International Multilingual Journal of Science and Technology (IMJST)
ISSN: 2528-9810
Vol. 7 Issue 10, October - 2022

Modelling of the energy level and outage analysis for battery-powered IoT Sensor node with solar energy harvester

Oto-Obong Chijioke Onwunali[1]
Department of Electrical Electronic and Computer Engineering University of Uyo
Akwa Ibom State, Nigeria

Regina Aniebiet Udoh[2]
Department of Electrical and Electronic Engineering,
Akwa Ibom State University Mkpat Enin, Akwa Ibom State
reginaaniebiet@gamail.com

Ubong Ukomi[3]
Department of **Electrical and Electronic Engineering**,
Akwa Ibom State University Mkpat Enin, Akwa Ibom State
ubongukommi@aksu.edu.ng

Abstract— **In this paper, modelling of the energy level and outage analysis for battery-powered IoT sensor node with solar energy harvester is presented. The model considered the sensor node that goes through periodic cycles where in each cycle it goes through some states where it draws different amount of current and spends different amount of time. The model focus is on sizing the battery and solar cell and determining how the size of the two components affect the daily energy level of the battery, the outage probability and the excess energy that are lost in the process. The daily solar irradiation dataset is obtained for the site with latitude of 5.05 and longitude of 7.90. The data was extracted from NASA website through the meteorological download tool in PVSyst software. Sample numerical example was implemented with sensor node that has cycle time of 576000 ms, duty cycle of 1 % and average current of 0.628806 mA. The results obtained when the yearly mean of daily solar irradiation value of 4704.6 Wh/m^2 per day was used to size the battery show that to ensure zero power outage the minimum days of autonomy required is 2.6 days with a solar cell area of 3.9 cm^2. Also, the required battery capacity is 56.3 mAh which will store 2.7 Wh energy when fully charged. On the other hand, when the yearly minimum daily solar irradiation of 593.0 Wh/m^2/day was used, the minimum days of autonomy required is about 0.8 days (less than one day) and the solar cell area of 9.7 cm^2 is required. The required battery capacity is 17.2 mAh which will store 0.9 Wh energy when fully charged. Generally, the results show that sizing with the mean solar irradiation value and using the minimum irradiation value affect the battery capacity and solar cell size; in the first case, larger battery capacity is required whereas in the second case, larger solar cell size is required. Also, the results show that it is possible to achieve zero power outage even when the battery capacity is less than the daily required capacity.**

Keywords — Outage Analysis, Solar Irradiation, Battery-Powered, Solar Energy Harvester, IoT, Energy Level, Loss of Load

1. Introduction

The world today is rapidly perfecting the concept of global village were every one anywhere in the world can connect and interact [1,2,3,4,5,6,7]. However, beyond human connectivity, the advancement in electronic and communication technologies has led to the emergence of Internet of Things (IoT), whereby anything can be made to connect and interact with any other human or things. In this IoT world, sensors and wireless networks are key to facilitating the connectivity [8,9,10,11,12,14,15].

Wireless network as a driver for IoT implementations has grown over the years and has extended from the terrestrial networks to satellite-to-earth and satellite-to-satellite communications [16,17, 18,19, 20,21, 22,23, 24,25, 26, 27]. In all these diverse forms of wireless network implementations, there is need for adequate power supply for the various components of the communication system. At the transmitter, enough power is required to generate signal strength that can withstand the various propagation loss mechanisms that abound in the signal path [26,27,28,29,30,31,32,33,34,35,36]. Notably, the spreading loss, diffraction loss, multipath loss, atmospheric losses and other fade mechanisms are required to be accommodated in the wireless network design [37,38,39,40,41,42,43,44]. In view of this, the required transmitter power must produce transmitted signal strength that can transverse the signal path length and reach the receiver with sufficient signal strength that is above or at least equal to the receiver sensitivity [45,46,47,48,49,50,51,52,53,54,55]]. Also, in the bid to establish sensor-to-satellite communication link, adequate transmitter power is also required to generate the required signal strength for the long distance communication path [56,57,58,59,60].

Furthermore, wireless sensor network which forms the bedrock of the IoT implementations rely mainly on resource constrained sensor nodes [61,62,63]. The sensor nodes are usually battery-powered and installed remotely where they have no access to the power grid [64.65,66,67,68,69,70]. In such cases, different energy harvesting approaches have been adopted to sustain the power supply for the sensor nodes. Among the different options, solar photovoltaic energy harvesting approach is widely adopted [71,72,73,74,75,76,77,78,79,80]. In order to determine the appropriate size of the required battery capacity and solar cell for powering a sensor node detailed analysis is required. The focus in this paper is on providing mathematical models that can be used to conduct such analysis so as to determine the smallest sizes for the solar cell and battery capacity that will effectively power the sensor node without incurring power outage. This is because the sensor nodes are in most cases deployed in large numbers and any excess cost due to undue oversizing of the components will amount to huge sum of money in the overall network implementation.

2. Methodology

2.1 The Mathematical Model

The model is presented for a single sensor node that goes through periodic cycles, with periodic time t_{cycl}. In each cycle, the sensor node goes through n states, where the states 1, 2, 3, ... , n-1 constitute the active part of the sensor node and state n is the sleep state. In each state, i , the sensor node draws current, I_i for a time t_i. In most published works, apart from the sleep time of the sensor node, the time spent in the various states of the sensor nodes are given or determined from the sensor data specifications. The sleep state time, given in this paper as t_n is usually computed from the knowledge of the cycle time. In any case, sometimes, the cycle time is computed from the knowledge of duty cycle or the number of cycles the sensor goes through per day. As such, determination of the sleep time of the sensor node depends on what value is available. After the sleep time is computed, the average current, $\boldsymbol{I_{avg}}$ drawn by the sensor node in each cycle can then be computed. In this paper, three case are considered for the computation of the sensor node sleep time and allied parameters.

Case I: when the periodic cycle time, t_{cycl} is given, then, the sleep state time given as t_n, is computed as follows;

$$t_n = t_{cycl} - \sum_{i=1}^{i=n-1}(t_i) \tag{1}$$

The duty cycle, d_{cycl} is given as;

$$d_{cycl} = \left(\frac{\sum_{i=1}^{i=n-1}(t_i)}{t_{cycl}}\right) 100\ \% \tag{2}$$

The number of cycles per day or number of data capture by the sensor node in a day, n_{cypd} is given as;

$$n_{cypd} = \left(\frac{86400\ seconds/day}{t_{cycl}\ in\ seconds}\right) \tag{3}$$

Case II: when the duty cycle, d_{cycl} is given in % then;

$$t_{cycl} = \left(\frac{\sum_{i=1}^{i=n-1}(t_i)}{d_{cycl}}\right) 100\ \% \tag{4}$$

Then, the t_n can be computed from the value of t_{cycl} using Eq1.

