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IoT-Based Smart Energy Management for Smart Grids Applied in a Home

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Abstract. The growing demand for effective energy management in smart grids necessitates modern monitoring and optimization methods. Traditional energy distribution systems confront numerous issues, including high electricity costs, ineffective load management, and a lack of real-time data analytics. This study describes an IoT-based Smart Energy Monitoring System (SEMS) for continuous real-time energy tracking, with accurate current measurements provided via wireless transmission and predictive analytics. The system is designed to provide reliable and precise current measurements. The suggested system combines wireless data transmission and predictive analytics. The technology enables real-time energy monitoring and assists users in analysing consumption trends to make more informed decisions. It also allows for more efficient load control by identifying peak consumption periods. An energy audit validates the system, indicating considerable reductions in power losses as well as increased economic feasibility. The findings demonstrate that IoT-driven smart energy management improves sustainability, dependability, and cost effectiveness in modern smart grids.

Introduction

Energy management and planning are becoming more complicated due to the growing demand for power worldwide and the incorporation of renewable energy sources. Issues with traditional power networks such as poor load distribution, energy waste, and a lack of real-time monitoring. Without effective energy management, utilities have trouble managing peak loads, and customers pay high power costs as a result of inefficient energy use [1]. Smart grid technology, which combines automation, real-time monitoring, and predictive analytics, has been introduced to address these issues. The use of IoT-based smart energy meters is one of the most promising strategies in smart grids. These gadgets give consumers comprehensive insights into their power usage, enhance load balancing, and allow real-time tracking of energy consumption. These smart meters increase energy efficiency by enabling remote monitoring and management through cloud connectivity [2]. Existing IoT-based energy monitoring systems have drawbacks despite their benefits. Large-scale implementation is challenging due to the high cost of many commercially available smart meters. Furthermore, certain technologies don't integrate well with the grid's current architecture, and connection problems prevent them from delivering reliable real-time data. Another issue is the dependence on proprietary software and hardware, which restricts flexibility and modification for various energy management requirements [3]. For effective load control and real-time energy tracking in smart grids, this article suggests a low-cost, Internet of Things-based smart energy monitoring system. With its wireless transmission and real-time data collecting capabilities, this Internet of Things-based energy meter guarantees precise energy usage monitoring. Users may optimize electricity use, cut down on waste, and help create a more sustainable and efficient energy infrastructure by connecting this gadget into smart grids.

The creation, deployment, and performance assessment of the suggested smart energy monitoring system are the main topics of this study, which emphasizes the advantages it offers to utility companies and customers alike [4, 5].

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Methodology

An IoT-based Smart Energy Management System (SEMS) suited for smart grid applications is designed, developed, and evaluated in this study using a systematic, multi-phase methodology. After a thorough analysis of current technologies, the system's architectural design, component integration, data collection, and performance assessment using simulation and real-world testing come next. [6,7].

