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Modeling Of The Loss Of Load Probability For Standalone Solar Photovoltaic Energy Harvester Deployed In Battery-Powered Iot Sensor Node

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***Abstract*— In this paper, the modeling of the loss of load probability (LoLDP) for standalone solar photovoltaic energy harvester deployed in battery-powered IoT sensor node (IoTSN) is presented. The study focused on evaluating the effect of climatic parameters on the LoLDP. The study considered two different case study site with quite different solar radiation data. The study sites are Faculty of Engineering University of Uyo Akwa Ibom State with latitude and longitude of 5.041226 and 7.974248 respectively, another one at Sokoto State University with latitude and longitude of 12.941472 and 5.191147. Two sets of simulations were conducted. The first set of simulations were conducted with the PV panel area chosen using the annual mean solar radiation data (1936.164 Wh/m^2/day) of the UNIUYO site which gave PV area of 10.90816 m^2. The second set of simulations were conducted with the PV panel area chosen using the annual mean solar radiation data (3702 Wh/m^2/day) of the Sokoto State University site which gave PV area of 5.705024 m^2. The results showed that when PV area of 10.90816 m^2 was used, the IoTSN at UNIUYO had 8 days of power outage which amounted to loss of load probability (LoLDP%) of 2.191781% whereas the IoTSN at Sokoto State University had no power outage which amounted to loss of load probability (LoLDP%) of 0%. Also, when PV area of 5.705024 m^2 was used, the IoTSN at UNIUYO had 116 days of power outage which amounted to loss of load probability (LoLDP%) of 31.78082 % whereas the IoTSN at Sokoto State University had 8 days of power outage which amounted to loss of load probability (LoLDP%) of 2.191781%. The results showed that if the same solar panel are used, the two sites will have different loss of load probabilities, where the site with low solar radiation will witness high loss of load whereas the location with high solar radiation will experience low loss of load.**

Keywords*— *Loss of Load Probability, Standalone Solar Photovoltaic, Energy Harvester, IoT Sensor Node

1. Introduction

The world today is witnessing rapid transition to smart systems that are fueled by advancements in electronic and communication technologies (Mishra and Singh, 2023). At the same time, the power industry is transitioning to green and renewable energy solution (Kabeyi and

Olanrewaju, 2022). This dual transitions are simultaneously driving the energy sector for low power devices. Presently, many low energy devices like sensor nodes are battery powered. In order to sustain the energy supply to these devices, energy harvesting solution is included with battery storage as a backup for sustained energy supply in view of the stochastic nature of such energy systems like the solar and wind energies (Haleem, et al,.2022; Vassolo, Weisz and Laker, 2024).

One of the challenging consequence of using solar energy as energy source is its variability with respect to location and time (Beaudin, et al,.2010; Kruitwagen, et al., 2021). This spatio-temporal variations means that the design of such power solutions based on solar must account for the variability in the availability when selecting the system configuration. One of such key performance metrics used to capture the effectiveness of the power supply system is the loss of load probability which measures the percentage of time in a given time frame when there was power outage due to lack of power supply to the load (Umunnakwe, et al., 2021). In this case, the energy source failed to supply the required amount of energy because there is insufficient energy to do so. When such outage occurs some systems may suffer serious damage or losses. As such, in this paper, modelling and evaluation of the loss of load probability for solar powered sensor node with battery backup. The study seek to examine the solar power solution for a sensor node at two different locations in Nigeria with different climatic conditions. The study will use analytical models to characterize the variations in the energy yield and energy consumptions in the system over time and thereby determine the probability of power outage over a year. In this way, the possibility of loss of load over the daily and seasonal weather conditions are captured,

2. Methodology

2.1 Modeling of the loss of load probability for the battery–powered IoT sensor node (IoTSN) with solar energy harvester

In this work, solar photovoltaic power (SPVP) is used as energy harvesting technic to power the IoT sensor node and also charge the backup battery (Bathre and Das, 2023; Mayer, Magno and Benini, 2022). When the solar power system is unable to do so, the backup battery will supply energy to the IoT sensor node (IoTSN). However, there may be occasions when both the SPVP and the backup battery are unable to provide the needed power. In such case, power outage or loss of load will occur (Borujeni, Ofetotse and Nebel, 2022; Gong and Ionel, 2021; Riskiono, Oktaviani and Sari, 2021). Generally, the loss of load probability (LoLD) is defined as the percentage of the total time in a year when the energy demanded is not supplied (Numan, Baig andYousif, 2023; Khoo, The and Lai, 2020). If in one year (that has 365 days) the total number of time expressed in days in which energy is not supplied to the load is denoted as n_{LD}, then the LoLD% can be expressed in % as follows;

$$LoLD\% = \left(\frac{n_{LD}}{365}\right) 100\ \% \quad (1)$$

According to Samuel and Effiong, (2022), the capacity of the battery (C_{BatDoA}) that will be used to power the IoTSN for days of power autonomy (D_{oA}) without needing a recharge is computed as;

$$C_{BatDoA} = \frac{24(D_{oA})(I_{avg})(S_{Bf})}{(C_{BUC})(C_{BTF})(\eta_{cBat})} \quad (2)$$

Where S_{Bf} is the safety factor (typically 1.2) for the battery sizing, η_{BC} (typically 97 %) is the battery charging efficiency, C_{BUC} is the battery useable capacity (typically 90 %) and C_{BTF} (typically 95 %) is the battery temperature dependent factor. The I_{avg} is the average current drawn by the IoTSN per cycle and it is computed as (Samuel and Effiong, 2022);

$$I_{avg} = \frac{I_{SLP}\ (t_{SLP}) + I_{mx}(t_{mx}) + I_{tx}(t_{tx}) + I_{rx}(t_{rx})}{t_{SLP} + t_{mx} + t_{tx} + t_{rx}} \quad (3)$$

$$I_{avg} = \frac{I_{SLP}\ (t_{SLP}) + I_{ACT}(t_{ACT})}{t_{SLP} + t_{ACT}} \quad (4)$$

