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Advancements in IoT-Based Smart Home Energy Management and Control

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Abstract: The increasing demand for energy efficiency and automation in modern house- holds has led to the evolution of Smart Home Internet of Things (IoT) systems for energy management and load control. These systems enable households to optimize energy usage through intelligent automation, real-time monitoring, and user-centric functionalities. This review highlights recent advancements in IoT- based smart home systems, focusing on key functionalities such as automatic power control, load balancing, user-defined device prioritization, timer scheduling, and energy consumption monitoring. The integration of big data analytics with IoT further enhances decision-making by providing actionable insights into energy consumption patterns. Additionally, this paper explores the compatibility of these systems with both smart and non-smart devices, their ability to issue alerts and notifications, and their user-friendly interfaces enabling remote control. This comprehensive analysis aims to guide future innovations and address challenges in developing sustainable and efficient energy management solutions for smart homes.
Keywords: Smart home, IoT, energy management, load control, automation, energy efficiency, big data analytics, smart devices, user-defined priorities, real-time monitoring.

I. INTRODUCTION

The increasing demand on energy efficiency and the growing interconnectivity of devices on household premises have triggered the rapid development of Smart Home systems. These systems rely on technologies associated with the Internet of Things (IoT) and track and control a considerable number of household functions especially concerning energy consumption. As a result, smart home systems include a large variety of installations such as lights, heating ventilation and air conditioning (HVAC) systems, domestic kitchen appliances, and security units, all within one central net- work. This connectivity enables them to work together intelligently by optimizing operations, enhancing convenience, reducing energy waste, and minimizing costs. The core goal is to create an efficient living environment that is user-centric and sustain- able. Real-time monitoring is at the heart of these smart systems, with sensors and connected devices continuously collecting data about energy usage. The data is then analyzed to identify patterns, predict energy demands, and provide actionable insights. Automation plays a crucial role in these systems; for example, by programming rou- tines or setting preferences, appliances can operate autonomously, turning off when not needed or adjusting their performance based on user behaviors. These features combine to optimize energy consumption and thus prevent waste of energy, reduce electricity bills, and support a living environment that is sustainable [1, 2]. On top of that, user control has been considered a unique hallmark for smart homes. Indeed, besides real-time monitoring enabled through IoT-based energy management systems, it allows users to use mobile applications or even voice assistants to control devices [3, 4]. Based on recent advancements in IoT-based energy management systems for smart homes, this review will emphasize functionalities, capabilities, and how big data analytics would fit. Big data plays a much significant role in smart home because it aggregates large datasets in different devices and sensors across the house, which is eventually analyzed to predict the type of energy usage and makes actual decisions in real-time by enhancing energy efficiency. Integrated with big data analytics, these systems become even more robust, as they enable users to monitor their energy consumption while initiating proactive actions to minimize losses and enhance efficiency. Besides, users may rank devices based on the energy they consume, schedule timing, and even get alerts of unusual energy consumption or failures [5–7]. At such convenience levels, users should be able to change appliance settings, like turning out lights when not in home and managing thermostat without physical presence at their premises. These systems will, of course, also consider load balancing: this should mean that the energy draw would be well distributed in any multiple devices used so circuits get overload and vital devices' requirements get met appropriately [8–10].

Advanced technologies such as IoT, predictive modeling, and data-driven approaches significantly changed the energy management scenario in a residential set- ting. The current research highlights an increased significance of occupant behavior, environmental factors, and energy consumption patterns in affecting energy usage [11]. Hybrid models and machine learning data-driven techniques emerge as frontier solu- tions for prediction and optimization of energy demand. These methods use real-time IoT-enabled sensor data to derive actionable insights that help with dynamic energy control and better resource utilization [12].

IoT technologies in smart homes not only allow for the real-time monitoring but also help in operational efficiency through the integration of various systems, such as HVAC, lighting, and security. For example, the frameworks, based on IoT-based technology such as RNN-based neural networks, predict energy usage accurately as related to the ambient temperature and occupancy pattern [13]. It further predicts that minimization of wasted energy helps in saving the extra energy with less cost in relation to the reduction in carbon emission through energy use with corresponding renewable generation.

Apart from these, energy-efficient algorithms and elastic management strategies are currently trendy for balancing loads in houses with renewable sources of energy [14]. Such types of approaches are designed to adjust automatically according to changing supplies of energy so that at all times, the production of energy matches its consumption. Communication protocols and semantic tagging in the IoT network make seamless interaction between smart devices, hence making a very responsive and interconnected ecosystem for energy management [15].

Nonetheless, there are several challenges including a relatively high installation cost, interoperability, and security issues that will continue to restrain its proliferation. With further research on these technologies, new emphasis will be placed on limiting them through innovative solutions so as to provide scalable, secure, and cost-effective energy management systems tailored to a range of residential needs [16]. In this regard, the scope of the approaches and technologies making the modern smart home energy system what it is today—to capability and then toward the limitations and towards the future directions—is reviewed.

Energy management technologies have exhibited a high potential for strong growth in the last few years and deep connections to convergence, Internet of Things, smart homes, and novel architectural frameworks [17]. This shift toward smart home environ- ments has spread energy sources within smart homes, which include systems powered by IoT in energy management. These have contributed to optimizing household energy consumption and integration of energy management into broader architectures for smart grids, thus ultimately providing decentralized energy generation with resource sharing [18]. For example, RINA is one of those promising advance network frame- works that ensures smart sensors with edge devices have reliable as well as efficient communication that leads toward scalable and reliable energy management in smart buildings [19]. Moreover, an innovative paradigm of integrating peer-to-peer energy sharing within the microgrid introduces IoT-based trust mechanisms for secure and efficient energy trade [20]. These systems stress the incorporation of digital trust management toward enhancing energy distribution networks mainly in resource-constrained domains. Sim- ilarly, elastic management strategies of energy have become prevalent to mitigate the intermittence of renewable energy sources and to ensure dynamic consumption behavior to balance the energy supply and demand.

These notwithstanding, interoperability, scalability, and user engagement remain huge challenges. Studies underscore the critical roles of occupant behavior and pre- dictive modeling in enhancing the accuracy of energy forecasts and the responsiveness of smart systems . Hybrid and AI-driven approaches, such as neural networks, fur- ther enhance the ability of these systems to align with fluctuating energy needs. This evolving ecosystem necessitates the strength of frameworks and innovative method- ologies to overcome the complexity inherent in modern energy management systems. The following sections unfold the approaches, challenges, and future directions that are framing this field.

