehensive study of electrical power systems is a key element of many curricula in engineering education. A PV System has been designed and realized at the Faculty of Engineering and Technology (FET), University of Buea used both as a power source to some units of the lab and as an instructional resource for teaching electrical power system and renewable energy concepts. The system consists of photo-voltaic arrays, charge controllers, lead-acid storage batteries, inverter units to convert DC power to AC power, electrical loads, several fuse and junction boxes and accompanying wiring, and measuring instruments for currents, power factors, voltages and harmonics in the system. This solar PV system is extensively used to illustrate electrical concepts in the laboratories. In this paper, we used the PVSYST software, a solar simulator, to optimally model a standalone PV System for load parameters in the Department of Electrical and Electronic Engineering. This is a powerful simulator as it gives meaningful guidance on critical aspects of the installation process like optimum tilt angle and number of the battery / solar panel strings. The simulation was performed over a full year in hourly steps and provides a complete report on the PV System. This application showed the most optimum way a 2.5 kW standalone PV System can be designed, sized and installed with minimum system loses and high capacity to harness the solar potential of the site. The paper further established an experimental set up whose aim was to characterize the photovoltaic (PV) modules before subsequent installation. Then a practical sizing application of the PV system supplying the Power Systems Laboratory in the Faculty of Engineering and Technology, University of Buea was done by dissecting the different component sizes and their capacities. Interestingly, the feedback from this pilot PV project indicates that it is a more valuable experience as students through this exposure can design and implement a real-life PV system. The obtained simulation results showed that the PV System comprising of PV modules, charge controller, battery and inverter is optimal in terms of efficiency, reliability and environmental friendliness.

Index Terms— Standalone Solar Photovoltaic, PVSYST software, Instructional Resource, Simulation, Power Systems

1 Introduction

The famous argument about what is the supreme and most effective way of teaching student is now as vigorous as ever. In the field of technologies, the hands-on or practical application approach is by far the leading effort in making education more effective [1]. Making the training approach in Electrical engineering more practical facilitates the understanding of the seemingly virtual concepts involved in this subject. It is in this regard that, the Electrical and Electronic Engineering Department at the University of Buea is trying to actively incorporate such approach into various courses within the program.

Owing to the developmental challenge, the excruciatingly slow pace of rural electrification in Cameroon is due to several challenges that need to be addressed. Some of the issues are technical while others are non-technical.

Within the spectrum of possible sources, solar energy is by far the hottest topic because of its relative abundance in all parts of Cameroon. The deployment of solar energy on a community scale is technically very feasible, but very expensive for rural communities to finance. This has become both the solar challenge and the solar dilemma which stakeholders in Cameroon need to address with the utmost urgency. Therefore, FET is bridging the technical challenge by empowering its students with the needed expertise to exploit this abundance insolar resources. By switching over to solar energy, not only will it be beneficial to the environment, but also will prove to be cost-effective and a real means of development. Energy from the Sun is increasingly becoming a major energy substitute because the abundance of solar energy falls on the Earth [1]. The primary concern for the implementation of Solar PV is the upfront cost [2]. Installing a system to harness Solar Energy at a university could cost millions of FCFA. However, looking at it for the long run, after the initial cost, solar energy costs next to nothing.

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2 System Sizing / Characterization

Designing an appropriate PV System involves finding a cost-effective arrangement of array size together with all other system components that will meet the projected energy need sustainably. Sizing a PV System involves the following information.

i. The daily or hourly energy requirement
ii. The current-voltage (I-V) characteristics of the chosen PV module at various irradiances and temperatures
iii. The incident average daily irradiation on the solar array plane spread across the months of the year
iv. The optimum tilt and azimuth angles
v. The maximum number of uninterrupted cloudy days likely to be experienced
vi. The projected increase in cell temperature above ambient of the PV modules in the array
vii. The required security of supply
viii. The selected DC bus voltage
ix. The probable energy losses in the battery (in percentage), power conditioning equipment and control system
x. The probable array losses due to module mismatch, cable, dust and shading and voltage drop across blocking diodes

A technique similar to Siemens Solar in Germany [2] was used in the design of the system. The PV system design for the laboratory followed the procedure: load estimation, calculation of array current, battery sizing, array sizing, inverter sizing and cable sizing. The characterization of the component to determine whether they are functioning properly as stated in the manufacturer's manual was done before final installation.

