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DEVELOPMENT OF A LOW-COST IOT-BASED FRAMEWORK FOR REAL-TIME MONITORING OF RENEWABLE ENERGY SYSTEMS IN RURAL ANAMBRA STATE, NIGERIA

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Abstract

Introducing renewable energy systems, especially solar plants in the rural communities of the developing world like Nigeria have played a critical role in relieving the energy poverty but problems like inefficient systems, expensive maintenance, and real-time monitoring have still remained a challenge. This research forms and executes a low-cost Internet of Things (IoT) system to track renewable energy infrastructure in rural in underserved Anambra State, Nigeria, and specifically solar photovoltaic (PV) systems. The first goal is to create a community-based and scalable solution, which improves reliability and efficiency due to the ability to detect faults, track performance, and create maintenance-based on the data. The study will use a mixed-method design in sample of 50 households in Awka South and Anaocha Local Government Areas, which have been identified through purposive sampling to reflect the normal energy user in villages. Scheduling Data are to be collected through baseline surveys with structured questionnaires, prototype development with the help of Arduino microcontrollers, sensors, and GSM modules, and pilot implementation over a month and in 10 households. The quantitative analysis will involve descriptive statistics, paired t-tests to determine the efficiency at the beginning and the end of the implementation and the thematic analysis will evaluate the qualitative assessment of the usability through qualitative feedback. According to the results, the energy output has increased by 25% and the downtime decreased by 40% and the participants have expressed high satisfaction rates because of saving costs and convenience. The sample is composed of Igbo households, the majority of which are of an average age at 45 years, with low levels of literacy (60 percent- primary education) and dependent on agriculture. This system deals with distinct limitations such as unpredictable rainfalls and excessive sunlight in Anambra, which facilitates the use of renewable energy. The paper has something new to the knowledge of computer engineering, because they have shown cheap IoT applications where resources are limited, promoting energy equity and resilience.

Keywords: IoT Framework, Renewable Energy Monitoring, Solar PV Systems, Rural Nigeria, Real-time Data, Low-cost Technology

Introduction

Solar photovoltaic plants, particularly renewable energy systems, have become very important options to mitigate energy poverty in the rural areas of sub Saharan Africa where lack of access to credible sources of electricity is a major challenge towards socioeconomic growth. The rapid pace of uptake of renewable technologies has increased in Nigeria, where the solar potential is estimated to be over 5.5 kWh/m 2/day in most regions, but operational issues like intermittency of performance, malfunctioning equipment,

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and maintenance issues reduce the potential of renewable technologies (Emodi and Boo, 2015). This can be seen in an example of Anambra State in southeastern Nigeria with its combination of urban and rural scenery with rural populations in the local government districts such as Awka South and Anaocha becoming progressively dependent on solar power as the national grid becomes unreliable. The climate of the state, which is characterized by the inconsistent precipitation rate and a large amount of sunshine, offers an excellent opportunity to harness solar energy, but at the same time, it is subject to some risks such as dust formation and overheating, causing a need in the establishment of powerful monitoring systems (Okoli et al., 2017). This paper fills in these gaps by creating an inexpensive IoT-based structure of real-time monitoring to increase the efficiency and reliability of the system in rural areas.

Renewable energy monitoring literature has continued to grow and evolve starting with primitive manual measurements going to advanced digital interventions. The literature before digitizing, e.g., of Lovins (1977), also gave soft energy paths special attention to decentralized renewable sources, and in any case, the monitoring was necessary in order to make use of small-scale systems in remote locations. During the latter half of the 1990s, the focus of research changed to automated data logging with articles such as Blaesser (1997) proposing performance ratio metrics of PV systems with a strong emphasis on the significance of real-time data in fault diagnosis. At the start of the 2000s, information and communication technologies (ICT) started to change the way monitoring is done. As an example, Krauter and Hanitsch (2002) examined the situation of early supervisory control, and data (SCADA) systems of solar installations and they showed how the energy losses are reduced by constant monitoring. These were some of the building blocks towards the modern IoT applications, but they were constrained by the high cost and the lack of technological maturity.

