International Journal of Innovative Scientific & Engineering Technologies Research 12(2):6-14, April-June, 2024

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Development and Evaluation of a Hybrid Power Meter: A Machine Learning Approach to Usage Prediction and Analysis in an Epileptic Power Scenario

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ABSTRACT

Power management has been a cogent issue in developing countries for years. Nigeria, the subject of our study is one such country. The study discussed in this paper proposes a hybrid power meter system that uses a combination of highly functional devices namely; NodeMCU microcontroller, and PZEM energy monitor to solve power management issues. The capabilities of the system were further optimized by introducing machine learning and data visualization techniques to improve prediction accuracy and create an interactive web dashboard which allows users to view their power consumption trends and make adjustments based on the results. This paper contains documentation of the processes involved in designing, developing, and evaluating the performance of the hybrid power meter.The results achieved through the research shows that for the Random Forest Model,co-efficient of determination R^2 is 0.9997 and MSE is $4.88*10^{-9}$ while for the Gradient Boosting the value for R^2 is 0.9965 and MSE is 4.88×10^{-8} which shows a high correlation performance achieved. The machine learning model helped improve the efficiency of the hybrid power meter by providing accurate predictions and interactive visualization of the data trend via the web dashboard, making the system a tool for efficient power management in both household and industrial applications.

Keywords: power meter, Machine Learning, Energy Forecasting**.**

INTRODUCTION

Electricity is undeniably one of the crucial resources in the modern world, powering our homes, businesses and the diverse industries. The availability and quality of electricity are essentially one of the crucial factors that aid development of any nation. It powers industries, enabling manufacturing processes, powering machinery, and facilitating production. Beyond availability, developed countries around the world have recognised power management as one of the important domains that affect both the economy and the security of the countries (Burke et al., 2018; Ang *et al*., 2022). Developing countries grapple with the challenge of both availability and management as the power infrastructure in these countries tends to lack the capacity to meet the growing electricity demand, making energy management quite crucial. This rather sad and epileptic power supply situation is often characterized by load shedding, unannounced interruption and frequent, if not constant power outages (Lawrence *et al.*, 2020).

Varela Aldás et al., (2022), noted that the PZEM energy module essentially includes diverse sensors to measure various parameters of electricity such as the voltage, current, power and energy in a component. Its multifaceted functionality includes serial communications, a display of electrical

values and a clear feature. The PZEM monitor was chosen for this research because of its compactness, affordability, and effectiveness in measuring and storing parameters from the loads connected to it.NodeMCU controller is a low-cost device built for IoT devices, that provides users with the ability to connect dependent devices to the internet via Wi-Fi (Parihar, 2019). It is a popular choice for smart devices and systems because of its offer of wireless internet connection and ease of programming. Machine learning techniques have over the years shown significant potential in various fields, including energy management. The ability of these models to learn from historical data and understand the underlying relationship between the variables is a key factor in their effectiveness (Sarker, 2021). One of the most applicable solutions for developing countries is the integration of technology, particularly in power usage prediction and monitoring, which can potentially provide substantial improvement to the prevalent situation (Divya *et al*., 2023). A system that accurately forecasts power usage and provides real-time consumption monitoring could facilitate better power management as it essentially enables users to make informed decisions regarding their consumption patterns.

Power meters are crucial aspects of modern electrical systems, offering a reliable means to measure the amount of electrical power consumed by consumers including, residential, industrial or commercial as well as electrically powered devices and vehicles. Power meters play a crucial role in load balancing within electrical grids (Adebisi *et al*., 2024). They essentially enable customers to be billed for the electricity used and have evolved over the years from basic analog electrometrical models within use a rotating disk to more robust smart meters with machine learning integration. Power meters on their own are devices used to measure the amount of electricity consumed by a household device or corporate body (Babuta *et al*., 2021). The power meter developed in this research had its capabilities enhanced with the integration of different technologies such as microcontrollers and Artificial Intelligence (AI). Research by Feng et al., (2021), evaluated the potential of integrating machine learning into power management systems which highlights the importance of machine learning in understanding the power usage patterns in regions with unstable power supply. This study implements a machine learning model for the prediction of future energy consumption for proper energy planning management.