Where I_{SLP} is the current drawn by the IoTSN during the sleep mode which lasts for period of t_{SLP} per cycle. Also, I_{ACT} is the current drawn by the IoTSN during the active mode which lasts for period of t_{ACT} per cycle. Hence, a cycle time, t_{cl} is the sum of I_{ACT} and I_{SLP}. The mx, tx and rx stand for measure, transmit and receive respectively. The three phases are what make up the active mode of the sensor node where $t_{ACT} = t_{mx} + t_{tx} + t_{rx}$ and $I_{ACT}(t_{ACT}) = t_{ACT} I_{mx}(t_{mx}) + I_{tx}(t_{tx}) + I_{rx}(t_{rx})$ In addition, $C_{BatPday}$ which denotes the capacity of the battery that can supply energy demand of the IoTSN for one day without charging is computed as;

$$C_{BatPday} = \frac{C_{BatDoA}}{D_{oA}} \quad (5)$$

The area, A_{pv} of the solar panel needed for charge the C_{BatDoA} battery to its full capacity in T_{BoAC} days can be computed as;

$$A_{pv} = \frac{E_{PDay}}{G_{AnMn}} \quad (6)$$

Where G_{AnMn} denotes the annual mean of the daily solar irradiation for the solar panel installation site and E_{PDay} is the energy which can be harvested by the solar panel on each day. In that case, the battery will be fully capacity of C_{BatDoA} will be fully charged in t_{BFC} number of days where;

$$E_{PDay} = \frac{(C_{BatDoA})(V_{pv})(S_{pvf})}{(\eta_{pv})(t_{\text{BFC}})} = (A_{pv})(G_{AnMn}) \quad (7)$$

Where η_{pv} is the PV panel efficiency, V_{pv} is the PV panel terminal voltage while S_{pvf} is the safety factor used in the PV panel sizing which has typically of 1.2. In t_{BFC} days, the energy required from the solar panel to fully charge the battery is E_{PVBatC} where;

$$E_{PVBatC} = E_{PDay}(t_{\text{BFC}}) \quad (8)$$

Meanwhile, daily energy demand of the IoTSN is denoted as $E_{IoTSNPDay}$ where;

$$E_{IoTSNPDay} = \frac{E_{PVBatC}}{D_{oA}} \quad (9)$$

Notably, the solar irradiation data varies with day, so let $G_{Day(i)}$ denote the mean daily solar radiation in day i and the energy harvested by the PV panel in day i be $E_{PDay(i)}$ where;

$$E_{PDay(i)} = (A_{pv})(G_{Day(i)}) \quad (10)$$

Then, in each day, i the net daily energy after the supplying the IoTSN is $E_{NetDay(i)}$ where;

$$E_{NetDay(i)} = E_{PDay(i)} - E_{IoTSNPDay} \quad (11)$$

The $E_{NetDay(i)}$ does not include the battery. Now, let the energy already stored in the battery in day i be $E_{BatSDay(i)}$ and let the net energy in day i be $E_{NetBatDay(i)}$, then (Samuel and Effiong, 2022);

$$E_{NetBatDay(i)} = E_{NetBatDay(i-1)} + E_{NetDay(i)} \quad (12)$$

$$E_{NetBatDay(i)} = E_{NetBatDay(i-1)} + E_{PDay(i)} - E_{IoTSNPDay} \quad (13)$$

If we assumed that initially the battery is fully charged, then for i=1, $E_{NetBatDay(i-1)} = E_{NetBatDay(0)} = E_{PVBatC}$. Conversely, if we assumed that initially the battery is empty, then for i=1, $E_{NetBatDay(i-1)} = E_{NetBatDay(0)} = 0$. In the same way, the initial value $E_{NetBatDay(0)}$ can be assumed to be a fraction (denoted as α) of the full battery charge value, as such;

$$E_{NetBatDay(0)} = \alpha(E_{PVBatC}) \quad (14)$$

Where $0 \leq \alpha \leq 1$. The total energy stored in the battery at the end of day i denoted as $E_{BatStorDay(i)}$ is computed as follows;

$$E_{NetBatDay(i)} = maximum(0, [minimum\,(E_{PVBatC}, E_{NetBatDay(i)})]) \quad (15)$$

Let the days of power outage be $d_{poutage(i)}$ which is defined as $d_{poutage(i)} = 1$ if occur partial or total outage in day i and $d_{outage(i)} = 0$ if there occur no outage in day i. Hence;

$$d_{poutage(i)} = \begin{Bmatrix} = 1 & if\ E_{NetBatDay(i)} < 0 \\ = 0 & if\ E_{NetBatDay(i)} \geq 0 \end{Bmatrix} \quad (16)$$

There are some days when the energy generated by the V panel is so much that it is more than what can be stored in the battery and more than what the IoTSN and battery require. In that case, the excess energy is wasted , unused. Let the days with unused energy be $d_{UnuseE(i)}$ which is defined by assuming that $d_{UnuseE(i)} = 1$ when $E_{NetBatDay(i)} > E_{PVBatC}$ in day i and $d_{UnuseE(i)} = 0$ when $E_{NetBatDay(i)} \leq E_{PVBatC}$ in day i. Hence;

$$d_{UnuseE(i)} = \begin{Bmatrix} = 1 & if\ E_{NetBatDay(i)} > E_{PVBatC} \\ = 0 & if\ E_{NetBatDay(i)} \leq E_{PVBatC} \end{Bmatrix} \quad (17)$$

The amount of energy that is unused in day i is denoted as $E_{UnuseE(i)}$ where;

$$E_{UnuseE(i)} = maximum\,(E_{NetBatDay(i)} - E_{PVBatC}) \quad (18)$$

The number of days of power outage or loss of load in a year be denoted as n_{LD}, hence

$$n_{LD} = \sum_{i=0}^{i=365} (d_{poutage(i)}) \quad (19)$$

Hence, the LoLDP expressed in percentage can be computed from Equation 1 and Equation 19.

2.2 The IoTSN Installation site and the corresponding meteorological dataset

The study considered two different case study site with quite different solar radiation data. The first case study site for the installation of the IoTSn is at the Faculty of Engineering University of Uyo Akwa Ibom State with latitude and longitude of 5.041226 and 7.974248 respectively, as shown in Figure 1. The second case study site for the installation of the IoTSn is at Sokot State University with latitude and longitude of 12.941472 and 5.191147 respectively, as shown in Figure 2.

The model was simulated in Visual Basic for Application program that was implemented in Microsoft Excel environment. The simulations were conducted for the two case study locations in University of Uyo and Sokoto State University. The IoTSn , the solar panel and the battery parameters used in the simulation are presented in Table 1.

