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Development of IoT-Based Monitoring Systems for Electrical Energy Management

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Abstract

The growing demand for electricity has increased the need for effective monitoring and management of electrical energy in residential, commercial, and industrial environments. Conventional electricity meters typically provide cumulative consumption information but may offer limited detail about when and where electricity is used. Internet of Things (IoT) technologies can address this limitation by connecting electrical sensors, communication devices, data platforms, and user interfaces to support timely monitoring and informed decision-making. This article presents a review-based framework for developing an IoT-based electrical energy monitoring system. The proposed framework integrates voltage and current measurement, embedded processing, wireless communication, cloud or local data storage, visualization, and optional load control. It also discusses data analysis techniques for identifying unusual consumption, evaluating demand patterns, and supporting energy-saving strategies. Key development considerations include measurement accuracy, network reliability, cybersecurity, user privacy, and electrical safety. A hypothetical demand profile illustrates how monitoring information could guide load management; it does not represent experimental results. The article concludes that IoT-based monitoring can support electrical energy management when reliable measurements are combined with suitable operational decisions and evaluated using an appropriate baseline.

Keywords

Internet of Things, electrical energy management, smart monitoring, energy efficiency, smart meters

INTRODUCTION

Electrical energy is essential for homes, businesses, educational institutions, and industrial facilities. As the number of electrical appliances and connected devices increases, understanding consumption patterns becomes increasingly important. Energy managers need information about

not only the total amount of electricity consumed but also when consumption occurs, which circuits use the most energy, and whether equipment is operating efficiently. Traditional electricity bills usually report total consumption over a billing period. Although this information is useful for calculating costs, it does not necessarily identify the causes of peak demand or reveal appliances operating unnecessarily. An IoT-based monitoring system can provide more detailed information by measuring electrical parameters at regular intervals and making the data available through a local dashboard, website, or mobile application. IoT systems generally consist of connected physical devices that collect and exchange data. In energy applications, these devices may include smart meters, current sensors, voltage sensors, microcontrollers, communication modules, and remotely controlled switches. The resulting information can help users identify consumption patterns, investigate unexpected changes, and plan interventions. Existing research has explored IoT-based monitoring and control in homes and buildings, as well as the integration of monitoring with wider energy-management practices [1–3]. mdpi.com This article presents a conceptual framework for developing such a system. It discusses the main components, communication methods, data analysis, management strategies, security considerations, and evaluation requirements. No original experiment is claimed.

IoT-Based Electrical Energy Monitoring

IoT-based electrical energy monitoring involves the continuous or periodic collection of electricity-related measurements from connected devices. Depending on the design, a system can monitor a whole building, individual distribution circuits, or selected appliances. These measurements can be displayed to users and stored for later analysis. Common measurements include voltage, current, active power, energy consumption, and power factor. More advanced devices may also measure reactive power, frequency, and power-quality indicators. The choice of measurement depends on the system's purpose. For example, a household may require appliance-level consumption information, whereas a factory may also need to monitor three-phase loads and operating schedules. A useful distinction exists between monitoring and management. Monitoring provides information about electricity use. Management uses that information to make decisions, such as changing an operating schedule, maintaining equipment, or adjusting a controllable load. A monitoring system alone does not guarantee energy savings; its value depends on the actions taken in response to the data [1].

Proposed System Architecture

The proposed system consists of four connected layers: sensing, communication, data processing, and application. The sensing layer includes electrical meters or sensors installed at relevant measurement points. A microcontroller or gateway collects readings and attaches a device identifier and timestamp. Depending on the application, the system may also collect contextual data such as room temperature, occupancy, or equipment operating status. The communication layer transfers measurements to a local server or cloud platform. The data-processing layer stores and analyzes the incoming readings, while the application layer presents results through dashboards, reports, and alerts. An optional control component can send approved commands to compatible equipment.

This layered design allows a system to begin with a small number of monitored circuits and expand as needed. Similar building-monitoring architectures combine sensing, networking, data platforms, and user interfaces to support remote visibility of building operations [4, 5]. mdpi.com

Electrical Sensors and Measurement

The quality of an energy-management system depends on the quality of its measurements. Current transformers, Hall-effect sensors, and dedicated metering modules are among the technologies that can be used to measure electrical current. Voltage measurement requires a suitably rated and isolated sensing arrangement. For practical deployment, a certified energy

meter with a communication interface may be preferable to building a measurement circuit from individual components. For a single-phase alternating-current load under sinusoidal conditions, active power can be expressed as:

$$ P = V_{\mathrm{RMS}} \times I_{\mathrm{RMS}} \times \mathrm{PF} $$

where P is active power in watts, V_{RMS} is root-mean-square voltage, I_{RMS} is root-mean-square current, and PF is power factor. For distorted waveforms or complex three-phase systems, suitable metering devices must calculate power using appropriate waveform measurements. Electrical energy is obtained by accumulating active power over time. For example, a device using 1 kilowatt continuously for 2 hours consumes 2 kilowatt-hours. Measurement accuracy should be checked across relevant load levels by comparing the system with a calibrated reference meter. Electrical equipment must be installed by qualified personnel using suitable protective devices and isolation. Monitoring prototypes should not be connected directly to mains electricity without an appropriate safety design.