2.1 Load estimation in the Laboratory

Information on electrical appliances to be used by the solar PV system is very critical for designing the PV system. The factors considered include the power used up by the load; supply voltage type and magnitude required and for loads that use alternating current (AC), the power factor and frequency are critical. The most common types of loads in the lab are bulbs, digital storage oscilloscopes, function generators, DC supply, photocopier, variable resistor, computers (desktop as well as lap-top used by students) and printers (laser as well as inkjet).

Not all the loads listed are supplied by the designed PV system. Generally, the efficiency and power handling capability are better for units operating at a higher DC voltage [3]. However, this is advantageous in that the higher operating voltage has a lower current need to produce the same power. High current means large wire size, expensive and hard to get fuses, switches and connectors [4]. Considering these factors, the operating voltage of the system is selected to be 24 V DC. Below is a list of appliances in the electrical engineering lab.

Table 1: Energy Audit at the Electrical Engineering Lab

Load description	**Number in use**	**Power rating (watts)**	**Total rating (kW)**	**Hours Usage/day**	**Energy kWh/day**
Lighting (LED)	25	7	0.175	5	0.875
Digital Storage Oscilloscope	6	18	0.108	4	0.432
Function Generator	6	10	0.06	2	0.12
DC Supply	8	20	0.16	2	0.32
Photocopier	1	30	0.03	0.5	0.015
Variable Resistor	1	250	0.25	0.5	0.125
Variable Resistor	2	100	0.2	0.5	0.1
Soldering Iron	2	50	0.1	0.5	0.05
Laptop (for students)	7	60	0.42	1	0.42
Total			**1.503**		**2.457**

2.2 Sizing/Selection of Solar PV module

Information regarding the location where the solar PV system is going to be installed before determining the size of the PV module is essential in the design [5]. Data such as the number of sunshine days in the year, the month with maximum/minimum sunshine hour and the annual average sunshine hours. In this research, the University of Buea was used as the site and solar insolation data was obtained from Meteonorm Meteorology database and the average solar insolation was found to be 4.5 kWh/m²/day (or Peak Sun of 4.5 hours).
Total load = 2.5 kW

Period of operation or duration = 4.5 Hours
Then, Total Watt-Hour = 2.5 × 4.5= 11.5 kWh

The period of the solar panel exposed to the sun = 4.5 Hours (Averagely between 11 am and 3:30 pm). Therefore, solar array wattage = 2.5 kW
Hence solar panel of 2,500 W will be needed for this design. If solar panels of 200W / 47 V are used, the number of panels to be arranged in parallel to achieve 15,000 Watt is:

$$\text{No. of panel} = \frac{2500W}{200W} = 12.5$$

This shows 13 of 200 Watt solar panel will be required for this design

2.3 BATTERY SIZING

Battery sizing involves determining the capacity of the battery (Ampere-hour), the voltage of the battery (Volt) and type of battery (Ordinary battery or Deep Cycle battery). The battery capacity is calculated by using the following expression,

$$C_b = \frac{E}{n_b \times DOD \times V_{sys}} \times N_a \quad (1)$$

where, C_b = battery capacity (Ampere-hour or Ah), E = daily energy consumption (Wh), η_b = battery charging efficiency (normally 0.8 to 0.95), Vsys = system voltage (Volt), N_a = autonomy days, DOD = Depth of Discharge

$$C_b = \frac{11500}{0.95 \times 0.5 \times 24} \times 1 = 1008.77\ Ah$$

In order not to damage the chosen battery before its lifespan, an assumption is made such that only a quarter (¼) of the battery capacity will be utilised so that the battery bank will not be over-discharged. Consequently, the battery capacity now becomes;

$$C_b = 1008.77 \times 4 = 4035.08\ Ah$$

Now, for a 200 Ah, 12 V battery the number of batteries that will be needed is;

$$C_b = \frac{4035.08}{200} = 20\ batteries$$

Hence, for this design, 20 batteries will be needed.