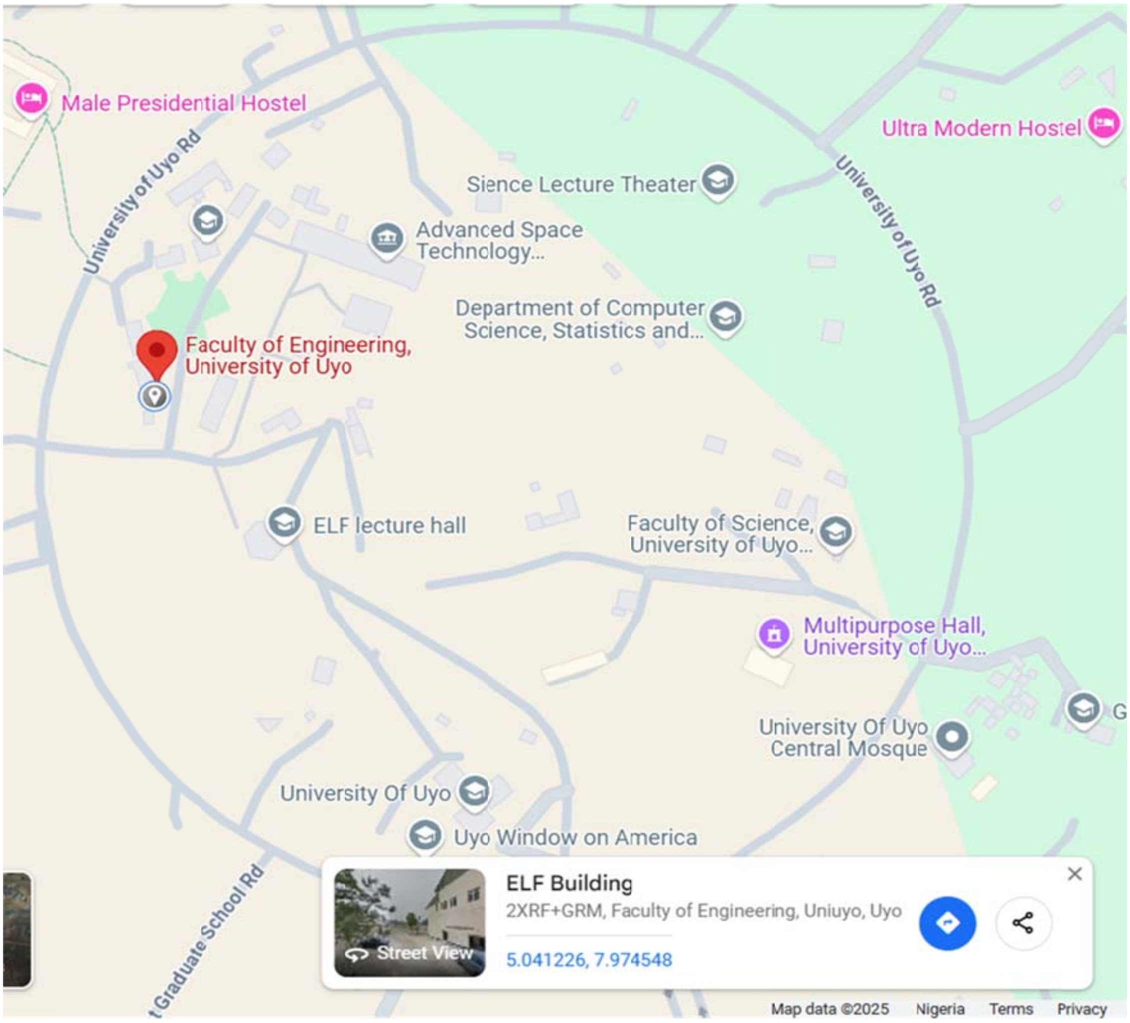

Figure 1 The first case study site at Faculty of Engineering University of Uyo, Akwa Ibom State with latitude and longitude of 5.041226 and 7.974248 respectively

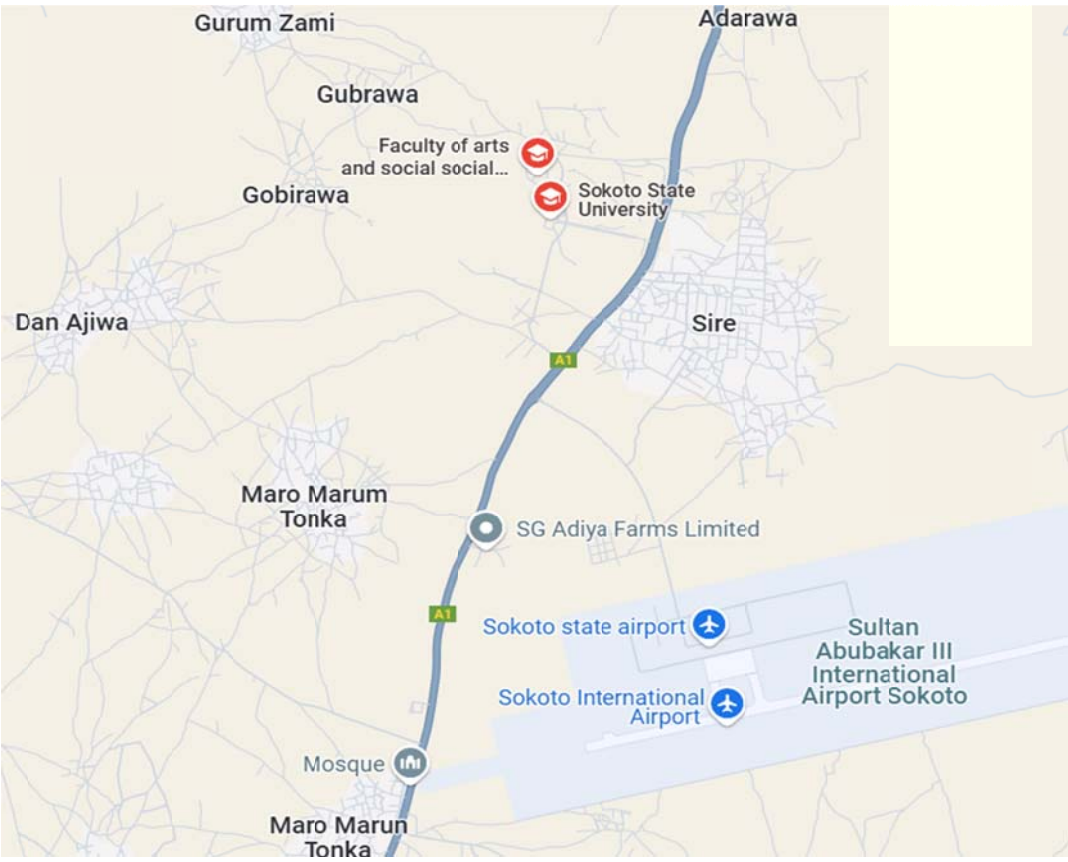

Figure 2 The second case study site at Sokot State University with latitude and longitude of 12.941472 and 5.191147 respectively

