



Design and Implementation of an IoT-Based Smart Energy Management System

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Abstract

This methodology paper presents a practical framework for the design and implementation of an Internet of Things (IoT)-based Smart Energy Management System (SEMS) for residential environments. The proposed system combines appliance-level sensing, wireless connectivity, edge control, cloud-based data logging, remote visualization, and demand-response-oriented scheduling. A NodeMCU/ESP8266-class controller is used as the local gateway, while smart energy sensors and relay modules provide real-time measurement and controllable switching of household loads. The system applies a rule-based scheduling strategy that separates critical, flexible, and thermostatically controlled appliances and shifts discretionary loads away from expensive peak periods without unnecessarily compromising user comfort. A representative 24-hour evaluation scenario is included to demonstrate how the methodology can be tested when a full field trial is not yet available. In that scenario, the managed profile reduces daily energy use from 20.45 kWh to 18.36 kWh, lowers the illustrative daily electricity cost from INR 143.82 to INR 124.13, and decreases peak demand from 2.35 kW to 1.68 kW. These results are presented as reproducible methodology-validation outputs rather than claims from a completed household deployment. The architecture and evaluation procedure are informed exclusively by literature published up to 2019.

Introduction

Residential electricity consumption has become increasingly dynamic because homes now contain a large number of electronic, heating, cooling, and motor-driven appliances. Conventional energy meters provide aggregate billing information but offer limited support for appliance-level visibility, automated control, or immediate feedback. Home energy management systems address this gap by coordinating monitoring, scheduling, and control so that users can reduce energy waste and respond to electricity-price or demand signals. Early demand-response research established that

changing the timing of electricity use can benefit both consumers and electricity systems, particularly during high-demand periods (Albadi & El-Saadany, 2008).

The IoT paradigm provides a technical foundation for implementing such systems because sensors, embedded controllers, communication networks, cloud services, and user interfaces can be integrated into a common sensing-and-actuation environment. Gubbi et al. (2013) described IoT as a convergence of sensing, Internet connectivity, and distributed computing, while Zanella et al. (2014) emphasized interoperable architectures for connecting

heterogeneous devices and services. These principles are directly applicable to residential energy management, where appliance data must move reliably from measurement nodes to control logic and then to a user-facing dashboard. For smart homes, a successful SEMS must do more than record electricity use. It should support real-time feedback, reliable switching, load categorization, user priorities, energy-cost awareness, and the ability to shift flexible loads. Reviews by Beaudin and Zareipour (2015) and Zhou et al. (2016) show that HEMS performance depends strongly on device modelling, scheduling strategies, timing constraints, uncertainty, and consumer comfort. Therefore, this paper focuses on a methodology that can be implemented with low-cost IoT hardware while retaining a structured approach to scheduling and evaluation.

Literature Review

The literature up to 2019 shows a clear transition from conceptual home energy management toward networked, intelligent, and user-configurable systems. Beaudin and Zareipour (2015) reviewed modelling complexity in HEMS and showed that appliance diversity, uncertainty, multiple objectives, and computational limits must be considered when defining a scheduling strategy. Zhou et al. (2016) extended this perspective by reviewing smart-home configurations, advanced metering, home area networks, renewable resources, storage, and appliance scheduling. Together, these studies support the need for a modular architecture in which sensing, communication, optimization, and control can be improved independently.

IoT-specific implementations strengthened the connection between energy monitoring and remote control. Al-Ali et al. (2017) proposed a smart-home energy management architecture in which IoT-enabled acquisition modules transmit appliance data to centralized analytics. Their work demonstrated the value of device-level data and remote control for large-scale energy management. Shareef et al. (2018) reviewed demand-response programs, smart technologies, and intelligent scheduling controllers and emphasized that HEMS can combine smart meters, wireless communication, appliance control, and optimization techniques. These studies motivate the use of low-cost sensing nodes and a central decision layer in the present methodology.

By 2019, several studies were demonstrating practical IoT-based smart energy management. Taştan (2019) designed a NodeMCU- and Android-based smart energy management system capable of real-time monitoring, data recording, remote control, and scheduling. Pawar and Vittal (2019) developed an advanced smart energy management system integrated with an IoT framework and demonstrated demand-response-oriented appliance prioritization and time-of-use cost optimization. Shah et al. (2019) reviewed energy-optimization techniques in IoT-based smart buildings and highlighted the importance of automation, sensing, and intelligent decision-making. Marikyan et al. (2019) additionally stressed that smart-home design must remain user-centered, because adoption depends on perceived usefulness, convenience, reliability, and control.