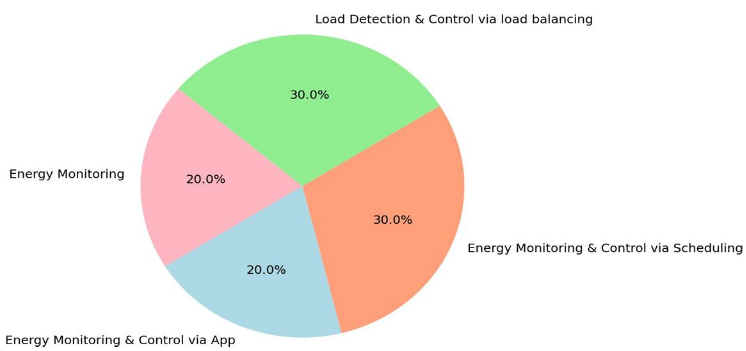

Fig. 1: Key functionalities reviewed in this paper

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Figure 1, Depicts a thorough overview of the key functions explored in the reviewed literatures of smart home energy management systems. It gives the realization that energy monitoring with mobile applications for monitoring and control presents two vital focal points in the study body. These are basic elements in following up and determining energy use in smart houses. Energy management by scheduling, which is the optimization of energy usage based on time or user preferences, also appears prominently, reflecting the growing interest in predictive and automated energy control strategies. Another crucial functionality highlighted is the implementation of load detection and balancing techniques, underlining the importance of managing peak energy demand and ensuring efficient distribution. Overall, this diagram stresses the multi-intelligence approach being taken in the smart development of home systems through incorporation of real-time monitoring and control and predictive scheduling as a means of gaining an energy efficiency and cost effectiveness for the smart home.

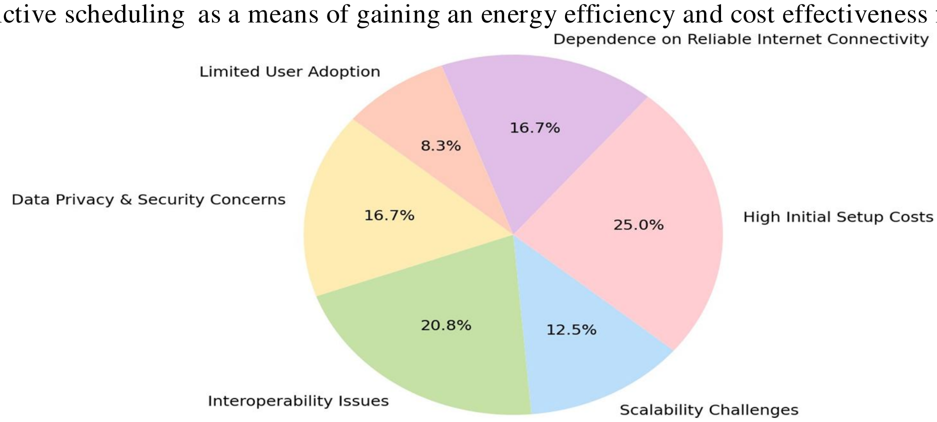

Fig. 2: Limitations in existing systems

Figure 2, shows the main limitations of smart home energy management systems, which point out the problems in their adoption and implementation. The chart indi- cates that interoperability issues and high initial setup costs are the most discussed limitations, which reflect the problem of integrating diverse devices and financial bar- riers to adopting smart home technologies. Another major concern is related to data privacy and security. Many studies have indicated the vulnerabilities of IoT systems collecting and transmitting sensitive data. The dependence on reliable internet con- nectivity further complicates the widespread adoption of these systems because a stable internet connection is required for the proper functioning of these systems. Another more prevalent problem is scalability. For example, the sheer expansion of smart devices puts considerable stress on network capacity and management systems. Finally, adoption is still limited. For most, adopting the new technology can be very intimidating, due either to its apparent complexity or general ignorance about such matters. The graph thus highlights the numerous problems to overcome in order to better optimize smart home energy management.

A. Problem Statement

The integration of smart home energy management systems, which utilize IoT tech- nologies, has the potential to revolutionize energy consumption patterns, enhance efficiency, and reduce costs. However, despite the promising benefits, the adoption and optimization of these systems face significant challenges. The main issue lies in the proper implementation, scalability, and adoption of these technologies due to con- straints like data privacy and security concerns, interoperability problems, high setup costs, and dependence on reliable internet connectivity. Another problem is the lack of standard solutions that can integrate a wide variety of devices and platforms to enable energy-efficient systems in homes. This review paper looks to analyze and synthesize the current state of research on smart home energy management systems, highlighting key functionalities, the challenges faced, and possible solutions to overcome these bar- riers, which would lead to a comprehensive understanding of the factors influencing the success of these systems.

B. Motivation

This motivation behind this review paper emanates from growing interest for renew- able energy solutions where smart home energy management systems, especially Internet of Things applications, seem to be a breakthrough tool that addresses such issues in residential buildings towards optimality and henceforth sustainability. With residential energy use increasing day-to-day, advanced technologies using Internet of Things application promises a bright potential future that would enhance a cut- throat competition in order to keep abreast with issues that characterize sustainability.

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Although smart home energy systems offer great potential, its adoption into mass usage is impeded by problems like the initial cost of setup, security concerns, issues with interoperability, and dependency on a good internet connection. These drawbacks limit the complete scale of deployment and integration of smart home technologies into residential buildings. Hence, the article intends to review the status of researches, discuss their key functionalities and limitations that exist with smart home energy systems, and determine possibilities for solutions to remove this barrier.

The goals that this paper will intend for are the following:

1) Analyzing the Key Barriers and Limitations Existing by the Integration and Adoption Process with Smart Home Energy Management.
2) Analyzing Effectiveness of Smart Home Technologies in Terms of Energy Monitor- ing, Control Optimization.
3) Explore the role of IoT technologies in enhancing energy efficiency in residential environments.
4) Explore the impact of smart home energy management systems on energy cost reduction and sustainability improvement.
5) Trends and future directions in smart home energy management research, with insights into more effective and user-friendly systems.
6) Provide recommendations to stakeholders such as researchers, developers, and policymakers to facilitate the adoption of smart home energy management systems.

The following parts of this paper give a comprehensive explanation of smart home energy management systems. Section 2, reviews recent developments and methods in energy monitoring and control, focusing on the aspects of IoT, big data analytics, and renewable energy systems. The section highlights innovations and limitations within existing approaches, including the challenges of scale and interoperability. Section 3, outlines different types of energy management frameworks using techniques such as real-time monitoring, remote control, scheduling, and load management. Detailed methodologies include design methodologies for IoT-enabled devices, algorithms for task scheduling and energy optimization, and case studies validating the efficacy of these systems in both residential and industrial contexts. Section 4, compares various energy management approaches. The performance of the system is compared in terms of energy savings, cost-effectiveness, scalability, and real-world implementation. Fur- ther, this section deals with the adaptability of the systems for specific applications like smart homes, solar PV systems, and grid-level load balancing. Section 5 Finally, the conclusion gives a glimpse into challenges and possible opportunities for future development of IoT-based energy management systems, recommending strategies for scalability, security, and user adoption to spur widespread adoption of smart energy solutions.

Table 1: List of Abbreviations and Their Full Forms

Abbreviation	**Full Form**
IoT	Internet of Things
HVAC	Heating, Ventilation, and Air Conditioning
SEMS	Smart Energy Management Systems
HEMS	Home Energy Management Systems
MQTT	Message Queuing Telemetry Transport
LHAS	Local Home Automation Server
BI	Business Intelligence
EMU	Energy Management Unit
TPC	Time-Priority-Cost
TOU	Time of Use
IBR	Inclining Block Rates
MILP	Mixed-Integer Linear Programming
ICT	Information and Communication Technolgy
ONN	Optimized Neural Networks
RINA	Recursive InterNetwork Architecture
LDR	Light Dependent Resistor

Table 1, shows an exhaustive list of abbreviations often used in the domain of smart home energy management systems and IoT-based technologies. This includes vari- ous communication protocols like MQTT that provide lightweight data transmission, frameworks like HEMS and SEMS, which form the backbone of efficient energy mon- itoring and control. Scheduling and optimization methodologies like TPC and MILP play a vital role in task allocation and cost minimization. Energy pricing models, such as TOU and IBR are dynamic pricing strategies, where analytics tools like BI provide better decision-making through actionable insights. Several key components, such as the EMU for choice of energy source and the LHAS for local automations, show the use of these technologies in furthering the management of Smart Home Ecosystems and can be used as valuable references for understanding the driver technologies in energy management and Internet of Things integration.

