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Estimation of Solar Potential for Low-Energy Applications in a Tropical Location

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Abstract— In order to meet the growing demand for energy consumption in the face of depleting global oil reserves, there is need to leverage on the clean, free, available and renewable properties of solar energy within a tropical region as Nigeria. This study attempts to estimate the potential electrical energy derivable from incident solar radiation over a tropical location for low-energy consumption application. One year (2011) archived data of solar radiation were extracted, from which solar energy potential was computed using the I-V specifications of a standard issue 200 watts mono crystalline photovoltaic panel. An inventory of low-energy consumption electrical and electronic appliances from a research facility was used to develop the energy demand profile. Model of the energy potential versus energy demand as well as storage potential for this facility was simulated using Simulink PV-project application. Results show that solar radiation within the location has varying intensities across different periods of the day and seasons of the year; which is however adequate to meet the projected 15 kW maximum cumulative load demand given sufficient storage facilities.

Index Terms— solar radiation, photovoltaic cell, renewable energy, diurnal variation, energy consumption, storage

1 Introduction

HARNESSING the renewable energy potentials of nature, such as sunlight, wind, water or geothermal resources around the globe becomes imperative in light of dwindling oil reserves and growing energy demands [1]; and it is enjoying considerable attention from scientists all over the world. The spate of epileptic power supply in developing countries such as Nigeria further necessitates the need for alternative power sources outside those currently obtainable. Modular power stations have also been recommended to reduce the heavy burden on the Nigerian power grid. To this end concerted efforts are being made to characterize solar power potentials in tropical regions such as Nigeria due to the abundance of high intensity sunshine available all year round. The energy coming from the sun naturally is renewable, sustainable and if properly harnessed, assures man of endless energy supply. Ozone layer depletion by man [2], earth's rotation and revolution, among other factors, causes the intensity of sun's energy to vary greatly with latitude, time of day, and season of the year [3], [4]. The sequence of occurrence of such solar energy alteration in the country is a good design variable in solar energy technology and manufacturing, and it must be considered for accurate estimation of solar power potential for the region [5].

The calculation and optimization of the energy output and economic feasibility of solar energy systems such as buildings and power plants requires detailed solar irradiance data measured at the site of the solar installation [6]. Also, installation programs should always include a sufficient service component [5] and a detailed analysis of projected performance evaluation. In recent times a good number of research works have focused on solar energy and solar power potentials in Nigeria. A few of such works include: [7], which investigated wind-solar hybrid power potential over Akure. [8], which examined the challenges of sustaining off-grid power generation in Nigerian rural communities while [5] studied the environmental solar energy technology needs in Nigeria. Furthermore, [9] worked on the planning and budgeting considerations of sustainable solar power system in Nigeria while [10] examined Solar Energy Potentials and Utilization in Nigerian Agriculture sector. Lastly, [11] investigated renewable energy technology in Nigerian resource availability and potential for application to agriculture. This will in addition to studying the diurnal and seasonal distribution of solar energy to estimating the solar power potential from measured solar radiation over a tropical location for low-consumption applications in an educational facility.

Any solar power generating scheme is concerned with trapping solar energy (insolation); provision of suitable thermal and mechanical converter, and a method of storing energy for use in non-solar or low solar periods [12], herein photovoltaic (PV) cells come in handy, being the electronic devices which convert the energy of sunlight into electricity based on fundamental principles of semiconductors [13]. The attendant advantage of Solar photovoltaic (PV) technology include supplying electricity without combustion, less maintenance need since nothing is consumed or worn-out during their operations, and possibility of conversion to other forms of energy [14].

Solar radiation models are desirable for designing solar energy systems and good evaluations of thermal environment in buildings [15]. Developing a good model for any solar power installation will be difficult without adequate knowledge of the DC voltage required by the system, daily average sunshine hour of the installation site and daily average energy demand in watt-hours. Since the power produced by a single solar panel module is seldom enough to meet residential requirements, it is often desirable to link the modules together in a PV array. The modules are usually first connected in series to obtain the desired voltage; then the individual strings are connected in parallel to allow the system to attain the desired current [16]. The efficiency of the solar panel, which is the ability of the panel to convert energy from sunlight into a form useable for human consumption, must also be known in order to ensure optimum performance of the photovoltaic system [17].

