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Development Of Power Outage Model For Solar-Powered Iot Sensor Node With Battery Backup For Remote Monitoring Of Lathe Machine

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***Abstract*— In this research work, development of power outage model for solar-powered Internet of Things (IoT) sensor node with battery backup for remote monitoring of lathe machine is presented. The analytical models are meant to characterize the various energy components in the solar-powered IoT sensor node for monitoring and controlling of the smart Lathe machine. The energy components are captured on daily basis and the power outage performance is represented in terms of loss of load and excess unused energy. The case study site is located in Akwa Ibom State Polytechnic having latitude of 5.156937492133076 and longitude of 7.668216975069745, annual mean daily solar radiation of 4.110307 kWhr/^s/day and annual mean daily temperature of 26.296 °C. The simulation results showed that for Days of Autonomy, Dof 3 days and days it take to fully charge battery, t set to 1.5 days, there will be 10 days of power outage in a year which is a loss of load probability (LoLDP%) of 2.74 %. Further simulation results show that as t increases, and D is constant, the battery capacity is kept constant but smaller PV panel is required which reduces the cost of the PV panel but at the same time increases the power outage in the system. In all, the results show that with the different configurations of the system, the desired quality of service for the solar power energy harvesting system can be realized.**

Keywords*— *Power Outage Model, Smart Lathe Machine, IOT Sensor Node, Solar Power System, Energy Harvesting

1. INTRODUCTION

The world is rapidly adopting smart systems which are based on Internet of Things (IoT) sensor networks [1,2,3]. Such networks rely on sensor nodes which are mainly resource constrained with limited power supply [3,4,5]. In many cases, the sensor nodes are powered with batteries which have limited lifespan [6,7]. In such cases, energy harvesting may be included to extend the battery lifespan and avoid unacceptable level of power outage in the sensor node [8,9].

Accordingly, in this work, the IoT sensor node with solar power energy supply and battery backup is studied [10,11]. In order to ensure acceptable power outage level in the system, analytical models are presented for accessing the solar energy harvest, the battery energy level and the power outage status of the sensor node. In this way, the designer of such system can effectively guarantee acceptable power supply quality to the sensor node an at the same time extend the battery lifetime by using the solar energy harvesting to replenish the energy in the battery by charging the battery with the energy harvested from the solar radiation on each day of operation.

2. METHODOLOGY

2.1 The analytical model development

The analytical expressions presented in this work are meant to characterize the various energy components in the solar-powered IoT sensor node for monitoring and controlling of smart Lathe machine. The energy components are captured on daily basis and the power outage performance is represented in terms of loss of load and excess unused energy. The energy components includes the daily energy output from the solar panel, the daily energy consumption by the IoT sensor node, the daily energy storage in the battery, the daily net energy in the system, the potential daily power outage (or loss of load) and the potential daily unused energy. The various parameter used to define the various parameters used in the model development are presented in Table 1 which is adopted from the works in [12].

Table 1 The various parameter used to define the various parameters used in the analytical model development

S/N	Parameter Symbol	Parameter Description	Parameter input value
1	I_{ACT}	Sensor active mode current	
2	t_{ACT}	Sensor active mode time duration	
3	I_{SLP}	Sensor sleep mode current	
4	t_{SLP}	Sensor sleep mode time duration	
5	I_{AVG}	Sensor average current per cycle	
6	η_c	Battery charging efficiency	97%
7	C_u	Battery useable capacity	90%
8	C_T	Battery temperature dependent useable capacity	95%
9	D	Days of power autonomy	
10	S_B	Safety factor for the sizing of the battery	1.2
11	C_B	Nominal or nameplate battery capacity	
12	Gt	Daily mean solar radiation	6.363643836 kW-hr/m^2/day obtained from the site dataset
13	t_f	Number of days required to fully charge the battery	
14	V_s	The terminal voltage of the solar panel	
15	S_s	The cell efficiency of the solar panel	15 %
16	S_s	Safety factor for the sizing of the solar panel	1.2
17	A_s	The cell area of the solar panel	
18	Gt_i	The mean solar radiation on day i	
19	$E_{R(i)}$	The energy output of the solar cell in day i with solar irradiation of $Gt_i$where the solar panel has area, A_s	
20	E_{RDay}	The IoT sensor node Daily energy demand expressed in (Wh)	
21	$E_{RN(i)}$	Net energy or the difference between the produced by the solar panel and the energy consumed by the IoT sensor node in day i, (Wh)	
22	$E_{R(FullBatCap)}$	The total energy that is stored in the fully charged battery (Wh)	
23	Ta	Annual mean of the daily mean atmospheric temperature	26.19627397 °C

The battery capacity (C_B), battery capacity for one day power autonomy $\left(C_{B/day}\right)$, the sensor node average current per cycle (I_{AVG}) and PV panel area (A_s) required are computed as follows [12];

$$C_B = \frac{24(D)\,(I_{AVG})(S_B)}{(C_u)(C_T)(\eta_c)} \quad (1)$$

$$C_{B/day} = \frac{C_B}{D} \quad (2)$$

$$A_s = \frac{E_R}{\text{Gt}} = \frac{C_B(V_s)(S_s)}{\left((\eta_s)(t_f)\right)(\text{Gt})} \quad (3)$$

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

$$E_{R(i)} = (A_s)Gt_i = \frac{C_B(V_s)(S_s)}{\left((\eta_s)(t_f)\right)} \quad (5)$$

$$E_{R(FullBatCap)} = (E_{R_s})(t_f) = \left(\frac{C_B(V_s)(S_s)}{(\eta_s)(t_f)}\right) t_f \quad (7)$$

$$E_{RDay} = \frac{(C_{B/day})(V_s)(S_s)}{(\eta_s)} \quad (8)$$

$$E_{RN(i)} = E_{R(i)} - E_{RDay} = \left[\frac{C_B(V_s)(S_s)}{\left((\eta_s)(t_f)\right)}\right] - \left[\frac{(C_{B/day})(V_s)(S_s)}{(\eta_s)}\right] \quad (9)$$

$$E_{RN(i)} = \frac{(V_s)(S_s)}{(\eta_s)}\left(\frac{C_B}{t_f}\right) - \left(C_{B/day}\right) \quad (10)$$