Case III: when the number of cycles per day or number of data captured by the sensor node per day, n_{cypd} is given, then;

$$t_{cycl}\ in\ seconds = \left(\frac{86400\ seconds/day}{n_{cypd}}\right) \tag{5}$$

Again, the t_n can be computed from the value of t_{cycl}. Once, t_n is obtained, the average current, I_{Avg} drawn by the sensor node in each cycle is given as;

$$I_{Avg} = \frac{\sum_{i=1}^{i=n}((I_i)(t_i))}{\sum_{i=1}^{i=n}(t_i)} \tag{6}$$

The required battery capacity denoted as C_{BatDut} that can power the sensor node without recharging for D_{Aut} number of days (D_{aut} is the number of days of power autonomy) is given as;

$$C_{BatDaut} = \frac{24(D_{Aut})\,(I_{Avg})(S_{Bat})}{(C_{UBat})(C_{TBat})(\eta_{cBat})} \tag{7}$$

Where S_{Bat} denote the battery sizing safety factor (typically 1.2), η_{cBat} denote battery charger efficiency (typically 97 %), C_{UBat} denote battery useable capacity factor (typically 90 %) and C_{TBat} denote the battery capacity temperature dependent factor (typically 95 %). Then, the battery capacity that can effectively supply energy to the sensor node for one day is $C_{BatPday}$ where;

$$C_{BatPday} = \frac{C_{BatDaut}}{D_{aut}} \tag{8}$$

The solar cell energy harvester area, A_{SCel} required to charge the $C_{BatDaut}$ battery to full capacity in T_{FBat} number of days is given as;

$$A_{SCel} = \frac{E_{HarvPDay}}{G_{DAvg}} \tag{9}$$

Where G_{DAvg} the yearly average of the daily solar irradiation of the study site and $E_{HarvPDay}$ is the energy harvested per day by the solar cell such that in T_{FBat} number of days the $C_{BatDaut}$ battery will be fully charged.

$$E_{HarvPDay} = \frac{(C_{BatDaut})(V_{SCel})(S_{SCel})}{(\eta_{SCel})(T_{\mathrm{FBat}})} \tag{10}$$

$$E_{HarvPDay} = (A_{SCel})(G_{DAvg}) \tag{11}$$

Where η_{SCel} is the efficiency of the solar cell, V_{SCel} is the terminal voltage of the solar cell and S_{SCel} is the safety factor for sizing the solar cell (typically, 1.2). Hence, the energy required to fully charge the battery in T_{FBat} number of days (that is energy required for full battery capacity) is denoted as $E_{HarvFulBat}$, where;

$$E_{HarvFulBat} = E_{HarvPDay}(T_{\mathrm{FBat}}) \tag{12}$$

Furthermore, the daily energy demand by the sensor node from the battery, $E_{DmandPDay}$ is given as;

$$E_{DmandPDay} = \frac{E_{HarvFulBat}}{D_{aut}} \tag{13}$$

Since the daily solar irradiation varies with time, in a year, the solar irradiation for day i is denoted as $G_{Day(i)}$, and then the energy harvested in day i is denoted as $E_{HarvDay(i)}$ where;

$$E_{HarvDay(i)} = (A_{SCel})(G_{Day(i)}) \tag{14}$$

The net daily energy, $E_{NetDay(i)}$ in day i is given as;

$$E_{NetDay(i)} = E_{HarvDay(i)} - E_{DmandPDay} \tag{15}$$

Let the energy stored in the battery in day i be denoted as $E_{BatStorDay(i)}$. The net energy in day i including the already stored energy in battery in the precious day is denoted as $E_{NetPlusBatDay(i)}$, then;

$$E_{NetPlusBatDay(i)} = E_{BatStorDay(i-1)} + E_{NetDay(i)} \tag{16}$$

$$E_{NetPlusBatDay(i)} = E_{BatStorDay(i-1)} + E_{HarvDay(i)} - E_{DmandPDay} \tag{17}$$

If it is assumed that the battery is initially fully charged, then for i=1, $E_{BatStorDay(i-1)} = E_{BatStorDay(0)} = E_{HarvFulBat}$. On the other hand, if it is assumed that the battery is initially empty, then for i=1, $E_{BatStorDay(i-1)} = E_{BatStorDay(0)} = 0$. Equally, the initial value $E_{BatStorDay(0)}$ can be a fraction of the full charge value, such as;

$$E_{BatStorDay(0)} = \alpha(E_{HarvFulBat}) \tag{18}$$

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;

$$E_{BatStorDay(i)} = maximum(0, [minimum\ (E_{HarvFulBat}, E_{NetPlusBatDay(i)})]) \tag{19}$$

Days of outage denoted as $d_{outage(i)}$ is determined by making $d_{outage(i)} = 1$ if there will be partial or total outage in day i and $d_{outage(i)} = 0$ if there will be no outage at all in day i. In this case,

$$d_{outage(i)} = \begin{Bmatrix} = 1 \ \ if\ E_{NetPlusBatDay(i)} < 0 \\ = 0 \ \ if\ E_{NetPlusBatDay(i)} \geq 0 \end{Bmatrix} \tag{20}$$

In some days, the battery is fully charged and more energy is generated than what can be stored in the battery. In such day, the excess energy will be wasted or lost. Days of unused energy denoted as $d_{UnuseE(i)}$ is determined by making $d_{UnuseE(i)} = 1$ if $E_{NetPlusBatDay(i)} > E_{HarvFulBat}$ in day i and $d_{UnuseE(i)} = 0$ if $E_{NetPlusBatDay(i)} \leq E_{HarvFulBat}$ in day i. In this case,

$$d_{UnuseE(i)} = \begin{Bmatrix} = 1 \ \ if\ E_{NetPlusBatDay(i)} > E_{HarvFulBat} \\ = 0 \ \ if\ E_{NetPlusBatDay(i)} \leq E_{HarvFulBat} \end{Bmatrix} \tag{21}$$

The unused energy denoted as $E_{UnuseE(i)}$ is given as;

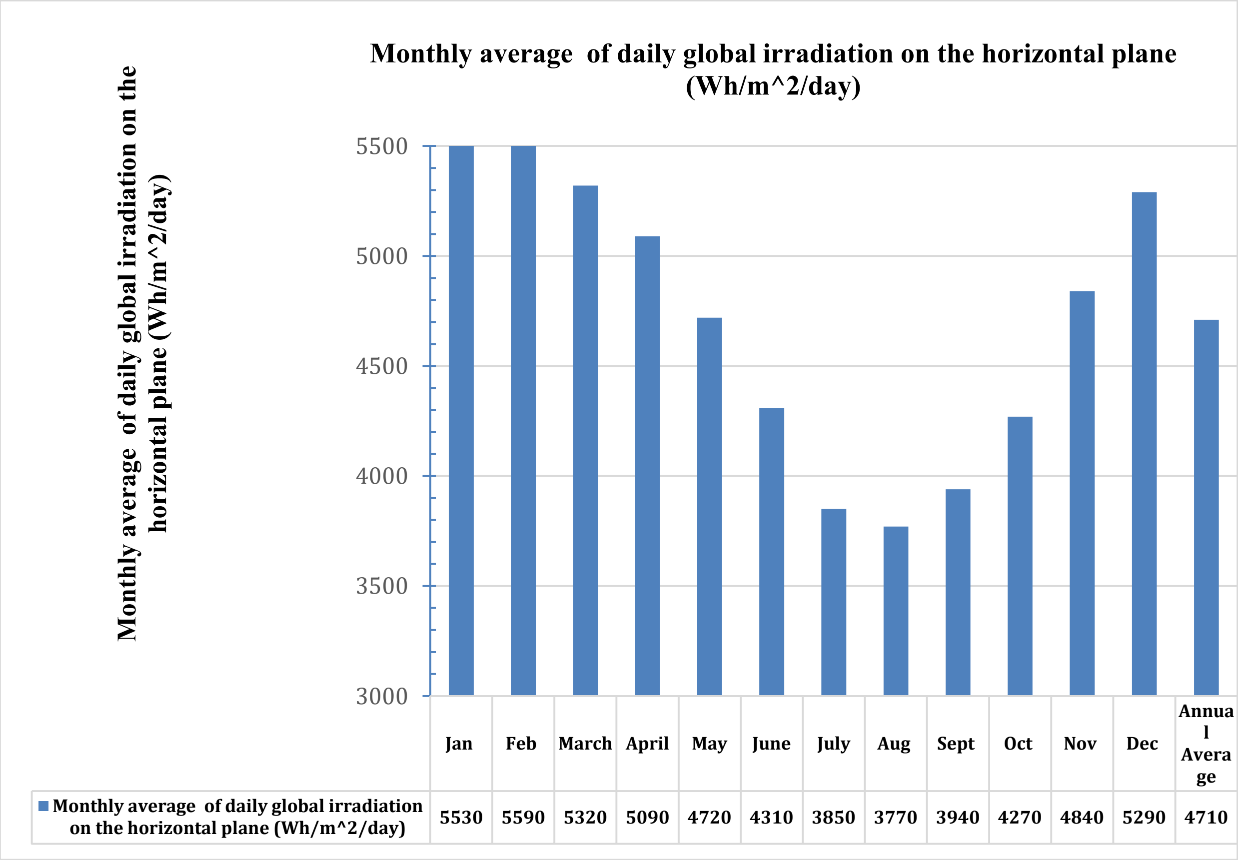
$$E_{UnuseE(i)} = maximum\ (E_{NetPlusBatDay(i)} - E_{HarvFulBat}) \tag{22}$$