2 Scope of Data

One year (2011) archived data of solar radiation from in-situ measurement of weather parameters at the communication/atmospheric research observatory of the Department of Physics, Federal University of Technology, Akure (FUTA); were extracted. The device used for the measurement is Davis 6162 Wireless Vantage Pro2 weather station. It is equipped with Integrated Sensor Suite (ISS) which houses the sensors for solar radiation, pressure, temperature, relative humidity and other weather parameters. The extracted solar radiation data were processed for diurnal, weekly and seasonal analysis. The low-energy consumption facility utilized for the study is Physics Department's complex, FUTA. Spread among its three blocks are eight (8) laboratories, about thirty (30) offices, a conference room, a departmental library and other components of a typical academic research facility. All the components of the facility are furnished with basic electrical and electronic appliances as itemized in Table 2.

3 Computational Techniques

The global formula to estimate the electrical energy generated from the output of a photovoltaic system is given by:

$$E = A \times r \times H \times PR \tag{1}$$

where E = Energy (kWh), A = Total solar panel Area (m²), r = solar panel yield or efficiency (%), H = Annual average solar radiation on tilted panels, and PR = Performance ratio.

The effective energy output (E_{out}) obtainable from the solar installation for this location is estimated from equation (2) as follows:

$$E_{out} = H_r \times \eta_{sp} \times \eta_i \times \eta_b \times \eta_{cc} \times A \times N \tag{2}$$

where H_r represents the received solar radiation at an instant of time, η_b, η_i and η_{cc} are analogous to performance ratio, and they represent battery, inverter and charge controller efficiencies respectively while η_{sp} represent solar panel efficiency. A is the area of each panel, and N represents the number of solar panels.

Table (1) shows the basic characteristics of a typical PV-solar panel having dimension 1.64 m X 0.992 m, and performance specification of 200 W, 24 V at standard test condition (STC) of 1000 W/m². The efficiency of the panel can be evaluated as the ratio of the maximum power density to the standard test condition (STC) and it comes down to 12.3% for the selected solar panel.

Also, Table (2) shows the inventory of electrical appliances being used at the facility, the sum of which represents the load to be powered by the PV installation. Having eliminated heavy-duty appliances such as air conditioners and refrigerators; and making allowances for very low consumption devices such as phones and tablets, the maximum cumulative load per time is projected at 15 kW. This inventory, along with a typical energy consumption chart obtained from www.energylens.com/output, on 3rd March, 2017; was used to develop one-week energy consumption profile for the facility.

Taking recommended values of 0.85, 0.80, 0.85 for the efficiencies of battery (both charging and discharging), the charge controller and the inverter respectively; a PV-project Simulink algorithm was developed to model the effective solar output and storage potential at the facility based on the one-week profile of both archived solar radiation data (obtained for both dry and wet seasons) and the estimated energy consumption.

The modeling of the energy potential, in view of consumption as well as storage profiles, was done using expression (3) below:

$$energy\_storage = solar\_output - load \tag{3}$$

where the projected energy stored is the difference between the solar output and the load consumption.

4 Results and Discussion

Incident solar radiation mapping showing one year diurnal distribution of solar irradiation at the facility is shown in Figure (1). From 06:30 local time (LT) to around 19:00 LT, the range of values is from a few values above zero to around 800 W/m². High intensity radiations were also recorded during wet and dry season months signifying the ability of solar installation to provide energy all year round at tropical locations irrespective of the prevailing weather condition. Although as expected, the peak values obtained during both seasons were of varying intensities, nevertheless, it is adequate for low energy applications.