Let $E_{RBatBG(0)}$ denote the energy initially stored in the battery in day 0, and $B_{RBatEN(i)}$ denote the energy stored in the battery in day i, where the battery is initially assumed to be fully charged in day 0, then;

$$E_{RBatBG(0)} = E_{R(FullBatCap)} \quad (11)$$

However, if the battery is no initially fully charged but has initial, energy $E_{RBat(0)}$, then;

$$E_{RBatBG(0)} = E_{RBat(0)} \quad (12)$$

The net energy in day 0, $B_{RBatEN(0)}$ is;

$$B_{RBatEN(0)} = E_{RBatBG(0)} + E_{R(0)} - E_{RDay} \quad (13)$$

Then, the actual energy stored in the battery in day 0, $E_{RSBatENLT(0)}$ after delivery some energy to the load is given as;

$$E_{RSBatENLT(0)} = \text{minimum}\left(B_{RBatEN(0)}, E_{R(FullBatCap)}\right) \quad (14)$$

The unused energy in day i, $E_{RUnUsed(0)}$

$$E_{RUnUsed(0)} = \max\left(0,\ \left(B_{RBatEN(0)} - E_{RSBatENLT(0)}\right)\right) \quad (15)$$

Let $n_{LoLD(i)}$ denote the flag for the occurrence of loss of load or power outage in day i and $n_{Unuse(i)}$ denote the flag for the occurrence of unused energy loss in day i where;

$$n_{LoLD(0)} = \begin{cases} 1 \ \ if\ E_{RSBatENLT(0)} < E_{R(FullBatCap)} \\ 0 \ \ if\ E_{RSBatENLT(0)} \geq E_{R(FullBatCap)} \end{cases} \quad (16)$$

$$n_{Unuse(0)} = \begin{cases} 0 \ \ if\ E_{RUnUsed(0)} < 0 \\ 1 \ \ if\ E_{RUnUsed(0)} \geq 0 \end{cases} \quad (17)$$

Hence, when i > 0 we have;

$$E_{RBatBG(i)} = \max\left(0,\ E_{RSBatENLT(i-1)}\right) \quad (18)$$

$$B_{RBatEN(i)} = E_{RBatBG(i)} + E_{R(i)} - E_{RDay} \quad (19)$$

$$E_{RSBatENLT(i)} = \text{minimum}\left(B_{RBatEN(i)}, E_{R(FullBatCap)}\right) \quad (20)$$

$$E_{RUnUsed(0)} = \max\left(0,\ \left(B_{RBatEN(i)} - E_{RSBatENLT(i)}\right)\right) \quad (21)$$

$$n_{LoLD(i)} = \begin{cases} 1 \ \ if\ E_{RSBatENLT(i)} < E_{R(FullBatCap)} \\ 0 \ \ if\ E_{RSBatENLT(i)} \geq E_{R(FullBatCap)} \end{cases} \quad (22)$$

$$n_{Unuse(i)} = \begin{cases} 0 \ \ if\ E_{RUnUsed(i)} < 0 \\ 1 \ \ if\ E_{RUnUsed(i)} \geq 0 \end{cases} \quad (23)$$

$$n_{TLoLD} = \sum_{i=0}^{i=365}\left(n_{LoLD(i)}\right) \quad (24)$$

$$n_{TUnuse} = \sum_{i=0}^{i=365}\left(n_{Unuse(i)}\right) \quad (24)$$

The loss of load probability, LoLDP and the unused energy probability, UEP are computed as;

$$LoLDP = \left(\frac{n_{TLoLD}}{365}\right) 100\ \% \quad (35)$$

$$\text{UEP} = \left(\frac{n_{TUnuse}}{365}\right) 100\ \% \quad (26)$$

2.2 The Case Study Site and Meteorological Data

The case study site is located in Akwa Ibom State Polytechnic. The Google map visualization of the site for the solar-powered IoT sensor node having latitude of 5.156937492133076 and longitude of 7.668216975069745 is presented in Figure 1. The solar radiation and also the ambient temperature of the study site were downloaded from NASA portal. The daily mean and annual mean solar radiation of the study site is presented in Figure 2; it has annual mean of 4.110307 kWhr/^s/day. Similarly, the daily mean and annual mean atmospheric temperature is presented in Figure 3; it has annual mean of 26.296 °C. The solar radiation and ambient temperature dataset along with the energy consumption data of the IoT sensor node were used to compute the solar power energy yield and the resultant power outage performance parameters.