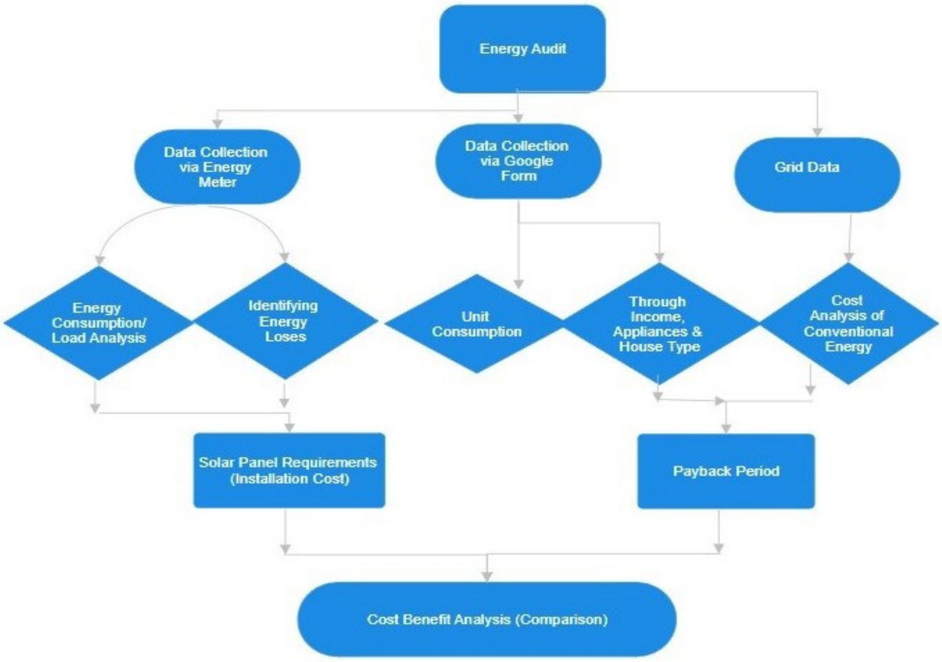

Fig. 1. Energy audit flowchart showing the overall process.

The proposed framework (Fig. 1) is designed using a layered architecture, integrating IoT devices, edge computing nodes, block chain networks, and machine learning algorithms. This stage includes defining system components, communication protocols, and data flow mechanisms. Smart meters and IoT sensors are deployed to gather 24-hour energy usage statistics, voltage fluctuations, and load profiles such as house hold or small-scale grid settings, to collect real-time energy consumption data, including usage patterns and load fluctuations. Data is processed locally to reduce delays and enable real-time analysis, with secure procedures in place to protect information and transactions. [8]. The planned IoT-based Smart Energy Management System (SEMS) was implemented and validated in residential structures with different structural configurations, categorized as single-, double-, and triple-unit homes. These residences varied in size from 05 to 20 Marla, and their floor patterns, occupant levels, and electrical load diversity became more complex. In contrast to double- and triple-unit residences, which house two or more households with separate consumption patterns and dispersed sub-loads, single-unit dwellings usually house one family and have a single load center. Different appliance densities, diversification variables, and usage simultaneity cause non-linear load characteristics in this variation. Consequently, the number of active households and the actual size of the residence were regarded as crucial factors for real-time energy profiling.Edge computing techniques pre-process the data, reducing latency and enhancing real-time decision-making. Advanced analytics, including predictive modelling, are applied to interpret the collected data, enabling forecasts of energy demand and optimization of resource distribution. The system is tested through simulations to evaluate performance metrics such as efficiency, responsiveness, and reliability. [9, 10]. Training datasets are collected from real-world energy consumption patterns. The proposed framework is simulated using Blynk. Blynk was chosen because of its compatibility with ESP8266 modules, capability for real-time cloud data visualization, and ease of integration with IoT hardware. It improves user accessibility and makes performance monitoring dashboards easy to use without requiring the creation of unique mobile apps. Comparative analysis with traditional energy management systems is conducted. A pilot implementation of the framework is conducted in a controlled environment, such as a micro grid or smart home setup, to evaluate real-world applicability and validate simulation results. The obtained results are analysed, and necessary modifications are made to enhance the efficiency, reliability, and security of the system [11]. Recommendations for future improvements and large-scale deployment strategies are provided. This research methodology ensures a systematic and scientific approach to developing a robust, scalable, and secure IoT-based Smart Energy Management system for Smart Grids [12, 13].

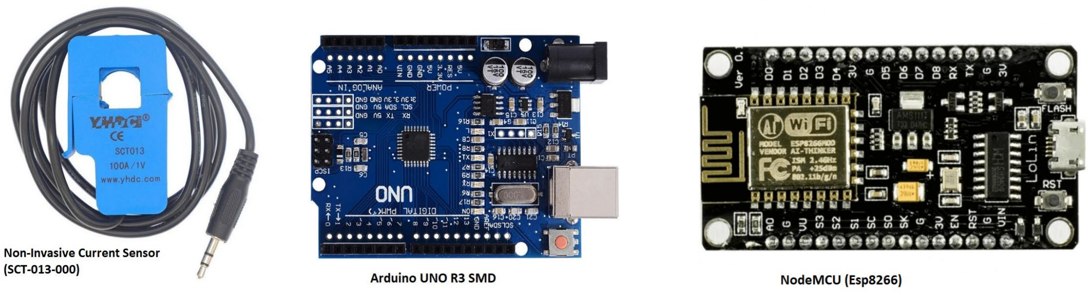

Fig. 2 Key hardware components of IoT-based smart energy monitoring system.