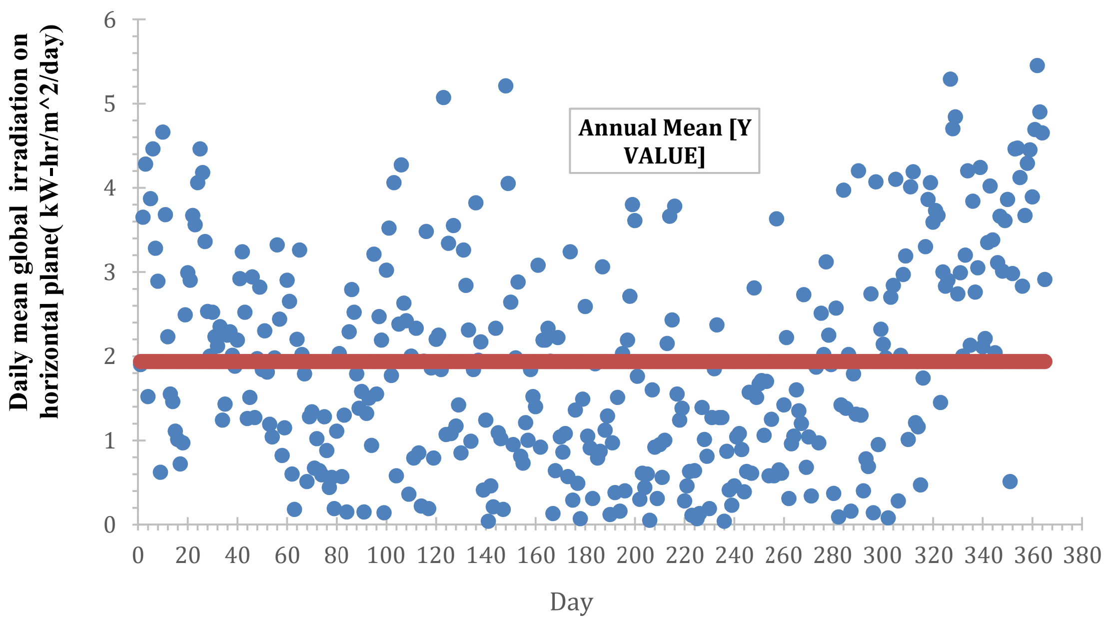

Figure 3 The daily mean global irradiation on horizontal plane for the first case study site at Faculty of Engineering University of Uyo, Akwa Ibom State

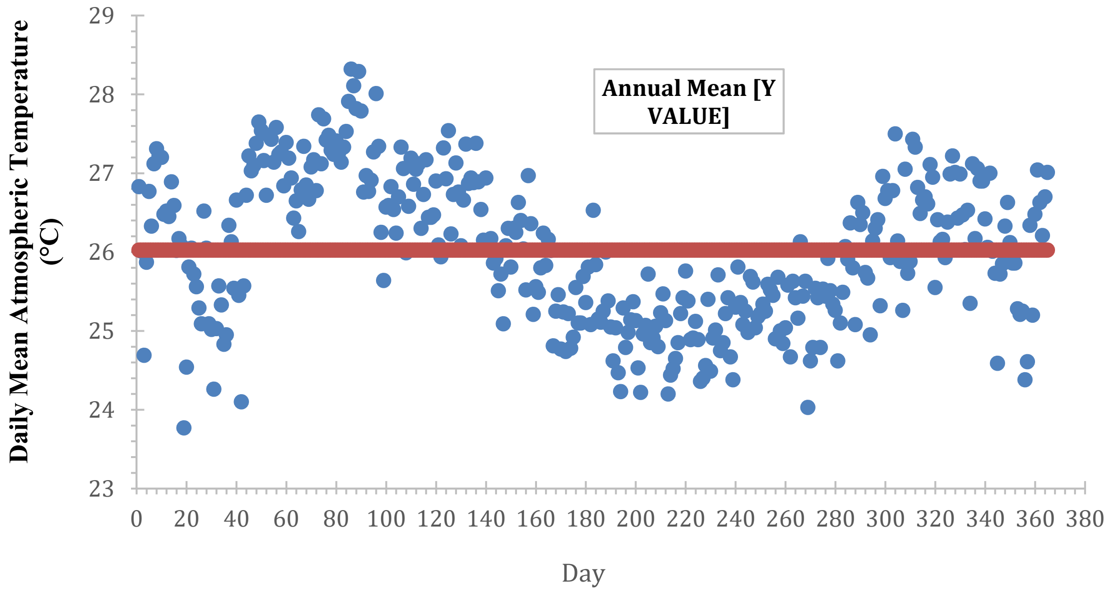

Figure 4 The daily mean atmospheric temperature for the first case study site at Faculty of Engineering University of Uyo, Akwa Ibom State

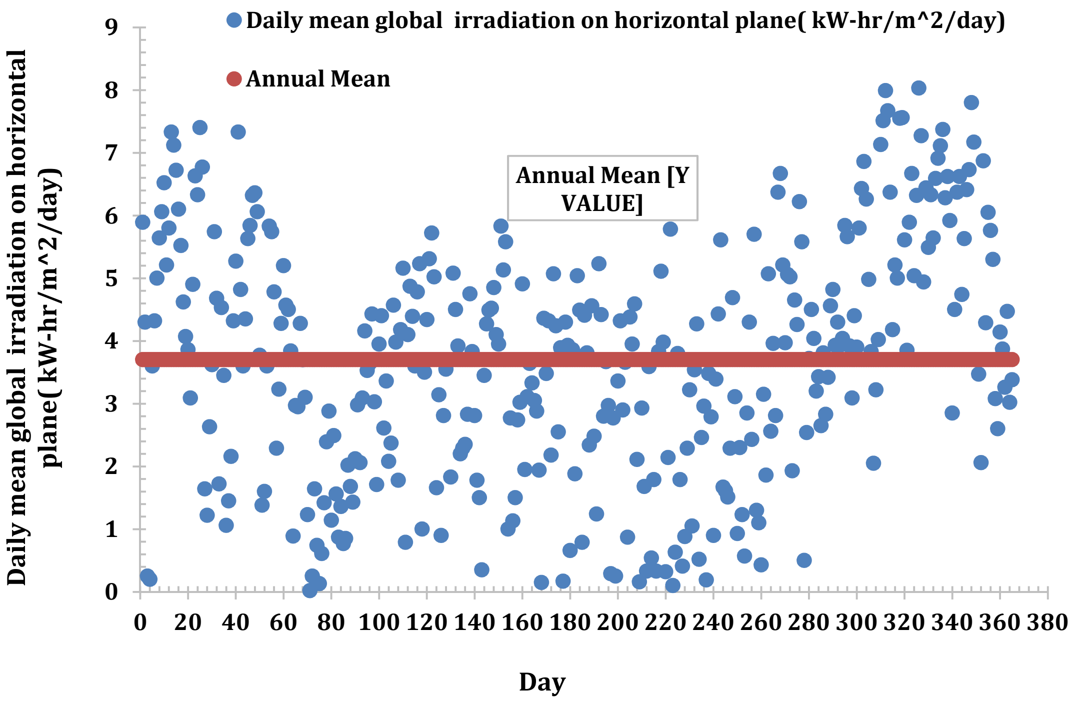

Figure 5 The daily mean global irradiation on horizontal plane for the first case study site at at Sokot State University