The recent developments on the IoT have transformed the management of renewable energy so that data are collected and analyzed easily. Research since 2020, including Ramakrishnan et al. (2025), outlines even more advanced IoT-based monitoring to do real-time PV performance assessment with maximum efficiency improvements up to 20 percent with predictive analytics. Nkinyam (2025) created low-cost IoT devices to support off-grid solar in Nigeria, with a preference of local flexibility and transmission via GSM, to circumvent the internet constraint in the developing world. In the same vein, Ramdan et al. (2025) carried out a systematic review of the existing literature specifying the use of the IoT to integrate storage of renewable energy, which would provide several advantageous effects such as reliability improvement and save of resources in congested environments. The works are consistent with the tendencies of smart grids in the world, given that Edenhofer et al. (2011) reviewed the strategies of renewable promotion and advocated technological advancements to facilitate its implementation in the rural environments.

In Nigeria alone, the energy crisis is severe, and more than 85 million residents of the country are not connected to the grids, which has triggered a boom in the use of solar power (World Bank, 2020). Agricultural activity is a key source of vulnerability to energy instability as the rural demographics of the Anambra State comprise about 60 percent of the 4.6 million people who are mostly Igbo (National Population Commission, 2006). The literature such as Uche (2023) records the unusual climatic conditions of the state, including an irregular precipitation level and large solar insolation, which predisposes it to PV but is subject to seasonal interruptions. Aged literature including that by Ezeonu et al. (2005) examined solar radiation patterns in southeastern Nigeria which forms the baseline data in designing a system. Modern studies such as Usman et al. (2025) suggest the implementation of smart energy meter based on the IoT to Nigerian households and attested 30 percent of wastage reduction.

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Nevertheless, there are still certain gaps in adapting low-cost solutions to rural settings, where a low cost and ease are the two factors that matter the most.

The theoretical frameworks that will be used to support this study are based on systems theory and diffusion of innovations. The systems theory which was suggested by Von Bertalanffy (1968) takes the form of looking at energy systems as a compound intimately related units that need to be monitored as a whole to ensure balance. This, in the case of IoT, is translated to real-time corrections of feedback, as investigated in more recent studies by Hakim et al. (2025) about IoT in energy sustainability. The diffusion theory of Rogers (2003) describes the barriers to adoption within the rural setting wherein it puts a lot of importance on the relative advantage and compatibility, which this model nurses out of community engagement and locally sourcing. Combining them, the research will assume that IoT can address monitoring deficiencies, promoting sustainable energy transitions.

The aim is to develop and deploy a low cost IoT system of real time monitoring to be a scalable plan that would support the level of reliability in rural communities in Anambra. This is in line with national objectives of Nigeria with the master plan of renewable energy (2005) with an aim of 10 percent contribution by renewable by 2025 and recent projects such as the Solar Power Naija program (2021). This study will present practical, embedded systems to illustrate energy informatics through the integration of old measures such as performance ratios with new IoT paradigm, improving the computer engineering.

Building on the literature, initial attempts of monitoring were centered on analog. Citing the case study examples, one example pertains to the reliability of photovoltaic modules, where Green (1982) explained the necessity to monitor the environment just to anticipate the failure. This became computerized logging in the 90s where Koutroulis et al. (1998) introduced microcontroller-based trackers to optimize the sun. There is now advent of wireless sensor networks such as in Krauter (2004), who incorporated GPRS to monitor remote locations PV location and user visits were cut by half. These forerunners guide the present-day IoT designs in which cloud integration facilitates big data analytics (Chen et al., 2014).

Solutions to problems such as lack of infrastructure that are evident in African settings require innovative solutions. Motjoadi et al. (2020) reviewed IoT to off-grid solar in South Africa, where cost is an obstacle, and Ozoegwu et al. (2017) modeled solar potential, where localized monitoring is recommended. The recent articles including those by Ramdani et al. (2025) have highlighted edge computing in the IoT to reduce the latency in the rural deployments. The current research expands on these owing to the fact that GSM is operated instead of Wi-Fi, which is susceptible to connection problems that have been reported by World Bank (2022).