In some days, there is excess energy above the daily energy demand but all the excess energy are stored in the battery; no energy is lost or unused. In such day, there is no power outage and there is no power loss or unused power. Let such day of no power loss and no power outage be denoted as $d_{NLossNOutage(i)}$ and it is determined by making $d_{NLossNOutage(i)} = 1$ if $0 < E_{NetPlusBatDay(i)} \leq E_{HarvFulBat}$ in day i and $d_{NLossNOutage(i)} = 0$ if $E_{NetPlusBatDay(i)} < 0$ or $E_{NetPlusBatDay(i)} > E_{HarvFulBat}$ in day i. In this case,

$$d_{NLossNOutage(i)} = \begin{cases} = 1 \ \ if\ 0 < E_{NetPlusBatDay(i)} \leq E_{HarvFulBat} \\ = 0 \ \ if\ E_{NetPlusBatDay(i)} < 0 \ \text{ or } \ E_{NetPlusBatDay(i)} > E_{HarvFulBat} \end{cases} \tag{23}$$

2.2 The daily solar irradiation dataset

The daily solar irradiation dataset that is used in this paper is obtained for site with latitude of 5.05 and longitude of 7.90. The data was extracted from NASA website through the meteorological download tool in PVSyst software. The monthly average of daily solar irradiation on the horizontal plane is shown in the bar chart of Figure 1 while the scatter plot of the daily average solar irradiation on the horizontal plane for the 365 days in a year is shown in Figure 2.



	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual Average
■ Monthly average of daily global irradiation on the horizontal plane (Wh/m^2/day)	5530	5590	5320	5090	4720	4310	3850	3770	3940	4270	4840	5290	4710

Figure 1 The monthly average of daily solar irradiation on the horizontal plane

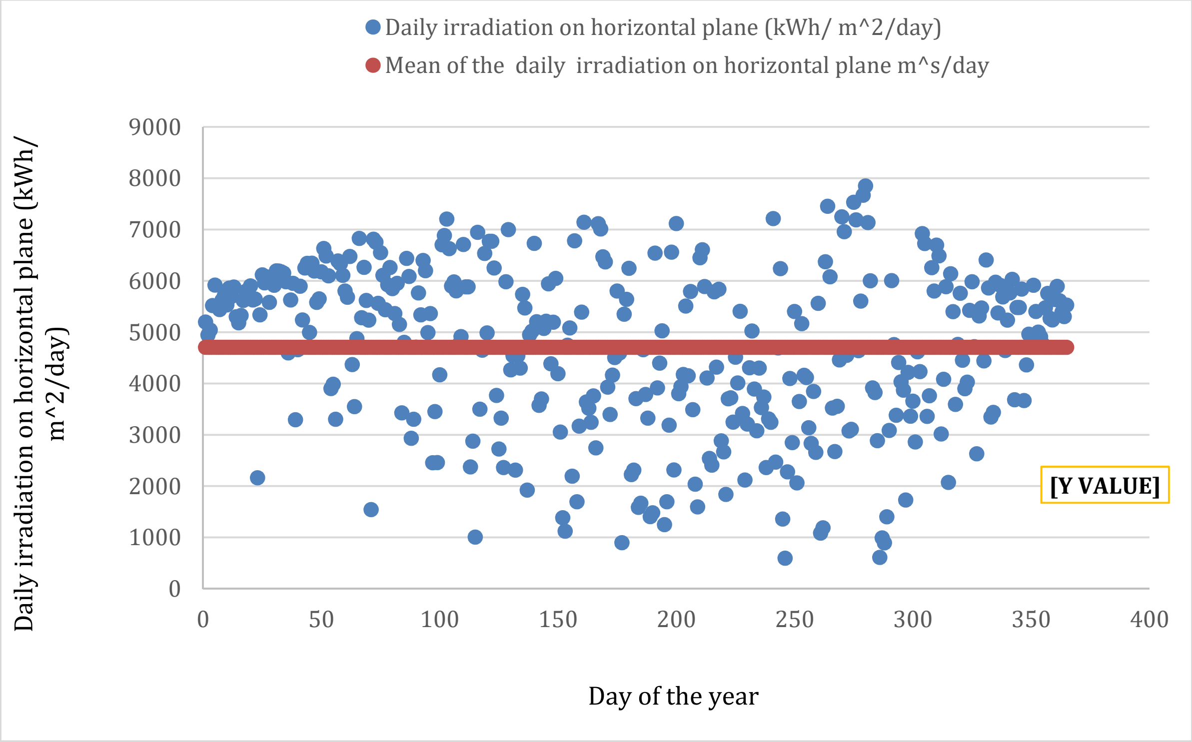


Figure 2 The daily average solar irradiation on the horizontal plane for the 365 days in a year

3. Results and discussions

Sample numerical examples showing the applicability of the mathematical model for the IoT sensor node energy level and power outage analysis is implemented with the solar irradiation data shown in Figure 2 with yearly mean of daily value of 4704.6 Wh/m^2 per day. Two sets of implementations are presented based on the given dataset. The two implementations are conducted with the dataset in Table 1 which shows a sensor node with cycle time of 576000 ms, duty cycle of 1 % and average current of 0.628806 mA. The results showing the key parameter for the first case of sizing the battery and solar cell based on the yearly mean of daily solar irradiation is shown in Table 2. The results show that with the yearly mean daily solar irradiation of 4704.6Wh/m^2/day and specified 1.5 days required to fully charge the battery that will ensure zero power outage (that is no loss of load), the minimum days of autonomy required is about 2.6 days and the solar cell size that can be used to achieve that has an area of 3.9 cm^2. The required battery capacity is 56.3 mAh which will store 2.7 Wh energy when fully charged. However, the daily required battery capacity is 22.8 mAh and the daily energy demand is 1.1 Wh. The number of days of excess energy is unused or lost is 305 days per year and the number of days of excess energy is completely stored 60 days per year.

The results showing the key parameter for the second case of sizing the battery and solar cell based on the yearly minimum of daily solar irradiation is shown in Figure 5 and Figure 6 while Table 3 where the comparison of the results showing the key parameter for the two s of sizing the battery and solar cell based on the yearly mean and yearly minimum of daily solar irradiation are presented. The results in Figure 5, Figure 6 and Table 3 show that the yearly minimum daily solar irradiation of 593.0 Wh/m^2/day. In this case, the minimum days of autonomy required is about 0.8 days (less than one day) and the solar cell size that can be used to achieve that has an area of 9.7 cm^2. The required battery capacity is 17.2 mAh which will store 0.9 Wh energy when fully charged. The daily required battery capacity is 22.8 mAh and the daily energy demand is 1.1 Wh. In this case, it is seen that the daily energy demand of the sensor node is quite higher than the energy storage capacity of the battery. In any case, due to the fact that the minimum solar irradiation data value is used in sizing the solar cell in this case, the energy harvested in each day is relative high enough to supply the daily energy need of the sensor node and also to replenish the energy drawn from the battery.

In all, it is seen that between the first and the second case, the solar cell size and the battery capacity are significantly affected. In the second case where the sizing of the battery and solar cell was done using the annual minimum solar irradiation data of 593.0 Wh/m^2/day, the battery capacity is 69.4% lower than that of case I where the annual mean value of 4704.6Wh/m^2/day was used. On the other hand, the solar cell size in the case II is 148.7 % higher than that of case one. In any case, in both cases zero power outage is achieved. However, the choice of which option to use depends on the relative cost of the battery and solar cell.