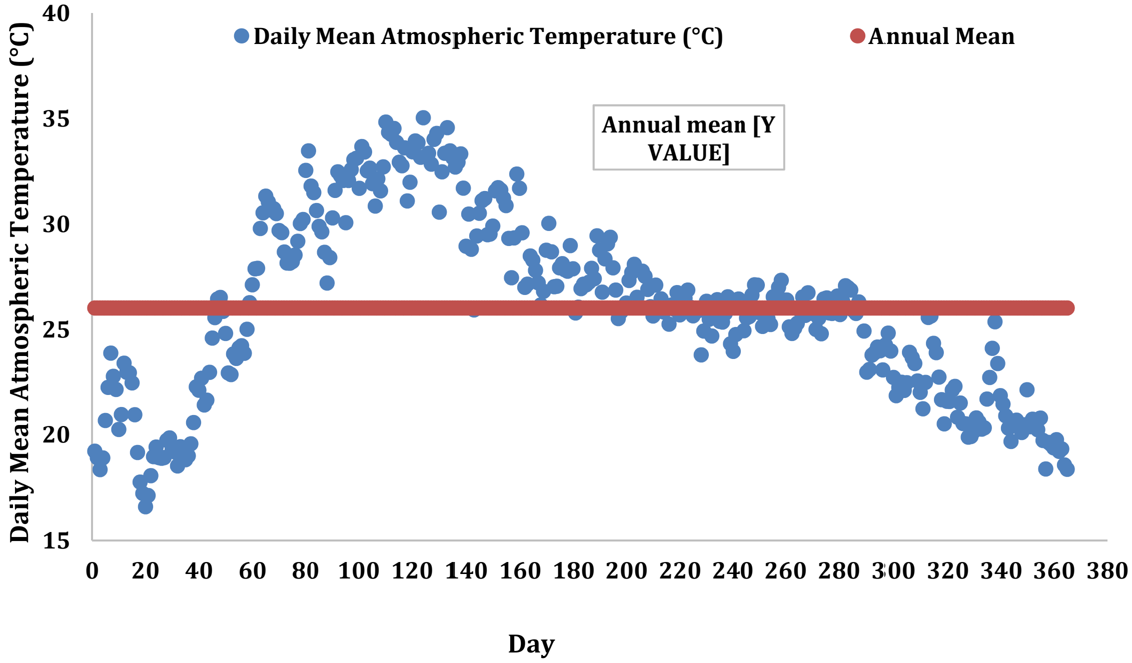

Figure 6 The daily mean atmospheric temperature for the first case study site at Sokot State University

Table 1 The IoTSN data, the solar panel and the battery parameters used in the simulation

S/N	Parameter	Simulation data used for the IoTSN solar power at University of Uyo	Simulation data used for the IoTSN solar power at Sokoto State University
1	I Transmit (mA)	83	83
2	I receive (mA)	32	32
3	I Measure (mA)	18	18
4	I Sleep (mA)	0.05	0.05
5	t Transmit (ms)	3000	3000
6	t receive (ms)	2500	2500
7	t Measure (ms)	260	260
8	t Sleep (ms)	570240	570240
9	t Cycle time(s)	576000	576000
10	Duty Cycle (%)	1	1
11	Number of cycles per day	150	150
12	Average Current, Iavg (mA)	0.628806	0.628806
13	Days of Autonomy,	3	3
14	Days it take to fully charge battery	1.5	1.5
15	Average daily solar irradiation (Wh/m^2/day)	1936.164	3702
16	Required battery capacity (mAh)	65.50769	65.50769

3. Results and discussion

Two sets of simulations were conducted. The first set of simulations were conducted with the PV panel area chosen using the annual mean solar radiation data (1936.164 Wh/m^2/day) of the UNIUYO site which gave PV area of 10.90816 m^2. The second set of simulations were conducted with the PV panel area chosen using the annual mean solar radiation data (3702 **Wh/m^2/day**) of the Sokoto State University site which gave PV area of 5.705024 m^2. It was observed that the ratio of the two PV areas is equal to the ration of the corresponding solar radiation data of the two sites, namely; 3702/1936.164 =10.90816/5.705024 =1.91203. The summary of the results of the two sets of simulations showing the key parameters are shown in Table 2 while the graphs showing the loss of load for the two study sites in the two simulations are presented in Figure 7, Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12.

The results showed that when PV area of 10.90816 m^2 was used, the IoTSN at UNIUYO had 8 days of power outage which amounted to loss of load probability (LoLDP%) of 2.191781% (as shown in Table 2, Figure 7 and Figure 8). On the other hand, when PV area of 10.90816 m^2 was used, the IoTSN at Sokoto State University had no power outage which amounted to loss of load probability (LoLDP%) of 0% (as shown in Table 2, Figure 9). Also, the percentage of days where excess energy is unused or lost was 63.0137 % for the UNIUYO site and 89.31507% for the Sokoto State University site.

Similarly, the results showed that when PV area of 5.705024 m^2 was used, the IoTSN at UNIUYO had 116 days of power outage which amounted to loss of load probability (LoLDP%) of 31.78082 % (as shown in Table 2 and Figure 10). On the other hand, when PV area of 5.705024 m^2 was used, the IoTSN at Sokoto State University had 8 days of power outage which amounted to loss of load probability (LoLDP%) of 2.191781% (as shown in Table 2, Figure 11 and Figure 12) Also, the percentage of days where excess energy is unused or lost was 27.94521 % for the UNIUYO site and 71.50685 % for the Sokoto State University site. Notably, the loss of load occurred when the net energy is less than zero.

