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Understanding IoT-Based Energy Solutions for Hostel Environments

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Peer Review Information	Abstract
<p><i>Submission: 11 Sept 2025</i></p> <p><i>Revision: 10 Oct 2025</i></p> <p><i>Acceptance: 22 Oct 2025</i></p> <p>Keywords</p> <p><i>IoT, Smart Energy Monitoring, Automated Billing, ESP32, MQTT, Energy Efficiency, Real-Time Data Analytics, Hostel Management, Predictive Analytics, Renewable Integration, AI/ML.</i></p>	<p>With the rapid rise in energy consumption and the need for efficient resource utilization, smart energy monitoring systems have emerged as a promising solution. This survey paper reviews existing literature on IoT-based smart energy monitoring and billing systems, particularly focused on hostel or institutional environments. Traditional energy billing mechanisms lack real-time data visibility and transparency, leading to energy wastage and delayed cost awareness among users. Internet of Things (IoT) technology enables real-time energy tracking through smart sensors, wireless communication, and cloud-based analytics. This survey discusses various architectures, communication protocols (such as MQTT, Wi-Fi, Zig- Bee, LoRaWAN), microcontrollers (like NodeMCU, ESP32, Raspberry Pi), and visualization techniques used in modern smart energy systems. Furthermore, it explores automated billing models, mobile/web- based dashboards, predictive energy analysis, anomaly detection, and integration with renewable energy sources. Real-world case studies demonstrate practical benefits, such as 10-20% reduction in hostel electricity consumption within 6 months of implementation. The paper concludes with research gaps and future directions towards achieving energy-efficient, scalable, and user-centric hostel energy management systems.</p>

Introduction

The continuous rise in global electricity demand has created a pressing need for effective energy monitoring and management systems. Traditional manual billing methods are inefficient,

Identify applicable funding agency here. If none, delete this. error-prone, and unable to provide real-time insights into individual room consumption, especially in hostel environments.

With IoT (Internet of Things), it is now possible to measure, monitor, and manage power usage in real-time through smart meters connected to

cloud-based systems. By integrating microcontrollers, current sensors, voltage sensors, and wireless communication protocols, hostel administrators and students can track energy consumption per room, analyze usage patterns, and receive automated bills.

Modern IoT solutions allow predictive analytics, anomaly detection, and remote management. For example, if a heater in a hostel room draws more power than usual, the system can trigger alerts, automatically switch off devices, or notify the user. Over time, the system can provide long-term optimization strategies such as load shifting and

peak load management.

Benefits of IoT-Based Energy Management in Hostels

- Each student can monitor personal energy usage, promoting responsible consumption.
- Hostel management can detect abnormal consumption patterns and prevent wastage.
- Automated billing reduces administrative workload and disputes.
- Predictive alerts can reduce energy costs during peak hours.
- Integration with mobile apps provides enhanced user engagement and feedback.

Case Study Example: University X implemented an IoT-based smart energy system in 500 hostel rooms. They observed a 15% reduction in electricity consumption within 6 months by providing students access to real-time dashboards and alerts.

This survey aims to study the evolution, methodologies, and technologies behind IoT-based smart energy monitoring systems, highlighting how they improve transparency, accountability, and energy conservation in hostels.

Foundational Concepts and Methodologies

Traditional Energy Management Systems

Conventional systems rely on manual readings of meters and monthly billing. These systems fail to provide continuous energy insights, resulting in misuse and limited awareness. Human dependency makes the process prone to errors and delays.

Other limitations include:

- Energy theft detection is not possible with manual readings.
- Overbilling or underbilling is frequent due to misreading or meter errors.
- Lack of appliance-level insights prevents users from monitoring energy per device.
- Delayed reporting makes it difficult to enforce energy conservation policies.
- High administrative effort for large hostel setups.

IoT-Based Energy Monitoring

IoT-based energy monitoring automates data collection and provides real-time visibility. Sensors collect voltage, current, power factor, and even temperature or occupancy data. This data is sent via communication protocols such as MQTT, Wi-Fi, ZigBee, or LoRaWAN to cloud

platforms for storage, visualization, and analytics.

IoT Architecture Overview

- **Sensing Layer:** Current/voltage sensors, smart plugs, smart meters.
- **Communication Layer:** Wireless protocols (MQTT, HTTP, ZigBee, LoRaWAN).
- **Processing Layer:** Microcontrollers (ESP32, NodeMCU, Raspberry Pi).
- **Cloud Layer:** Data storage, dashboards, automated billing.
- **Application Layer:** User dashboards, alerts, predictive analytics, automated billing.