Table 1 The results of the energy level and outage analysis for the case of 2.5774105 days of autonomy with 1.5 days required to fully charge the battery

S/N	Parameter	Value	S/N	Parameter	Value
1	Transmit current (mA)	83	7	Measure time (ms)	260
2	Receive current (mA)	32	8	Sleep time (ms)	570240
3	Measure current (mA)	18	9	Cycle time (s)	576000
4	Sleep current (mA)	0.05	10	Duty Cycle (%)	1
5	Transmit time (ms)	3000	11	Number of cycles per day	150
6	Receive time (ms)	2500	12	Average Current, (mA)	0.628806

Table 2 The results showing the key parameter for the case of sizing the battery and solar cell based on the yearly mean of daily solar irradiation.

S/N	Parameter	Results for Sizing with the annual mean solar irradiation value	S/N	Parameter	Results for Sizing with the annual mean solar irradiation value
1	Average daily solar irradiation (Wh/m^2/day)	4704.6	8	Daily energy demand (Wh)	1.1
2	Days of autonomy	2.6	9	Number of days of power outage	0.0

3	Days it take to fully charge the battery	1.5	10	Percentage of days of power outage (%)	0.0
4	Required battery capacity (mAh) at full charge	56.3	11	Number of days of excess energy is unused or lost	305.0
5	Required battery capacity (mAh) at daily energy demand of sensor (mAh)	22.8	12	Percentage of days excess energy is unused or lost (%)	83.6
6	Solar cell size (cm^2^2)	3.9	13	Number of days of excess energy is completely stored	60.0
7	Energy store in fully charged battery (Wh)	2.7	14	Percentage of days excess energy is completely stored (%)	16.4

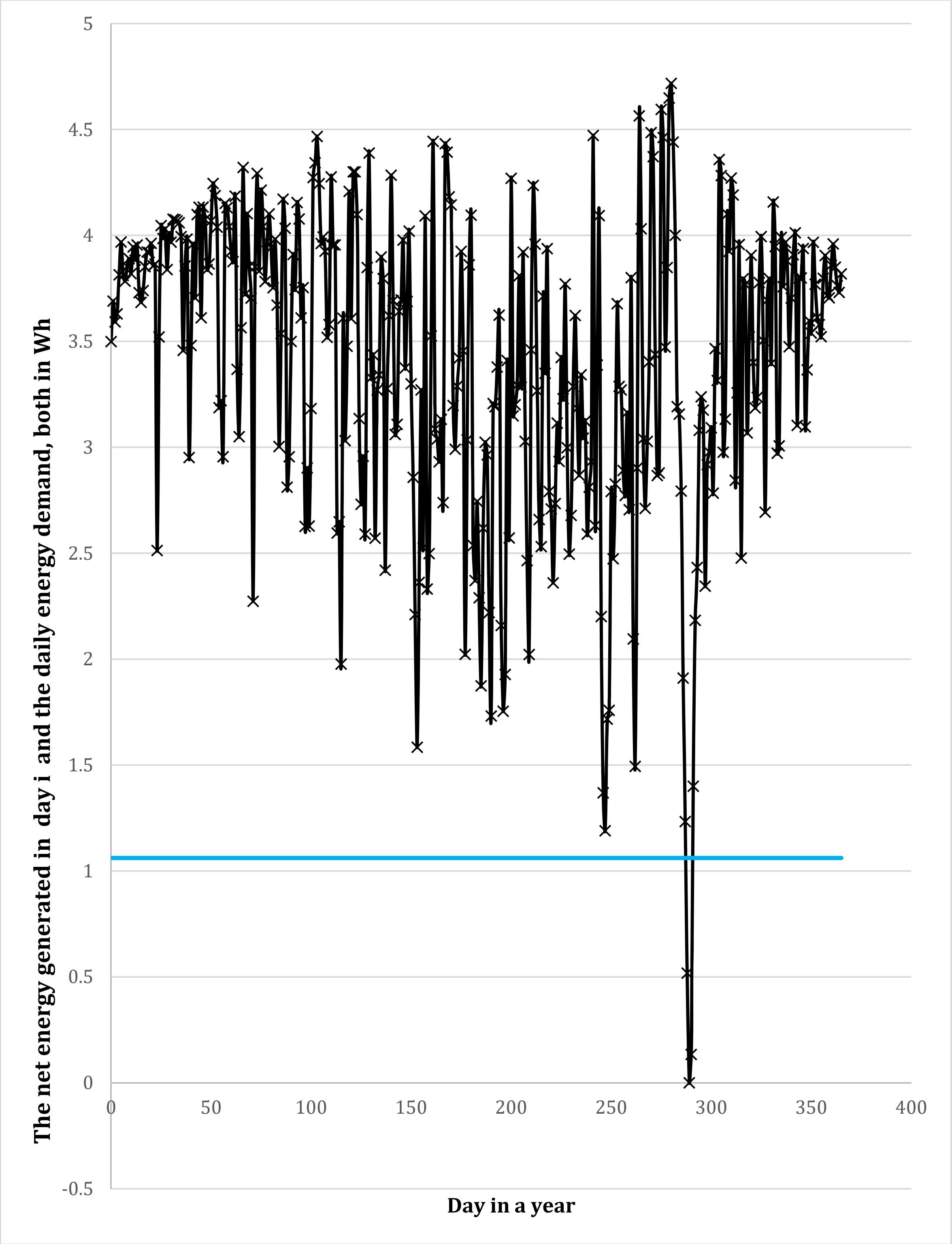


Figure 3 The net energy generated in day i and the daily energy demand, both in Wh for the case I: sizing the battery and solar cell based on the yearly mean of daily solar irradiation.