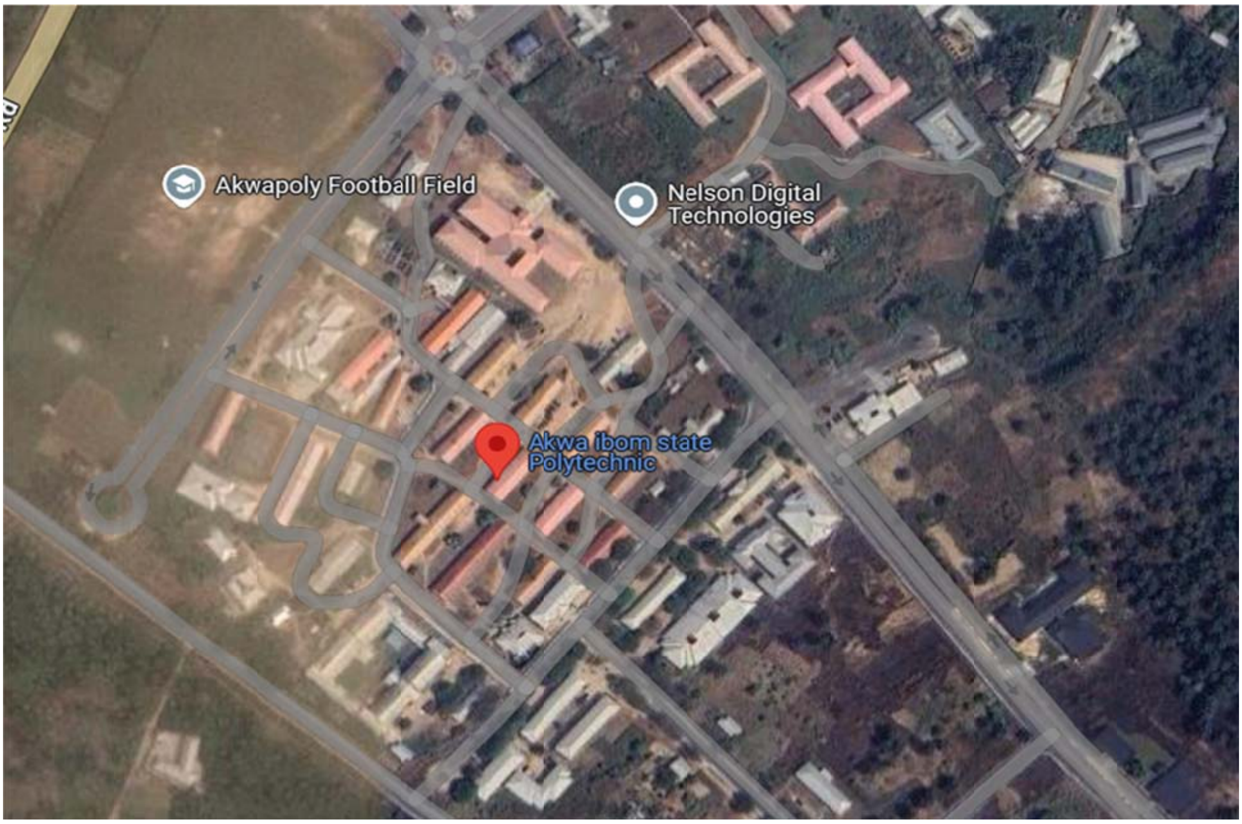

Figure 1 The Google maps visualization of the site for the solar-powered IoT sensor node having latitude of 5.156937492133076 and longitude of 7.668216975069745

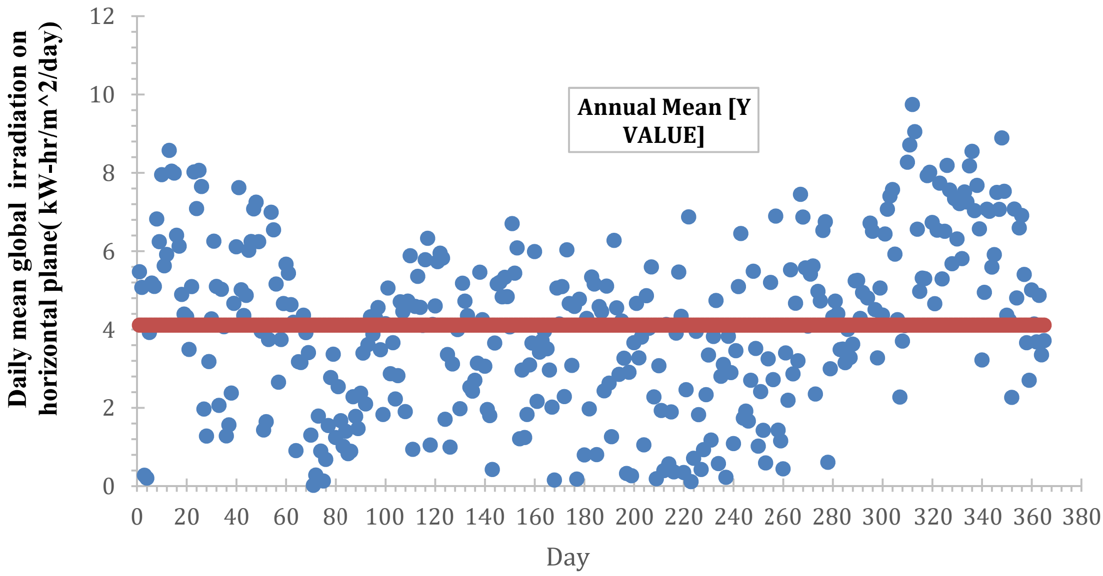

Figure 2 The daily mean and annual mean solar radiation

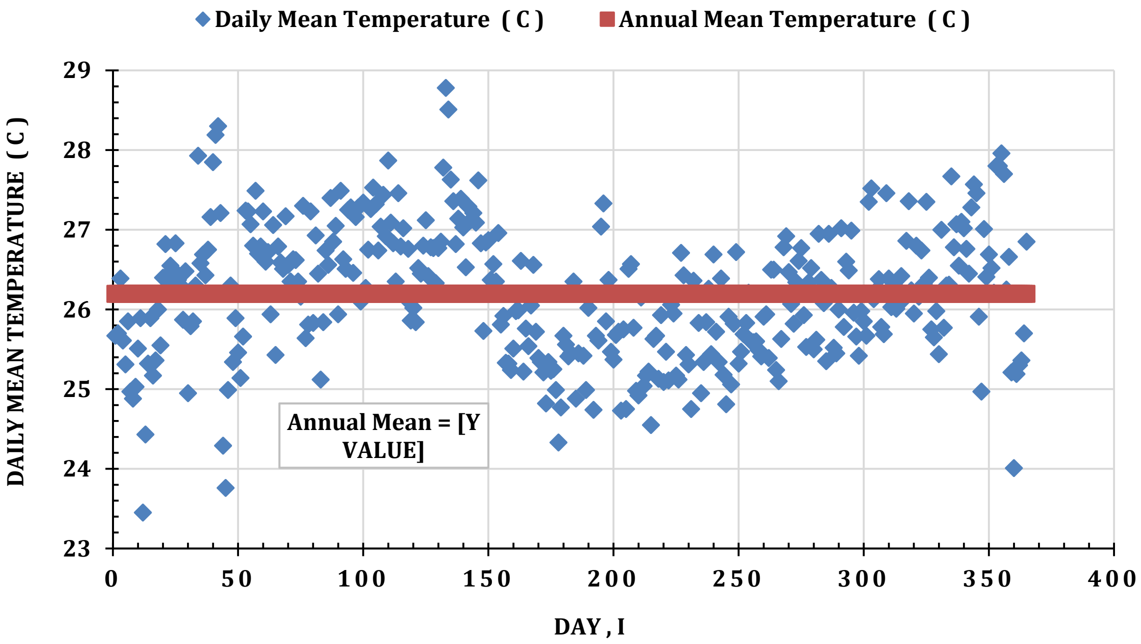

Figure 3 The daily mean and annual mean atmospheric temperature

3. RESULTS AND DISCUSSION

The simulation parameter dataset and the first batch of the simulation results are presented in Table 1. The simulation results presented Table 1 for Days of Autonomy, DoA of 3 days show that with days it take to fully charge battery, t set to 1.5 days, there will be 10 days of power outage in a year which is a loss of load probability (LoLDP%) of 2.74 %. The graph for the net energy per day and the energy demand per day for days of power autonomy, D = 3 days and batter charging time, t =1.5days is shown in Figure 4 and also in Figure 5 for the days with the power outage. In Figure 4 and Figure 5, all the net energy points below zero indicate days of power outage, and they are ten as shown in Figure 5.