2.4 Charge Controller Sizing

A charge controller should be sized such that it should be able to support the short circuit current (I_{SC}) of the array and the maximum battery to load current (I_L max) [5]. The following equation is used to calculate the load current;

$$I_L = \frac{P_T}{V_{sys}} \quad (2)$$

where, I_L = maximum battery to load current (Ampere), V_{syt} = system voltage (Volt), P_T = Total power (Watt). The load current becomes;

$$I_L = \frac{2500}{24} = 104.2\ A$$

Usually, the charge controller should be selected with a current-carrying capacity of two times that of I_{Lmax} and I_{SC}. However, there are no inductive loads with high surge currents connected to the PV System in the lab hence the scaling factor can be ignored but this aspect becomes critical when loads with high surge currents are part of the system. The voltage rating of the charge controller should be the same as the operating voltage of the PV system. Therefore, a charge controller of 120 A / 24 V is needed to charge the battery banks.

2.5 Sizing/Selection of the Inverter

Hence the input DC voltage of the inverter should be 24 V with an output AC voltage of 220 V and the frequency of inverter should be that of the national grid frequency (50 Hz). The inverter power rating is calculated by using the following equation below;

$$P_{inverter} = \frac{P_{load}}{PF \times \eta_{inv}} \quad (VA) \quad (3)$$

where, $P_{inverter}$ = Power rating of the inverter (VA), P_{load} = Load power (Watt), PF = Load Power factor, η_{inv} = Inverter Efficiency.

Usually, during inverter sizing, the power factor (PF) is taken as 0.8 and efficiency is taken as 0.8 [5]. A critical point in inverter sizing is the fact that during turning ON of some appliances, the initial power consumed by the device becomes higher than the rated power. To carter for this surge power, the power rating of the choice of the inverter should be 2 to 3 times the calculated power [5].

$$P_{inverter} = \frac{2500}{0.8 \times 0.8} = 3906.25\ VA$$

Since the total load is 2.5 kW it is advisable to size the required inverter to be 4 kVA as designed for solar panel ratings. Hence 4 kVA pure sign wave inverter is recommended in other to prolong the lifespan of the inverter.

2.6 Wire size for PV system

The voltage drop between the solar module and the charge controller depends on the inner diameter of the conductor. The conductor's thickness shows how much energy can be dissipated along the conductor. The Standard Wire Gauge (SWG) formula is used in the sizing of the wires used in the design. The wire cross-section area is calculated by the equation below;

$$S = \frac{0.3 \times L \times I_M}{\Delta V} \quad (mm^2) \quad (4)$$

where, S = Cross-Sectional Area of wire (mm2), L = Length of wire joining solar module and charge controller (meter), I_M = current flowing from the solar module to charge controller (Ampere), ΔV = maximum allowed voltage drop percentage (5 %). ΔV indicates the voltage drop or voltage loss across the wire.

2.7 Characterization of the Solar panels

In other to verify the properties of the panels if they tie with the manufacturer's specification, an experiment was carried out for a week. A solar module Analyser was used to measure the following parameters; maximum voltage, open-circuit voltage, maximum current, short circuit current, maximum power and fill factor, a solar power meter was used to measure the amount of irradiance, a thermocouple to measure the temperature of the module and a thermometer to measure the ambient temperature. The protractor was used to measure the tilt angle which the solar panel made with the horizontal. Magnetic declination, the angle difference between magnetic south and true solar south were taken into account when determining proper solar array orientation. The solar panel was mounted in an open space at a tilt angle of 10^0 to the horizontal.

Fig. 1. Experimental Set up

From literature, for countries in the northern hemisphere, solar panels should always face true South and true north for countries in the southern hemisphere. South West region is located near the equator but partly in the northern hemisphere, so using a compass, the solar panel was oriented to face the true south [6]. The voltage, current, power generated with the corresponding atmospheric temperature, module temperature, irradiance was collected every 5 minutes with the assumption that there is little change in solar intensity during measurement. The same procedure was repeated for a week and average values were obtained and presented below.