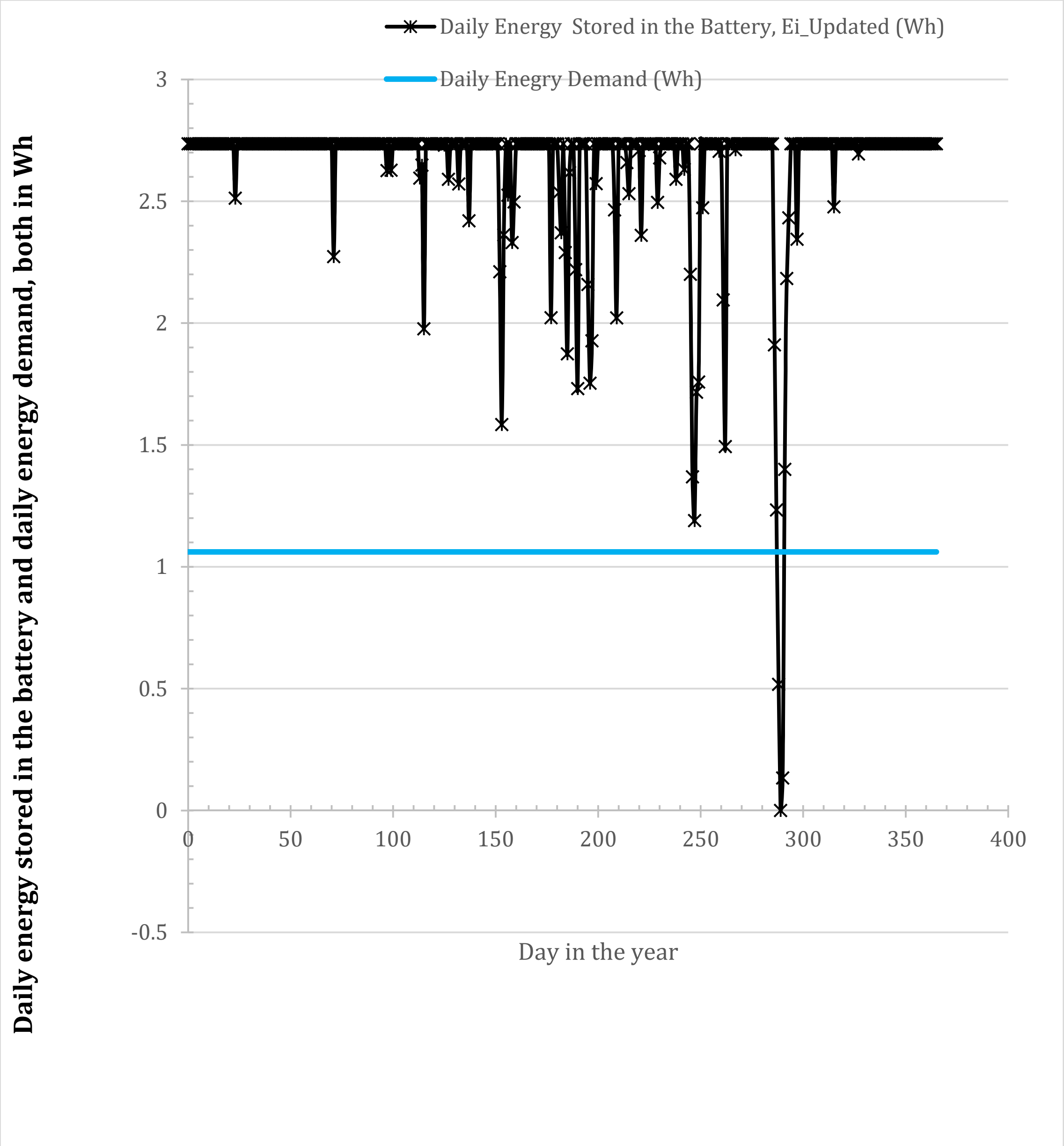


Figure 4 Daily energy stored in the battery and daily energy demand, both in Wh for the case I: sizing the battery and solar cell based on the yearly mean of daily solar irradiation.

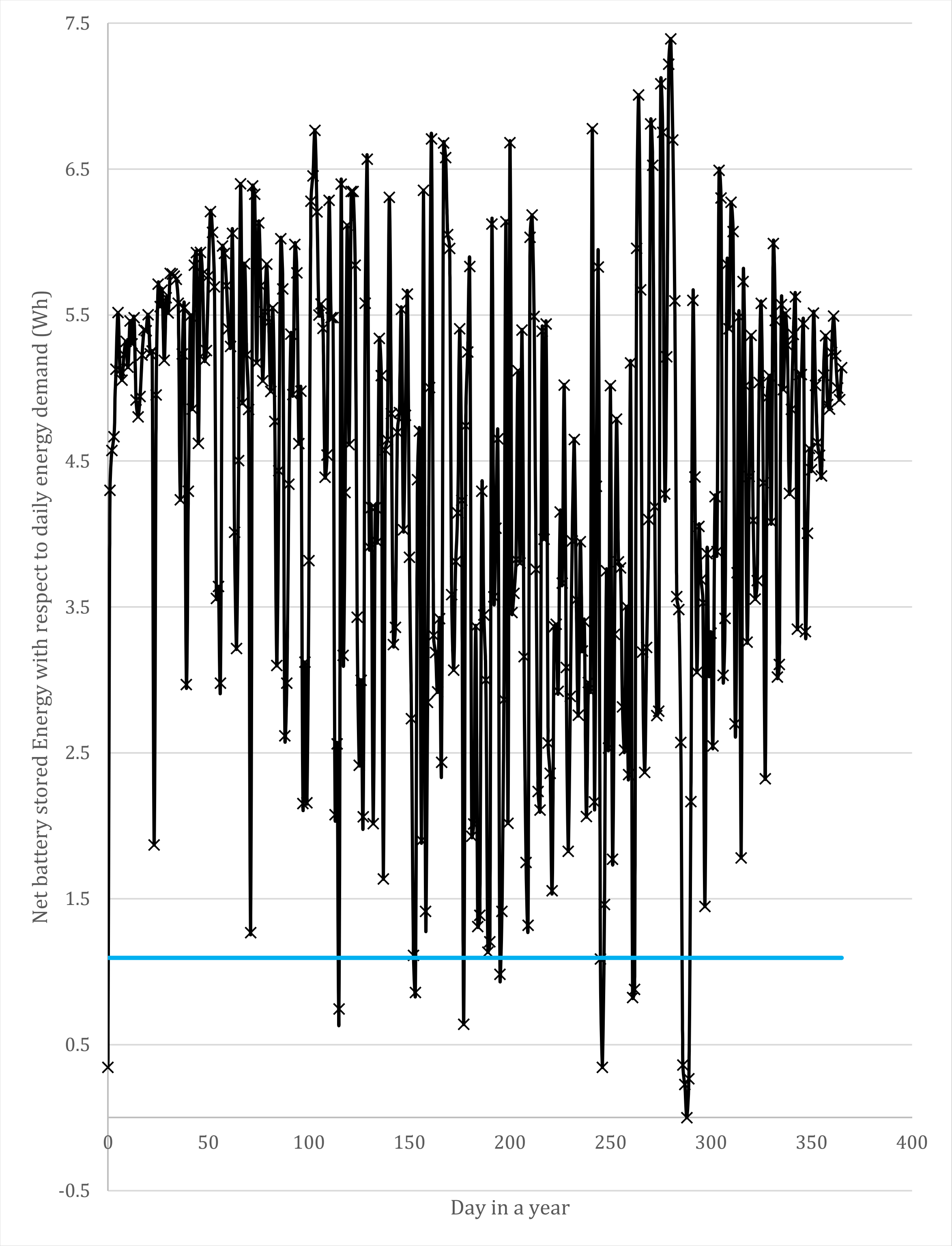


Figure 5 The net energy generated in day i and the daily energy demand, both in Wh for the case II sizing the battery and solar cell based on the yearly minimum of daily solar irradiation.