1. **NodeMCU ESP8266 Wi-Fi**

   The NodeMCU ESP8266 Wi-Fi Module is a small development board that is perfect for Internet of Things projects. A Wi-Fi-enabled microcontroller that wirelessly transmits the processed energy data from the Arduino to a cloud platform. [26]

2. **Non-Invasive Current Sensor (SCT-013-000):**

   A clamp-on current sensor that detects AC current without making direct electrical contact is a non-invasive current sensor (YHDC SCT-013-000). It offers a practical and secure means of keeping an eye on electrical systems' energy usage [27].

3. **Arduino UNO R3 SMD**

   A microcontroller board built on the ATmega328P (SMD version) is the Arduino UNO R3 SMD variant. It has six analog inputs and fourteen digital I/O ports. [28]

4. **Energy Meter Circuit**

   The Energy Meter Circuit combines the NodeMCU, current sensor, and Arduino with capacitors for power stability, resistors for signal scaling, and wires for interface. This configuration effectively measures, processes, and communicates energy usage data.

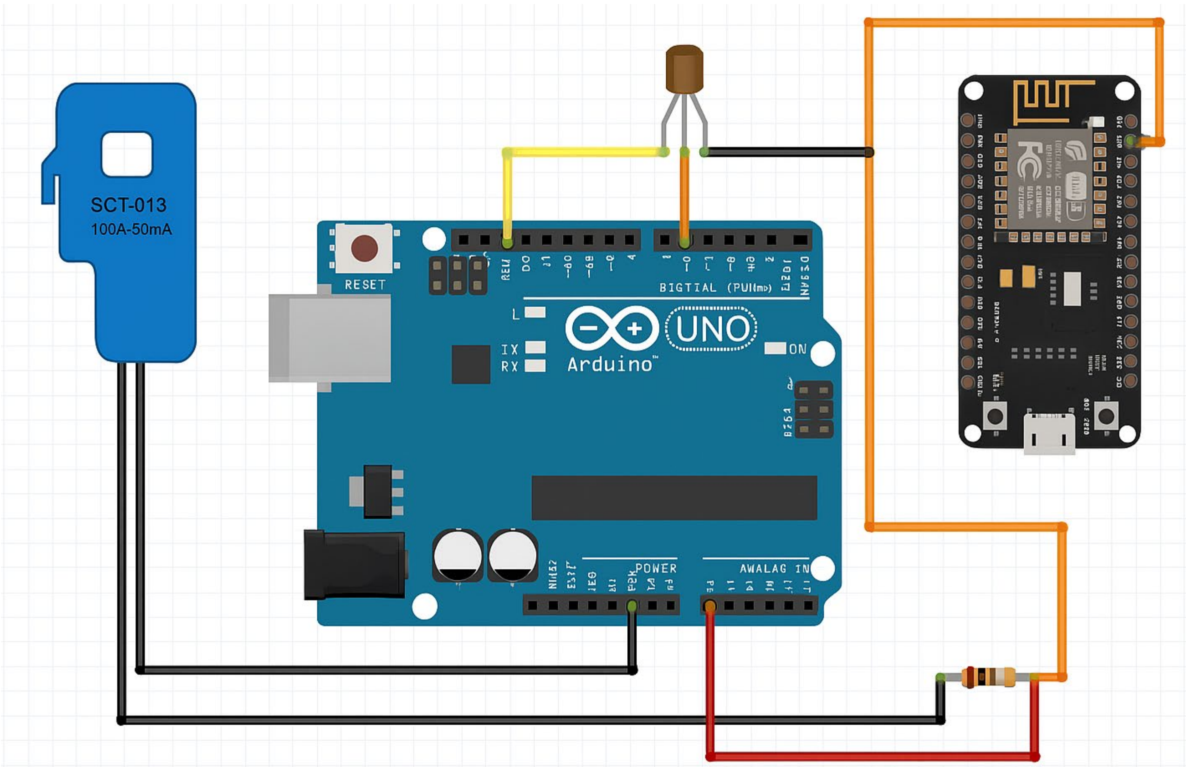

Fig. 3(a)