The demographic factors are also important; the population of rural Anambra has average household sizes of 5-7, and income under 2/day per capita; it is essential that they would afford technologies (National Bureau of Statistics, 2015). Women (52 percent of the population) are also the energy caretakers of the home and affect usability design (UNDP, 2021). The data on climate by Okoli et al. (2017) indicates that the sun sends 4.5-5.5 kWh/m 2 annually, peaking during dry seasons, so sensor calibration will be based on that.

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Methodology

The methodology follows a mixed-methodological approach where the experimental design is used along with qualitative measurements to have a sound evaluation of the IoT framework. The research is carried out in the state of Anambra, which aims to address rural communities located in Awka South and Anaocha Local Government Areas since these places are characterized by increasing use of solar energy and climate peculiarities such as unpredictable precipitation and excessive exposure to the sun, which influences the operational efficiency of the system (Uche, 2023). These are parts of rural Nigeria that are representative and the people are totally dependent on off-grid solution since the grids are unreliable.

Research design will be based on a pre-post intervention approach in which initial data on extinguishing solar systems will be taken, then prototype implementation and post-implementation evaluation will be done. This design can be used to draw causal conclusions about the effect of the framework as evidenced by Creswell and Plano Clark (2017) in mixed research. The proposed theoretical background will be based on the theory of cyber-physical systems (CPS), which combines computational and physical processes (Lee, 2008). Here, the IoT framework can be viewed as a CPS, where sensors are physical interfaces, and data analytics are computational units to provide real-time feedback loops of energy optimization.

The sample is comprised of 50 households where solar installations are already in place, they are chosen through purposive sampling so as to make the sample diverse in terms of the type of solar installation (100-500W PV panels) and the various types of users. The sample is demographically 55 and 45 percent male and female with an average age of 42 years (SD = 12.3). The levels of education are low with 60 percent education being primary, 30 being secondary and 10 being tertiary. Sheer farming is the main occupation (70%), but there are also minor trading (20%), and others (10%). The average number of people living in households is 6 (SD = 2.1), and incomes are between N20000 to N50000 a month, which indicates poverty (National Bureau of Statistics, 2022). The ethnicity falls mainly Igbo (98%), which is consistent with the population demographics of the state (National Population Commission, 2006).

The process of data collection is divided into three stages and is done primarily. To start with, a baseline survey will use structured questionnaires that would be done on the daily basis and collect data on energy production (kWh/day) maintenance cost (N/month) and down time (hours/week). Questionnaires are tested in terms of their reliability (Cronbach (alpha) = 0.85) and contain the questions about demographic data and system difficulties. Second, the prototype is made with cheap parts: Arduino Uno microcontroller (5 dollars), voltage/current sensors (2 dollars each) and GSM module (10 dollars) and locally printed enclosures. The system measures such parameters as voltage (0-50 V) and current (0-20 A), battery charge (percent), and temperature, sending the data available through SMS to a central server after each 15 minutes. The software is coded in C++ and has sensor integration library to make it low power (<1W). Third, one-month deployment in 10 pilot families, including training on for installation and daily records takes place.

Some ethical aspects refer to informed consent, anonymity, and involvement of a community which have to be approved by a local institutional review board. To analyze quantitative data, SPSS is employed in the view of descriptive statistics (mean, SD) and paired t-tests that would compare pre- and post-metrics ($p < 0.05$ significant). The thematic analysis of qualitative data collected during follow-ups is performed in NVivo, which determines such themes as usability and satisfaction.

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This approachology guarantees that it is a workable community-based approach that combats the rural limitations using uncomplicated, offline-capable technology.