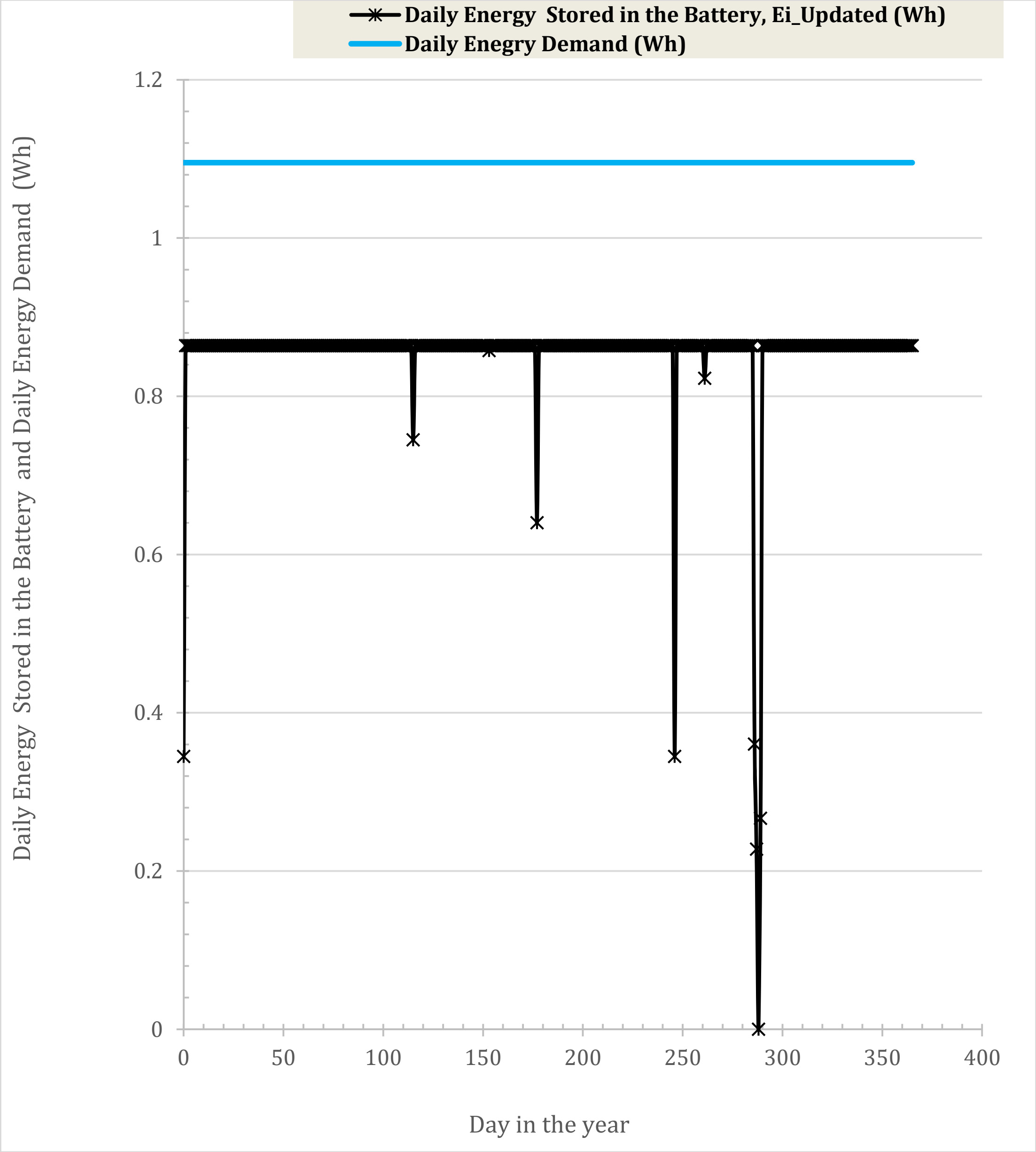


Figure 6 Daily energy stored in the battery and daily energy demand, both in Wh for the case II sizing the battery and solar cell based on the yearly minimum of daily solar irradiation.

Table 3 Comparison of the results showing the key parameter for the two s of sizing the battery and solar cell based on the yearly mean and yearly minimum of daily solar irradiation.

S/N	Parameter	Results for Sizing with the annual mean solar irradiation value	Results for Sizing with the annual minimum solar irradiation value	Percentage Change in value (%)
1	Average daily solar irradiation (Wh/m^2/day)	4704.6	593.0	-87.4
2	Days of autonomy	2.6	0.8	-69.4
3	Days it take to fully charge the battery	1.5	1.5	0.0
4	Required battery capacity (mAh) at full charge	56.3	17.2	-69.4
5	Required battery capacity (mAh) at daily energy demand of sensor (mAh)	22.8	22.8	0.0

6	Solar cell size (cm^2^2)	3.9	9.7	148.7
7	Energy store in fully charged battery (Wh)	2.7	0.9	-68.4
8	Daily energy demand (Wh)	1.1	1.1	3.2
9	Number of days of power outage	0.0	0.0	0.0
10	Percentage of days of power outage (%)	0.0	0.0	0.0
11	Number of days of excess energy is unused or lost	305.0	356.0	16.7
12	Percentage of days excess energy is unused or lost (%)	83.6	97.5	16.7
13	Number of days of excess energy is completely stored	60.0	9.0	-85.0
14	Percentage of days excess energy is completely stored (%)	16.4	2.5	-85.0

4. Conclusion

The model for analyzing the variations in the daily energy level of a single sensor node that is powered with a battery and has solar cell for energy harvesting to charge the battery is presented. The model considered the sensor node that goes through periodic cycles where in each cycle it goes through some states where it draws different amount of current and spends different amount of time. In this paper, the emphasis is on sizing the battery and solar cell and determining how the size of the two components affect the daily energy level of the battery, the outage probability and the excess energy that are lost in the process. The mathematical models were applied to a case study data using a 365 days daily solar radiation data of a case study site. The results show that sizing with the mean solar irradiation value and using the minimum irradiation value affect the battery capacity and solar cell size; in the first case, larger battery capacity is required whereas in the second case, larger solar cell size is required. Also, the results show that it is possible to achieve zero power outage even when the battery capacity is less than the daily required capacity.

References

1. Rao, P. S. (2019). The role of English as a global language. *Research Journal of English*, *4*(1), 65-79.
2. Wellman, B., & Gulia, M. (2018). Net-surfers don’t ride alone: Virtual communities as communities. In *Networks in the global village* (pp. 331-366). Routledge.
3. Porter, P. (2015). *The global village myth: Distance, war, and the limits of power*. Georgetown University Press.
4. Driedger, L. (2016). Mennonites in the global village. In *Mennonites in the Global Village*. University of Toronto Press.
5. Samovar, L. A., Porter, R. E., McDaniel, E. R., & Roy, C. S. (2014). *Intercultural communication: A reader*. Cengage Learning.
6. Wellman, B. (2018). *Networks in the global village: Life in contemporary communities*. Routledge.
7. Kurtz, L. R. (2015). *Gods in the global village: the world's religions in sociological perspective*. Sage Publications.
8. Madakam, S., Lake, V., Lake, V., & Lake, V. (2015). Internet of Things (IoT): A literature review. *Journal of Computer and Communications*, *3*(05), 164.
9. Srinivasan, C. R., Rajesh, B., Saikalyan, P., Premsagar, K., & Yadav, E. S. (2019). A review on the different types of Internet of Things (IoT). *Journal of Advanced Research in Dynamical and Control Systems*, *11*(1), 154-158.
10. Suresh, P., Daniel, J. V., Parthasarathy, V., & Aswathy, R. H. (2014, November). A state of the art review on the Internet of Things (IoT) history, technology and fields of deployment. In *2014 International conference on science engineering and management research (ICSEMR)* (pp. 1-8). IEEE.
11. Kaur, N., & Sood, S. K. (2015). An energy-efficient architecture for the Internet of Things (IoT). *IEEE Systems Journal*, *11*(2), 796-805.
12. Dudhe, P. V., Kadam, N. V., Hushangabade, R. M., & Deshmukh, M. S. (2017, August). Internet of Things (IOT): An overview and its applications. In *2017 International Conference on Energy, Communication, Data Analytics and*

Soft Computing (ICECDS) (pp. 2650-2653). IEEE.