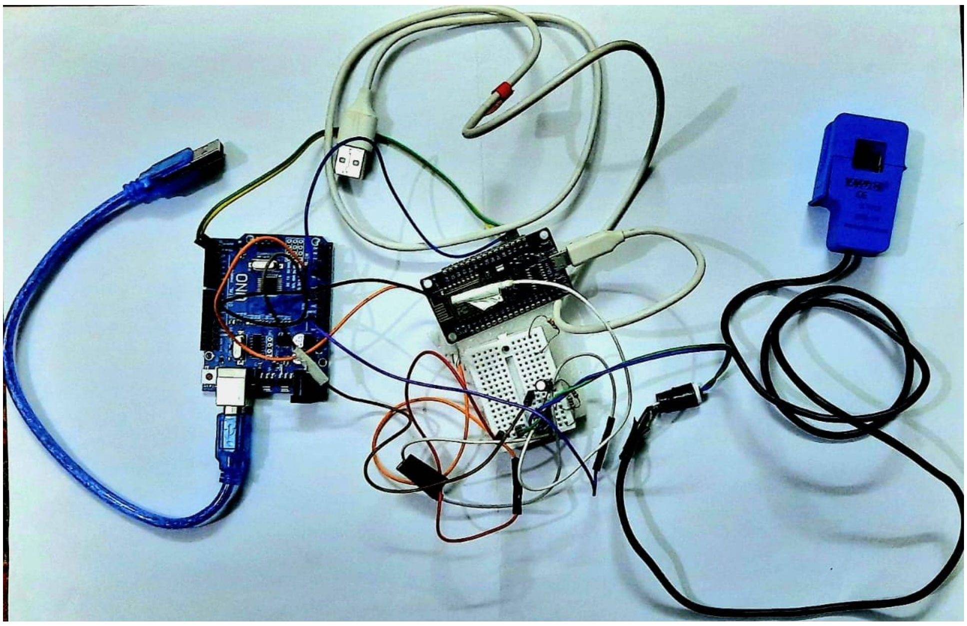

Fig. 3(b)

Fig. 3(a). Wiring Diagram of the IoT-Based Energy Monitoring Circuit
Fig. 3(b). Experimental Prototype of IoT-Based Energy Monitoring System

The real hardware prototype, which consists of an Arduino UNO, NodeMCU ESP8266, and SCT-013 current sensor constructed on a breadboard, is shown in Fig. 3(a). The system's full wiring schematic is shown in Fig. 3(b) for clarity. It displays the power and signal connections between the microcontroller boards, resistors, capacitor, and sensor. The structure and implementation of the energy monitoring circuit for real-time data collecting are made easier to understand thanks to this graphic representation.