Table 1 The simulation parameter dataset and the first batch of the simulation results

S/N	Simulation Parameter Description	Value	S/N	Parameter Results Description	Value
1	I_{tx}, Transmit Current (mA)	103	13	Days of Autonomy, DoA	3
2	I_{rx}, Receive Current (mA)	72	14	Days it take to fully charge battery, t	1.5
3	Ims, Measure Current (mA)	110	15	Average daily solar irradiation (Wh/m^2/day)	4138.74
4	Islp, Sleep Current (mA)	0.05	16	Required battery capacity (mAh)	101.2
5	T_{tx}, Transmit Time (ms)	2800	17	Solar cell size (cm^2)	7.9
6	T_{rx}, receive Time (ms)	1760	18	Energy store in fully charged battery	4.896
7	T_{ms}, Measure Time (ms)	302	19	Daily Energy Demand (Wh)	1.632
8	T_{slp}, Sleep (ms)	481338	20	Number of days of power outage or loss of load	10
9	Tcy Cycle time(s)	486200	21	Percentage % of days of power outage or loss of load probability (LoLDP%)	2.74
10	Duty Cycle (%)	1	22	Number of days of excess energy is unused or lost	258
11	Number of cycles per day	177.7046	23	Percentage % of days excess energy is unused or lost	70.68
12	Average Current, Iavg (mA)	0.971631	24	Number of days of excess energy is completely stored	97
13	Days of Autonomy,	3	25	Percentage % of days excess energy is completely stored	26.58

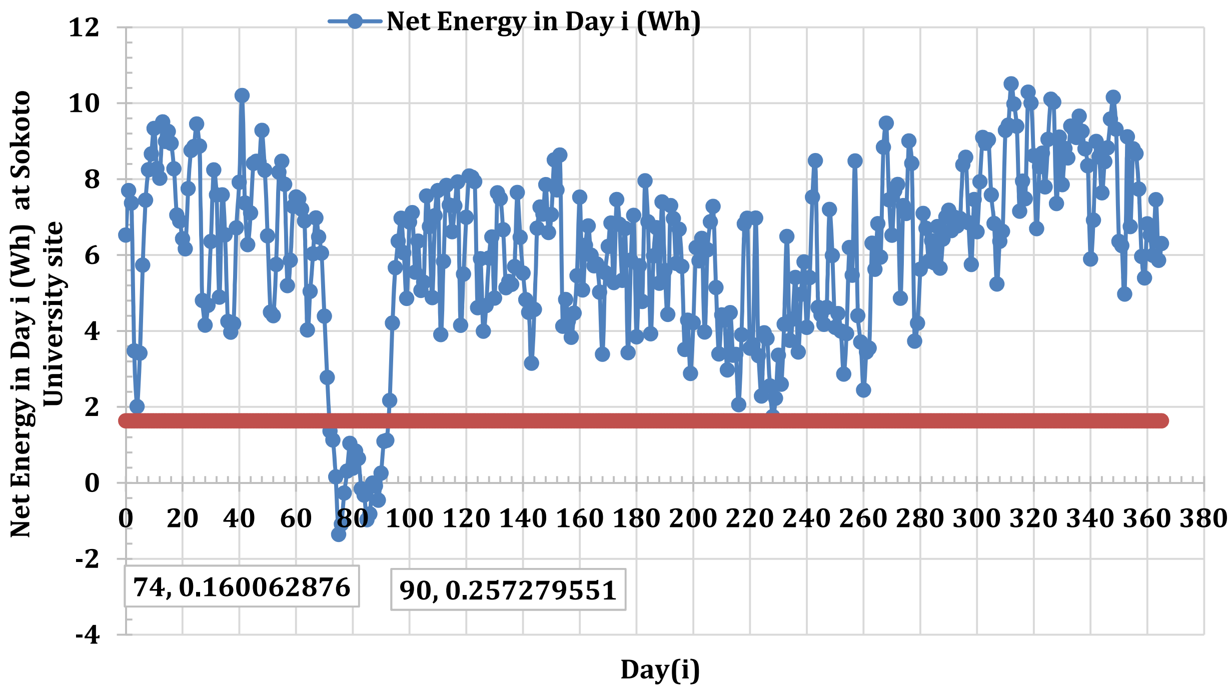

Figure 4 The graph for the net energy per day and the energy demand per day for days of power autonomy, D = 3 days and batter charging time, t =1.5days