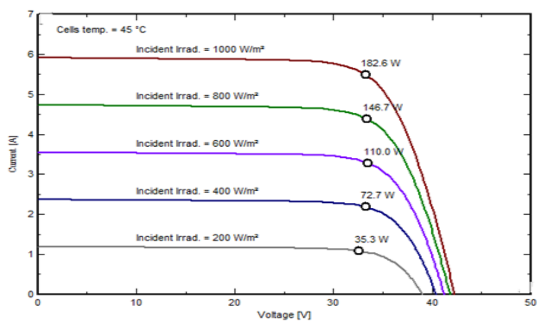

Fig. 2. I – V curve of the module

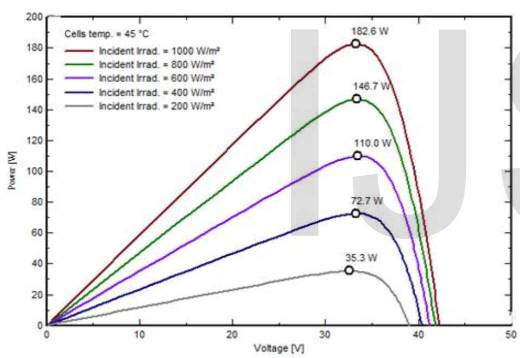

Fig. 3. P – V curve of the module

The data collected was analysed as follows; the values of the power output of each irradiance was determined by plotting maximum power against voltage from the irradiance that yielded the maximum power output. Other parameters like the open-circuit voltage, short circuit voltage and fill factor were also analysed. The variation of solar irradiance with time was also analysed alongside the weather conditions that could influence this variation. Data computation was done by R - Statistics Software. The climate of Buea is humid with an extended period of rainfall characterized by incessant drizzle, which can last for weeks.

The experiment was carried out in days of both sunny and cloudy days. Data was collected and the following areas were looked into; photovoltaic parameters assessment, solar radiation distribution and the choice of an optimum tilting angle for the location. The results were analysed periodically and daily with each day having an average of values collected.

3 Simulation of the Solar PV System

The simulation was done with PVSYST software [7], a photovoltaic application developed by the University of Geneva. PVSYST is a tool used by researchers, engineers and architects and it is also an essential pedagogic tool. It also has many tools to simulate the behaviour of PV modules and cells according to radiation, temperature, shadings. The simulation process starts by inserting the inputs into the PVSYST software like the tilt angle, load data, choice of solar panel, charge controller, battery and inverter. The system voltage has to be set. Below is the system architecture of the simulated system.

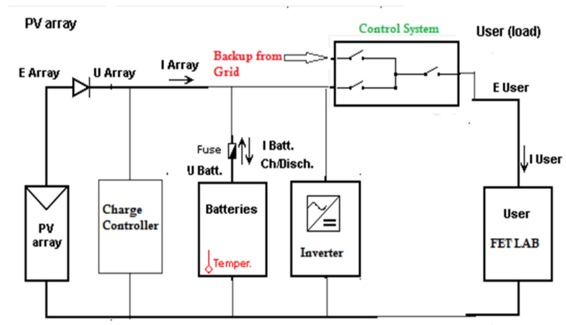

Fig. 4. Typical layout of the PV System

The design aimed at selecting appropriate power generating and storage components that will utilize the available solar irradiance to meet the load in the electrical engineering lab. The components used include PV solar panels, batteries for storage, power converter and a grid for backup. An initial simulation interface displaying some site information is shown below.