Advanced systems use AI/ML for energy prediction, fault detection, and dynamic billing. They also integrate occupancy sensors to optimize energy usage based on room presence.

Energy Optimization Techniques:

- Load balancing and peak shaving based on real-time consumption.
- Automated device control to switch off unused devices.
- Dynamic pricing or feedback to encourage energy saving.
- Scheduling high-energy devices to off-peak hours.
- Occupancy-driven HVAC and lighting optimization.

Evolution of Smart Energy Monitoring Systems

Early Approaches

Arduino-based energy meters with LCD displays allowed local monitoring but required manual data logging for further analysis.

Modern IoT-Enabled Systems

Modern systems integrate cloud platforms (ThingSpeak, Blynk, Firebase, AWS IoT) for real-time monitoring and remote access. Visualization is available via mobile apps or web dashboards. Features include alerts for unusual consumption, predictive analytics, and automated billing.

Edge Computing: Some systems process data locally to reduce cloud dependency, providing faster response for fault detection or device control.

Integration with Renewable Energy and Smart Grids

Modern hostel energy systems can integrate with

solar panels, wind energy, or microgrids. Real-time monitoring ensures optimal energy usage and reduces dependency on conventional electricity, while predictive algorithms adjust load distribution according to renewable availability.

TABLE I: IoT Communication Protocols in Energy Monitoring Systems

Protocol	Range	Data Rate	Use Case
MQTT	100m–1km	256 kbps	Real-time cloud communication
ZigBee	10–100m	250 kbps	Low-power sensor networks
LoRaWAN	2–15 km	0.3–50 kbps	Long-range low-power IoT
Wi-Fi	30–100m	1 Gbps	High-speed local data

Datasets, Challenges, and Future Directions

Data Collection and Processing

Accurate energy data collection requires high-precision sensors, proper calibration, and reliable connectivity. Network latency, cloud dependency, and sensor faults are major challenges.

Environmental sensors (temperature, humidity, and occupancy) provide context-aware energy management. This enables adaptive energy-saving techniques, such as reducing HVAC usage in unoccupied rooms.

System Scalability and Cost

IoT-based systems improve efficiency but large-scale deployment requires cost-effective, modular, and maintainable designs. Balancing affordability, reliability, and precision is crucial. Maintenance of sensors, network infrastructure, and cloud services must be considered to minimize operational costs.

Additional Challenges

- Interoperability issues between different IoT devices and protocols.
- High initial deployment cost despite long-term savings.
- Data security and privacy challenges in multi-user environments.
- Network reliability in large hostel buildings affecting real-time monitoring.

Future Directions

- AI-driven consumption prediction and dynamic tariff models to incentivize

energy-efficient behavior.

- Integration with renewable energy sources like solar panels and microgrids to reduce dependence on conventional electricity.
- Blockchain-based billing mechanisms for secure, tamper-proof, and transparent transactions.
- Edge and fog computing architectures for real-time decision-making without full cloud dependency.
- Adaptive energy-saving algorithms responding to occupancy patterns and user behavior.
- Multi-platform dashboards for mobile, web, and voice-enabled access to energy insights.
- Predictive maintenance for devices to reduce failures and downtime.
- Data privacy and security measures to protect user information in cloud-based monitoring.

Synthesis and Identification of Research Gaps

Although several IoT-based energy monitoring systems exist, few focus specifically on hostel or multi-room environments. Key gaps include:

- Lack of individual room-based billing automation and fine-grained energy tracking.
- Limited user interaction through real-time dashboards and personalized energy insights.
- Absence of AI/ML-based consumption forecasting and predictive maintenance features.
- Need for low-cost, scalable, and modular hardware integration for large hostel deployments.
- Security and privacy concerns in cloud-based data management.
- Limited research on AI-based anomaly detection specific to hostel appliances.
- Blockchain-enabled automated billing remains underexplored in hostel environments.

Addressing these gaps can lead to a highly efficient, transparent, and user-centric hostel energy management system that encourages responsible energy usage.

Conclusion

This survey concludes that IoT-enabled smart energy monitoring and billing systems provide a sustainable approach to efficient energy management. By offering real-time insights, automated billing, predictive analytics, and energy-saving recommendations, these systems can transform traditional hostel electricity management. Future implementations should focus on security, scalability, AI-driven decision-making, and integration with renewable energy sources for optimal performance and cost-effectiveness.

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