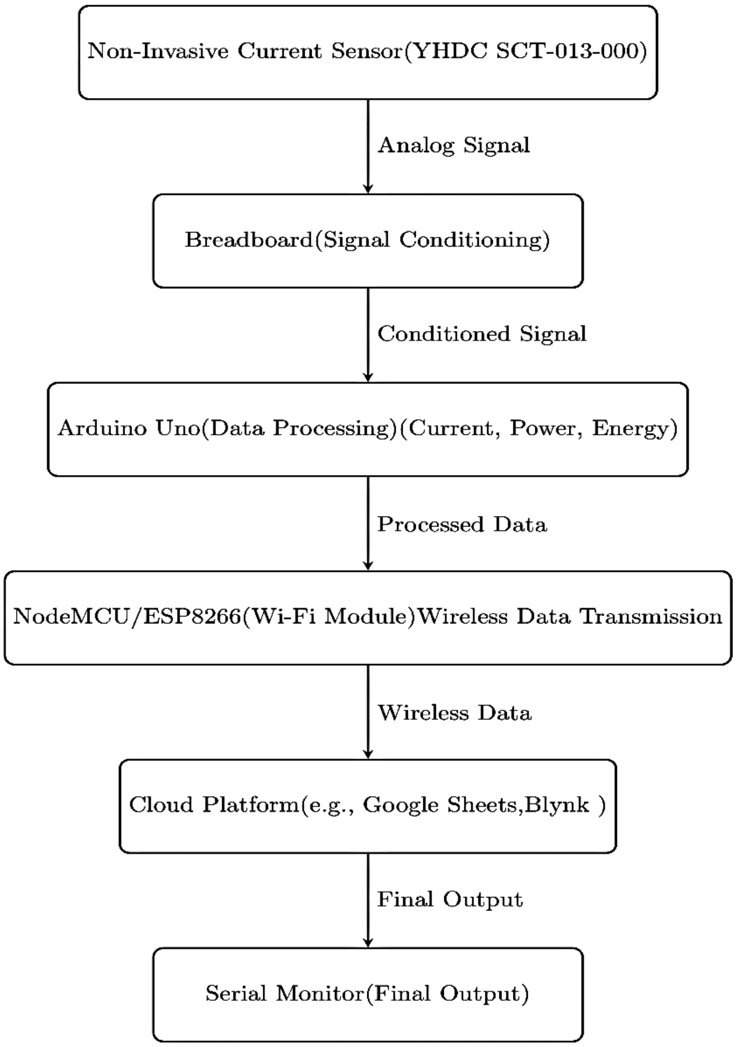

Fig. 4 Block diagram of the data processing workflow in the IoT-based energy monitoring system.

The data processing workflow of an IoT-based smart energy monitoring system is depicted in the flowchart (Fig. 4). A breadboard-based signal conditioning circuit is used to condition the analog signal produced by the Non-Invasive Current Sensor (YHDC SCT-013-000), which detects AC current. After processing the conditioned signal, the Arduino Uno computes the current, power, and energy usage. The NodeMCU (ESP8266), a Wi-Fi module for wireless connectivity, receives the processed data after that. The NodeMCU allows for real-time data storage and display by sending the processed data to a cloud platform like Google Sheets or Blynk. This makes it possible to remotely monitor and analyse patterns in energy consumption. Applications for the smart grid operate more efficiently thanks to this methodical approach, which also improves energy management and optimization.

Results

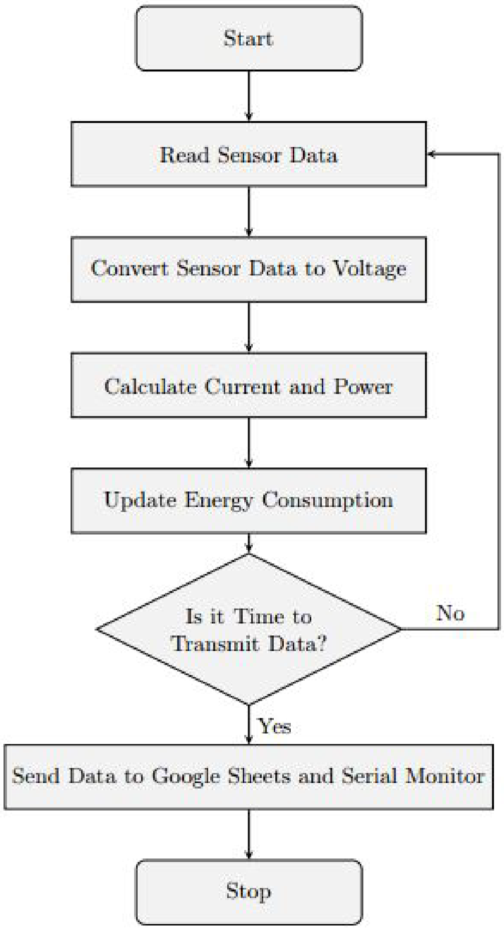

Fig. 5 Flowchart of the IoT-based energy monitoring system from data acquisition, processing, to cloud transmission.