Over the years researchers and industry experts have designed and implemented diverse variants of power meters with different features and limitations. Khalid *et al*., (2021), worked on a novel IoT-based meter that leveraged the ATmega328p microcontroller and google cloud store to provide smart metering functionality. The developed meter essentially sends data to the Google Cloud Store for the visualisation of a real-time database of energy consumption at the residential building. Similarly, Abed & Naser, (2020), worked on an ESP32-based smart power meter, that leveraged the PZEM-00T energy module to offer smart energy monitoring and visualisation functionalities. The design also included the functionality of storing the energy reading remotely in an SQL database and included a web dashboard.

Machine learning models essentially identify patterns and inherent correlations in provided datasets that might not be immediately apparent to humans and this is then used to make predictions on new data. Applying a machine learning model in this system significantly boosted the accuracy of the power usage predictions (Bhamare and Suryawanshi, 2018). Diverse machine-learning techniques have been developed over the years for different tasks and purposes. These techniques range from relatively simple models such as linear regression to more complex models such as deep learning algorithms. Each technique has its unique strengths and limitations and consequently their suitability for certain tasks. Brownlee, 2020), noted that models such as decision trees are more suitable for classification tasks due to their interpretability and relative ease of use while neural networks and other robust models tend to be favoured for more complex tasks such as pattern recognition. Recent studies indicate that the application of machine learning for energy management includes the detection of anomalies in energy usage, prediction of energy consumption as well as optimisation of energy distribution (Chou and Telaga, 2022).

A study conducted by Bourhnane *et al*. (2020), investigated the diverse machine-learning algorithms used for predicting and scheduling energy consumption in smart buildings. The study explored models such as Artificial Neural Networks (ANN) and Genetic Algorithms in energy management and emphasised that predicting energy consumption plays a crucial role in deploying efficient energy

management systems. Eskandarnia *et al*. (2022) explored the use of deep learning techniques for smart meter data analytics and noted that deep clustering techniques performed better than classical techniques in smart meter data analysis. The study also emphasised the importance of data reprocessing, analytical algorithms and evaluation methods in the use of machine learning for smart meter data analytics. Wang *et al*. (2018) conducted an application-oriented review of smart meter data analytics and identified key areas of application such as load analysis, load forecasting, and load management. The study also discussed research trends, data issues and key concepts such as data privacy and security in the integration of machine learning into energy management.

The aforementioned literature essentially highlights the potential of machine learning in the development of robust smart meters with prediction and pattern analysis capabilities. The overall aim of this paper is to design, develop and evaluate the performance of the proposed hybrid meter. The various components and their contribution to the performance of the system will be discussed. The functional components include a PZEM energy monitor and NodeMCU controller. The system was optimized using a machine-learning model. The combination of these made the hybrid power system efficient in compiling power data, providing real-time data usage trends and predicting users' data consumption.

MATERIALS AND METHODS

The major components that were used for the construction of the hybrid power meter system include PZEM-004T Energy Monitor, NodeMCU Microcontroller, Python, LCD and Web Dashboard. Other components employed for the assembly of the system were wires and resistors. The function of each component is shown in Table 1.

Table 1: List of Components and Their Functions

Component	Function
PZEM-004T Energy Monitor	It is used in measuring voltage, current, power factor, and energy consumption.
NodeMCU Microcontroller	An open-source development kit and firmware are beneficial for devising Internet of Things (IoT) applications. Used for its robust connectivity and ease of programming.
Python	A high-level programming language recognised for its versatility and simplicity. In this project, it is used to develop a machine-learning model for predicting power consumption.
LCD Display	It serves to provide real-time, easy-to-understand information about power usage directly on the device, enhancing the user's ability to monitor and manage consumption.
Web Dashboard	The interface for users to visualise their power consumption patterns and machine learning predictions in an interactive, user-friendly format.
Miscellaneous Components	Other components such as connecting wires, resistors, etc., are important for the assembly and functioning of the hybrid power meter.