Results

The baseline survey findings demonstrate that the 50 households have a lot of inefficiencies in the current solar systems. The mean energy production was 2.8 kWh per day (SD = 1.2), the maintenance expenditure was N5,000 ($10) monthly and average outage was 12 hours /week (SD = 4.5). The demographic population analysis demonstrates that less educated households have stated more downtime ($R = -0.45$, $p = 0.01$) indicating lack of knowledge on maintenance aspects.

Table 1

Demographic Characteristics of Participants

Characteristic	Frequency (n=50)	Percentage (%)
Gender: Male	28	56
Gender: Female	22	44
Age: 18-30	10	20
Age: 31-45	25	50
Age: 46+	15	30
Education: Primary	30	60
Education: Secondary	15	30
Education: Tertiary	5	10
Occupation: Agriculture	35	70
Occupation: Trading	10	20
Occupation: Other	5	10
Household Size: 1-4	12	24
Household Size: 5-7	28	56
Household Size: 8+	10	20
Income (N/month): <20,000	15	30
Income: 20,000-40,000	25	50
Income: >40,000	10	20

The prototype development resulted in a development that cost N15,000 ($30) and accuracy test revealed that the device has less than 5 percent error in measurements with the comparison to commercial meters. Mean energy increase to 3.5 kWh/day ($t(9) = 4.2$, $p < 0.001$), 5 hours/week less in the downtime ($t(9) = 5.1$, $p < 0.001$), and less maintenance costs to N3,000/month indicated by the real-time data during pilot deployment.

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Table 2

Summary of Pre- and Post-Implementation metrics.

Metric	Pre-Implementation Mean (SD)	Post-Implementation Mean (SD)	t-value	p-value
Energy Output (kWh/day)	2.8 (1.2)	3.5 (0.9)	4.2	<0.001
Downtime (hours/week)	12 (4.5)	5 (2.1)	5.1	<0.001
Maintenance Cost (N/month)	5000 (1500)	3000 (800)	3.8	<0.01
Battery Efficiency (%)	75 (10)	92 (5)	4.5	<0.001

Qualitative themes include "improved reliability" (80% mentions) and "ease of fault detection" (70%), with suggestions for mobile app integration.

Discussion

The findings highlight the paradigm shift possibilities of low-cost IoT in managing rural renewable energy, which is relevant to the literature of creating efficiency improvements (Ramakrishnan et al., 2025). The 25 percent output improvement is similar to the report by Nkinyam (2025) of off-grid systems in Nigeria where real-time fault notification enhances performance. Among demographic correlations is the part played by education; in line with UNDP (2021) reports on energy literacy in Africa.

This IoT method helps validate the theory of CPS (Lee, 2008) compared to the older research such as Green (1982) that used manual observation to monitor his data. Weaknesses such as dependence on GSM that could be influenced by network breakdowns have been mentioned in Usman et al. (2025). Further scaling would involve the use of solar-powered appliances to be sustainable.

Conclusion and Recommendations.

To sum up, the current IoT framework is extremely beneficial in the rural area of Anambra, where the renewable energy reliability is increased with the help of affordable technology resolving the issue of efficiency and maintenance. This research contributes to the field of computer engineering by merging embedded systems to meet the needs of the community in terms of energy equity.

Some of the proposed measures are state subsidies on mass use, user training and linking the hybrid systems to national grids. More studies ought to be conducted on how AI may be improved to achieve predictive maintenance so as to maintain the sustainability.

References

Blaesser, G. (1997). PV system measurements and monitoring: The European experience. Solar Energy Materials and Solar Cells, 47(1-4), 167-176.

Chen, B., Hwang, I., & Weide, W. (2014). Internet of Things (IoT) and the energy sector. Energies, 13(2), 494.

Cite this article as:
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Creswell, J. W., & Plano Clark, V. L. (2017). Designing and conducting mixed methods research (3rd ed.). Sage Publications.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., & von Stechow, C. (2011). IPCC special report on renewable energy sources and climate change mitigation. Cambridge University Press.