Communication Technologies and Data Transmission

Communication technology determines how reliably readings reach the monitoring platform. Wi-Fi is convenient where network coverage and electrical power are available. Ethernet offers a wired alternative for locations where a stable connection is desirable. Other options, including cellular networks and low-power wide-area networks, may be appropriate when devices are distributed across larger areas. The communication choice depends on factors such as transmission distance, power consumption, operating costs, data frequency, and building construction. Electrical installations in basements, metal enclosures, or large industrial sites may experience wireless interference or weak signal coverage. Protocols such as MQTT can support lightweight data exchange between devices and a server. A typical message may contain a device identifier, timestamp, voltage, current, power, and cumulative energy. To improve reliability, an edge gateway can temporarily store readings during a network interruption and transmit them after connectivity returns. The system should also record communication failures and missing measurements. These gaps matter because incomplete data may produce misleading consumption reports or inaccurate estimates of energy savings.

Data Storage, Visualization, and Alerts

A monitoring platform should organize readings so that users can examine electricity use over different periods. Time-series storage can support detailed records, while daily and monthly summaries make longer-term trends easier to interpret. A practical dashboard may show current demand, energy consumption by circuit, historical trends, and periods of unusually high usage.

Visual presentation should reflect user needs. A household user may prefer a simple display of daily consumption and estimated cost. A facility manager may need circuit-level comparisons, demand peaks, equipment schedules, and exportable data. Cost estimates should clearly state the tariff assumptions used because actual bills may include several charges and tariff conditions.

Alerts can be configured for events such as unexpectedly high demand, loss of sensor communication, or equipment operating outside scheduled hours. However, alerts should be carefully designed to avoid excessive notifications. A useful alert should identify the affected device, the time of the event, and the reason it needs attention.

Energy Management and Load Control

Monitoring data can support several forms of energy management. Users may identify equipment left running after working hours, compare consumption across similar rooms, or investigate an increase in electricity use after a change in operating conditions. The appropriate response depends on the cause: switching off an unused device, adjusting a schedule, or inspecting faulty equipment may each address different problems. Where suitable equipment and safeguards are available, the system can support automatic control. For example, a nonessential load could be

scheduled outside a high-demand period, or lighting could be controlled according to occupancy. Smart home energy-management research has also considered coordinating appliances with energy costs and operational constraints [6–8]. mdpi.com Automatic control should preserve essential services and allow authorized users to override or disable it. The system must not interrupt safety-critical equipment or exceed manufacturer operating limits. Control decisions should be logged so that facility staff can understand what happened and restore normal operation if necessary.

Cybersecurity, Privacy, and Reliability

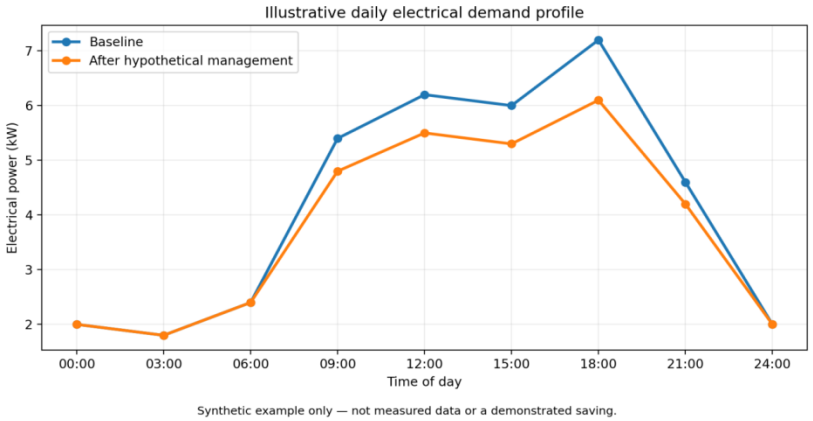
Connecting meters and control devices to a network introduces cybersecurity and privacy concerns. Detailed electricity data can reveal patterns of building occupancy or equipment activity. Unauthorized access to a control system could also disrupt equipment operation. A practical security strategy includes unique device credentials, encrypted communications, access controls, software updates, and separation of the monitoring network from other sensitive systems. Users should receive only the permissions necessary for their responsibilities. Default passwords should be changed, and equipment should be maintained throughout its operating life.

Reliability is equally important. A system should define how it behaves when a sensor fails, a server becomes unavailable, or the network disconnects. Where control is implemented, safe local operation should remain possible during a communication failure. Researchers have identified security and privacy as significant considerations in connected smart-building systems [4, 10]. mdpi.com

Evaluation, Limitations, and Future Development

A proposed monitoring system should be evaluated before its results are used to support operational decisions. Measurement performance can be assessed by comparing voltage, current, power, and energy readings with those from a calibrated reference instrument. Network performance can be examined through data loss, availability, and recovery after disconnection.

Energy-management outcomes require a baseline and a clear evaluation period. Researchers should document the building or equipment monitored, the intervention, the measurement interval, and any relevant changes in weather, occupancy, or operating schedules. Results should distinguish reductions in total energy consumption from reductions in peak demand: these are related but different outcomes. Future development may include more effective anomaly detection, integration with rooftop solar generation and battery storage, and forecasting of electricity demand. Machine-learning techniques may help detect unusual patterns, but they require suitable data and validation under real operating conditions. Further research is also needed on interoperability, long-term maintenance, cybersecurity, and the cost-effectiveness of deployment across different types of buildings [1, 9, 12].



Summary

IoT-based monitoring systems can provide detailed information about electrical energy use by combining sensors, communication technologies, data storage, and user interfaces. The proposed framework supports visibility of consumption patterns and can help users identify opportunities for operational improvement. Effective development requires accurate measurement, dependable communication, electrical safety, cybersecurity, and clear presentation of information. Monitoring can support decisions about scheduling and load control, but actual savings must be established through measured data and an appropriate baseline. The graph in this article is an illustrative example and should not be presented as experimental evidence.

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