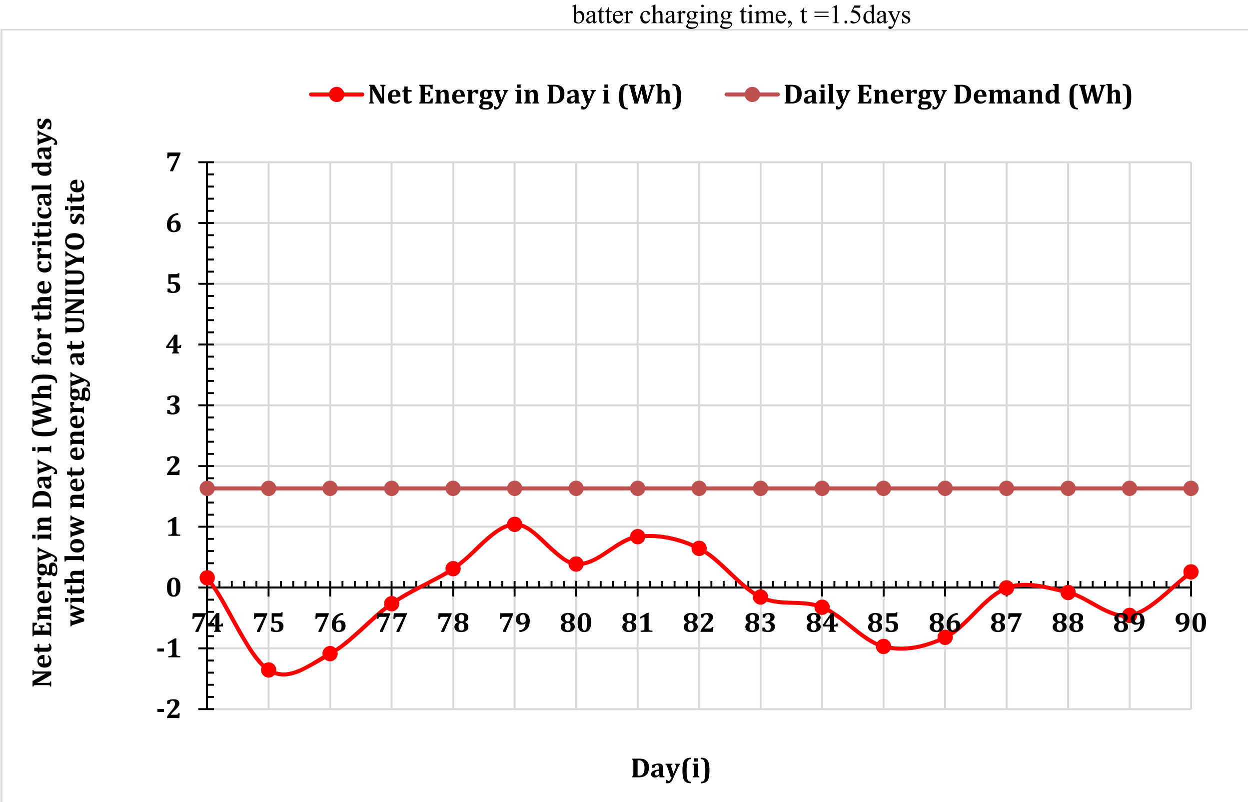

Figure 5 The graph for day 74 to day 90 showing the net energy per day and the energy demand per day for days of power autonomy, D = 3 days and batter charging time, t =1.5days

Again, the results of the simulation of the solar power performance for a case where the days of power autonomy is kept constant at 3 days while t which is the required number of days for charging the battery is varied from 1 day to 2 days in the steps of 0.25 are shown in Table 2, Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10. The results show that as t increases from 1 to 2 days, the required PV panel area (that is PV panel size) decreases from 11.7 m^2 to 5.9 m^2 respectively. Also, the number of days of power outage in a year increases from 1 day to 21 when t increased from 1 to 2 days. In all these cases, the total energy stored in the fully charged battery remained constant at 4.9. The implication of this results is that as t increases, the battery capacity is kept constant but smaller PV panel is used which reduces cost of the PV panel but at the same time increases the power outage in the system.

Table 2 The results of the simulation where D is kept constant at 3 days while t is varied from 1 day to 2 days in the steps of 0.25

Parameter Description	Experiment 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
D	3	3	3	3	3
t	1	1.25	1.5	1.75	2
CB	101.22	101.2225	101.2225	101.2225	101.2225
Energy store in fully charged battery	4.9	4.9	4.9	4.9	4.9
Solar cell size (cm^2)	11.7	9.5	7.9	6.8	5.9
Number of days of power outage or loss of load	1	3	8	13	21
Percentage % of days of power outage or loss of load probability (LoLDP%)	0.273973	0.821918	2.191781	3.561644	5.753425
Number of days of excess energy is unused or lost	311	284	261	233	204
Percentage % of days excess energy is unused or lost	85.20548	77.80822	71.50685	63.83562	55.89041

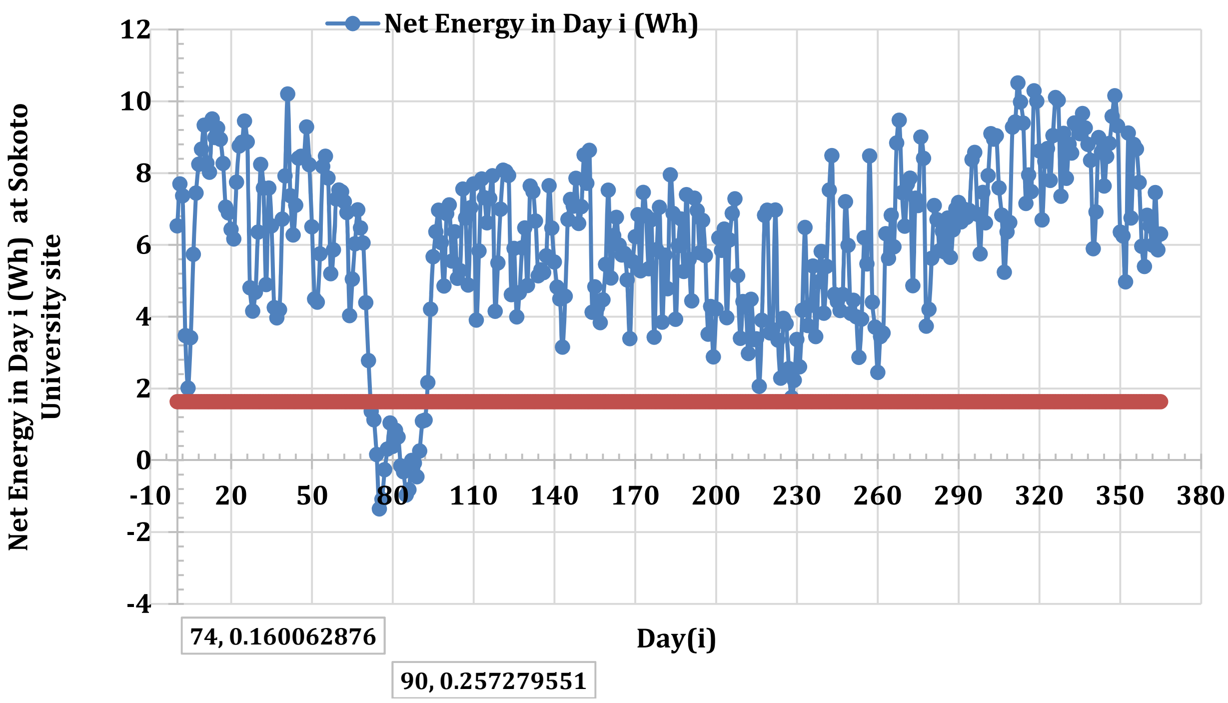

Figure 6 The graph for the net energy per day and the energy demand per day for days of power autonomy, D = 3 days and batter charging time, t =1. Day