In all, the Sokoto State University site with higher annual mean solar radiation had higher energy yield from the solar panel and hence for any given solar panel area, the energy produced at the Sokoto State University site is higher than the energy yield at UNIUYO site. This made it possible to deliver energy without any loss of load or no power outage all through the year when the solar panel area of 10.90816 m^2 was used. In any case, when the solar panel area was reduced to almost half the value, the IoTSN suffered power outage amounting to loss of load probability of 2.191781 % per year.

Table 2 The summary of the results of the two sets of simulations showing the key parameters

S/N	Parameter	Result for University of Uyo Site with PV cell area of 10.90816 cm^2	Result for Sokoto State University Site with PV cell area of 10.90816 cm^2	Result for University of Uyo Site with PV cell area of 5.705024 cm^2	Result for Sokoto State University with PV cell area of 5.705024 cm^2 Site
1	Solar cell size (cm^2)	10.90816	10.90816	5.705024	5.705024
2	Energy store in fully charged battery	3.168	6.057301	1.65688	3.168
3	Daily Energy Demand (Wh)	1.056	1.056	1.056	1.056
4	Number of days of power outage or loss of load	8	0	116	8
5	Percentage % of days of power outage or loss of load probability (LoLDP %)	2.191781	0	31.78082	2.191781
6	Number of days of excess energy is unused or lost	230	326	102	261
7	Percentage % of days excess energy is unused or lost	63.0137	89.31507	27.94521	71.50685
8	Number of days excess energy is completely stored	127	39	147	96
9	Percentage % of days excess energy is completely stored	34.79452	10.68493	40.27397	26.30137

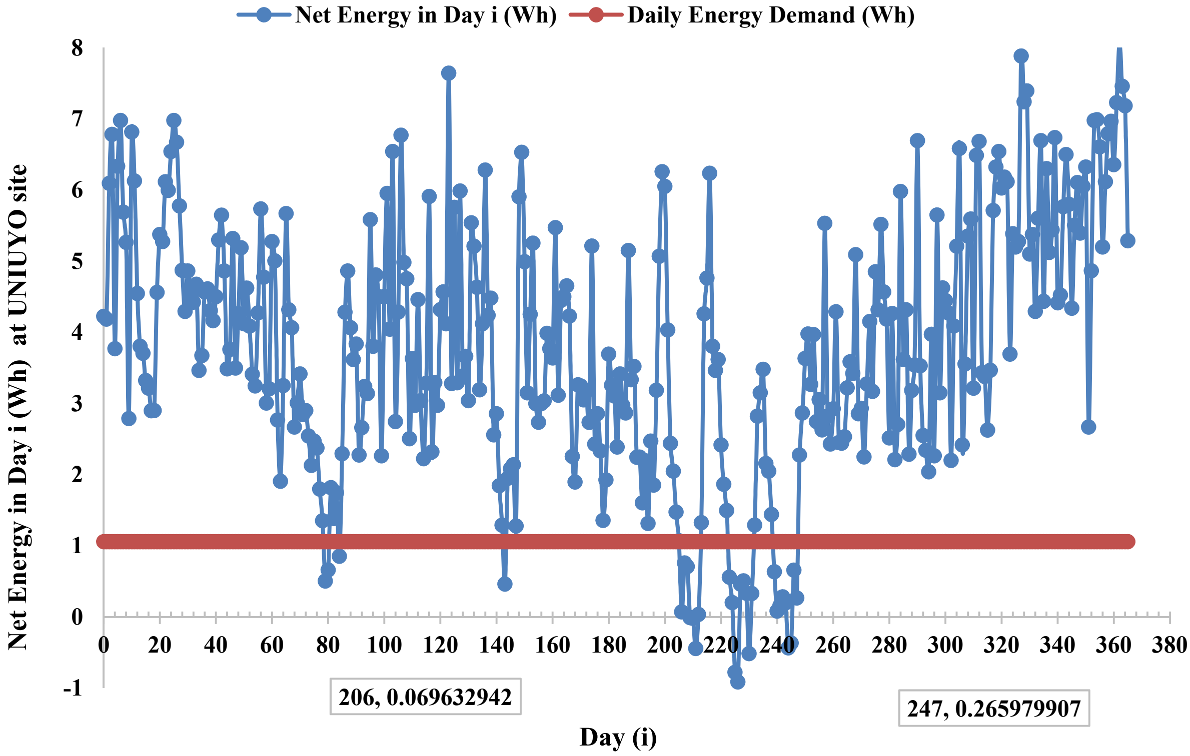

Figure 7 The net energy in day i (Wh) at UNIUYO site when PV area of 10.90816 m^2 was used

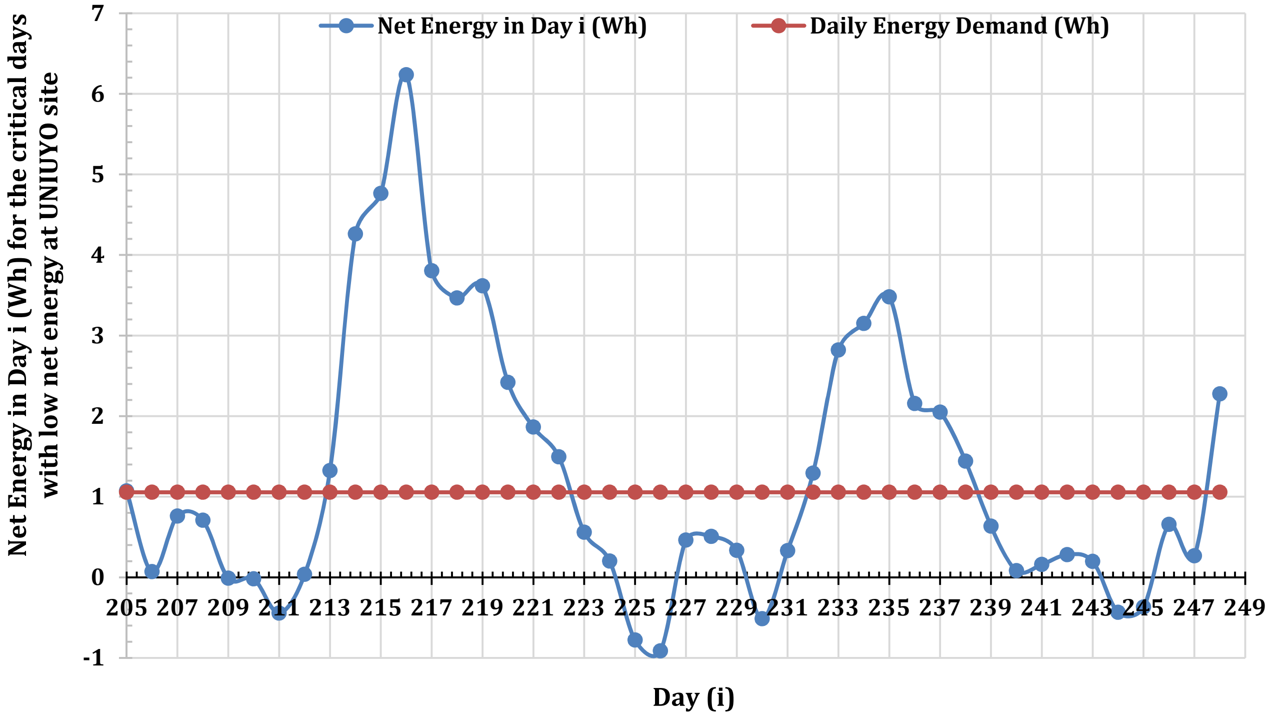

Figure 8 The net energy in day i (Wh) for the critical days with low net energy at UNIUYO site when PV area of 10.90816 m^2 was used