Similarly, figure 2 shows the distribution of solar radiation intensity and the estimated load consumption for a typical day at the facility under investigation. For the received solar radiation, between midnight and 06:30 local time (LT) the readings were 0 W/m² as well as between 18:30 and 23:30 in the 24 hour window. However, varying intensities of solar radiation were recorded between 07:00 and 18:30 LT, which peaks at 690.3 W/m²) around 13:00 LT in response to the sunrise and sunset dynamics of the location. This trend of solar radiation distribution is typical of the tropical region and is often the pattern all year round (figure 1); with slight variations experienced in the times of sunrise and sunset as well as in the intensities of the radiation, and its peak and off peak periods. Whereas, the estimated power consumption profile shows the minimum load at about 5.8 kW around midnight which steadily increased till the projected peak power consumption is approached around 08:30 LT. This is maintained (with minimal variations) all through the active working hours till around 16:00 LT when the values gradually and steadily receded back to its threshold around 21:30 (LT).

Figure 3 shows a 7-day profile of estimated daily average energy consumption demand at the facility. Based on the standard energy consumption profile obtained from www.energylens.com/output, and the inventory analysis of electrical and electronics appliances at the facility (table 2), a time series model was developed in which the peak and off-peak values of energy consumed in the obtained profile was equated to the peak and off-peak values of load demand from the inventory. Following this pattern, the peak and threshold values obtained are about 15 kW and 5.8 kW respectively.

Figure 4 and figure 5 also show one week real time energy consumption profiles from monthly averaged solar irradiation for January representing the dry season of the year and June representing the wet season period of the year. The profile for both January and June show variations in the intensities of the solar power output for the different days. While some days recorded peak values of around $4.4x10^4$ W in January others were below it, with the least being $3.8x10^4$ W in that month. Interestingly in June, representing wet season, the peak value recorded is $4.8x10^4$ W while the off-peak value was around $3.4x10^4$ W. although a significant period of each day's profile recorded values below that required to meet the projected maximum load of the facility, a good storage system will ensure even supply of electrical energy during such "downtime" moments.

Consequently, figure 6 and figure 7 represent one week real time energy storage profile for the month of January representing the dry season of the year and June representing the wet season period of the year. Using the storage expression in equation (3); a breakdown of the consumption profiles shows that high number of solar panel, (about 500 units of the standard issue) are required to sustain the energy supply chain during the low radiation periods of the day (between 06:30 am and 10:00 am LT in the morning, and between 17:30pm and 19:00 pm LT in the evening). This is reflected in the storage profile pattern in which the stored energy records negative values consistently in January. The same high number of solar panels as January is required for sustaining the supply and storage in June, with little differences in the details of each month's profile. Although the profile for June appears to be more sustainable, high number of panels are also needed to ensure real time energy balance between supply and consumption. Although it is significant to know that the solar power installation has the potential to sustain energy demand all through the year irrespective of dry or wet season, the high number of solar panels required to achieve this feat can be addressed.

In order to address the high number of solar panels required for optimal performance, a possible reversal of order, in which the storage system would have been charged before the system powers the load, was considered. Fig. 8 shows one week storage profile (without load) at the location using only 200 solar panels (N=200). The energy potentially available for storage is seen to increase steadily attaining peak value of about $8.5x10^3$ kW at the end of the seventh day. This is far above the projected 15 kW peak value of the consumption profile. This implies that sustainability can be achieved even with minimal units of solar panels, provided adequate energy storage system is provided.

TABLE1: STANDARD SPECIFICATIONS OF A SELECTED SOLAR PANEL

Manufacturer	Nature power
Product name	200 watt solar panel
Product type	Mono crystalline Photovoltaic solar panel
Voltage	12, 24 volts DC
Maximum	Up to 200 watts Up to 6.74 Amps
Transform efficiency	13-18%

TABLE 2: INVENTORY OF ELECTRICAL AND ELECTRONICS APPLIANCES AT THE FACILITY

Electrical Appliances	**Unit**	**Rating per unit (W)**	**Estimated Power Rating (W)**
Big Bulbs	51	85	2,335
Small Bulbs	23	40	920
Air Conditioners	**36**	**750**	**27,000**
Big Fans	48	70	1,960
Medium-sized Fans	20	55	1,100
Big Laptops	24	65	1,560
Medium-sized Laptops	35	50	1,750
Refrigerators	**2**	**400**	**800**
Television sets	2	350	700
Computer sets	3	450	1,350
Total/ Net	**246**	**2,315**	**41,145/ 13,345**