II. RELATED WORKS

A. *Energy Monitoring*

Usage and efficiency will be promoted by these systems, with real-time monitoring providing trends in energy consumption supported by IoT technologies for smooth data acquisition, analysis, and transfer. Equipped with sophisticated sensors, they measure key parameters such as voltage, current, and power while presenting user- friendly data visualization via cloud platforms and dashboards.

Notifications and alerts keep users up to date about energy usage, allowing for timely decision-making. By utilizing microcontrollers for data processing and transmission, these systems enhance reliability and performance while supporting remote access for monitoring and control. They emphasize sustainability and efficiency, empowering users to reduce costs and contribute to broader energy conservation goals [1, 2].

Smart Energy Monitoring System Using ESP32 Microcontroller addresses the issues of energy in the Gaza Strip, which has shown shortage of electricity and expen- sive dependency on private generators, raising the demand for management in energy usage. This is a low-cost IoT-based system that will track and monitor energy usage in real time. Using the ESP32 microcontroller and the Blynk platform, the system allows for the user to get data on real-time voltage, current, power, and accumulated energy.

The platform will be using WhatsApp to make the notification for the con- sumers. The importance of ICT to optimize resource allocation, guarantee stability of the grid, and increase efficiency in consumption. Monitoring is real-time is key in detecting anomalies, cost cutting, and furthering the agenda of sustainability. The system includes smart sensors and IoT modules, thereby showing the potential for large-scale industrial and residential implementations [1].

The study underlines the capabilities of ESP32 microcontrollers, namely connec- tivity, low power consumption, high processing power, and cost-effectiveness, which are necessary for a widespread deployment in smart energy systems. It presents the practicality and accuracy of the system, besides discussing challenges such as depen- dency on the internet and the limits of the Blynk platform, including scalability and potential security vulnerabilities. Conclusion The study concludes with underlining the transformative role of IoT and AI in creating intelligent energy management systems that allow users to monitor and control energy consumption efficiently [1].

IoT-Based Intelligent Smart Energy Monitoring for Solar PV Systems focuses on integrating IoT technologies in the energy monitoring, particularly on the renewable energy source which includes photovoltaic systems. A research on SEMS emphasized on the real-time collection of data in ensuring enhanced microgrid stability and maxi- mization of the PV system. The system monitors solar energy parameters like voltage, current, power, temperature, and sunlight intensity through IoT. The system is capa- ble of transmitting real-time data to the cloud using Arduino microcontrollers, current and voltage sensors, and the NodeMCU Wi-Fi module. It enables remote monitor- ing through web interfaces and mobile apps, offering detailed insights into energy production and consumption trends [2].

The study stresses SEMS for optimizing energy usage, incorporating renewable sources with utility grids, and enabling load management according to time-of-use pricing. Experimental results demonstrate the variations in solar parameters at var- ious times of the day and thus depict the accuracy and reliability of the system. It also covers user-friendly interfaces and graphical data presentations for easier interac- tion. Finally, it concludes by stating that SEMS is scalable and cost-effective for the promotion of renewable energy adoption and sustainable energy management [2].

Table 2: Literature Survey on Energy Monitoring

S. No	Title	Author (Journal)	Methodology	Key Findings	Gaps
1	A Smart Energy Monitoring System Using ESP32 Micro-controller [1]	Hala Jarallah El-Khozondar et al. (e-Prime - Advances in Electrical Engineering, Electronics and Energy, 2024)	Developed a low-cost IoT-based energy monitoring system using ESP32 micro-controller and Blynk platform. Integrated WhatsApp for real-time notifications. Data collected from energy meters (voltage, current, power). Real-time monitoring of energy consumption for both utility and private sources, leveraging secure Wi-Fi connectivity.	Accurately tracks and transmits energy consumption data in real time. Reduces human error and helps users monitor hourly, daily, and monthly usage. Enhances user control over energy costs. Promotes sustainability in energy management.	Dependence on stable internet connectivity; Blynk platform limitations (scalability, security). Limited hardware upgrades due to financial constraints.
2	An IoT-Based Intelligent Smart Energy Monitoring System for Solar PV Power Generation [2]	Challa Krishna Rao, Sarat Kumar Sahoo, and Franco Fernando Yanine (Energy Harvesting and Systems, 2024)	Designed a solar PV monitoring system using Arduino and NodeMCU. Utilized sensors for voltage, current, and temperature data collection. Integrated ThingSpeak IoT platform for cloud-based data analysis and visualization. Conducted experiments to measure solar parameters during different times of the day (morning, afternoon, evening).	Provides real-time monitoring of solar energy parameters. Enables remote access to data through IoT platforms, improving system reliability and user convenience. Highlights solar energy's potential in addressing energy crises and achieving sustainability goals.	Limited focus on improving SEMS efficiency under varying environmental conditions. Hardware scalability for larger solar setups remains unaddressed. Heavy reliance on ThingSpeak's cloud services.

B. Energy Monitoring and Remote Control

Smart home energy management systems have similar core functionalities to optimize energy efficiency and user control. It uses IoT technologies for monitoring and con- trolling the real-time consumption of energy from any appliance that is connected in the smart home. Through data collection, analysis, and visualization, users gain actionable insights. It may use a mobile application as an access tool. Energy sav- ings are ensured with automation of appliance operations and wastage elimination by scalable architectures that focus on the individual home or may scale up to even higher utility-level implementations. They are IoT protocol enabled for communica- tion between devices to take place, even including not so smart appliances through the intermediates. User interactivity is improved through nice intuitive interfaces, and easy authentication measures ensure safe and effective operation. Ultimately, these systems are energy-optimized, accessible, and adaptable to different environments [3, 4].

A Smart Home Energy Management System Using IoT and Big Data Analytics Approach studies the combination of Internet of Things and Big Data towards energy management in smart homes, targeting the Arab Gulf region in which HVAC usage takes most of the consumed electricity. The system will link household appliances with the acquisition modules based on IoT. This will ensure real-time monitoring and con- trol of such appliances. Centralized servers utilize Big Data analytics and BI tools to generate insights, including consumption trends and efficiency predictions, accessible to stakeholders through mobile applications. The study emphasizes scalability, secu- rity, and user interaction, offering features like remote appliance control and energy consumption benchmarking across multiple residential units [3].

The architecture provides edge devices equipped with sensors that monitor tem- perature, humidity, and power use. These communicate to a middleware using MQTT. There are analysis tools to ensure data is turned into workable information for both specific homeowners and utilities at community, state, and national levels. Validation via lab prototypes with HVAC systems indicated immense potential for huge energy conservation. The authors have focused on the system's limited scalability and inter- operability but stated that the system is relatively modular and should not hold back its widespread adoption from happening nationwide [3].