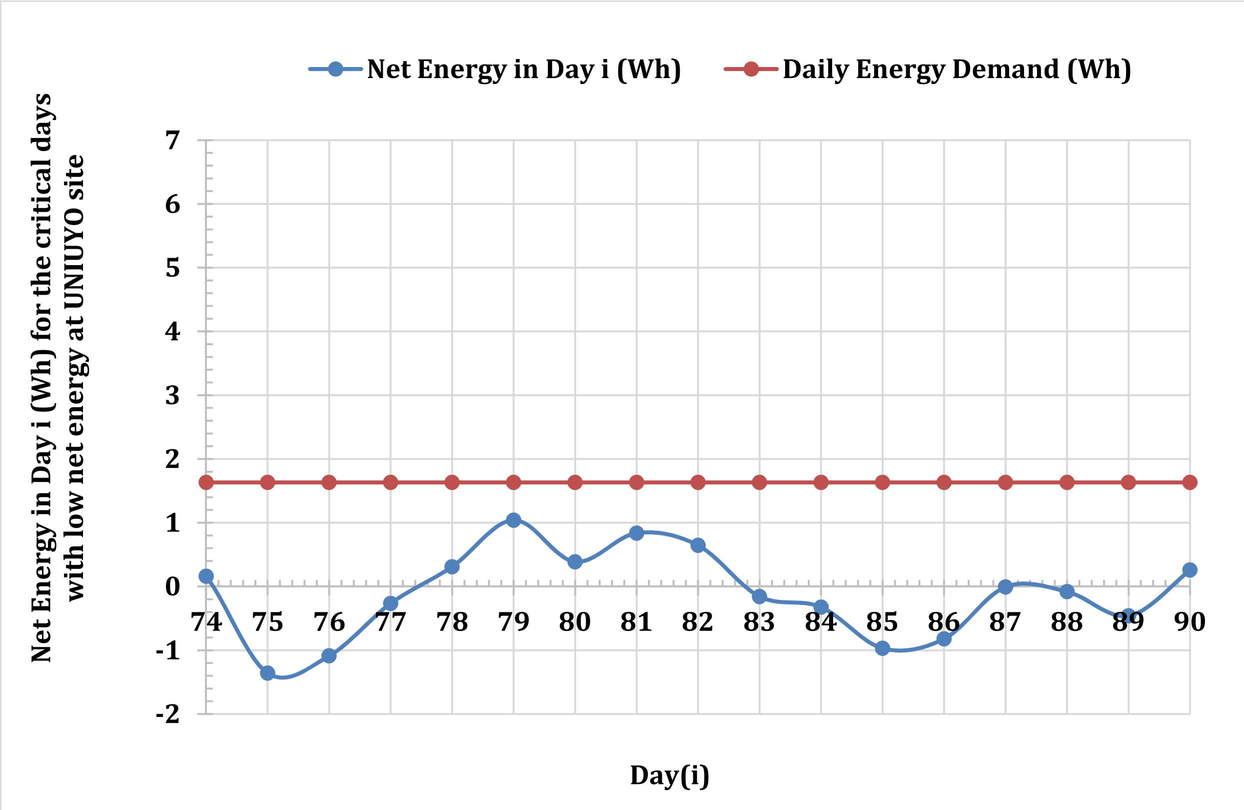

Figure 7 The graph for day 74 to day 90 showing the net energy per day and the energy demand per day for days of power autonomy, D = 3 days and batter charging time, t =1. Day

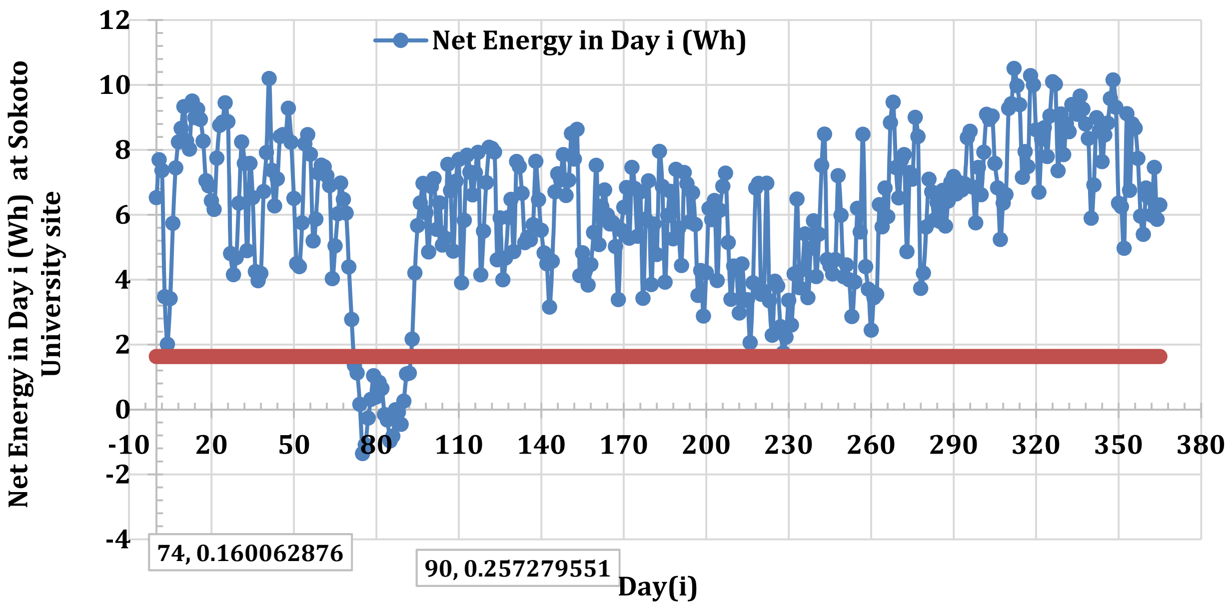

Figure 8 The graph for the net energy per day and the energy demand per day for days of power autonomy, D = 3 days and batter charging time, t =1.25 days

