

Smart Household Energy Monitoring and Demand Forecasting Using ESP32 and Machine Learning

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Abstract - In recent years, household electricity consumption has increased rapidly due to the growing use of electrical appliances and smart devices. Monitoring and predicting energy demand has become important for reducing energy wastage and improving efficient power utilization. This paper presents an IoT-based household energy demand prediction system using Machine Learning techniques.

In the proposed system, voltage and current sensors are connected to an ESP32 microcontroller for measuring real-time electrical parameters such as voltage, current, and power consumption. The collected data is transmitted to the Firebase cloud database through WiFi. A Python Flask web application is used to fetch, process, and visualize the data. Machine learning algorithms such as Linear Regression, Random Forest, and LSTM are applied to predict future household energy demand based on historical consumption patterns.

The system provides real-time monitoring along with future energy forecasting, helping users understand their energy usage behavior and reduce unnecessary electricity consumption. Experimental results show that the proposed system achieves good prediction accuracy and can be effectively used for smart home energy management applications. The proposed approach is low-cost, scalable, and easy to implement.

Key Words: Internet of Things (IoT), Machine Learning, Energy Demand Prediction, ESP32, Firebase, Flask, Smart Home, Energy Monitoring, Random Forest, LSTM, Real-Time Monitoring, Cloud Computing.

1.INTRODUCTION

1.1 Background

Electricity consumption in households is increasing continuously due to the usage of various electrical appliances and smart devices. Traditional energy monitoring systems only provide monthly billing information and do not help users understand their real-time energy usage. With the development of IoT and Machine Learning, it is possible to monitor and predict household energy demand efficiently.

1.2 Problem Statement

Existing household energy systems lack real-time monitoring and future energy prediction capabilities. This results in inefficient energy usage, increased electricity bills, and difficulty in managing power consumption during peak hours.

1.3 Objectives

- To measure voltage, current, and power using sensors and ESP32
- To upload real-time energy data to Firebase cloud database
- To develop a Flask-based web application for monitoring
- To apply Machine Learning algorithms for energy demand prediction
- To improve energy management and reduce power wastage

1.4 Scope of Work

The project focuses on real-time household energy monitoring and prediction using IoT and Machine Learning. The system collects electrical parameters using sensors, stores data in Firebase, and predicts future energy demand using ML models. The proposed system can be used in smart homes for efficient energy management.

2. LITERATURE REVIEW

2.1 IoT-Based Energy Monitoring

IoT-based energy monitoring systems are widely used for collecting and analyzing real-time electricity consumption data. These systems use smart sensors, microcontrollers, and cloud platforms to monitor voltage, current, and power usage continuously. Recent studies show that IoT technology improves energy efficiency and enables remote monitoring in smart homes and buildings. Researchers have used ESP32, smart meters, and cloud databases such as Firebase for real-time energy management applications.

2.2 Machine Learning for Energy Prediction

Machine Learning algorithms are increasingly used for predicting household energy demand because they can identify patterns from historical consumption data. Techniques such as Linear Regression, Random Forest, LSTM, and hybrid deep learning models have shown good prediction performance. Among these methods, LSTM networks are highly effective for time-series forecasting because they can learn temporal dependencies in energy usage data. Recent research also focuses on explainable AI and federated learning for improving prediction accuracy and data privacy.

2.3 Existing Systems and Research Gap

Existing energy prediction systems mainly focus on either IoT-based monitoring or machine learning-based forecasting separately. Some systems provide real-time monitoring but lack accurate prediction capabilities, while others use advanced ML models without real-time IoT integration. Many existing solutions are expensive, complex, or not suitable for small-scale household applications. Additionally, limited research has combined ESP32, Firebase, Flask, and machine learning into a single low-cost real-time prediction framework. Therefore, there is a need for an integrated and cost-