Circuit Design and System Architecture

Figure 1 shows the System Architecture. The circuit design was aimed at enhancing the connectivity of the measuring device (PZEM-004T energy monitor) and the NodeMCU microcontroller. To ensure the transmission of power data between the two components and to allow users to have access to live monitoring of their power usage, the PZEM-004T energy monitor was interconnected to the power source and the output was linked to the NodeMCU microcontroller which was connected to the internet to facilitate transmission of data to the web dashboard.

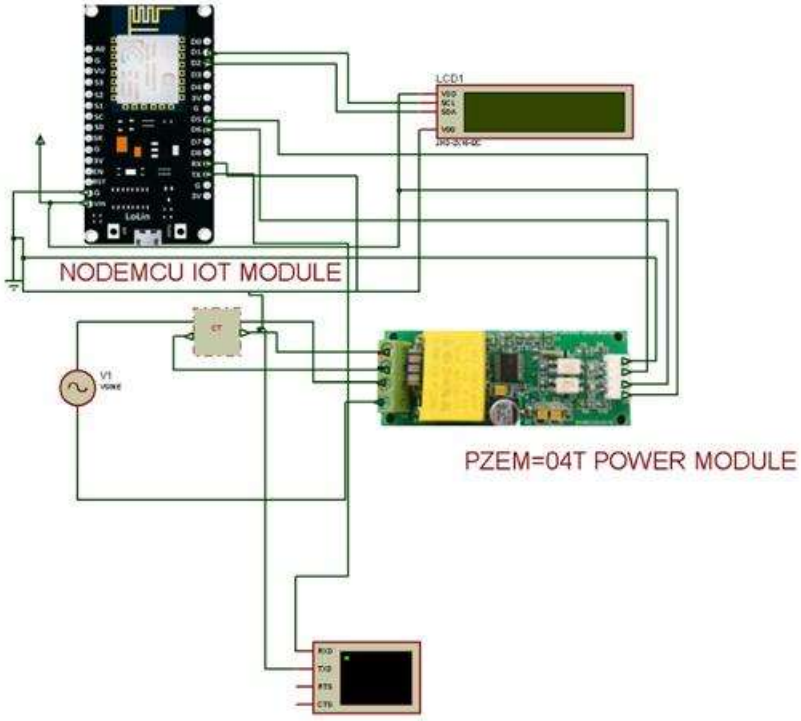

Figure 1: Circuit design and System architecture of the hybrid power meter

Furthermore, to analyze and give predictions for the power data, a Phython-based machine-learning model was programmed with the NodeMCU microcontroller to ensure that the machine-learning language uses the most recent data for analysis, reduces error and increases the accuracy of its prediction. The design of the system ensures that the machine learning model can receive new power data from the microcontroller, analyze it and send its prediction back to the microcontroller. Moreover, to ensure that the system maintains a stable efficiency overtime, the design of the system architecture allows system improvement and troubleshooting which makes the system capable of real-time data analysis and power usage prediction.

Development of the Machine Learning Model

Power usage prediction requires a machine learning model that could adequately record the pattern and trends of data due to the sequential nature of power usage data. Python being an exceptional programming language for data analysis and machine learning was employed to develop the machine learning model, using a time series prediction model. The power usage data was collected in real-time from the PZEM-004T energy monitor through the NodeMCU microcontroller for thirty days. To make the power usage data suitable for the machine learning model, data pre-processing operations which included cleaning (removal of missing data and outliners), normalizing (setting data to the standard range) and formatting were done.The machine learning model was developed with the preprocessed data and the developed model was validated with a different set of data. The model was then programmed to the NodeMCU microcontroller, enabling it to produce real-time power usage predictions based on the data received from the PZEM-004T energy monitor.

Data Visualization

Data visualization is an effective tool for improving power management. The use of visuals such as charts engages the user to understand and control their power consumption. The importance of implementing user-friendly dashboards in displaying power consumption data cannot be over-emphasized. Recent studies have suggested that the integration of the PZEM energy monitor, NodeMCU microcontroller, machine learning and data visualization in a single system will help increase the accuracy of power consumption predictions (Rodríguez-Navarro *et al*., 2023). Data visualization will enhance user engagement and a better understanding of the predictions.