"Homergy" connects both intelligent and non-intelligent home appliances to an energy-effective IoT framework. It will specially be targeted at the impoverished regions of Africa where intelligent devices are less penetrating the market. Homergy Box serves as a gateway where the non-intelligent apparatus is connected to the IoT- based framework through microcontrollers, relays, and the Wi-Fi module. It connects to a cloud-based NoSQL database and offers a secure mobile application for real-time monitoring and appliance control [4].

This energy-saving system, Homergy, has an Arduino Mega microcontroller and NodeMCU, supported by protocols such as I2C and WebSockets, for smooth interactivity. Its cloud architecture enables energy-saving functionalities both at home and in small offices. Results from the field tests show that significant savings in energy are gained in all scenarios, though it is better than its counterparts in high-consumption settings. The system is very affordable and adaptable, which makes it a practical solution for energy management in both developing and advanced markets [4].

Table 3: Literature Survey on Energy Monitoring and Remote Control

S. No	Title	Author (Journal)	Methodology	Key Findings	Gaps
1	A Smart Home Energy Management System Using IoT and Big Data Analytics Approach [3]	A. R. Al-Ali, Imran A. Zualkernan, Mohammed Rashid et al. (IEEE Transactions on Consumer Electronics, 2017)	IoT-based data acquisition modules connected to appliances. MQTT protocol for communication. Big Data analytics for insights. Prototyping HVAC systems in lab.	Real-time monitoring and control of appliances. Significant energy savings in HVAC systems. Scalability across multiple stakeholders, from homes to national utilities. Mobile app for user control and visualization.	Focused primarily on HVAC systems, limiting generalizability. Scalability testing limited to prototypes. Lacks extensive real-world deployment data.
2	Smart Home Energy Management System Based on the Internet of Things (IoT) [4]	Emmanuel Ampoma Affum, Christian Adumatta Gyampomah et al. (International Journal of Advanced Computer Science and Applications, 2021)	Development of the "Homergy Box" for IoT integration. Use of Arduino Mega and NodeMCU. NoSQL database for data management. Tested in low-, mid-, and high-consumption environments.	Demonstrated energy savings: 0.5 kWh for low-consumption households, 0.35 kWh for offices, and 13 kWh for high-consumption households. Effective integration of non-smart appliances into IoT. Affordable and adaptable for low-income markets.	Limited to small-scale tests in controlled environments. Lack of exploration into long-term usability and maintenance. Security and privacy concerns require further evaluation.

C. Energy Monitoring and Control via Scheduling

Smart home energy management systems integrate advanced energy management frameworks with IoT technologies to optimize household energy consumption. These systems stress efficient scheduling of appliances based on energy cost, user preferences, and availability, using real-time data to make informed decisions. Devices and com- munication protocols such as ZigBee and MQTT enable seamless interaction between smart appliances and centralized energy management units. User-centric designs prioritize comfort and cost savings, aligning with smart grid requirements to support renewable energy sources, cooperative energy models, and energy trading. Low-cost implementation and real-world applicability make these systems ideal for converting conventional homes into energy-efficient smart homes [5–7].

The Time-Priority-Cost (TPC)-Aware Energy Management System introduces an innovative framework for reducing energy costs using IoT. This incorporates ZigBee- enabled sensors into the network to track consumption across government electricity, private generators, and renewable energy. The core EMU implements scheduling in real time on time, priority, and cost considerations. This permits optimal energy usage while adhering to user requirements. Simulations show a decrease in monthly energy expenses of up to 33%. These results indicate that this system can be flexible for the dynamic needs of different situations.

Its multilayered architecture combines local decision-making at the EMU with cloud-based analytics for comprehensive energy management. The efficient scheduling algorithm maximizes renewable energy use and resolves scheduling conflicts. Future enhancements aim to incorporate partial task execution across energy sources and advanced machine learning for improved decision- making [5].

An optimization framework for appliance scheduling expands the scope of energy management by introducing consumer-defined monthly bill targets. The system uses MILP to schedule appliances over a multi-day horizon under dynamic pricing schemes such as TOU and IBR. This framework categorizes appliances into shiftable and reducible types to make tailored adjustments in energy usage. It also enables energy trade among households, thus supporting cooperative cost reduction with user com- fort. Validations of the system ability to reach targeted bill convergence with minimum disruption are made by means of simulations. Further relaxing comfort constraints and allowing energy trading enhance optimization results and demonstrate the significance of consumer-centric design in smart grids [6].

Finally, low-cost IoT-based controller boards make possible scalable solutions for retrofitting conventional homes into smart homes. Through ESP microcontrollers and open-source platforms like Hassio, it is creating a Local Home Automation Server, LHAS for device to device communication through MQTT protocols. Innovations here comprise modules for energy monitoring, environmental sensing, and appliance control. Real-time testing shows that this technology will definitely work and it provides almost the same functionalities with a commercial system at very small costs. Future research aims to integrate advanced energy forecasting along with wider interoperability in smart grid components towards more improved energy optimization and load profiling [7].

Table 4: Literature Survey on Energy Monitor and Control via Schedulingl

S. No	Title	Author (Journal)	Methodology	Key Findings	Gaps
1	Internet-of-Things-Based Smart-Home Time-Priority-Cost (TPC)-Aware Energy Management System for Energy Cost Reduction [5]	Haitham Ismail, Imad Jahwar, Bilal Hammoud (IEEE Sensors Letters, 2023)	Designed a multi-layer IoT-based system with ZigBee protocol, TPC-aware EMU algorithm for real-time energy scheduling, and integration of user preferences in task execution. Simulated cost reduction results.	Demonstrated up to 33% reduction in monthly energy costs. Efficiently utilized multiple energy sources while maintaining user comfort. Optimized scheduling prioritized renewable sources when available.	Limited to atomic task execution on one source. Does not address advanced scenarios like partial task execution across multiple energy sources. Machine learning integration for improved scheduling was suggested as future work.
2	Optimal Household Appliance Scheduling Considering Consumer's Electricity Bill Target [6]	Il-Young Joo, Dae-Hyun Choi (IEEE Transactions on Consumer Electronics, 2017)	Developed MILP-based HEMS optimization framework for multi-day appliance scheduling under TOU and IBR pricing. Integrated monthly bill targets and trade between households for cooperative optimization. Simulated energy costs and comfort outcomes.	Successfully minimized energy costs while achieving consumer-specified monthly bill targets. Demonstrated improved energy trade cooperation among multiple households. Highlighted significant cost savings and minimal comfort compromise.	Did not explore real-world implementation or test under various external conditions like erratic energy pricing or peak load crises. Limited flexibility in appliance scheduling for diverse scenarios.
3	Design and Implementation of Controller Boards to Monitor and Control Home Appliances for Future Smart Homes [7]	Abdulkadir Gozuoglu, Okan Ozgonenel, Cenk Gezegin (IEEE Transactions on Industrial Informatics, 2024)	Designed ESP-based IoT control boards integrated with open-source Hassio for LHAS. Employed MQTT communication and developed modules for energy monitoring, environmental sensing, and appliance control. Validated through real-world application.	Provided a cost-effective solution to retrofit homes into smart homes. Achieved seamless integration of devices and efficient energy management using open-source tools. Tested successfully in a real house with data supporting smart grid integration.	Limited scalability for larger-scale implementations or highly complex energy systems. Further work is needed to integrate advanced data analysis like deep learning and extend system compatibility with emerging smart grid protocols.

