

AI-Based Home Energy Monitoring, Consumption Prediction and Automated Load Control System

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Abstract: *This project presents an AI-Based Home Energy Monitoring with automated load system designed to monitor and manage household electricity consumption ,efficiently ,ON/OFF controlling sysyem. The system uses voltage and current sensors to measure real-time electrical parameters to provide values of current and voltage to calculate the power value, which are processed and transmitted using an ESP32 microcontroller. The microcontroller will process the data in into computer singles data .The collected data is stored in a database for continuous tracking and evaluation. Artificial intelligence techniques are applied to analyze household energy habits, forecast future power usage, estimate electricity costs, and highlight instances of unnecessary energy waste. To take proactive action, the system integrates a six-channel relay module that can automatically switch specific appliance loads on or off based on predicted energy trends and preset safety conditions. A web-based dashboard is provided to display real-time usage data, load statuses, billing estimates, and system alerts. Overall, the system offers a practical and low-cost solution for real-time monitoring and automated load management in smart homes.*

Keywords: *AI-Based Home Energy Monitoring*

I. INTRODUCTION

Electricity consumption in homes is increasing due to the growing use of electrical appliances, resulting in higher electricity bills.

To address this lack of real-time awareness, various Smart Home Energy Management Systems (SHEMS) and IoT-based monitoring solutions have been developed in recent years. While these existing systems allow users to view current voltage and power metrics via digital screens or mobile applications, their functionality is largely limited to passive data reporting and simple threshold alerts.

They still depend entirely on manual human adjust heavy electrical loads when usage becomes excessive. This manual dependency reduces overall energy efficiency, as users are not always present or available to take immediate corrective action.

To bridge this gap between data collection and practical power management, this paper presents an intelligent, automated home energy monitoring system powered by the ESP32 microcontroller and Artificial Intelligence (AI). The system uses dedicated voltage and current sensors to measure live electrical parameters and continuously transmit this data to a central database. Beyond basic sensing, the system integrates AI algorithms to analyze historical consumption habits, forecast future power demands, estimate real-time electricity costs, and identify instances of energy waste.

A key contribution of this project is its proactive control mechanism. By linking machine learning predictions with predefined user rules and safety thresholds, the system automatically controls selected high-power household appliances using a multi-channel relay board. Additionally, a web dashboard provides users with real-time operational status, billing forecasts, and automated control logs. By combining continuous monitoring, predictive analytics, and automated load control, the proposed system provides a low-cost, scalable approach to modern smart home energy management.



A major feature of this system is its proactive and automated control capability. By combining machine learning predictions with customizable user rules and safety thresholds, the system can automatically switch selected household appliances ON or OFF using a six-channel relay module. Furthermore, users can set monthly budget limits and prioritize critical loads during peak electricity tariff hours. An interactive web dashboard displays live power metrics, appliance statuses, financial forecasts, and control logs. Ultimately, by integrating real-time sensing, AI-driven forecasting, flexible user settings, and automated load control, the proposed system provides a low-cost, scalable, and practical solution for smart home energy management.

II. PROBLEM STATEMENT

Modern homes use many electrical appliances, leading to high electricity bills. However, standard energy meters only show total usage at the end of the month, so people cannot track daily power spikes or find inefficient devices in time. Current smart monitoring devices can show usage on a screen, but they still require users to manually turn off appliances to save power. Additionally, these systems cannot predict future energy use or estimate upcoming bills. There is a need for a smart system that measures energy in real time, predicts power consumption, and automatically turns off unnecessary appliances to lower electricity costs.

III. RELATED WORK

1. Hardware and Sensor Setup

- **Microcontrollers and Communication:** Most modern energy systems use affordable microcontrollers like the ESP32. Some designs also include GSM modules so the system can send alerts even when regular internet connection fails.
- **Electrical Sensors:** Systems typically use voltage sensors (like the ZMPT101B) and current sensors (like the ACS712), or dual-module meters like the PZEM-004T. These measure live voltage, current, active power, and total energy usage.
- **Cloud Platforms:** The collected data is sent to cloud databases (such as Firebase or MySQL) or IoT platforms (like MQTT or Blynk) to power live web dashboards and control safety relays remotely.