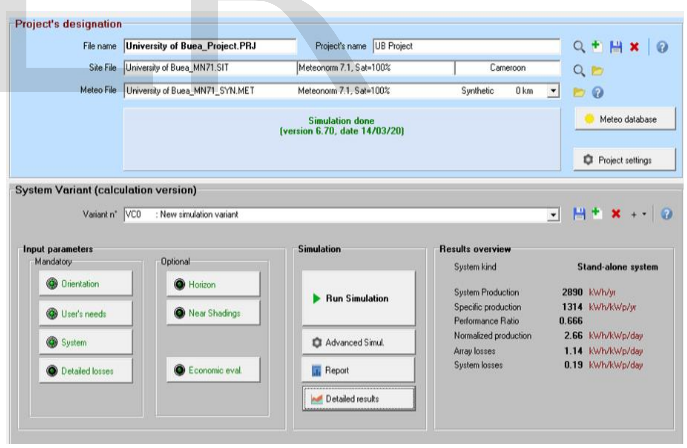

Fig. 5. Simulation dashboard of the PV System

Solar resource assessment for the University of Buea was done by obtaining solar irradiance data from Meteonorm 7.1 meteorology database. The location of the installation site within the University is latitude 4.15^0 and longitude 9.28^0 and this information was used to obtain solar resource for the design. The annual average solar radiation was scaled to be 3.991 kWh/m2/day. There is the availability of solar radiation during the year; hence, a substantial quantity of PV power output can be generated. The average monthly distribution of irradiance for the University of Buea is displayed below;

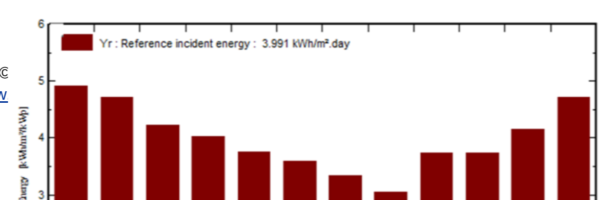

Fig. 6: Monthly Incident Irradiance at the University of Buea

The simulation of the system began by allocating an optimal tilt angle for the orientation of the panels. This was done by using information from literature and comparing with the experiment we conducted and it was realized that 10^0 was the best angle where more solar energy was harnessed from the panels. The value was immediately incorporated into the application as shown below;

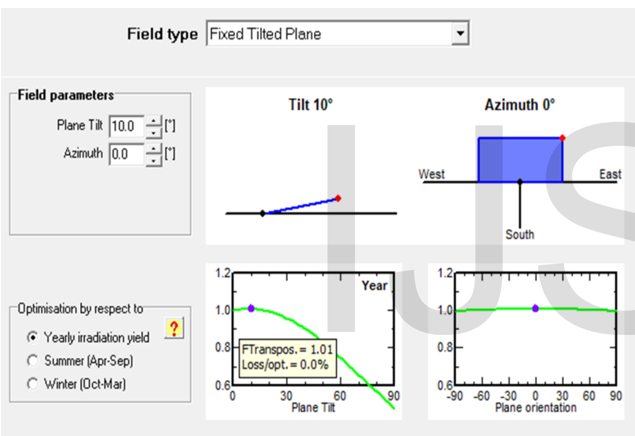

Fig. 7. Tilt angle assignment

Based on the energy audit of the laboratory, the load data, PV modules, charge controllers, battery bank, and inverters, were meticulously sized into the system and simulated. The nominal energy generated by the simulated system was 2.22 kW and was sufficient to power the loads presented without any unreliability issues. The distribution of the energy produced is shown below.

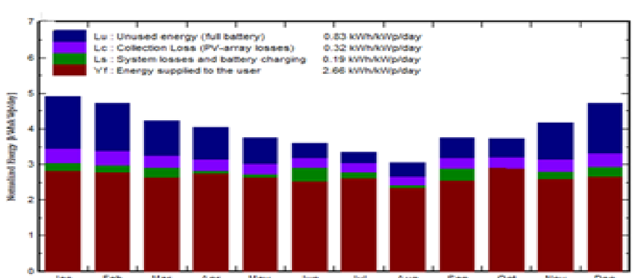

Fig. 8. Monthly Normalized Energy Production

Fig. 8 shows a cross-section of the various energy matrix in the system. The system energy is distributed as follows; energy supplied to the loads is 2.66 kWh/day, unused energy when the battery bank is fully charged is 0.83 kWh/day, PV array losses is 0.32 kWh/day, and the system losses due to battery charging is 0.19 kWh/day. The excess energy after the battery bank is fully charged is an indication that the system was properly sized and can carter for any growth in the energy demand. The losses in the energy system have to be factored in the design so that the system can be stable self-perpetuating. The overall energy dynamics in terms of percentage is illustrated below;