D. Energy Monitoring and Load Control and Optmization

IoT-based energy management systems essentially focus on real-time monitoring of energy, load, and optimization. Such an IoT system will measure the voltage, current, power, and energy consumed, which helps obtain the required analysis accurately due to its advanced IoT techniques. Wireless protocols and Cloud infrastructures help in seamless transmission and storage for easy retrieval and visualization. The user- friendly interfaces - mobile and web applications enable remote control of devices, scheduling of operations, and prioritization of loads for energy-efficient utilization. Scalable and adaptable, these systems are applied in individual homes, smart grids, and large distribution networks. Automation further enhances energy usage optimiza- tion, and the data-driven insights allow for decisions that will promote energy efficiency and sustainability [8–10].

IoT Applications in Smart Homes, deals with the increasing need for efficient systems that arise from the growth of population and industrialization. IoT-based solutions help overcome the shortcomings of traditional power systems, such as poor monitoring and control, which leads to financial inefficiencies. A notable implementa- tion makes use of a Wi-Fi-enabled ESP8266 microcontroller to monitor and control appliances. Sensors measure voltage, current, and power, and the real-time data is visualized through cloud servers. Mobile and desktop applications offer real-time mon- itoring and appliance control. Case studies with three connected devices illustrate the system's ability to monitor loads, prevent overloads, and switch appliances on or off. Comparative analyses of the IoT protocols Zigbee and Z-Wave discuss their scopes and limitations in applications. The outcome of the research is the verification of the system's reliability and scalability, indicating its suitability for integration with smart cities and renewable energy systems [8].

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Optimizing Three-Phase Feeder Load Balancing, minimizes technical losses caused by unbalanced phases. An approach using smart meters integrates real-time data acquisition with load reconfiguration to achieve phase balance, enhancing efficiency and stability. A Case study involving the Irbid District Electricity Company demon- strated annual loss reductions of 253 JDs after implementing the system. The methodology leverages CYME load flow software, MATLAB/Simulink, and ONN for feeder reconfiguration. Results show improved voltage profiles, reliability, and opera- tional efficiency. Automation advantages in phase switching using smart meters over traditional manual balancing, showcasing both economic and technical benefits [9].

IoT Smart Meter with Load Control, design of an IoT-enabled smart meter with integrated load control addresses challenges from increasing electricity consumption. The smart meter, using a microcontroller (ESP32) and current and voltage sensors, allows for real-time monitoring of electrical parameters such as active and reactive power. Users can manage appliances through a web application by prioritizing loads and scheduling operations for optimized energy use. The system was accurate to within 1% error under laboratory conditions and is scalable for easy integration into stan- dard electrical setups. It supports bidirectional communication and fosters dynamic interaction between users and power grids, advancing smart grid functionality. The research emphasizes its role in promoting energy efficiency and reducing reliance on non-renewable energy sources [10].

Table 5: Literature Survey on Load Control

S. No	Title	Author (Journal)	Methodology	Key Findings	Gaps
1	IoT Application for Energy Management in Smart Homes [8]	M.A. Khan, I.A. Sajjad, M. Tahir, A. Haseeb (Eng. Proc., 2022)	Designed an IoT-based energy monitoring system using the ESP8266 microcontroller. Wi-Fi-enabled data transmission to a cloud server. Real-time control of appliances via mobile and desktop applications. Case studies to validate the system's performance.	Enabled real-time monitoring of voltage, current, and power. Demonstrated efficient energy management for three appliances. Stored live data in the cloud for periodic retrieval. Highlighted potential applications in smart cities and renewable energy integration.	Limited scalability evaluation for larger IoT networks. Focused on basic IoT protocols without exploring advanced cybersecurity measures. No analysis of long-term performance or integration with renewable energy systems.
2	Optimization of Three-Phase Feeder Load Balancing Using Smart Meters [9]	Lina Alhmoud, Waleed Marji (IEEE Canadian J. Electrical & Computer Engineering, 2022)	Developed a load-balancing framework using heuristic techniques and optimized neural networks (ONN). Integrated smart meters for real-time data collection. Employed CYME load flow software and MATLAB/Simulink for modeling and analysis. Conducted a case study in Irbid District Electricity Company.	Reduced power losses by balancing loads across three-phase feeders, achieving a loss reduction of 253 JDs/year. Improved voltage profiles and system reliability. Highlighted the economic benefits of smart meter integration. Demonstrated technical feasibility of real-time load reconfiguration using ONN.	Limited exploration of scalability to larger networks or urban areas. Lack of discussion on the cost-effectiveness of smart meter installations on a broader scale. Did not explore alternative algorithms for load balancing.
3	Design and Development of an IoT Smart Meter with Load Control for Home Energy Management Systems [10]	Omar Munoz, Adolfo Ruelas, Pedro Rosales, et al. (Sensors, 2022)	Designed a custom IoT-enabled smart meter integrating ESP32 microcontroller. Monitored advanced electrical parameters such as power factor, reactive power, and apparent power. Validated device performance with less than 1% error in laboratory experiments. Demonstrated real-life application for appliance control via web applications.	Achieved accurate monitoring of multiple electrical parameters. Enabled remote and automated load control, reducing overall energy consumption. Addressed user comfort by prioritizing and scheduling appliances. Highlighted scalability in microgrids and renewable energy systems. Demonstrated practical integration with existing electrical setups.	Did not explore user adoption challenges or cybersecurity concerns. Focused primarily on laboratory setups, with limited exploration of real-world challenges. Lacked detailed cost-benefit analysis for scaling the system across multiple households.

III. METHODOLOGIES

A. *Methodologies on Energy Monitoring*

A Smart Energy Monitoring System Using ESP32 Microcontroller, employs a low- cost IoT-based approach for monitoring and managing energy usage. The system is designed to capture real-time energy data using an ESP32 microcontroller, which acts as the central processing unit. Energy meters are installed to measure parameters such as voltage, current, and active power from two distinct sources: utility electricity and private generators.

The energy meter provides pulses based on the amount of energy used, and this information is processed by the ESP32 microcontroller. In order to have a smooth transmission of data, the ESP32 sets up a secure Wi-Fi connection with the Blynk platform as it is the interface to visualise the data as well as to interact with it. Figure 3, depicts the entire mechanism of the system, including hardware and data flow.

Fig. 3: Mechanism of Smart Energy Monitoring System Using ESP32 Microcontroller [1]

The Blynk platform offers a mobile and web application for the monitoring of energy consumption. Energy consumption data are viewed by the user in real time; this includes daily, monthly, and total usage. The interface includes reading sections for energy usage, trends in consumption, and limits on usage. It uses WhatsApp integration for notifications and alerts, such as consumption that surpasses predefined thresholds, for timely updates. The hardware parts include relays for switching between power sources, a 16×2 LCD for displaying backup data, and LEDs for indications of system statuses. This system is powered by a 5V DC battery, employing optocouplers that isolate the circuits, capacitors for voltage stabilization and transistors for controlling the relays. Real-time data is obtained by continuously monitoring energy pulses. In this case, the ESP32 calculates the energy used by multiplying the pulse count with a pre-determined value of energy per pulse.