5 CONCLUSION

This work has estimated the solar potential for low-energy applications using solar radiation data from a tropical location. It has been shown that solar energy can effectively service the low-energy needs of an establishment using an arm of a higher institution with peak load in the neighborhood of 15 kW as a case study. This can be achieved with as low as 200 units of solar panels at the standard specifications. Based on a modeled consumption profile, the system will be able to sustain its energy supply throughout the day and all through the year irrespective of wet or dry season; and given appropriate storage mechanism.

The economic implication of such a solar energy installation, which is not the focus of this work, may appear enormous, but the spate of epileptic power supply in this country, the financial, ecological and biological as well as health implications of fossil-fuelled engines; make solar installation a worthy venture. Lastly, although solar may not be able to meet all human energy needs just yet, it is however adequate for low-energy applications and as such should be maximized.

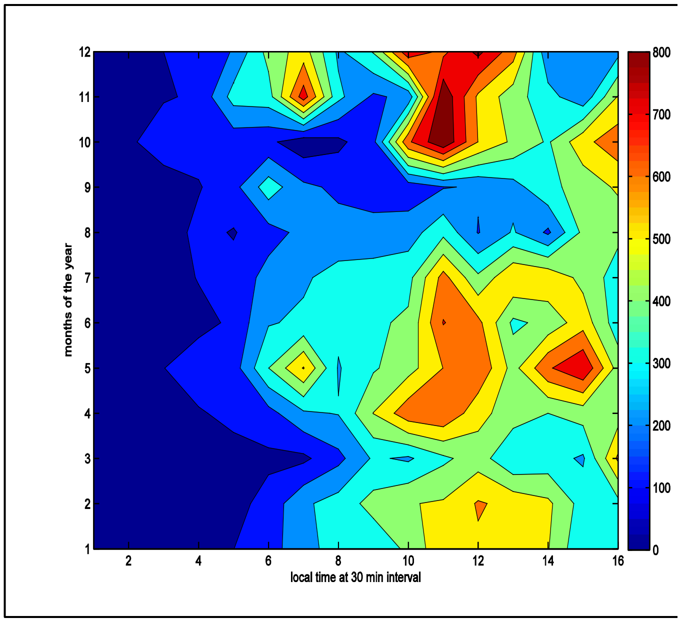

Figure 1: one year distribution profile of incident solar radiation at the location

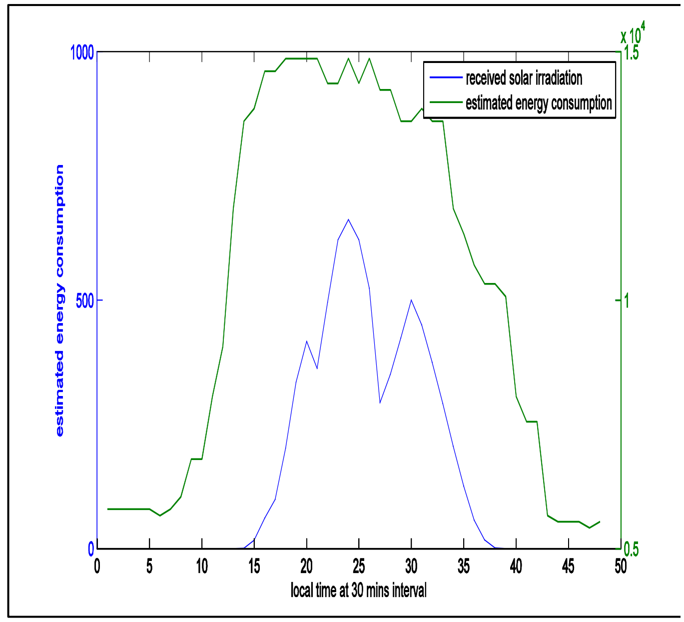

Figure 2: A typical day profile of received solar radiation and estimated power consumption at the facility.