Table 1. Literature foundations for the proposed methodology

Study	Year	Main contribution	Methodological implication
Beaudin & Zareipour	2015	HEMS modelling and complexity review	Use explicit appliance classes, objectives, and constraints.
Zhou et al.	2016	HEMS configurations and scheduling strategies	Adopt modular sensing, networking, scheduling, and control.
Al-Ali et al.	2017	IoT and analytics for smart-home EMS	Collect device-level data and enable remote monitoring/control.
Shareef et al.	2018	DR, smart technologies, intelligent controllers	Include demand-response signals and user comfort constraints.
Taştan	2019	NodeMCU/Android IoT energy management	Use low-cost Wi-Fi controller and mobile/web dashboard.
Pawar & Vittal	2019	IoT-integrated SEMS with appliance priority	Implement priority-based shedding/scheduling and ToU logic.

The research gap addressed by this methodology is not the existence of energy monitoring itself, but the integration of low-cost IoT monitoring

with controllable smart sockets, user-configurable priorities, tariff-aware scheduling, local fail-safe logic, and a transparent evaluation

procedure. The proposed system therefore combines ideas that were separately emphasized in earlier research and organizes them into an implementation sequence suitable for a small residential prototype.

Methodology

1. Research Design and System Objective

The study follows a design-science and prototype-evaluation methodology. The principal objective is to design an IoT-enabled system that measures appliance-level power use, communicates measurements to a central controller, stores and visualizes the data, and automatically manages selected loads according to energy demand, tariff period, and user priority.

The design is intentionally modular so that sensors, communication protocols, dashboards, and scheduling algorithms can be replaced without changing the complete system.

The proposed architecture has six functional layers: (1) electrical loads, (2) sensing and actuation, (3) an edge controller, (4) an IoT/cloud layer, (5) a user interface, and (6) external tariff or demand-response input. This organization is consistent with IoT architectures that separate physical sensing from communication and service layers (Gubbi et al., 2013; Zanella et al., 2014), while the appliance-scheduling component follows HEMS principles summarized by Zhou et al. (2016) and Shareef et al. (2018).

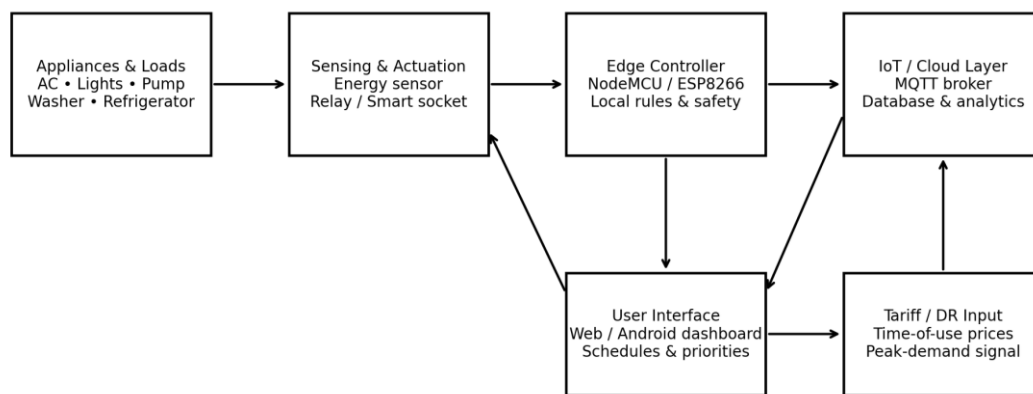


Figure 1. Proposed architecture of the IoT-based Smart Energy Management System.

2. Step-by-Step Design Procedure

Step 1 - Load identification and classification. Household appliances are first inventoried and grouped into critical loads (refrigerator, router, essential lighting), flexible loads (washing machine, water pump, water heater), and controllable comfort loads (air conditioner or space heating). For each appliance, rated power, expected operating duration, allowed operating window, and user priority are recorded. This classification reduces the complexity of the control problem and prevents indiscriminate switching of important devices.

Step 2 - Energy sensing and smart-socket interface. Each controllable branch uses an energy-measurement module capable of reporting voltage, current, active power, and cumulative energy. A relay or contactor is selected with a rating above the appliance current and is electrically isolated from the microcontroller. The sensing node periodically samples energy variables and passes them to the edge controller. Electrical protection, enclosure, fuse selection, and isolation are treated as mandatory implementation requirements rather than optional features.