Energy Calculation Method:

- The energy meter sends pulses for the amount of energy consumed.
- Each pulse has a certain amount of energy, which is calculated as follows: Energy per Pulse=1/Pulses per kWh
- The total energy consumed is calculated by multiplying the pulse count by the energy per pulse: Energy Consumed=Pulse Count × Energy per Pulse.

Cost Calculation

The cost of energy consumption is calculated using a fixed price per kWh: Cost=Energy Consumed × Price per kWh

Integrity of data is ensured through scripts that periodically reconnect in case of internet connectivity issues, and communication stability is ensured through secure Wi-Fi protocols. This design not only increases the accuracy of monitoring but also allows users to optimize their energy usage and reduce costs [1].

Table 6: Components of Smart Energy Monitoring System Using ESP32 Micro- controller

Category	Component	Description
Hardware	ESP32 Microcontroller	Core processing unit for data collection and communication with Blynk platform.
	Energy Meter	Measures voltage, current, power, and energy consumption.
	Relays (2)	Switch between utility and private generator power sources.
	16×2 LCD Screen	Displays energy readings and system status.
	LED Indicators	Show operational status (power source in use, system output status).

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	Buzzer	Provides audible notifications for events like Wi-Fi disconnection or energy source changes.
	Optocouplers	Isolate microcontroller circuits from high- voltage circuits.
	Capacitors and Resistors	Stabilize voltage and regulate current flow.
	Transistors	Control relay operations.
	5V DC Power Supply	Powers ESP32 and other components.
Software	Blynk Platform	User-friendly interface for monitoring energy usage and controlling limits.
	WhatsApp Integration	Sends real-time notifications and alerts.
	Custom Firmware for ESP32	Programmed with Arduino IDE for data col- lection, processing, and communication.

An IoT-Based Intelligent Smart Energy Monitoring System for Solar PV Power Generation, monitors the generation and usage of solar PV energy through an IoT- enabled system. The setup consists of solar panels connected to a battery for energy storage, with sensors installed to measure voltage, current, temperature, and sunlight intensity. A microcontroller, specifically an Arduino Uno, is used to process data from the sensors. The system transmits real-time data to the ThingSpeak IoT platform through a NodeMCU Wi-Fi module, which allows for remote monitoring and analysis. Figure 4, depicts the components and architecture of the system, with an emphasis on its reliance on IoT technology for real-time energy management.

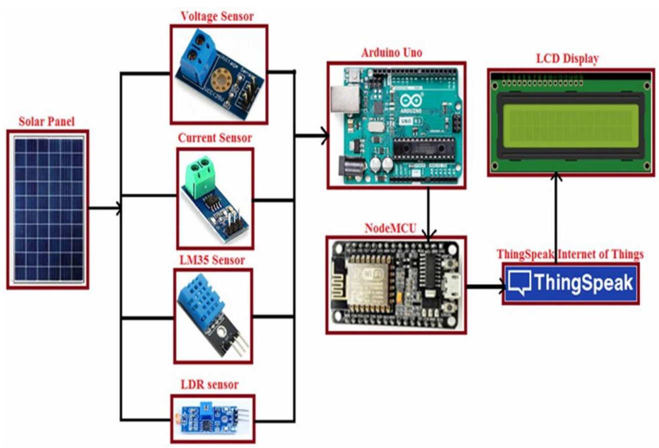

Fig. 4: Energy Monitoring System for Solar PV Power Generation [2]

The current and voltage sensors capture the electrical parameters of the solar pan- els, which are digitized by an analog-to-digital converter. The Arduino microcontroller performs the calculation of power and energy consumption, depending on sensor read- ings, updating those values in real time. Data are transmitted to the cloud through HTTP protocols, which stores and visualizes it via ThingSpeak's graphical interface. This allows users to monitor remote solar performance, including important parame- ters such as energy production, environmental conditions, and the status of the device. The system has a user-friendly interface that can be accessed via web or mobile appli- cations. It provides detailed graphs and historical data for daily, weekly, and monthly trends, thus enhancing energy management capabilities. The hardware setup con- sists of a breadboard connecting components such as sensors, the Arduino, and the NodeMCU. Other features include an LM35 sensor to monitor panel temperature and LDR to measure sunlight intensity. The EMC interface ensures real-time updates and control, while ZigBee modules are used for data transmission between solar and util- ity sources. Load balancing is achieved by shifting between solar and utility power according to consumption patterns and availability. The system emphasizes reliabil- ity and scalability by integrating cloud storage and wireless communication, which makes it possible to monitor energy efficiently from a remote location for a variety of applications [2].

Table 7: Components of IoT-Based Intelligent Smart Energy Monitoring System for Solar PV Power Generation

Category	Component	Description
Hardware	Arduino Uno	Main microcontroller for processing sensor data.
	NodeMCU Wi-Fi Module	Facilitates wireless data transmission to the ThingSpeak cloud platform.
	Current and Voltage Sensors	Measure the electrical parameters of the solar PV panels.
	Temperature Sensor (LM35)	Monitors the surface temperature of solar panels.
	Light-Dependent Resistor (LDR)	Measures sunlight intensity to evaluate solar panel performance.
	Load Transfer Switches	Automatically switch between solar power and utility power sources based on availability.
	Breadboard	Connects the Arduino, NodeMCU, and sensors for prototyping.
	Battery	Stores energy generated by solar panels for system operation during low sunlight or at night.
Software	ThingSpeak IoT Platform	Cloud-based platform for data storage, visualization, and historical trend analysis.
	Arduino IDE	Used to program the Arduino Uno and NodeMCU microcontrollers.
	NodeMCU Firmware	Enables communication with ThingSpeak for data upload.
	Custom C Code for Arduino	Handles sensor data processing and power calculations.

B. Methodologies on Energy Monitoring and Remote Control

A Smart Home Energy Management System Using IoT and Big Data Analytics Approach, makes use of IoT and Big Data technologies to develop a scalable and effi- cient Energy Management System (EMS) for smart homes, with special consideration given to optimizing HVAC systems [3]. IoT-enabled data acquisition modules are inte- grated with household appliances, forming a wireless mesh network where each device is assigned a unique IP address. Sensors, including those for temperature, humidity, and power usage, collect real-time data to track environmental conditions and appli- ance performance. This data is continuously transmitted for analysis, enabling precise energy monitoring.Figure 5, presents a sequence diagram demonstrating data flow from IoT devices, cloud, and up to the user interface representing the system's functionality.