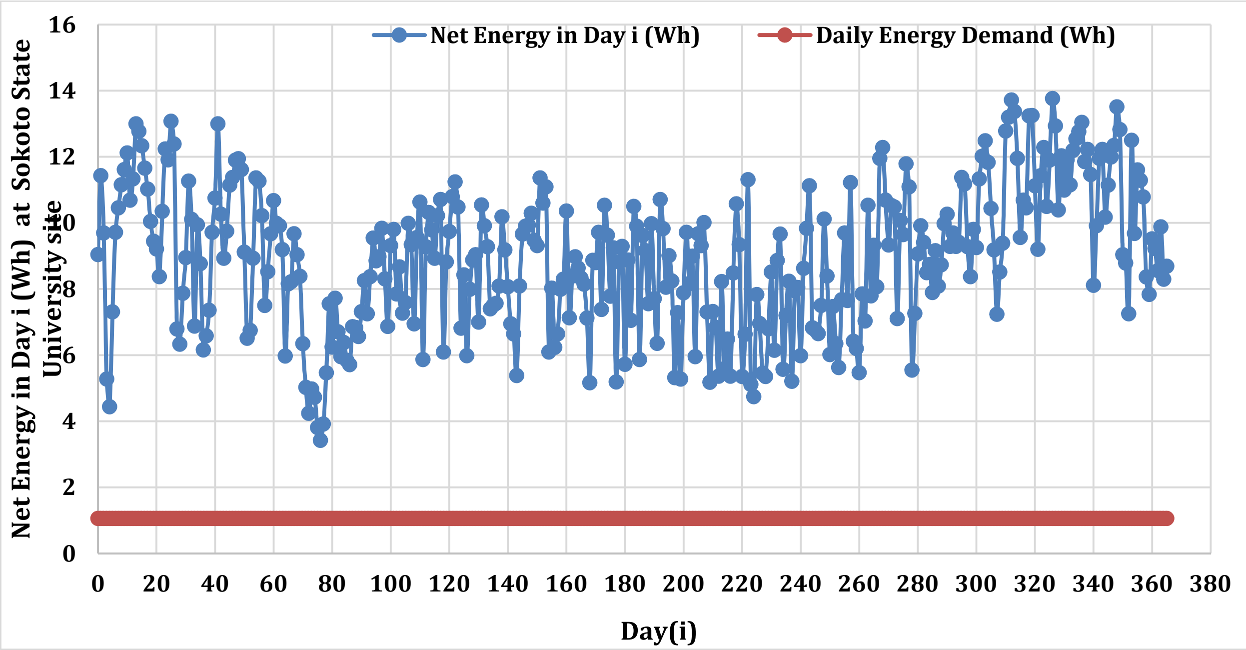

Figure 9 The net energy in day i (Wh) at Sokoto State University site when PV area of 10.90816 m^2 was used

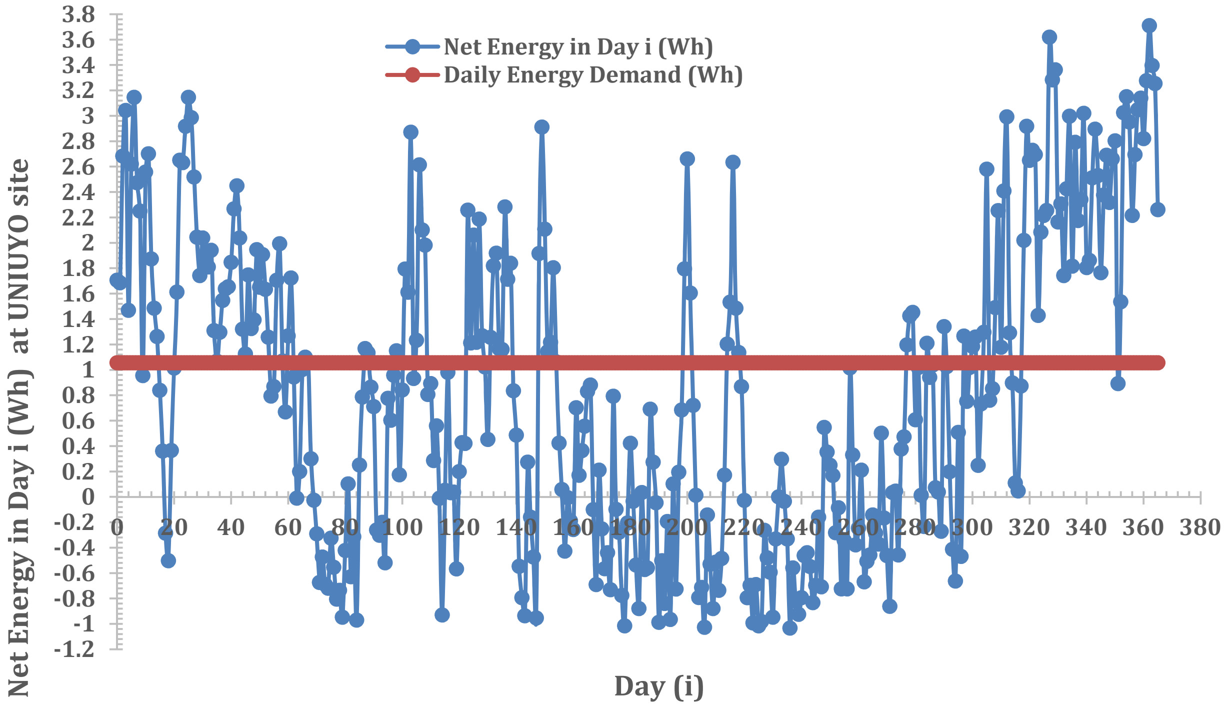

Figure 10 The net energy in day i (Wh) at UNIUYO site when PV area of 5.705024 m^2 was used