This flow diagram (Fig. 5) depicts the operational logic of an IoT-based system, likely for energy monitoring or management. The diagram outlines the steps involved in:

1. **Data Acquisition:** Reading sensor data.
2. **Data Processing:** Converting sensor data to voltage, calculating current and power, and updating energy consumption.
3. **Data Transmission:** Determining when to transmit data and sending it to Google Sheets and a serial monitor.

Observations and Considerations:

- **Real-Time Monitoring:** The loop between "Calculate Current and Power" and the "Is it Time to Transmit Data?" decision point indicates that the system is performing real-time monitoring and processing.
- **Data Logging:** Sending data to Google Sheets implies that the system is logging data for analysis and historical records.
- **Flexibility:** The "Is it Time to Transmit Data?" decision point provides flexibility in how often data is sent.
- **Potential Enhancements:**
    - **Error Handling:** The diagram doesn't show any error handling. For example, what happens if sensor data is invalid or transmission fails?
    - **Data Validation:** Adding data validation steps would improve the reliability of the system.
    - **User Interface:** The diagram doesn't show how users interact with the system.
    - **Specific Sensors:** The diagram doesn't specify the types of sensors used.

The flow diagram (Fig. 5) represents a basic yet functional IoT system for energy monitoring. It highlights the core steps involved in data acquisition, processing, and transmission. Adding error handling, data validation, and user interface considerations would further enhance the system's robustness and usability.

Table 1. Unit consumption (kWh) by building type as measured by Energy Meter

S. No	Type of Building	Unit Consumption (kWh)
1	Single	2.82
2	Double	11.34
3	Triple	19.64

The unit consumption numbers (Table 1) reveal a significant difference in energy usage between single, double, and triple-unit constructions. A single-unit building consumes 2.82 kWh, while a two-unit building uses 11.34 kWh. Similarly, a triple-unit building uses 19.64 kWh. This mismatch suggests that energy demand increases disproportionately with building size, most likely due to the growing number of electrical appliances, lights, and heating/cooling systems in multi-unit complexes.

Table 2. Conventional load for single storey house.

CONVENTIONAL LOAD SINGLE STOREY HOUSE					
S. No.	**Load type**	**Load of one appliance (W)**	**Hours**	**No's of Appliances**	**Total load of the building (Wh)**
1	Tube light	45	6	5	1350
2	Ceiling fans	80	8	5	3200
3	LED TV	70	1	1	70
4	Exhaust fans	45	2	1	90
5	LED lights	25	10	8	2000
6	Refrigerator	150	24	1	3600
7	Water Motor	1000	.5	1	500
		Total			**10710** **10.71kWh**

Let's analyze "Table 2 Load Calculation - Conventional Load - Single Storey House" in the context. Table 1 provides a useful estimate of the conventional electrical load for a single-story house. A conventional single-story house's computed daily energy consumption is 10.71 kWh, based on the projected power ratings and usage hours of various household appliances. However, the energy meter measures energy consumption at 2.82 kWh, which is much lower. This mismatch occurs because the computation assumes that all appliances function for their entire projected hours, when actual usage varies throughout the day.

Table 3. Conventional load for double storey house.

CONVENTIONAL LOAD DOUBLE STOREY					
S. no.	**Load type**	**Load of one appliance (W)**	**Hours**	**No's of Appliances**	**Total load of the building (Wh)**
1	Tube light	45	8	9	3240
2	Ceiling fans	90	8	10	7200
3	LED TV	90	6	2	1080
4	Exhaust fans	45	2	2	180
5	LED lights	25	8	18	3600
6	Refrigerator	150	24	1	3600
7	Water Motor	1000	1	1	1000
		Total			**19900** **19.9kWh**

A conventional double-story house's daily energy consumption is calculated to be 19.9 kWh based on the expected power ratings and usage hours of various household appliances. However, the energy meter measures energy use at 11.34 kWh, which is much lower. This discrepancy occurs because the computation assumes that all appliances operate for the full predicted duration, whereas actual usage differs.