Web Dashboard Design and Implementation

The web dashboard was designed to ensure a user-friendly interface for the user to interact with their power usage by displaying a visual illustration (the use of graphs and charts) of both the real-time power usage data received from the NodeMCU and the predictions made by the machine learning model. This gives users access to more detailed predictions from the machine learning model and to view their power usage data at intervals.

Source and Purpose of the Dataset

The dataset used for the analysis was obtained from a smart meter system designed for a residential. The main objective of the dataset is to enhance efficient energy planning by observing the patterns and trends of energy usage through analysis and developing a machine-learning model for power usage.

Dataset Characteristics

The dataset is made up of detailed readings of electricity usage for thirty days with a total of 2,419 entries. The parameters of the dataset include:

i. Voltage (V): the reading represents the voltage level per time and can fluctuate based on different load usages,
ii. Current (A): it indicates the electrical load per time,
iii. Power (W): it represents the power consumption reading per time,
iv. Energy (kWh): it indicates the total energy usage per time,
v. Appliance: gives information about the type of appliance in use and its energy consumption pattern,
vi. Appliance Count: gives information about the number of appliances in use, and
vii. Timestamp-related Features: Including 'Day of Week', 'Hour of Day', 'Day of Month', 'Month', and 'Year', these features give more information about the data and help in identifying consumption patterns over time.

RESULTS AND DISCUSSION

Data Visualization

The energy consumption over time and power consumption distribution were displayed in visuals (charts and plots) to make it understandable to the user.

Power consumption distribution

Power consumption distribution identifies the average levels of power usage and detects changes (below or above the average power usage). It was derived using the Kernel Density Estimate (KDE) and the result is displayed as a histogram in Figure 2.

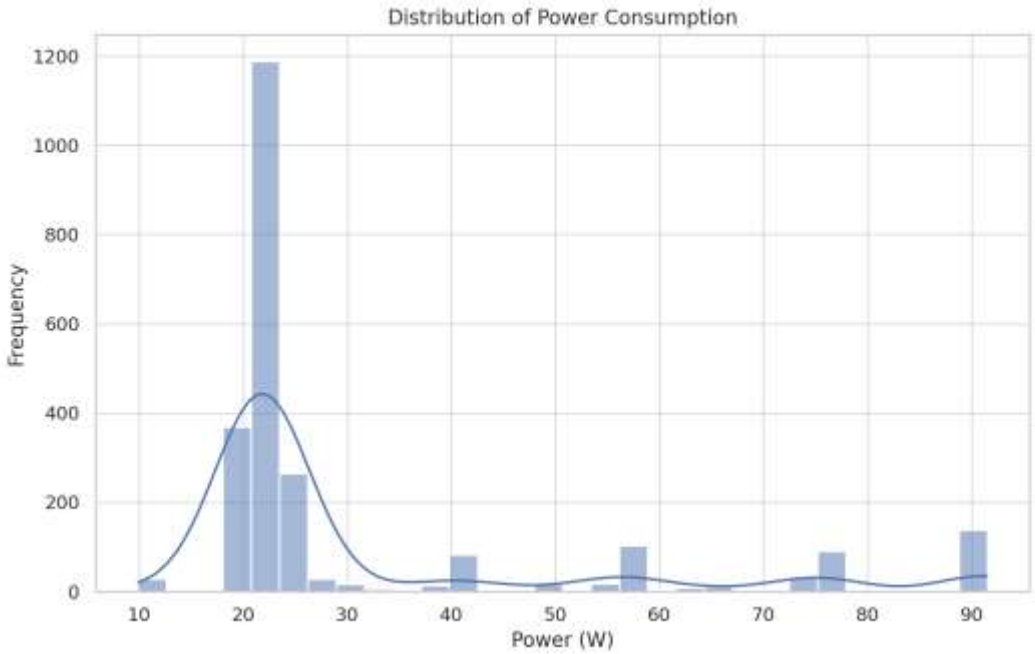

Figure 2: A lineplot showing the energy consumption over time

The central tendency indicates the most common range of power consumption suggesting a common power usage rate for majority of the time within the test period. Beyond this a significant variability was noted in the power consumption and a right skew is observed indicating that there were periods of unusual high power consumption

Heat Map Correlation Matrix

The results of the correlation are presented in Figure 3. The correlation coefficient essentially ranges from -1 to 1, where 1 indicates a perfect positive correlation and -1 indicating a perfect negative correlation, and 0 suggests the absence of linear correlation.