13. Bertino, E., Choo, K. K. R., Georgakopolous, D., & Nepal, S. (2016). Internet of Things (IoT) smart and secure service delivery. *ACM Transactions on Internet Technology (TOIT)*, *16*(4), 1-7.
14. Abdul-Qawy, A. S., Pramod, P. J., Magesh, E., & Srinivasulu, T. (2015). The internet of things (iot): An overview. *International Journal of Engineering Research and Applications*, *5*(12), 71-82.
15. Kodali, R. K., Swamy, G., & Lakshmi, B. (2015, December). An implementation of IoT for healthcare. In *2015 IEEE Recent Advances in Intelligent Computational Systems (RAICS)* (pp. 411-416). IEEE.
16. Banafa, A. (2016). IoT standardization and implementation challenges. *IEEE Internet of Things*, *12*.
17. Kalu, C., Ozuomba, Simeon. & Udofia, K. (2015). Web-based map mashup application for participatory wireless network signal strength mapping and customer support services. *European Journal of Engineering and Technology, 3 (8)*, 30-43
18. Ahmad, I., & Pothuganti, K. (2020, August). Design & implementation of real time autonomous car by using image processing & IoT. In *2020 Third International Conference on Smart Systems and Inventive Technology (ICSSIT)* (pp. 107-113). IEEE.
19. Elijah, O., Rahman, T. A., Orikumhi, I., Leow, C. Y., & Hindia, M. N. (2018). An overview of Internet of Things (IoT) and data analytics in agriculture: Benefits and challenges. *IEEE Internet of things Journal*, *5*(5), 3758-3773.
20. Simeon, Ozuomba (2014) "Fixed Point Iteration Computation Of Nominal Mean Motion And Semi Major Axis Of Artificial Satellite Orbiting An Oblate Earth." *Journal of Multidisciplinary Engineering Science and Technology (JMEST) Vol. 1 Issue 4, November – 2014*
21. Samuel, Wali, **Simeon Ozuomba,** and Philip M. Asuquo **(2019).** EVALUATION OF WIRELESS SENSOR NETWORK CLUSTER HEAD SELECTION FOR DIFFERENT PROPAGATION ENVIRONMENTS BASED ON LEE PATH LOSS MODEL AND K-MEANS ALGORITHM. EVALUATION, 3(11). ***Science and Technology Publishing*** *(SCI & TECH) Vol. 3 Issue 11, November - 2019*
22. Chang, C., Srirama, S. N., & Buyya, R. (2019). Internet of things (IoT) and new computing paradigms. *Fog and edge computing: principles and paradigms*, *6*, 1-23.
23. Simeon, Ozuomba. (2016) "Comparative Analysis Of Rain Attenuation In Satellite Communication Link For Different Polarization Options." *Journal of Multidisciplinary Engineering Science and Technology (JMEST) Vol. 3 Issue 6, June – 2016*
24. Chen, J., Hu, K., Wang, Q., Sun, Y., Shi, Z., & He, S. (2017). Narrowband internet of things: Implementations and applications. *IEEE Internet of Things Journal*, *4*(6), 2309-2314.
25. Samuel, W., **Ozuomba, Simeon,** & Constance, K**. (2019).** SELF-ORGANIZING MAP (SOM) CLUSTERING OF 868 MHZ WIRELESS SENSOR NETWORK NODES BASED ON EGLI PATHLOSS MODEL COMPUTED RECEIVED SIGNAL STRENGTH. ***Journal of Multidisciplinary Engineering Science and Technology*** *(JMEST) Vol. 6 Issue 12, December – 2019*
26. Li, S., Da Xu, L., & Zhao, S. (2018). 5G Internet of Things: A survey. *Journal of Industrial Information Integration*, *10*, 1-9.
27. Simeon, Ozuomba. (2017). "Determination Of The Clear Sky Composite Carrier To Noise Ratio For Ku-Band Digital Video Satellite Link" *Science and Technology Publishing (SCI & TECH) Vol. 1 Issue 7, July – 2017*
28. Njoku, Felix A., **Ozuomba Simeon**, and Fina Otosi Faithpraise **(2019).** Development Of Fuzzy Inference System (FIS) For Detection Of Outliers In Data Streams Of Wireless Sensor Networks. ***International Multilingual Journal of Science and Technology*** *(IMJST) Vol. 4 Issue 10, October - 2019*
29. Prajapati, A., & Trapasiya, S. D. (2016, May). Cross layer design approch for energy optimization in underwater acoustic sensor network. In *2016 IEEE International Conference*

on Recent Trends in Electronics, Information & Communication Technology (RTEICT) (pp. 1282-1286). IEEE.

30. Johnson, Enyenihi Henry, **Simeon Ozuomba**, and Ifiok Okon Asuquo. **(2019).** Determination of Wireless Communication Links Optimal Transmission Range Using Improved Bisection Algorithm. ***Universal Journal of Communications and Network,*** *7(1), 9-20.*
31. Chung, J., Han, D., Kim, J., & Kim, C. K. (2017, February). Machine learning based path management for mobile devices over MPTCP. In *2017 IEEE International Conference on Big Data and Smart Computing (BigComp)* (pp. 206-209). IEEE.
32. Ansah, M. R., Sowah, R. A., Melià-Seguí, J., Katsriku, F. A., Vilajosana, X., & Banahene, W. O. (2020). Characterising foliage influence on LoRaWAN pathloss in a tropical vegetative environment. *IET Wireless Sensor Systems*, *10*(5), 198-207.
33. Simeon**, Ozuomba. (2020).** "Analysis Of Effective Transmission Range Based On Hata Model For Wireless Sensor Networks In The C-Band And Ku-Band." ***Journal of Multidisciplinary Engineering Science and Technology*** *(JMEST) Vol. 7 Issue 12, December - 2020*
34. Jiang, E., Xu, Z., Wang, M., Yan, T., Huang, C., Zhou, X., ... & Shang, Z. (2019). Tumoral microvesicle–activated glycometabolic reprogramming in fibroblasts promotes the progression of oral squamous cell carcinoma. *The FASEB Journal*, *33*(4), 5690-5703.
35. Matsufuji, R., Cavendish, D., Kumazoe, K., Nobayashi, D., Ikenaga, T., & Oie, Y. (2016, November). Performance Characterization of Streaming Video over Multipath TCP. In *IARIA 8th International Conference on Evolving Internet* (pp. 42-47).
36. Papadopoli, D., Boulay, K., Kazak, L., Pollak, M., Mallette, F. A., Topisirovic, I., & Hulea, L. (2019). mTOR as a central regulator of lifespan and aging. *F1000Research*, *8*.
37. Imoh-Etefia, Ubon Etefia, Ozuomba Simeon, and Stephen Bliss Utibe-Abasi. (2020). "Analysis Of Obstruction Shadowing In Bullington Double Knife Edge Diffraction Loss Computation." *Journal of Multidisciplinary Engineering Science Studies (JMESS) Vol. 6 Issue 1, January – 2020*
38. Goktas, P., Topcu, S., Karasan, E., & Altintas, A. (2015, July). Multipath fading effect on terrestrial microwave LOS radio links. In *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting* (pp. 918-919). IEEE.
39. Simeon**, Ozuomba. (2020).** "APPLICATION OF KMEANS CLUSTERING ALGORITHM FOR SELECTION OF RELAY NODES IN WIRELESS SENSOR NETWORK." ***International Multilingual Journal of Science and Technology*** *(IMJST) Vol. 5 Issue 6, June – 2020*
40. Simeon, Ozuomba, Ezuruike Okafor SF, and Bankole Morakinyo Olumide (2018). Development of Mathematical Models and Algorithms for Exact Radius of Curvature Used in Rounded Edge Diffraction Loss Computation. Development, 5(12). *Journal of Multidisciplinary Engineering Science and Technology (JMEST) Vol. 5 Issue 12, December – 2018*
41. Series, R. P. (2015). Propagation data and prediction methods required for the design of terrestrial line-of-sight systems. *Recommendation ITU-R*, 530-12.
42. Nnadi, N. C., Jacob, H. A., & Eze, G. N. (2020). LINK BUDGET ANALYSIS FOR LINE OF SIGHT WIRELESS COMMUNICATION LINK WITH KNIFE EDGE DIFFRACTION OBSTRUCTION. *In practice*, *4*(6).
43. Dialoke, Ikenna Calistus, Ozuomba Simeon, and Henry Akpan Jacob. (2020) "ANALYSIS OF SINGLE KNIFE EDGE DIFFRACTION LOSS FOR A FIXED TERRESTRIAL LINE-OF-SIGHT MICROWAVE COMMUNICATION LINK." *Journal of Multidisciplinary Engineering Science and Technology (JMEST) Vol. 7 Issue 2, February - 2020*