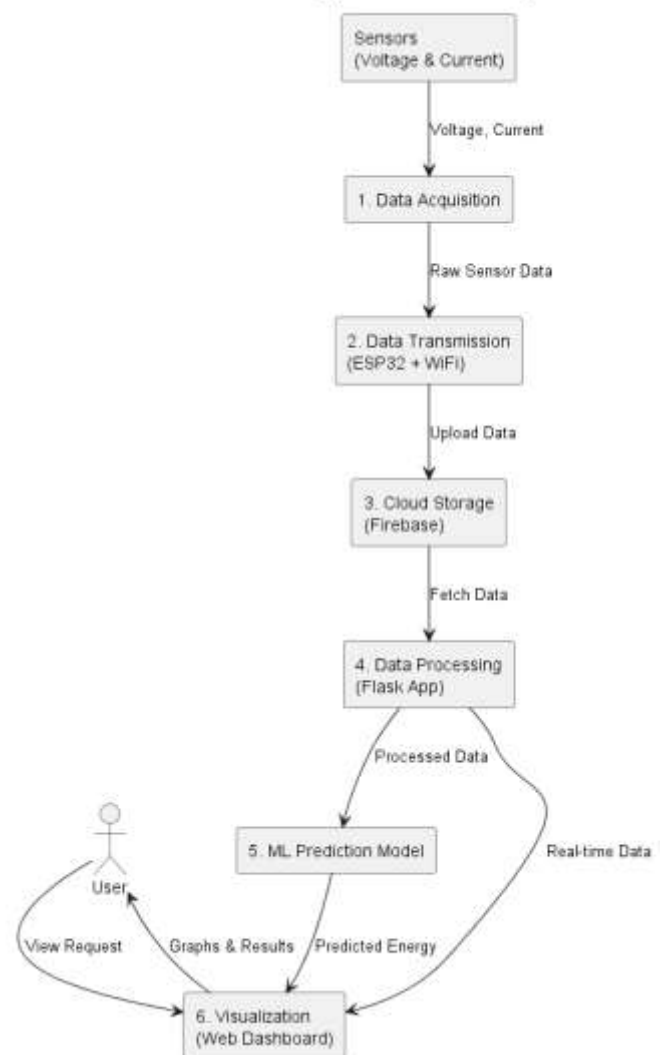
effective system that can perform both real-time monitoring and accurate household energy demand prediction.

3. PROPOSED SYSTEM

3.1 System Architecture

The proposed system consists of voltage and current sensors connected to an ESP32 microcontroller for measuring real-time electrical parameters. The ESP32 sends the collected data to the Firebase cloud database using WiFi. A Python Flask web application fetches the stored data, processes it, and applies machine learning algorithms to predict future household energy demand. The predicted results and real-time energy data are displayed on a web dashboard.

DFD Level 1 - Household Energy Demand Prediction System



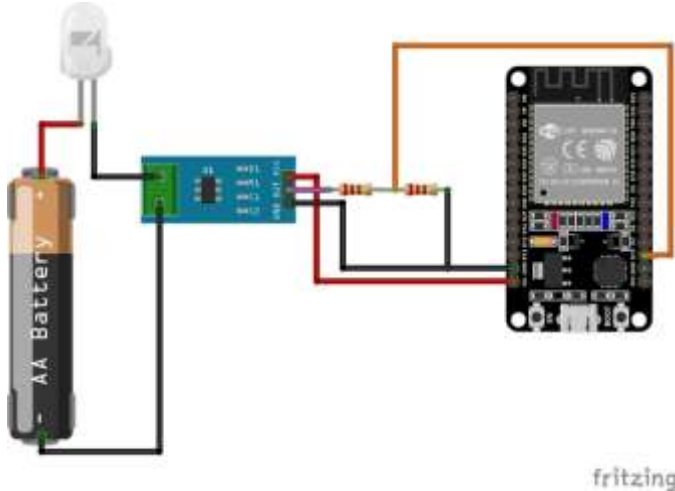
3.2 Hardware Components

The hardware components used in the system are:

- ESP32 Microcontroller: Used for data collection and WiFi communication
- Voltage Sensor: Measures supply voltage
- Current Sensor: Measures current consumption

- Power Supply: Provides required operating voltage
- Connecting Wires and Breadboard: Used for circuit connections

These components work together to collect real-time energy consumption data.