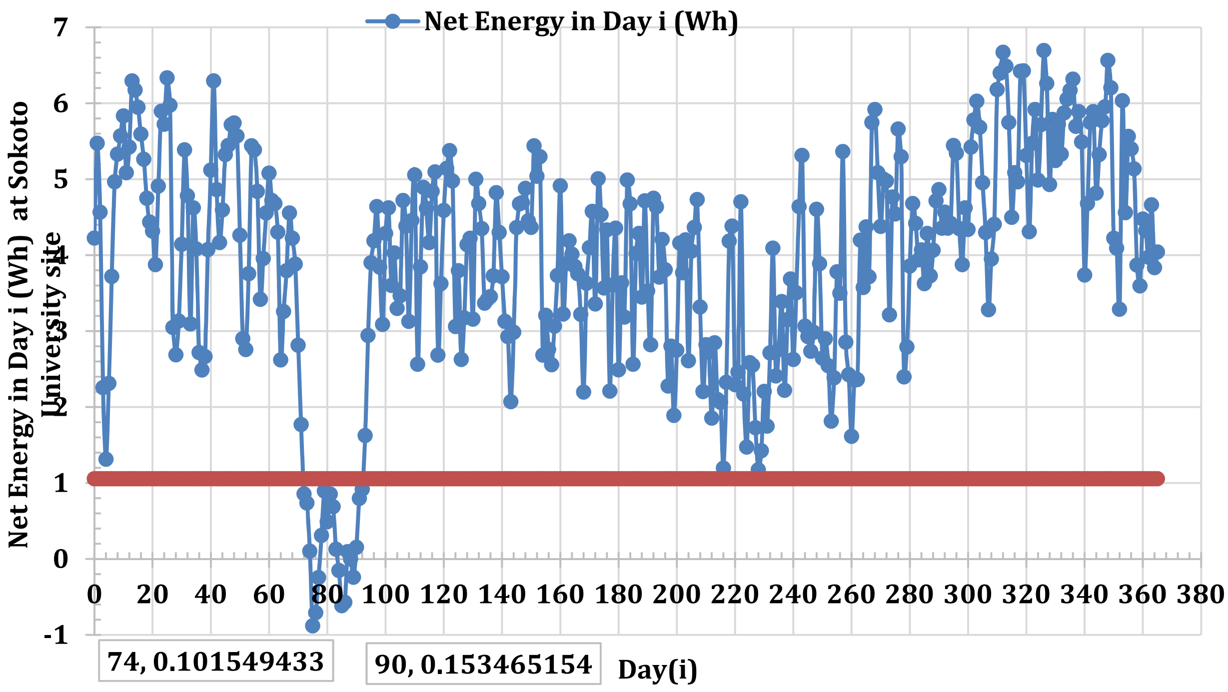

Figure 11 The net energy in day i (Wh) at UNIUYO site when PV area of 5.705024 m^2 was used

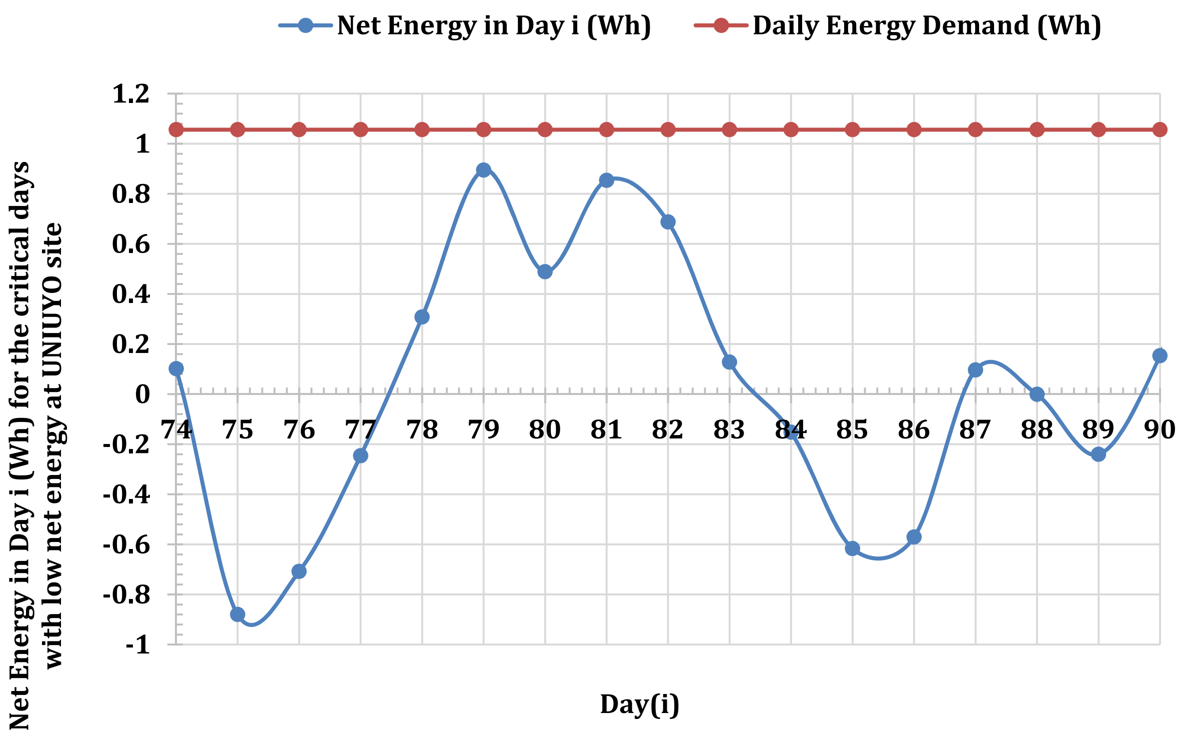

Figure 12 The net energy in day i (Wh) for the critical days with low net energy at UNIUYO site when PV area of 5.705024 m^2 was used

4. Conclusion

The solar power system for powering an IoT sensor node with battery storage as backup is presented. The focus was to study the loss of load probability of the solar power system especially in the face of different climatic conditions. The study considered two different locations, one with low solar radiation and another location with fairly high solar radiation. The results showed that if the same solar panel are used, the two sites will have different loss of load probabilities, where the site with low solar radiation will witness high loss of load whereas the location with high solar radiation will experience low loss of load. Finally, the idea presented in this study will help PV power designers for IoT applications to adjust the parameter settings of their PV system based on the meteorological data.

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