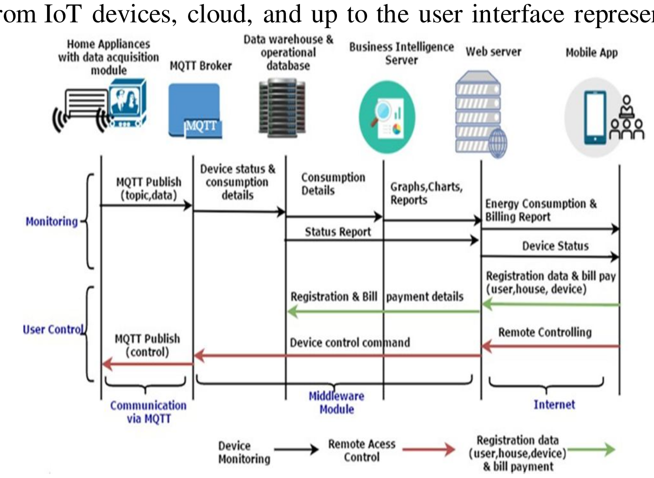

Fig. 5: Sequence Diagram of Home Energy Management System Using IoT and Big Data Analytics Approach [3]

To facilitate communication, the EMS employs the lightweight MQTT protocol, which is well-suited for real-time applications due to its low latency and minimal bandwidth requirements. The collected data is transmitted to a centralized server for aggregation and processing. Advanced Big Data analytics tools are used by the server in analyzing trends on energy consumption and predicting inefficiencies. BI software gives actionable insights to stakeholders in visual dashboards where they can easily identify trends, track usage, and evaluate efficiency metrics.

A mobile application serves as the main user interface for the EMS. It allows users to monitor energy consumption from a distance, control connected appliances, and adjust settings based on real-time feedback. The APIs ensure that communication between the mobile app and the centralized server is secure and efficient in terms of data exchange. The app also provides users with a detailed overview of their energy usage trends and allows them to implement schedules or preferences for better energy management.

The system was tested in a lab environment with regards to prototyping, center- ing on HVAC units emulated by fans that act under the control of modules from IoT. Sensors attached at these units collected environmental information, which was transmitted wirelessly through edge devices to be processed at the central server. Scalability testing was performed when simulating multiple concurrent users to test performance using metrics such as latency and throughput and resource utilization during these tests.

For secure operation, HTTPS protocols were implemented into the communica- tion infrastructure. These protocols protect the transmission of data between the IoT devices, the server, and the mobile application by keeping user information private and maintaining system integrity. Key performance indicators such as responsiveness of the system, energy saving, and user satisfaction assessed the effectiveness of the system, thereby establishing its capability to optimize energy usage while offering actionable insights to users.

Table 8: Components of Smart Home Energy Management System Using IoT and Big Data Analytics Approach

Category	Component	Description
Hardware	Temperature and Humidity Sensors	Measure environmental conditions for HVAC system optimization.
	Current Sensors	Monitor power consumption of HVAC units.
	Solid-state Relays	Control HVAC appliances (ON/OFF opera- tion).
	High-end Microcontroller (SoC)	Acts as an edge device, collecting sensor data and managing device controls.
	Servers (High-end PCs)	Host MQTT broker, analytics engine, data storage, and web server.
	Prototype HVAC Units	Simulated using 220V AC fans in a lab envi- ronment.
Software	MQTT Protocol	Enables lightweight and efficient communication between IoT devices and the server.
	Big Data Analytics Tools	Analyze large volumes of data to extract consumption patterns and trends.
	Business Intelligence (BI) Tools	Generate actionable insights and visualizations (graphs, dashboards) for various stakeholders.
	Mobile Application	Provides users with remote control capabilities and energy usage monitoring.
	Web APIs	Enable communication between the mobile app and the centralized server for real-time data exchange.
	Security Protocols (HTTPS)	Ensures secure communication between users and the system.

Smart Home Energy Management System Based on the Internet of Things (IoT), is a concept which presents ”Homergy” as an IoT framework integrating smart and non- smart appliances for an energy-efficient smart home. This system is specially tailored for low-income regions like Africa, where penetration of smart devices is still very low. The Homergy Box is the gateway that integrates non-smart devices with the IoT system by using microcontrollers, relays, and Wi-Fi modules. It connects with a cloud- based NoSQL database and offers a secure mobile application for real-time monitoring as well as appliance control. Figure 6, depicts the system architecture, showing how the Homergy Box fills the gap between traditional appliances and smart appliances into one IoT ecosystem.

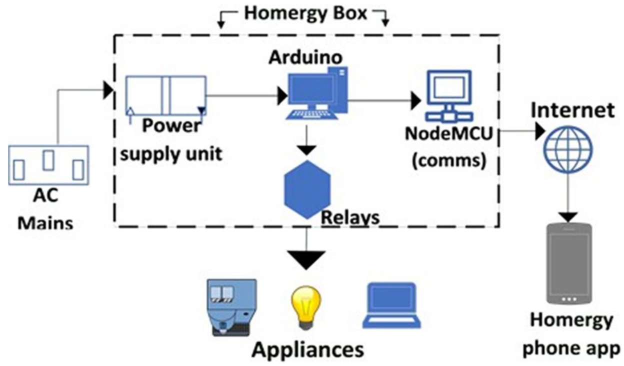

Fig. 6: System Architecture of Smart Home Energy Management System Based on the IoT [4]

The Homergy Box is the core hardware component that bridges non-smart appli- ances with the IoT ecosystem. It is equipped with an Arduino Mega microcontroller for appliance control, a NodeMCU module with Wi-Fi capabilities for communication, and opto-coupled relay modules for safe switching of high-voltage appliances. A total of 16 relay channels allow multiple devices to be integrated into the system. An AC- DC converter steps down household voltage (240V AC) to a safe 5V DC for internal components. Besides that, a 16x4 I2C LCD display offers live feedback to the user: instructions for setup, the status of the system, and any error messages.

The system makes use of different protocols in order to be fully operational. Internally, an I2C protocol provides an efficient interface for the Arduino Mega micro- controller in order to exchange data with connected components, whereas HTTP and WebSocket protocols allow communication between the mobile application and the cloud database. The Firebase Realtime Database is a NoSQL cloud solution, which stores the user commands and appliance states in structured JSON format. It supports real-time streaming of updates to the Homergy Box. The cloud-based architecture does not allow much latency while providing scalability for small and medium-scale applications.

The mobile application, developed by using the Flutter framework, is used as the interface for controlling and monitoring the connected appliances. It supports real- time updates, customizable names of appliances, and a rewards scheme to encourage energy-efficient behavior. Users can access the Android and iOS platforms with this app, designed for friendly interaction such as scanning of QR codes for setting devices. The app also deploys strong security measures that involve encrypted QR codes, and access codes to avert unauthorized control of the Homergy Box.

It further has to be tested in real conditions, and for this, the system was tested in three environments: low-consuming households, one-man offices, and high-consuming homes. There are results over eight weeks from a test, both with and without the system, which have ensured that the system does cut energy consumption considerably, even more so in high-consuming environments.

Security and privacy were also integral to the design. Database access rules and encrypted QR codes ensure only authorized users can control the system. Each Home- rgy Box has a unique identifier linked to a secure access code, which users must authenticate to establish control. These measures safeguard data and appliance control while maintaining user accessibility.

The Homergy system has affordability, ease of use, and energy savings as priorities, making it a practical solution for regions with low IoT penetration. However, the methodology recognizes the need for future improvements, particularly in scalability testing and integration of advanced analytics, to further enhance system performance and applicability [4].