2. Machine Learning for Predicting Energy Use

- **Time-Series Models:** Researchers frequently use Long Short-Term Memory (LSTM) neural networks—and hybrid models like LSTM combined with XGBoost—to forecast hourly and daily power spikes based on past habits.
- **Load Monitoring (NILM):** Some studies use energy disaggregation techniques to figure out what individual appliances are running by looking at the main power line, avoiding the need to install smart plugs on every single device.
- **Algorithm Testing:** Many studies compare different machine learning models, such as Random Forest, Support Vector Regression, and Gradient Boosting, to find out which algorithm works best for short-term or long-term predictions.

3. Automated Appliance Control

- **Smart Optimization:** Advanced frameworks use reinforcement learning and particle swarm optimization to schedule when heavy appliances should run, helping cut down peak-hour power usage.
- **Relay Switching:** Microcontrollers like the ESP32 are connected to relay boards to automatically switch appliances on or off based on pre-set power limits, budget caps, or changing electricity rates.
- **Balancing Comfort and Savings:** Recent research focuses on making sure these automated controls actually save money and reduce energy waste without making the home uncomfortable for the people living there.



IV. OBJECTIVES

1. To monitor household electrical parameters such as voltage, current, power, and energy consumption in near real time.
2. To develop an ESP32-based system for collecting electrical measurements and transmitting data to a cloud server.
3. To design a web dashboard for displaying live readings, historical energy consumption, and usage analytics.
4. To estimate monthly electricity bills based on recorded energy consumption and the configured electricity tariff.
5. To generate alerts when electrical parameters exceed predefined thresholds or abnormal conditions are detected.
6. To implement remote ON/OFF control of connected appliances using a relay module and a web interface.
7. To establish a foundation for future AI-based energy prediction and automated load control using calibrated measurements and sufficient historical data.

V. HARDWARE AND SOFTWARE PART

• Hardware Requirements

S. No.	Hardware Component	Specification / Rating	Purpose
1	ESP32 Development Board	3.3 V logic,	Reads sensors and communicates with the server
2	ZMPT101B Voltage Sensor	230 AC supply	Measures AC supply voltage
3	ACS712 Current Sensor	5 A / 20 A / 30 A	Measures load current
4	5-Channel Relay Module	5 V DC, 5 relay channels	Switches connected appliances remotely
5	OLED Display (SSD1306)	0.96-inch, 128 × 64, I ² C	Displays electrical readings
6	AC-DC Power Supply	Regulated 5 V DC output	Powers the low-voltage electronics
7	Household Lamps, Mini Fan	230 V AC	Demonstration load
8	Breadboard/ PCB	Compatible with ESP32 and modules	Circuit assembly and connections
9	Connecting Wires	Suitable voltage and current ratings	Electrical and signal connections

• Software Used

S. No.	Software Used	Specification /Platform	Purpose
1	Arduino IDE	Embedded C/C++ programming	Programs the ESP32 microcontroller.
2	Python	Python programming language	Supports data processing and prediction-related tasks.
3	C++	Programming language	Handles sensor readings and relay control in the ESP32.
4	SQL	Programming language	Manages and retrieves stored energy consumption data.
5	Firebase	Cloud database platform	Stores and manages energy-monitoring data.
6	Mobile App / Web Dashboard	User interface	Displays energy consumption, bill estimates, alerts and appliance status.
7	AI (Linear Regression)	Machine-learning technique	Intended to predict future energy consumption.

D. Energy monitoring

voltage and current measurements are obtained and processed to estimate electrical power and energy consumption. For a single-phase AC system, the basic relationship is:

$$P = VI \cos \phi$$



Where:

- P = real power in watts
- V = RMS voltage
- I = RMS current
- $\cos \phi$ = power factor

Energy consumption can be calculated as:

$$E = \int P(t) dt$$

For approximately constant power over a time interval:

$$E = P \times t$$

When power is expressed in kilowatts and time in hours, energy is measured in kWh.

Explain the actual measurement method used by your system.

E. AI-based consumption prediction

- historical data the system uses. For prediction
- the data is prepared and prediction algorithm you use.
- the model is trained and evaluated.
- The prediction is displayed on the dashboard.

F. Automated load control

- the controller communicates with the relay module.
- Appliances can be switched ON and OFF.
- In specific conditions trigger automatic control.
- the system prevents unnecessary switching.
- appliances are suitable for automated control.

VI. LITERATURE REVIEW

The literature on smart home energy management highlights several key developments, ranging from basic parameter measurement to intelligent data analytics and load control.

- Real-Time Data Acquisition and Sensing:

Existing smart energy meters focus primarily on replacing traditional electromechanical meters with digital sensors.