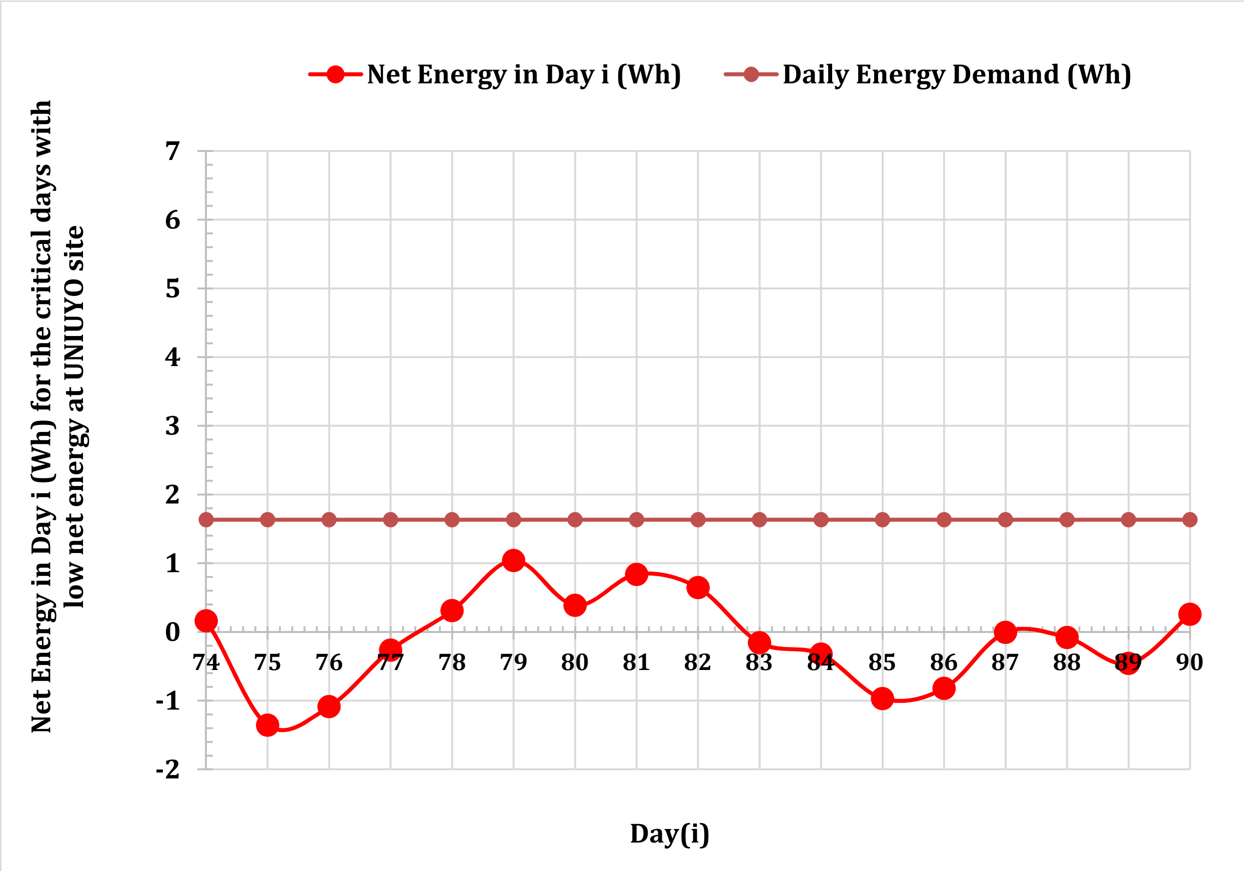

Figure 9 The graph for day 74 to day 90 showing the net energy per day and the energy demand per day for days of power autonomy, D = 3 days and batter charging time, t =1.25 Day

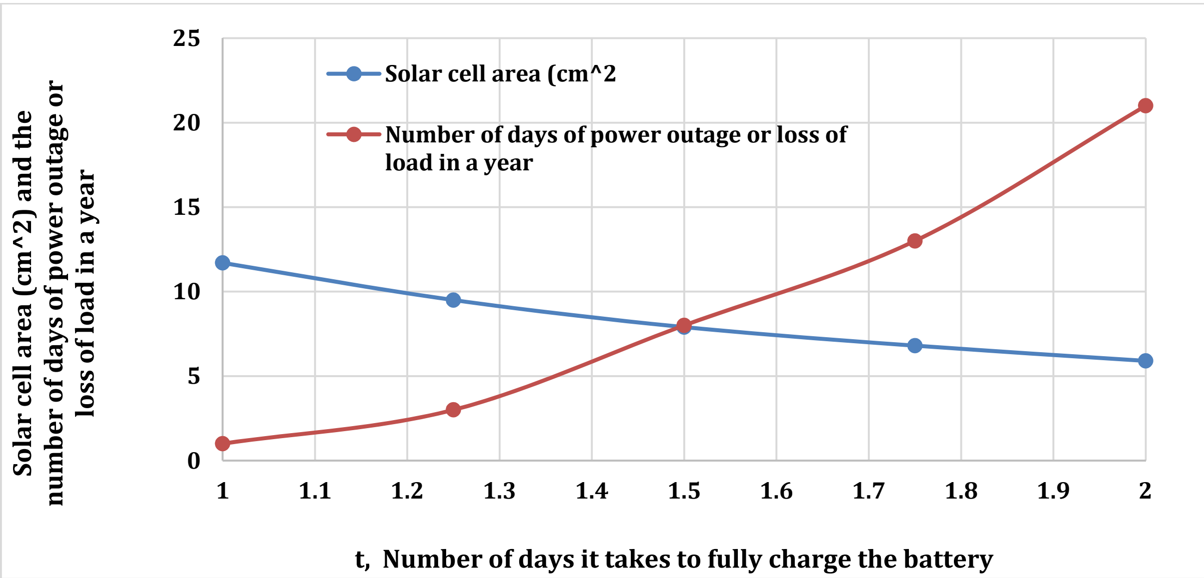

Figure 10 The graph for Solar cell area (cm^2) and the number of days of power outage or loss of load in a year for D = 3 days and, $1 \leq t \leq 2$

Once more, the results of the simulation of the solar power performance for a case where the days of power autonomy is varied from 1 day to 3 days in the steps of 0.5 while t which is the required number of days for charging the battery is kept constant at 1 day are shown in Table 3, Figure 11 and Figure 12. The results show that as D increases from 1 to 3 days, the required solar cell area increased from 3.9cm^2 to 11.7 cm^2 and at the same time, the energy stored in the fully charged battery also increased from1.6 mWh to 4.9 mWh. In addition, the number of days of power outage or loss of load (days/year) decreased from 123 days per year to 1 day per year as D increased from 1 to 3 while the number of days of excess energy is unused increased from 102 days per year to 311 day per year as D increased from 1 to 3. In all, the results show that with the different configurations of the system, the desired quality of service for the solar power energy harvesting system can be realized.