44. Wang, X., & Zhang, S. (2017). Evaluation of multipath signal loss for AIS signals transmitted on the sea surface. *Ocean Engineering*, *146*, 9-20.
45. Ozuomba Simeon (2019) Evaluation Of Optimal Transmission Range Of Wireless Signal On Different Terrains Based On Ericsson Path Loss Model Vol. 3 Issue 12, December – 2019 Available at : http://www.scitechpub.org/wp-content/uploads/2021/03/SCITECHP420157.pdf
46. Augustin, A., Yi, J., Clausen, T., & Townsley, W. M. (2016). A study of LoRa: Long range & low power networks for the internet of things. *Sensors*, *16*(9), 1466.
47. Bor, M. C., Roedig, U., Voigt, T., & Alonso, J. M. (2016, November). Do LoRa low-power wide-area networks scale?. In *Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems* (pp. 59-67).
48. Block, K. T., Chandarana, H., Milla, S., Bruno, M., Mulholland, T., Fatterpekar, G., ... & Sodickson, D. K. (2014). Towards routine clinical use of radial stack-of-stars 3D gradient-echo sequences for reducing motion sensitivity. *Journal of the Korean Society of Magnetic Resonance in Medicine*, *18*(2), 87-106.
49. Faragher, R., & Harle, R. (2015). Location fingerprinting with bluetooth low energy beacons. *IEEE journal on Selected Areas in Communications*, *33*(11), 2418-2428.
50. Krikidis, I., Timotheou, S., Nikolaou, S., Zheng, G., Ng, D. W. K., & Schober, R. (2014). Simultaneous wireless information and power transfer in modern communication systems. *IEEE Communications Magazine*, *52*(11), 104-110.
51. Marais, J. M., Malekian, R., & Abu-Mahfouz, A. M. (2017). LoRa and LoRaWAN testbeds: A review. *2017 Ieee Africon*, 1496-1501.
52. Goursaud, C., & Gorce, J. M. (2015). Dedicated networks for IoT: PHY/MAC state of the art and challenges. *EAI endorsed transactions on Internet of Things*.
53. Andrews, J. G., Buzzi, S., Choi, W., Hanly, S. V., Lozano, A., Soong, A. C., & Zhang, J. C. (2014). What will 5G be?. *IEEE Journal on selected areas in communications*, *32*(6), 1065-1082.
54. Petäjäjärvi, J., Mikhaylov, K., Yasmin, R., Hämäläinen, M., & Iinatti, J. (2017). Evaluation of LoRa LPWAN technology for indoor remote health and wellbeing monitoring. *International Journal of Wireless Information Networks*, *24*(2), 153-165.
55. Hannun, A. Y., Rajpurkar, P., Haghpanahi, M., Tison, G. H., Bourn, C., Turakhia, M. P., & Ng, A. Y. (2019). Cardiologist-level arrhythmia detection and classification in ambulatory electrocardiograms using a deep neural network. *Nature medicine*, *25*(1), 65-69.
56. Birkeland, R. (2014). An overview of existing and future satellite systems for arctic communication. *Proceedings of ESA small satellites systems and services*, *2014*.
57. Radhakrishnan, R., Edmonson, W. W., Afghah, F., Rodriguez-Osorio, R. M., Pinto, F., & Burleigh, S. C. (2016). Survey of inter-satellite communication for small satellite systems: Physical layer to network layer view. *IEEE Communications Surveys & Tutorials*, *18*(4), 2442-2473.
58. Di Lillo, P., Simetti, E., Wanderlingh, F., Casalino, G., & Antonelli, G. (2020). Underwater intervention with remote supervision via satellite communication: Developed control architecture and experimental results within the dexrov project. *IEEE Transactions on Control Systems Technology*, *29*(1), 108-123.
59. de La Beaujardiere, J., Mital, R., & Mital, R. (2019, July). Blockchain Application Within A Multi-Sensor Satellite Architecture. In *IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium* (pp. 5293-5296). IEEE.
60. Oliveira, L. B., Aranha, D. F., Morais, E., Daguano, F., López, J., & Dahab, R. (2007, July). Tinytate: Computing the tate pairing in resource-constrained sensor nodes. In *Sixth IEEE International Symposium on Network Computing and Applications (NCA 2007)* (pp. 318-323). IEEE.
61. Ali, I., Khan, E., & Sabir, S. (2018). Privacy-preserving data aggregation in resource-constrained sensor nodes in Internet of Things: A review. *Future Computing and Informatics Journal*, *3*(1), 41-50.
62. Sheng, Z., Wang, H., Yin, C., Hu, X., Yang, S., & Leung, V. C. (2015). Lightweight management of resource-constrained sensor devices in internet of things. *IEEE internet of things journal*, *2*(5), 402-411.
63. Patan, M., Tricaud, C., & Chen, Y. (2008). Resource-constrained sensor routing for parameter estimation of distributed systems. *IFAC Proceedings Volumes*, *41*(2), 7772-7777.

64. Brandt, A., Buron, J., & Porcu, G. (2010). *Home automation routing requirements in low-power and lossy networks* (No. rfc5826).
65. Mekonnen, T., Porambage, P., Harjula, E., & Ylianttila, M. (2017). Energy consumption analysis of high quality multi-tier wireless multimedia sensor network. *IEEE Access*, *5*, 15848-15858.
66. Sudevalayam, S., & Kulkarni, P. (2010). Energy harvesting sensor nodes: Survey and implications. *IEEE communications surveys & tutorials*, *13*(3), 443-461.
67. Rice, J., Creber, B., Fletcher, C., Baxley, P., Rogers, K., McDonald, K., ... & Green, D. (2000, September). Evolution of Seaweb underwater acoustic networking. In *OCEANS 2000 MTS/IEEE Conference and Exhibition. Conference Proceedings (Cat. No. 00CH37158)* (Vol. 3, pp. 2007-2017). IEEE.
68. Khan, J. A., Qureshi, H. K., & Iqbal, A. (2015). Energy management in wireless sensor networks: A survey. *Computers & Electrical Engineering*, *41*, 159-176.
69. Carratù, M., Ferro, M., Paciello, V., Pietrosanto, A., & Sommella, P. (2017). Performance analysis of wM-bus networks for smart metering. *IEEE Sensors Journal*, *17*(23), 7849-7856.
70. Callebaut, G., Leenders, G., Van Mulders, J., Ottoy, G., De Strycker, L., & Van der Perre, L. (2021). The Art of Designing Remote IoT Devices—Technologies and Strategies for a Long Battery Life. *Sensors*, *21*(3), 913.
71. Wang, P., Zhu, H., Shen, W., Choo, F. H., Loh, P. C., & Tan, K. K. (2010, February). A novel approach of maximizing energy harvesting in photovoltaic systems based on bisection search theorem. In *2010 Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)* (pp. 2143-2148). IEEE.
72. Selvan, K. V., & Ali, M. S. M. (2016). Micro-scale energy harvesting devices: Review of methodological performances in the last decade. *Renewable and Sustainable Energy Reviews*, *54*, 1035-1047.
73. Cammarano, A., Petrioli, C., & Spenza, D. (2012, October). Pro-Energy: A novel energy prediction model for solar and wind energy-harvesting wireless sensor networks. In *2012 IEEE 9th International Conference on Mobile Ad-Hoc and Sensor Systems (MASS 2012)* (pp. 75-83). IEEE.
74. Kausar, A. Z., Reza, A. W., Saleh, M. U., & Ramiah, H. (2014). Energizing wireless sensor networks by energy harvesting systems: Scopes, challenges and approaches. *Renewable and Sustainable Energy Reviews*, *38*, 973-989.
75. Vullers, R. J. M., van Schaijk, R., Doms, I., Van Hoof, C., & Mertens, R. (2009). Micropower energy harvesting. *Solid-State Electronics*, *53*(7), 684-693.
76. Shaikh, F. K., & Zeadally, S. (2016). Energy harvesting in wireless sensor networks: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *55*, 1041-1054.
77. Philipps, S. P., Peharz, G., Hoheisel, R., Hornung, T., Al-Abbadi, N. M., Dimroth, F., & Bett, A. W. (2010). Energy harvesting efficiency of III–V triple-junction concentrator solar cells under realistic spectral conditions. *Solar Energy Materials and Solar Cells*, *94*(5), 869-877.
78. Antony, S. M., Indu, S., & Pandey, R. (2020). An efficient solar energy harvesting system for wireless sensor network nodes. *Journal of Information and Optimization Sciences*, *41*(1), 39-50.
79. Femia, N., Petrone, G., Spagnuolo, G., & Vitelli, M. (2017). *Power electronics and control techniques for maximum energy harvesting in photovoltaic systems*. CRC press.
80. Wilson, J. I. B., & Mather, R. R. (2015). Photovoltaic energy harvesting for intelligent textiles. In *Electronic Textiles* (pp. 155-171). Woodhead Publishing.