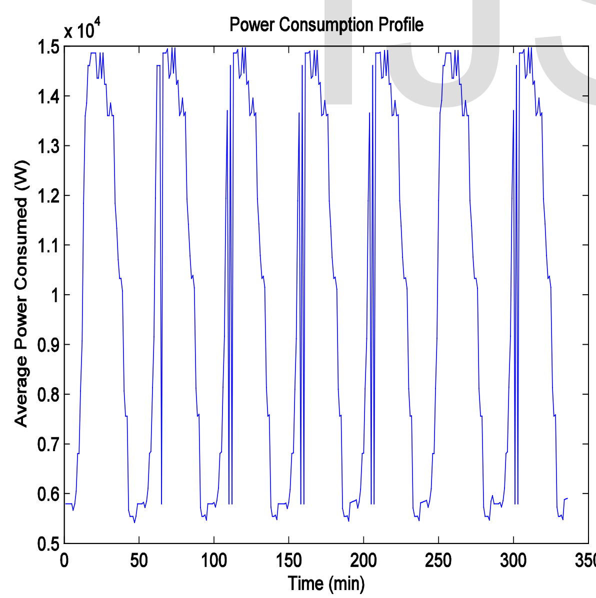

Figure 3: Electrical load distribution profile over one week period for the facility

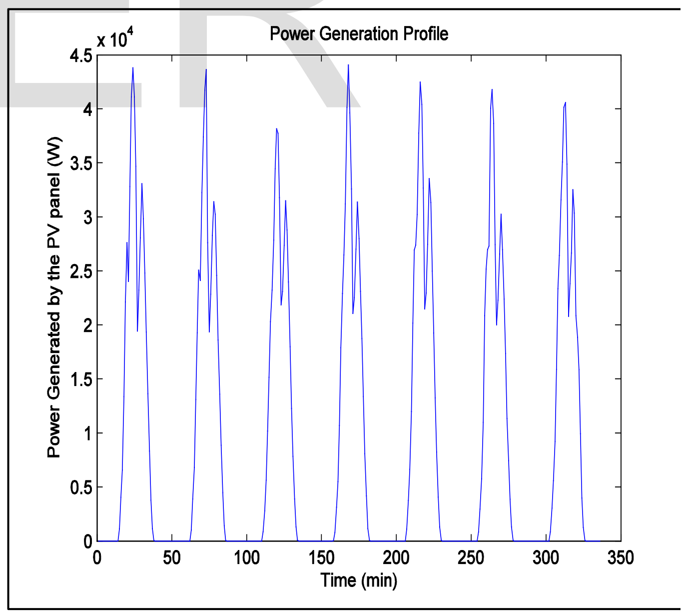

Figure 4: power generated by the PV panel for a typical week in January, 2016 (dry season)

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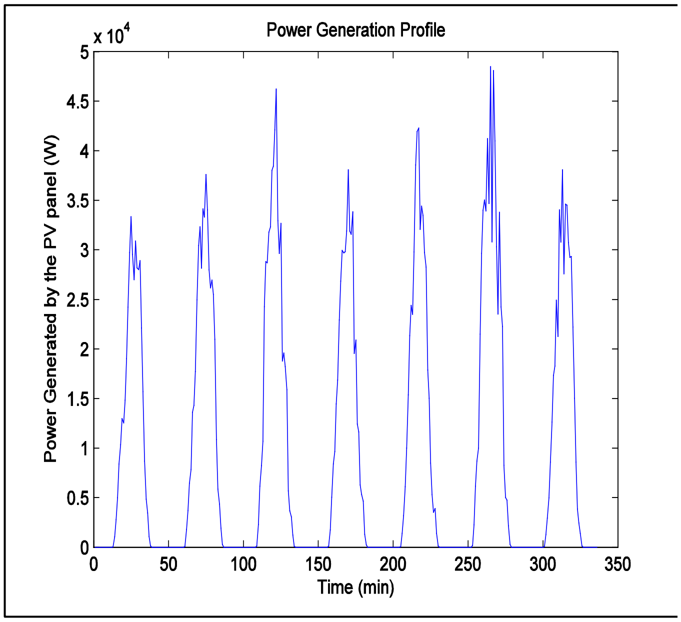