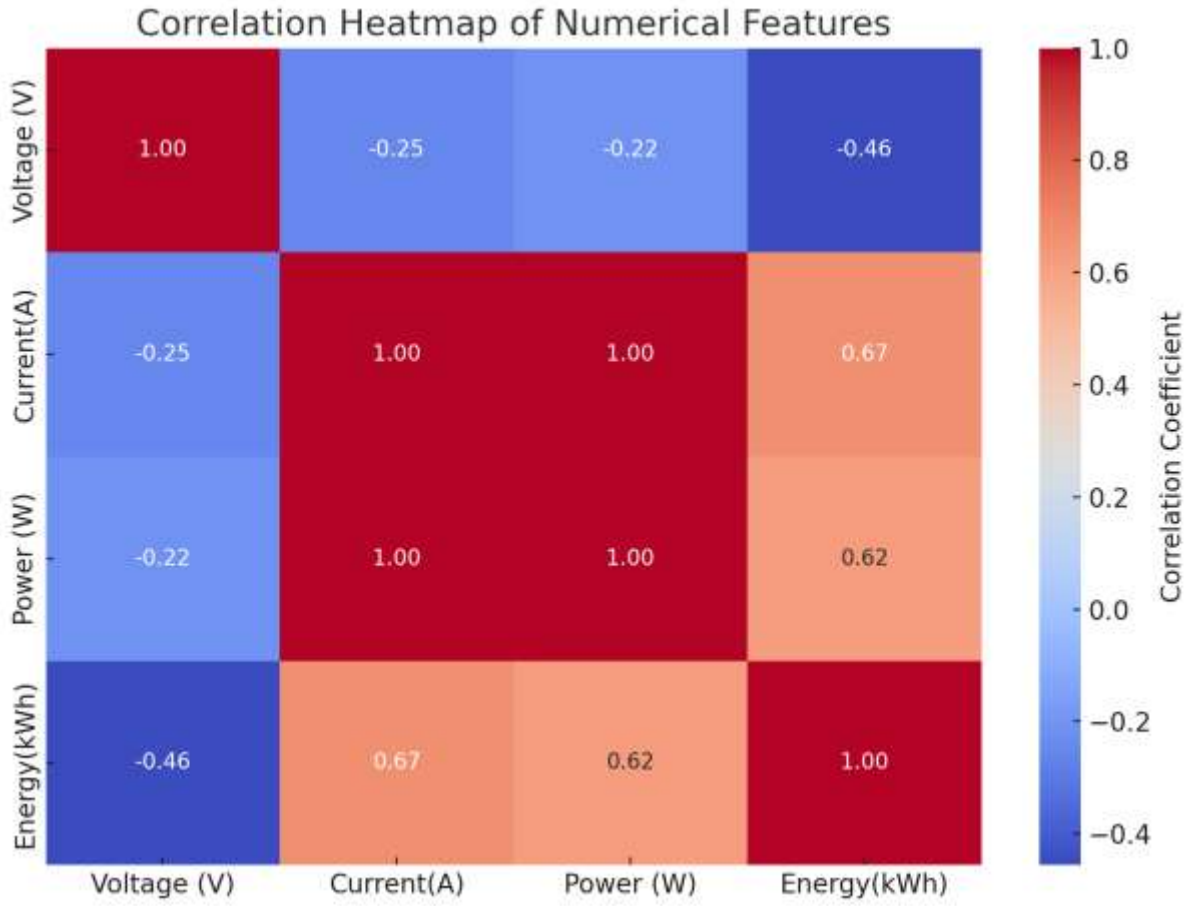

Figure 3: Correlation matrix results

The correlation matrix highlights the inherent relationship between the numerical features in the dataset: Voltage (V), Current (A), Power (W), and Energy (kWh). The key insights from the correlation heat map indicates that a strong positive correlation exists between Power (W) and energy (kWh) consumption. This is expected since energy is essentially an integral of power over time. Furthermore, a strong positive correlation was observed between current (A) and power (W) suggesting that as electrical load increases and more current is drawn, the power also increased. The correlation between Voltage (V) and power (W) is also positive although this might be less direct depending on the type of appliances as well as their operation modes.