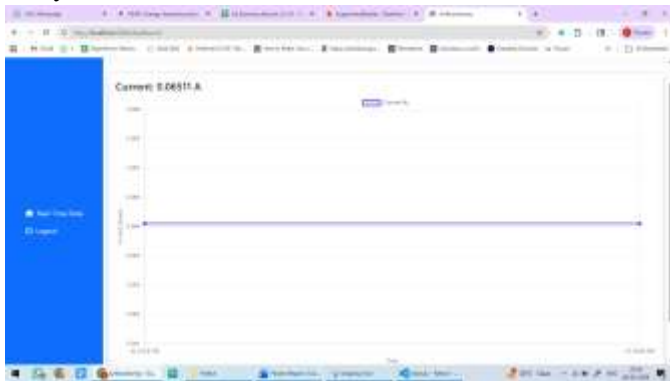


3.3 Software Framework

The software framework consists of:

- Arduino IDE for ESP32 programming
- Firebase Realtime Database for cloud data storage
- Python Flask for web application development
- Machine Learning Libraries such as Scikit-learn and TensorFlow for prediction

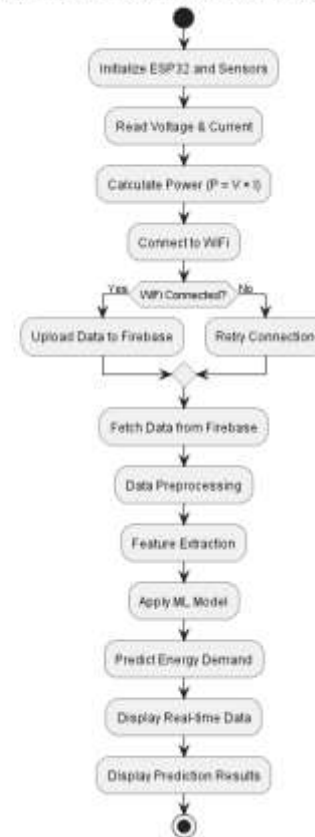
The software framework enables data collection, storage, analysis, and visualization.



3.4 Working Methodology

The system continuously reads voltage and current values using sensors. The ESP32 calculates power consumption and uploads the data to Firebase through WiFi. The Flask application retrieves the stored data and performs preprocessing such as cleaning and feature extraction. Machine learning algorithms are then applied to predict future energy demand based on historical usage patterns. Finally, the results are displayed on the dashboard for user monitoring and analysis.

Activity Diagram - Household Energy Demand Prediction System



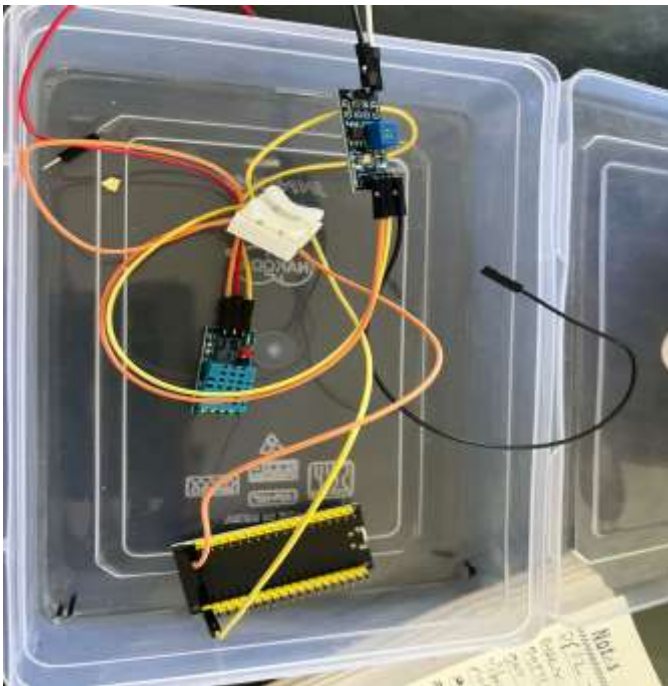
3.5 Machine Learning Model

Machine learning models such as Linear Regression, Random Forest, and LSTM are used for energy demand prediction. Historical energy consumption data is used for training the models. The trained model analyzes consumption patterns and predicts future energy demand. Among the models tested, LSTM provides better accuracy because it is effective for time-series prediction tasks.