Table 3 The results of the simulation where t is kept constant at 1 day while D is varied from 1 day to 3 days in the steps of 0. 5

Parameter Description	Experiment 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
D	3	2.5	2	1.5	1
t	1	1	1	1	1
CB	101.2225	84.35211	67.48168	50.61126	33.74084
Energy store in fully charged battery	4.9	4.1	3.3	2.4	1.6
Solar cell size (cm^2)	11.7	9.9	7.9	5.9	3.9
Number of days of power outage or loss of load	1	3	10	36	123
Percentage % of days of power outage or loss of load probability (LoLDP%)	0.273973	0.821918	2.739726	9.863014	33.69863
Number of days of excess energy is unused or lost	311	297	260	212	102
Percentage % of days excess energy is unused or lost	85.20548	81.36986	71.23288	58.08219	27.94521

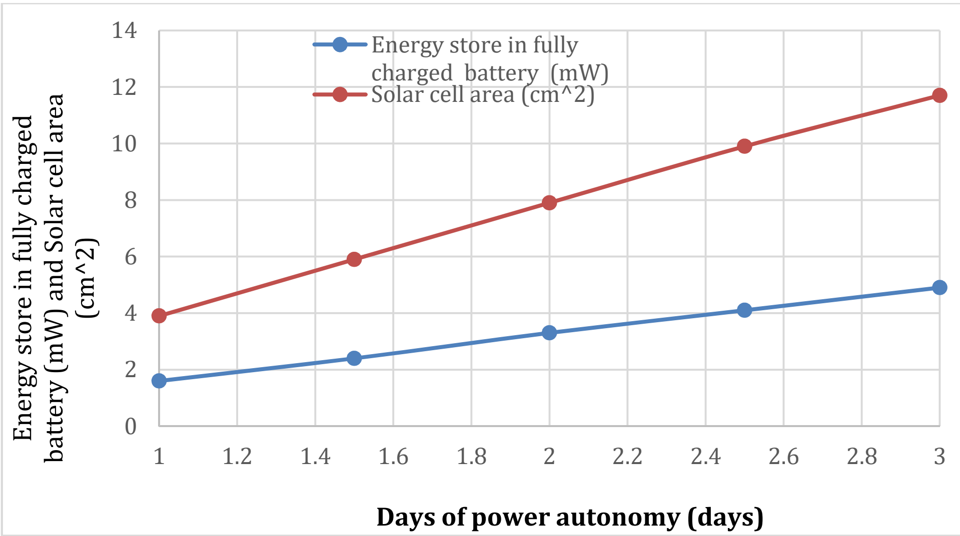

Figure 12 The graph for Solar cell area (cm^2) and the energy stored in the fully charged battery for t = 1 day and, 1 ≤ D ≤3

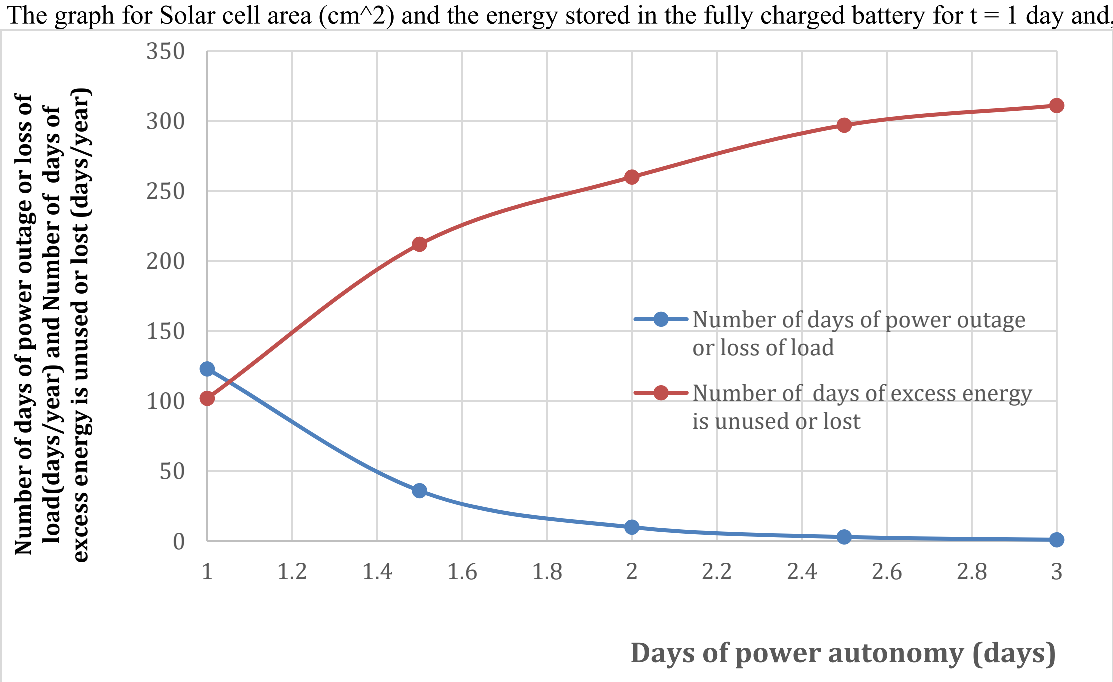

Figure 13 The graph for number of days of power outage or loss of load (days/year) and Number of days of excess energy is unused or lost (days/year) for t = 1 day and, 1 ≤ D ≤3

4. CONCLUSION

The analytical modeling of solar energy harvesting system for an IoT sensor node with battery backup for remote monitoring of lathe machine is presented. The study carried out parametric analysis of the system focusing on the power outage, days of power autonomy, the battery charging duration and the solar panel size requirement. All these parameters are considered and their effects on the quality of service of the solar energy harvesting system are examined. The results showed that condition of no loss of load or no power outage can be achieved by proper selection of the PV panel size, days of power autonomy and the battery charging duration.

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