Research shows that using dedicated voltage (e.g., ZMPT101B) and current sensors (e.g., ACS712 or non-invasive SCT-013 CT sensors) allows systems to capture continuous electrical parameters such as voltage, current, active power, and total energy consumption with reasonable accuracy.

- IoT and Microcontroller-Based Architectures:

Recent studies widely utilize low-cost, high-performance microcontrollers like the ESP32 and ESP8266 for smart home applications. Due to their built-in Wi-Fi and Bluetooth capabilities, these microcontrollers efficiently process sensor measurements at the edge and transmit data wirelessly to cloud platforms, web interfaces, or mobile applications for real-time visualization.

- Machine Learning for Consumption Prediction:

Application of Artificial Intelligence (AI) and Machine Learning (ML) techniques—such as Linear Regression, Random Forest, and Time-Series Forecasting models (e.g., ARIMA or LSTM networks)—has been extensively explored. These algorithms analyze historical consumption data to detect usage patterns, estimate electricity bills, and forecast short-term and long-term household energy demands.



- Cloud Data Storage and Analytical Platforms:

Researchers commonly implement cloud databases (such as Firebase, ThingSpeak, or MySQL) to manage continuous streams of telemetry data. Storing long-term consumption history in the cloud allows central analytical engines to train predictive models, identify abnormal power spikes, and generate automated performance reports.

- Gaps in Automated Load Control Integration:

While existing literature covers real-time monitoring, AI forecasting, and alert generation (via SMS, email, or app notifications), most published systems remain passive. They rely heavily on manual user intervention to switch off high-power appliances when usage exceeds budget limits. Integrating predictive AI analytics directly with hardware control modules (such as multi-channel relays) provides a more active, closed-loop energy management system.

VII. RESEARCH GAP

1. Lack of Proper Sensor Calibration: Many low-cost energy-monitoring systems focus on collecting electrical measurements, but the accuracy of voltage and current readings depends on proper sensor calibration and validation.
2. Limited Integration of Monitoring and Appliance Control: Some systems focus mainly on monitoring electricity consumption, while integrating real-time monitoring, cloud storage, alerts and remote appliance control into one platform can make energy management more convenient.
3. Insufficient Historical Data for Prediction: Machine-learning models require sufficient and reliable historical energy-consumption data. During the initial stage of a monitoring system, limited data can make it difficult to train and evaluate accurate prediction models.
4. Limitations of Electricity Bill Estimation: Basic energy-monitoring systems often calculate electricity costs using a fixed tariff rate. This may not accurately represent actual electricity bills that include slab-wise rates and additional charges.
5. Limited Intelligent Load Automation: Remote appliance control allows users to switch appliances manually, but automatic load management based on predefined rules or predicted energy consumption requires additional control logic and testing.
6. Need for Reliable Data Communication: Communication failures, missing readings and incorrect energy calculations can affect the reliability of the monitoring system. Proper data validation, storage and error handling are therefore important.
7. Security and Hardware Validation: Connected electrical systems require secure device communication and appropriate access control. Physical testing is also necessary to verify sensor accuracy, relay operation and the reliability of the complete system.



VIII. RESULTS AND DISCUSSION

Experiment	What to evaluate
Energy monitoring	Accuracy of voltage, current, power, and energy measurements
Consumption prediction	Prediction error and model performance
Bill estimation	Difference between estimated and reference bills
Load control	Successful ON/OFF operation and response time
Alerts	Correct detection of defined abnormal-consumption conditions
Dashboard	Correct display of measurements and appliance status

IX. ADVANTAGES, LIMITATIONS, FUTURE SCOPE AND CONCLUSION

Advantages :

- Real-time energy monitoring.
- Better awareness of electricity consumption.
- Forecasting of future energy requirements.
- Automated control of selected appliances.
- Centralized monitoring through a dashboard.

Limitations :

limitations such as sensor accuracy, internet dependence, prediction performance, or hardware cost.

Future Scope :

Possible improvements include:

- More advanced prediction algorithms.
- Integration with solar energy monitoring.
- Mobile application development.
- Integration with smart meters.
- Improved anomaly detection.
- Optimization of load scheduling.

Conclusion :

In conclusion, this system helps users monitor their home electricity usage in real time. It can predict future energy consumption and control electrical appliances automatically. It also helps reduce electricity wastage and manage electricity bills.

Overall, this system makes home energy management easier and more efficient.



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