4. PROPOSED FRAMEWORK

4.1 ESP32 and Sensor Integration

In the proposed system, voltage and current sensors are connected to the ESP32 microcontroller for measuring electrical parameters. The ESP32 reads analog sensor values and calculates power consumption using voltage and current data. The microcontroller is programmed using Arduino IDE and configured to connect with a WiFi network for internet communication.



4.2 Firebase Cloud Integration

Firebase Realtime Database is used as the cloud platform for storing sensor data. The ESP32 uploads voltage, current, power, and timestamp values to Firebase through WiFi. The cloud database enables real-time data storage and easy accessibility from the Flask application.



4.3 Flask Web Application

A Python Flask web application is developed for monitoring and visualization of energy data. The Flask app fetches data from Firebase, processes it, and displays real-time energy parameters on a dashboard. The application also shows predicted energy demand using graphical visualization.



4.4 Data Collection and Preprocessing

The system continuously collects energy consumption data from sensors. The collected dataset contains voltage, current, power, and time information. Before training the machine learning model, preprocessing techniques such as data cleaning, normalization, and feature extraction are applied to improve prediction performance.

4.5 Model Training and Prediction

Machine learning models are trained using historical energy consumption data. Algorithms such as Linear Regression, Random Forest, and LSTM are used for prediction. The dataset is divided into training and testing sets for performance evaluation. The trained model predicts future household energy demand, and the results are displayed through the Flask dashboard.

5. RESULTS AND DISCUSSION

5.1 Experimental Setup

The proposed system was tested using ESP32, voltage sensor, and current sensor for collecting real-time household energy data. Firebase was used for cloud storage, and a Flask web application was developed for monitoring and visualization. Machine learning models were trained using historical energy consumption data collected from the system. The experiments were performed on a computer with Python, Scikit-learn, and TensorFlow libraries installed.

5.2 Prediction Accuracy

Different machine learning algorithms such as Linear Regression, Random Forest, and LSTM were tested for energy demand prediction. Among these models, LSTM achieved the highest prediction accuracy of around 94–95%, while Random Forest achieved approximately 91–92% accuracy. Linear Regression provided lower accuracy compared to other models.

5.3 Actual vs Predicted Results

The predicted energy demand values were compared with actual household energy consumption data. The results show that the predicted values closely follow the actual energy usage pattern. Small variations were observed during sudden load changes, but overall prediction performance was satisfactory and reliable for practical applications.

5.4 Performance Analysis

The proposed system successfully performs real-time energy monitoring and future demand prediction. The integration of IoT, cloud computing, and machine learning improves energy management efficiency. The system is low-cost, scalable, and suitable for smart home applications. Experimental analysis shows that the proposed approach can help users monitor energy usage and reduce unnecessary electricity consumption.

CONCLUSION & FUTURE SCOPE

6.1 Conclusion

This paper presented an IoT-based household energy demand prediction system using Machine Learning techniques. The system uses voltage and current sensors with ESP32 to monitor real-time energy consumption and upload data to Firebase cloud storage. A Flask web application was developed for visualization and analysis of energy data. Machine learning algorithms such as Linear Regression, Random Forest, and LSTM were used for predicting future energy demand.

The experimental results showed that the proposed system provides accurate prediction and effective real-time monitoring. Among all models, LSTM achieved the best performance for energy forecasting. The proposed system is low-cost, efficient, and suitable for smart home energy management applications.

6.2 Future Scope

In future, the system can be improved by integrating additional environmental parameters such as temperature and humidity for better prediction accuracy. Advanced deep learning models and hybrid algorithms can also be used to enhance forecasting performance. The system can be extended for appliance-level monitoring and automated energy control. Mobile application support and renewable energy integration

can further improve the functionality of the proposed system for smart city and smart grid applications.

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