Table 4. Conventional load for triple storey house.

CONVENTIONAL LOAD TRIPLE STOREY					
	Load type	**Load of one appliance (W)**	**Hours**	**No's of Appliances**	**Total load of the building (Wh)**
1	Tube light	46	8	18	6624
2	Ceiling fans	88	5	16	7040
3	LED TV	70	8	5	2800
4	Exhaust fans	55	2	3	330
5	Ceiling light	60	10	24	14400
7	Refrigerator	180	24	3	12960
8	Water Motor	1000	1.5	2	3000
		Total			**47154** **47.15kWh**

The calculated daily energy consumption of a conventional triple-storey house is 47.15 kWh, based on the estimated power ratings and usage hours of various household appliances. However, the measured energy consumption from the energy meter shows 19.64 kWh, which is significantly lower. In conclusion, comparison of estimated and measured energy consumption for single, double, and triple-story dwellings reveals the disparity between theoretical estimates and actual usage. While calculations imply that all appliances run continuously, actual consumption is much lower due to occasional appliance operation, user behaviour, and energy-saving efforts. The energy meter gives real-time information on actual usage patterns, highlighting the significance of data-driven monitoring for accurate energy management. These findings emphasize the need of efficient energy planning and IoT-based smart monitoring systems for optimizing electricity consumption and reducing waste.

Discussion

The results presented in this article provide valuable insights into energy consumption patterns in Pakistan, which highlight the potential for IoT-based smart energy management systems to address the region's energy challenges. The analysis of household energy consumption revealed a variable relationship between house size and energy usage. While larger houses generally consume more energy, there were significant variations within the dataset. This suggests that factors beyond house size, such as occupancy levels, appliance types, and usage habits, play a crucial role in determining energy consumption [14, 15, 24]. The load calculations for single, double, and triple-story houses showed a surprising consistency in total load, despite the increasing size of the dwellings. This unexpected trend raises questions about the accuracy of the data or potential variations in appliance usage patterns across different house types [16, 22, 23].

The flow diagram outlining the IoT-based energy monitoring system demonstrates the potential for real-time data acquisition, processing, and transmission. The system's ability to send data to a cloud platform such as Google Sheets enables remote monitoring and analysis, which can be particularly valuable in areas with limited accessibility [17, 22]. The implementation of IoT-based smart energy management systems offers numerous benefits. Real-time monitoring and analysis of energy consumption data enable better management of the electricity grid, particularly during peak demand periods. By understanding energy usage patterns, residents can be encouraged to adopt energy-saving practices and invest in energy-efficient appliances [18, 19]. Additionally, these systems help balance the load on the grid by optimizing appliance usage and promoting energy conservation during peak hours. As a result, optimizing energy consumption can lead to a significant reduction in electricity bills for residents [20].The study acknowledges certain limitations in the data, including potential inconsistencies and the need for further validation.

Future Recommendations

Future research should prioritize enhancing the accuracy and consistency of energy consumption data through improved measurement techniques and validation processes. Additionally, incorporating contextual information such as occupancy levels, appliance types, and usage habits can provide a more comprehensive understanding of energy consumption patterns [21, 25]. Another crucial area of focus is evaluating the scalability of the IoT-based system for a larger population and exploring its integration with existing energy infrastructure. Lastly, a detailed cost-benefit analysis is essential to evaluate economic viability.

Conclusion

This study highlights the transformative potential of IoT-powered solutions for optimizing energy usage, improving grid dependability, and promoting sustainability in residential settings. The large difference between calculated and measured energy use in single, double, and triple-story structures highlights the necessity of real-time monitoring to capture actual usage patterns, allowing for more accurate energy planning and waste reduction. The suggested Smart Energy Monitoring System provides predictive analytics, significant cost savings, improved load balancing, and safe data management. While constraints such as data discrepancies and scalability issues persist, the findings lay a solid platform for future improvements, facilitating broader adoption wider implementation in smart grid frameworks and contributing to a more efficient and sustainable energy economy.

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