Figure 5: power generated by the PV panel for a typical week in June, 2016

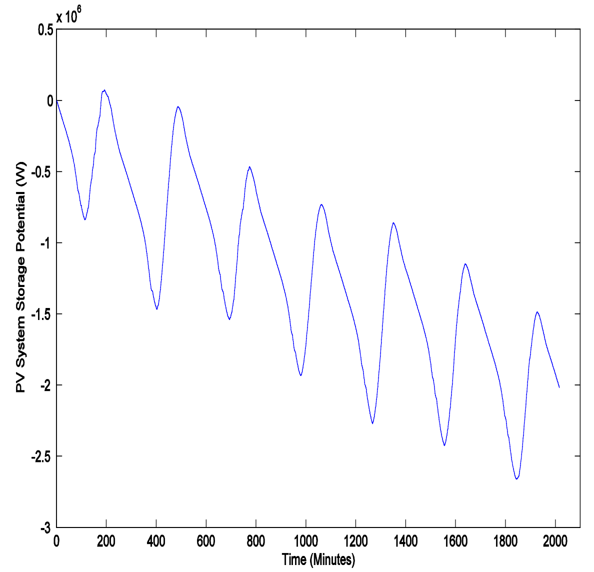

Figure 6: PV power system Storage potential for January, 2016

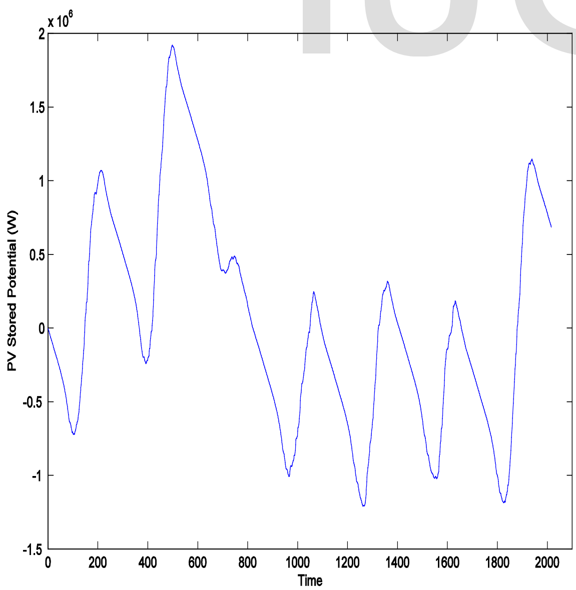

Figure 7: PV power system Storage potential for June, 2016

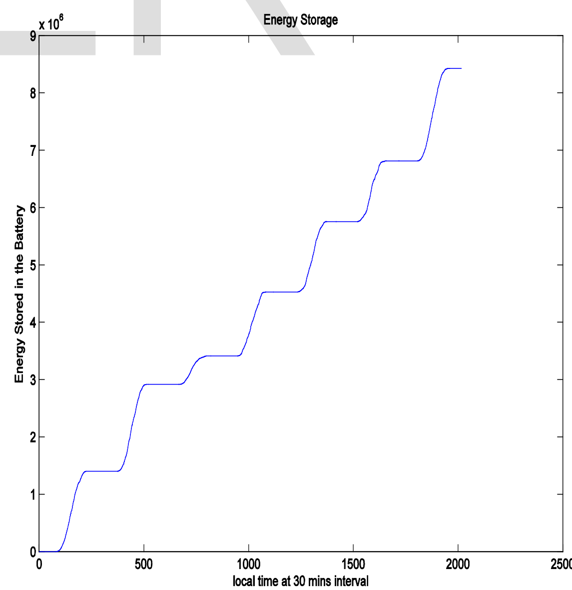

Figure 8: PV power system Storage potential before load

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