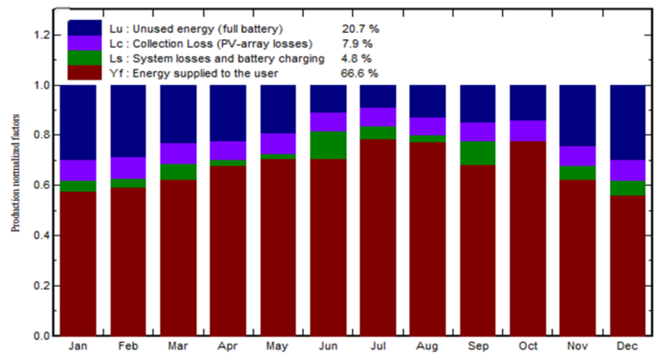

Fig. 9. Normalised energy production and loss factors

Fig. 9 indicates that the total system losses amount to 12.7 % and this is reasonable for the system. It is observed that the energy output at the solar array within July and August are lower as shown in figure 8. This is because, in Buea, these months are usually very cloudy with frequent rainfall,

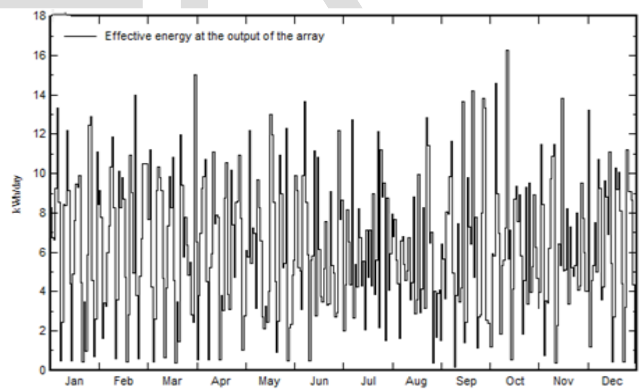

Fig.10. Solar Array output Energy

The average monthly state of charge of the battery bank is fairly constant in months where the solar irradiance is high and relatively stable than months with fast changing weather. Figure 11 show the mean monthly state of charge of the battery bank.

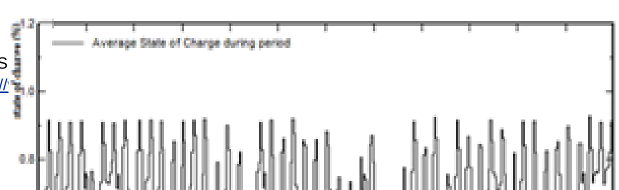

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Fig. 11. Battery State of charge distribution

The average monthly state of charge of the battery bank is fairly constant in months where the solar irradiance is high and relatively stable than months with fast changing weather. Figure 11 show the mean monthly state of charge of the battery bank.

The monthly energy generated and monthly solar energy incident on the panels for the entire system is presented below. This information can be used in making forecasts on the future projected energy the system can generate. The monthly details based on the simulation are shown below.

Table 2: Annual simulation data

Month	Available Solar Energy / kWh/m^{2}day	Unused Energy (full battery) / kWh	Energy Supplied to the Lab / kWh
January	4.66	99.94	193.6
February	4.58	83.25	172.5
March	4.22	66.04	180.3
April	4.13	58.79	181.1
May	3.94	48.63	180.4
June	3.79	25.98	167.2
July	3.50	20.53	179.3
August	3.12	26.14	160.4
September	3.77	36.16	168.3
October	3.67	35.50	198.3
November	3.98	66.31	171.0
December	4.44	95.56	181.1
Total		**662.84**	**2133.4**

4 Estimated Project Cost

The pilot project being a venture within a state University in Cameroon, the procurement process did not incur any huge financial implications. Some aspects of the logistics of ordering equipment by a state institution through Cameroon's purchasing system where items must go out for bid unless they are ordered from a vendor on the state's contract list. The department had to abide by Cameroon's purchasing policies and the researchers did not have much control over this issue. However, for pedagogic reasons, the local cost of materials was used in the analysis. The construction cost of different items of work for different components of a project used in this paper is based upon unit prices and lump sum prices. The quantities of work have been calculated from the actual dimension of the actual work whereas the cost portion has been derived from previous locally executed projects. These cost estimates have been prepared in local currency i.e. Central African Franc.