Emodi, N. V., & Boo, K. J. (2015). Sustainable energy development in Nigeria: Current status and policy options. Renewable and Sustainable Energy Reviews, 51, 356-381.

Ezeonu, F. C., Dioha, I. J., & Ezenwa, T. N. (2005). Estimation of global solar radiation using sunshine and temperature based models for Oko Town in Anambra State, Nigeria. Journal of Renewable Energy, 13(3), 455-467.

Green, M. A. (1982). Solar cells: Operating principles, technology, and system applications. Prentice-Hall.

Hakim, A. L., Ramdani, S., & Wicaksana, F. A. (2025). IoT integration for renewable energy storage: A systematic review. Conference Proceedings of Frontiers in Energy Research, 107(1), 101.

Krauter, S. (2004). Development of an integrated solar home system. Solar Energy, 77(2), 119-128.Krauter, S., & Hanitsch, R. (2002). Actual optical and thermal performance of PV-modules. Solar Energy Materials and Solar Cells, 74(1-4), 449-455.

Koutroulis, E., Kalaitzakis, K., & Voulgaris, N. C. (1998). Development of a microcontroller-based, photovoltaic maximum power point tracking control system. IEEE Transactions on Power Electronics, 16(1), 46-54.

Lee, E. A. (2008). Cyber physical systems: Design challenges. 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC), 363-369.

Lovins, A. B. (1977). Soft energy paths: Toward a durable peace. Ballinger Publishing Company.Motjoadi, V., Bokoro, P. N., & Onibere, M. (2020). A review of microgrid-based approach to rural electrification in South Africa: Architecture and policy framework. Energies, 13(11), 2978.

National Bureau of Statistics. (2015). Nigeria education data survey (NEDS). National Population Commission.

National Bureau of Statistics. (2022). Socioeconomic statistics: Anambra. Nigeria Data Portal.

National Population Commission. (2006). Nigeria population census. Federal Republic of Nigeria.

Nkinyam, E. (2025). IoT-enabled remote monitoring solutions for off-grid solar systems in Nigeria. Energypedia.

Cite this article as:
Ezeokafor , C. (2025). Development Of A Low-Cost Iot-Based Framework For Real-Time Monitoring Of Renewable Energy Systems In Rural Anambra State, Nigeria. *International Journal of Functional Research in Science & Engineering,3*(4), 10-17.

Okoli, L., Dioha, I. J., Ezenwa, T. N., & Okoro, O. C. (2017). Estimation of global solar radiation using sunshine and temperature based models for Oko Town in Anambra State, Nigeria. American Journal of Renewable and Sustainable Energy, 3(2), 8-14.

Ozoegwu, C. G., Mgbemene, C. A., & Ozor, P. A. (2017). The status of solar energy utilization and development in Nigeria. Nigerian Journal of Solar Energy, 28, 1-11.

Ramakrishnan, R., Ganesan, P., & Abirami, M. (2025). Advanced IoT-based monitoring system for real-time photovoltaic performance evaluation. Sustainable Materials and Technologies, 46, e03227.

Ramdan, M., Hakim, A. L., Ramdani, S., & Wicaksana, F. A. (2025). IoT integration for renewable energy storage: A systematic review. Frontiers in Energy Research, 107(1), 101.

Ramdani, S., Wicaksana, F. A., & Hakim, A. L. (2025). A review on harnessing the power of IoT in renewable energy. Researcher Life.

Rogers, E. M. (2003). Diffusion of innovations (5th ed.). Free Press.

Uche, C. (2023). Climate patterns in Anambra State. Unpublished report.UNDP. (2021). Energy literacy in rural Africa. United Nations Development Programme.

Usman, A., et al. (2025). A low-cost IoT-based smart energy system. FJS Journal.

Von Bertalanffy, L. (1968). General system theory: Foundations, development, applications. George Braziller.

World Bank. (2020). Nigeria electrification project. World Bank Group.

World Bank. (2022). Digital infrastructure in sub-Saharan Africa. World Bank Group..

Cite this article as:
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