Modelling Procedures

Linear Regression, Random Forest and Gradient Boosting were adopted in this project to predict energy consumption because of their suitability in handling regression tasks.

Linear Regression

The linear regression model is a simple and easy-to-understand model that assumes a linear relationship between the input variables and the output. It is generally used to identify the baseline performance of the system.

Random Forest

The random forest model was used because of its unique characteristics of handling non-linear data effectively, its ability to run in parallel and its high accuracy. It operates by constructing several decision trees during training and presenting the average prediction of individual trees as the output.

Gradient Boosting

The gradient boosting model uses a technique that boosts the model in an orderly pattern that allows the new trees to help correct the errors made by the previous trees. This gives the model a higher accuracy than a Random forest.

Model Evaluation and Result

The three models were evaluated with two commonly used goodness-of-fit parameters which are the coefficient of determination (R^2) and the Mean-Squared Error (MSE) and the results are presented in Table 2.

Table 2: Results from the model evaluation

Model	**Mean- Squared Error (MSE)**	**R-Squared (R^2)**
Linear Progression	1.23×10^{-5}	0.67
Random Forest	4.88×10^{-9}	0.9997
Gradient Boosting	6.37×10^{-8}	0.9965

A good model is characterized by a high (close to 1) coefficient of determination and a low mean-squared error. From Table 2, the Random Forest model has the best performance because it has the highest value of R^2 (0.9997) and the lowest value of MSE (4.88×10^{-9}), hence it has a strong fit to the data. Gradient boosting is relatively good with a minimized error of 6.37×10^{-8} and 0.9965 while Linear regression has the highest error of 1.23 x 10-5 and lowest R2 of 0.67. It was deduced from the evaluation that Random Forest and Gradient Boosting are suitable for complex patterns while linear regression is good for baseline.

The visualisation above essentially presents the evaluation results of the aforementioned models, comparing key metrics such as Mean Squared Error (MSE) and R-Squared (R^2). The MSE typically measures the average squared differences between the estimated value and the actual values as such a lower MSE indicates a better model performance. The plot indicates the Random Forest Model had the lowest MSE indicating its superior prediction accuracy. The R-squared metric provides insight into the proportion of the variance of the dependent variable that is explained by the independent variables in the model. Typically, an R^2 value closer to 1 indicates a relatively better fit indicating that the model significant captured the observed variability. From the visualisation, it could be seen that the Random forest demonstrated the highest R^2 value supporting the result of the MSE.

CONCLUSIONS

The study gives a detailed report on the development and evaluation of a hybrid power meter. Although there are numerous of research on hybrid power meters as it is important to know the energy consumption per time, this study adopts a different approach by using a Python-based machine learning model to analyze and predict the energy consumption and power requirement overtime. First, the circuit design and the system architecture were done. PZEM-004T Energy Monitor was connected to the power source to measure voltage, current, power factor, etc and output was connected to the NodeMCU microcontroller to get the real-time data. Modelling was done by using three different models with Random Forest and the Gradient Boosting models showing an excellent performance with minimized error. These models can be adapted to forecast energy consumption and will help power distribution companies to plan and distribute energy resources evenly. To improve the efficiency of the hybrid power meter, weather prediction predictors should be incorporated into the systems. Also, the strength of two or more models can be combined to enhance predictive performance.

RECOMMENDATIONS

1. Utility companies should adopt standard predictive models to improve load forecasting and energy budgeting.
2. Researchers should carry on more research on the integration of smart grid technologies and machine learning.
3. Consumers leverage meters with integrated prediction capabilities to optimize their energy usage.

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