The entire cost of the 2.5 kW was found to be 7,500,000 XAF. This includes the cost of pre-feasibility studies of the site, preparation of detailed construction drawing, supervision/ inspection or construction work. It includes all cost of these types, whether incurred by the owner or the engineer, in addition to the salary costs; it includes equipment and supplies, communication and transport.

5 Setting up of the PV Unit

The energy unit at the lab comprises two independent generating small PV plants (System 1 & 2) connected in parallel to a 24V DC line. System 1 comprises of 8 solar panels with ratings 200 W / 47 V, 6 batteries of ratings 200 Ah / 12 V connected to a charge controller while System 2 is made up of 4 solar panels 200W / 47 V. Since the two systems are not interconnected, they each have a charge controller with ratings 24 V/ 60 A. The power is next connected to a DC to AC inverter and is then supplied from the inverter's output to a single-phase 60 Hz, 220 V AC load. The solar panels are 47 V DC units and were chosen for their ultra-clear tempered glass that is manufactured for long term durability. The inverters used for Systems 1 & 2 have a power rating of 1.563 kVA (or 1000 WP) and 3.125 kVA (or 2000) respectively. The battery banks contain 6 deep-cycle lead-acid batteries connected in parallel. The overall project structure is presented in Figure 12.

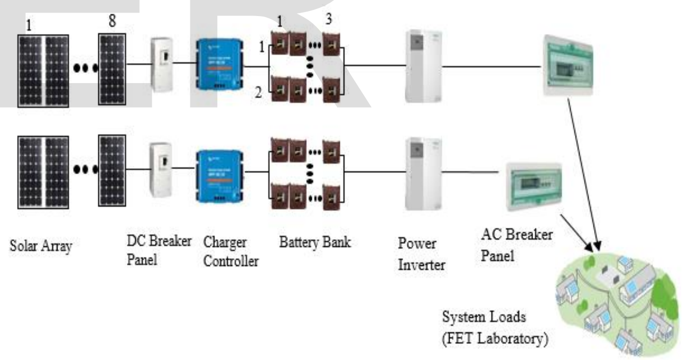

Fig. 12. Installed PV System (adapted from [8])

Fig. 13. Installed PV System

6 Recommendations

In other to scale up the rate of knowledge acquisition, effi-

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ciently utilise energy generated by the PV system and enhance awareness on the use of solar PV for power generation in Cameroon, the following recommendations will be useful.

- The installed PV system at the Department of Electrical and Electronic Engineering are two separate small PV systems which supply energy to different units of the Laboratory. These two systems should be integrated to exploit the situation of excess energy in any of the systems thereby minimizing energy wastage.
- The government should fund research institutions like universities, polytechnics to develop pilot solar PV plants that will serve as a training ground to practically facilitate the somewhat virtual concepts in the design of such systems.
- The government should use legislative instruments to reduce the cost of importation of Renewable Energy Technologies (RET) most especially solar PV to reduce the high cost in Cameroon.

7 Conclusion

The manual calculations used in this system show a positive correlation with the practical performance of the system. It is observed that the PV array can supply power to operate the AC appliances for 5 hours per day from Monday to Friday. Power supply with this system is completely eco-friendly and most effective in November to March (the heart of dry season in Buea – Cameroon). Due to economies of scale, large scale power production systems (like in kW or GW) are cost-effective. The tilt angle of 10^0 was used in the simulation, however, tilt angles of 0 to 15° are optimal for the site of the installation.

Arguably, a large PV system to power all the equipment in the lab and beyond, will be too expensive for the Department of Electrical and Electronic Engineering. However, similar dividends could still be realized from a small scale system like the installation at the Department of Electrical Engineering. The enhancement to training, specifically in making electrical power knowledge transfer more physical, intuitive, and practical are substantial and the cost involved in adapting the small scale PV setup is reasonable. The PV System is a timely choice for power system students in the University of Buea as these are energy sources of technological, political, and economic significance to a developing country like Cameroon with enormous solar potentials. The crucial fundamentals of this testbed notion presented in this paper are the design procedures involved in PV systems with their complex electrical interactions.

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