Step 3 - Edge communication. A NodeMCU/ESP8266-class Wi-Fi controller is configured to publish measurements and receive control commands. MQTT is used as the lightweight messaging layer because it supports publish/subscribe communication and makes it easy to separate sensor nodes from dashboards and databases. Local logic is retained so that basic safety and priority rules continue to operate if cloud connectivity is unavailable.

IoT Platform, Control Logic, and Implementation Step 4 - IoT data layer and dashboard. The gateway publishes timestamped appliance data to an MQTT broker. A server or cloud service subscribes to the topics, stores readings in a time-series database, and exposes current power, daily energy, estimated cost, and device state through a web or Android dashboard. This approach reflects the real-time monitoring and mobile interaction demonstrated by Taştan (2019) and the data-management role described by Al-Ali et al. (2017). User inputs include appliance priority, permitted start/end times, maximum demand threshold, and optional manual override.

Step 5 - Tariff-aware scheduling. The scheduler receives the current household demand $P(t)$, a maximum demand limit P_{max} , the tariff $C(t)$, and

the state of each load. If $P(t)$ exceeds P_{max} or the system enters a high-cost period, controllable loads are ranked by priority and flexibility. The controller first postpones flexible loads whose allowed time window remains feasible. If additional reduction is required, thermostatic loads are duty-cycled within a bounded comfort range. Critical loads are not disconnected by the scheduling rule. The objective is to minimize the weighted sum of energy cost, peak-demand penalty, and user-discomfort penalty.

$$\text{Minimize } J = \sum_t [C(t) \cdot P(t) \cdot \Delta t + \lambda_1 \cdot \text{PeakPenalty}(t) + \lambda_2 \cdot \text{Discomfort}(t)]$$

Step 6 - Command execution and acknowledgement. After the scheduler selects an action, the command is published to the relevant

smart socket. The local node verifies the command, changes relay state, and publishes an acknowledgement. A timeout mechanism flags communication failures. Manual override is given higher priority than normal scheduling except where an electrical safety condition is detected.

Step 7 - Data logging and evaluation. All measurements and state changes are timestamped. The performance metrics are daily energy consumption, electricity cost under the selected tariff, maximum demand, peak-to-average ratio (PAR), command success rate, measurement error, and response latency. The before/after comparison uses an identical 24-hour demand scenario so that scheduling effects can be isolated.

Table 2. Suggested prototype components and functions

Component	Example selection	Function
Edge controller	NodeMCU ESP8266	Wi-Fi connection, local rules, MQTT client
Energy sensor	PZEM-004T or equivalent	Voltage, current, power, energy measurement
Actuator	Opto-isolated relay/contactors	Safe load switching under controller command
Messaging	MQTT broker	Telemetry publication and control topics
Data storage	Time-series/cloud database	Historical energy and event logging
User interface	Web or Android dashboard	Visualization, scheduling, manual override

3. Verification and Test Protocol

The prototype should be verified in three stages. First, sensor readings are compared with a trusted reference meter over several appliance types and power levels. Second, switching reliability and communication latency are tested using repeated ON/OFF commands and network interruptions. Third, the complete SEMS is evaluated using baseline and managed load profiles. The methodology requires the same tariff definition and appliance operating requirements in both cases. Because the present paper is a methodology study rather than a report from an already completed residential installation, the results below are generated from a documented, reproducible 24-hour test scenario. They illustrate how the proposed evaluation should be reported and should not be

interpreted as field measurements from an occupied home.

Results

A representative 24-hour profile was constructed to evaluate the control logic. The baseline profile contains low overnight demand, morning activity, a moderate daytime load, and a strong evening peak. The managed case applies three actions: reduction of unnecessary standby consumption during the lowest-demand hours, shifting of flexible appliance operation away from the evening peak, and bounded duty-cycle control of a high-power comfort load between 18:00 and 22:00. The illustrative time-of-use tariff is INR 4/kWh during 00:00-05:59, INR 6/kWh during shoulder periods, and INR 9/kWh during the evening peak. These tariff values are used only to demonstrate the evaluation method.

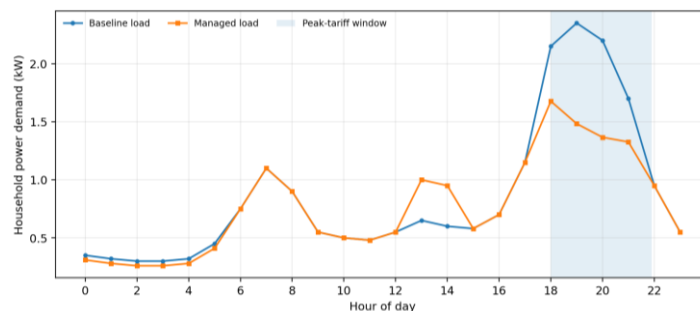


Figure 2. Representative baseline and managed household load profiles used for methodology validation.

Table 3. Representative performance of the proposed scheduling methodology

Metric	Baseline	Managed	Change
Daily energy consumption	20.45 kWh	18.36 kWh	-10.2%
Illustrative daily cost	INR 143.82	INR 124.13	-13.7%
Maximum demand	2.35 kW	1.68 kW	-28.6%
Peak-to-average ratio	2.76	2.19	-20.5%

The representative results show that the methodology reduces both the magnitude and concentration of evening demand. Daily energy decreases by 10.2% because standby reduction and bounded comfort-load control remove a portion of avoidable consumption. The cost reduction of 13.7% is larger than the energy reduction because flexible demand is also transferred from the high-cost period to lower-cost periods. Maximum demand falls by 28.6%, while PAR improves from 2.76 to 2.19. This distinction is important: a SEMS should not be evaluated only by total kWh, because peak reduction and time-of-use cost can improve even when some energy is simply shifted rather than eliminated.

The observed behavior is consistent with the rationale in earlier HEMS research. Beaudin and Zareipour (2015) emphasized scheduling trade-offs and user constraints; Shareef et al. (2018) described demand-response-based control as a central HEMS function; Taştan (2019) demonstrated real-time monitoring and appliance scheduling with NodeMCU; and Pawar and Vittal (2019) showed that priority and time-of-use logic can be integrated into an IoT-enabled energy management framework. The present results therefore serve as a methodological demonstration of those design principles in a compact prototype architecture.

Conclusion and Discussion

This paper has presented a step-by-step methodology for designing and implementing an IoT-based Smart Energy Management System for residential use. The methodology begins with appliance classification and safe energy sensing, continues through Wi-Fi/MQTT communication and cloud data handling, and ends with tariff-aware, priority-based control and a transparent evaluation protocol. The main contribution is the integration of these functions into a practical architecture that can be prototyped using low-cost hardware without losing the core HEMS requirements identified in the literature up to 2019. The proposed approach has several strengths. First, device-level sensing provides more actionable information than an aggregate household meter. Second, the use of a publish/subscribe IoT architecture separates the physical devices from the dashboard and analytics layer, which improves scalability and

maintainability. Third, local fail-safe logic reduces dependence on continuous Internet access. Fourth, user-configurable priorities limit discomfort and avoid the common weakness of energy-management schemes that optimize cost without respecting household preferences. Finally, the evaluation metrics cover energy, cost, peak demand, and PAR, so performance is not reduced to a single indicator. The representative evaluation produced a 10.2% reduction in daily energy consumption, a 13.7% reduction in illustrative daily cost, and a 28.6% reduction in maximum demand. These values are not presented as measurements from a completed field installation; they are outputs from the reproducible profile described in the methodology. Their purpose is to demonstrate how a future prototype or field study can compare baseline and managed operation. A completed implementation should replace these representative values with measurements collected from calibrated sensors over multiple days and should report uncertainty, missing data, and user overrides. Several limitations and future improvements should be acknowledged. Low-cost energy sensors require calibration and may show larger errors at low power factors or rapidly changing loads. Wi-Fi-based nodes can experience packet loss or router dependence, so acknowledgement and local fallback rules are essential. Relay switching is suitable for some loads but not for all appliances, particularly equipment with compressors, high inrush current, or internal electronic controls. Cybersecurity is also critical because remote switching creates a control path into the household electrical system. Device authentication, encrypted communication, access control, strong credentials, and secure firmware-update procedures should therefore be included in a production deployment. Future work can extend the methodology in four directions. The first is integration of rooftop photovoltaic generation and battery storage so that the scheduler can optimize both consumption and local generation. The second is predictive control using short-term load, occupancy, weather, and tariff forecasts. The third is learning-based preference modelling that adapts schedules to actual user behavior instead of relying only on static priorities. The fourth is long-duration field validation across different households and

seasons. These extensions are consistent with the move toward increasingly intelligent and user-centered smart homes identified in 2019 literature (Marikyan et al., 2019; Shah et al., 2019). In conclusion, an effective IoT-based SEMS should be viewed as a cyber-physical control system rather than merely an online energy meter. Its value comes from the closed loop between measurement, communication, decision-making, user preference, and safe actuation. The methodology developed here provides a structured basis for building and evaluating that closed loop using technologies and research foundations available through 2019.

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