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Table 9: Components of Homergy Box IoT-Based Smart Energy Management System

Category	Component	Description
Hardware	Homergy Box	The core hardware module integrating smart and non-smart devices with the IoT ecosystem.
	Arduino Mega Microcontroller	Controls appliance operations and interacts with the NodeMCU.
	NodeMCU (ESP8266)	Provides Wi-Fi connectivity for communication with the cloud database.
	Relay Modules (Opto-coupled)	Interface high-voltage appliances with the low-voltage control circuitry; 16 relay channels included.
	AC-DC Converter	Steps down 240V AC household current to 5V DC to power internal components.
	16x4 I2C LCD Display	Displays device status, setup instructions, and error messages during operation.
Software	Firebase Realtime Database (NoSQL)	Stores user commands and device states in a JSON format for real-time streaming to the Homergy Box.
	Flutter Framework	Used to develop a cross-platform mobile application for appliance control and monitoring.
	HTTP and WebSocket Protocols	HTTP: For initial communication between the app and the database. WebSocket: For continuous, real-time updates between the database and devices.
	Arduino IDE	Programs the Arduino Mega and NodeMCU for device control and communication.
	Security (Encrypted QR Codes)	Protects device access using unique QR codes for user authentication.

C. Methodologies on Energy Monitoring and Control via Scheduling

Internet-of-Things-Based Smart-Home Time-Priority-Cost (TPC)-Aware Energy Management System for Energy Cost Reduction revolves around designing an IoT- based energy management framework to optimize energy usage and cost in smart homes [5]. The system utilizes a TPC-aware Energy Management Unit (EMU), which employs real-time scheduling algorithms to allocate tasks based on time availability, energy source priority, and cost efficiency. Figure 7, the architectural design is based on this multi-layered approach regarding energy management from the accumulation of data to interaction with a user.

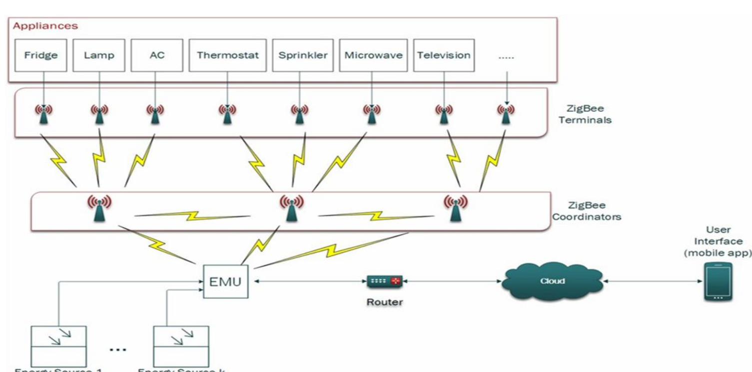

Fig. 7: Architecture of IoT Based TPC-Aware Energy Management [5]

The architecture consists of divided layers:

1) Perception Layer: There are deployed sensors involving motion detectors, humidity sensors, thermometers, and smart plugs that collect data concerning appliances' energy consumption and other environmental conditions. The sensors would either communicate directly with the EMU or via smart sockets.
2) Network Layer: The ZigBee protocol is used for communication between appliances and the EMU, provides low energy consumption, security, and data rate flexibility. It provides a mesh network for transmitting information to the middleware for processing.
3) Middleware Layer: The EMU would process data obtained from the network layer. A TPC-aware scheduling algorithm is running here to ensure tasks begin at their optimal times by also considering priority factors for their source of energy (e.g., renewables over grid energy). When handling data aggregated across more than one home, it could do cloud-based operations.
4) Application Layer: Users interact with the system through mobile applications or web interfaces. The system suggests optimized schedules but allows users to modify or override decisions based on their preferences.

Algorithm 1 Source Scheduling Algorithm

Require: Event details, source details, and current time (timeNow) Ensure: Start time of the scheduled event or *False* if scheduling fails

```
SourceSchedule(event, source, timeNow)
if source.startTime < timeNow then
    startTime ← timeNow
else
    startTime ← source.startTime
end if
while startTime + event.duration < source.getStopTime() and startTime < timeNow + event.tolerableDelay do
    sumCurrent ← getSumCurrentEvents()
    if sumCurrent < source.maxCurrent then
        event.startTime ← startTime
        EPQ.push(event)            ▷ Push event into Event Priority Queue
        return startTime
    else
        startTime ← getNearestTaskStopTime(startTime)
    end if
end while
return False
```

The Source Scheduling Algorithm 1, it optimally schedules event starts dependent upon availability and constraints in source utilization. It details on events, source information, and a variable named timeNow depicting the current time. Based on this algorithm, first it calculates the preliminary possible time for an event's beginning. If the source's set start time is less than or equal to the current time, the event's start time is set to the current time so that the event is not scheduled in the past; otherwise, it uses the source's designated start time. The algorithm iteratively checks for possible start times within a permissible window defined by the source's maximum allowed time (source.getStopTime()) and the event's tolerable delay. At every iteration, it calculates the sum of current load from all the events that are in action. If the sum load falls within the capacity limit for current sources, it sets the start time to start an event at this start time and pushes this event to the EPQ. This EPQ then follows tracking on this event, and then the start time is returned as the output. If the sum of the loads exceeds the source's capacity, the algorithm finds the earliest time at which one of the running tasks will complete (getNearestTaskStopTime) and adjusts the start time based on that. If it cannot find any valid start time within the bounds, the algorithm returns False to indicate the scheduling attempt has failed. This allows for optimal energy allocation under source capacity and event tolerable delay constraints.

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Table 10: Components of IoT-Based TPC-Aware Energy Management System

Category	Component	Description
Hardware	ZigBee Sensors	Motion detectors, humidity sensors, ther- mometers, thermostats, flame detectors, gas detectors.
	Smart Plugs	Connected appliances to monitor and control energy consumption remotely.
	Energy Sources	Government grid, local generators, and renew- able solar energy systems.
Software	EMU Algorithm	A scheduling algorithm based on time, priority, and cost (TPC) to optimize energy allocation.
	ZigBee Protocol	Used for communication between the sensors, appliances, and the EMU.
	Cloud Platform	Supports centralized data processing when multiple homes share an energy source.
	User Interface	Mobile application and web interface to allow users to view and modify suggested schedules.
	Simulation Tools	Custom discrete event simulation to evaluate energy costs and scheduling efficiency.

Optimal Household Appliance Scheduling Considering Consumer's Electricity Bill Target, presents a MILP framework for Home Energy Management Systems, focus- ing on cost minimization of electricity, yet ensuring user-defined monthly bill targets [6]. The framework introduces a sophisticated optimization approach that integrates dynamic pricing models and appliance-specific scheduling strategies to enhance house- hold energy management. By leveraging the Time-of-Use (TOU) and Inclining Block Rate (IBR) pricing schemes, the system incentivizes cost-effective energy usage through demand-shifting and consumption control. Its multi-household coordination feature further promotes resource sharing by allowing energy trade among households, reducing dependency on grid power and fostering cooperative efficiency. The opti- mization formulation incorporates user-defined constraints, such as comfort levels and monthly budget targets, along with a penalty function for relaxing thermal condi- tions when necessary. Simulations validate the model's ability to achieve considerable cost savings and maintain user comfort, making it a versatile and consumer-friendly approach for smart grid environments. Figure 8, represents the system model, focusing on appliance scheduling optimization based on monthly cost targets, energy priorities, and user preferences .

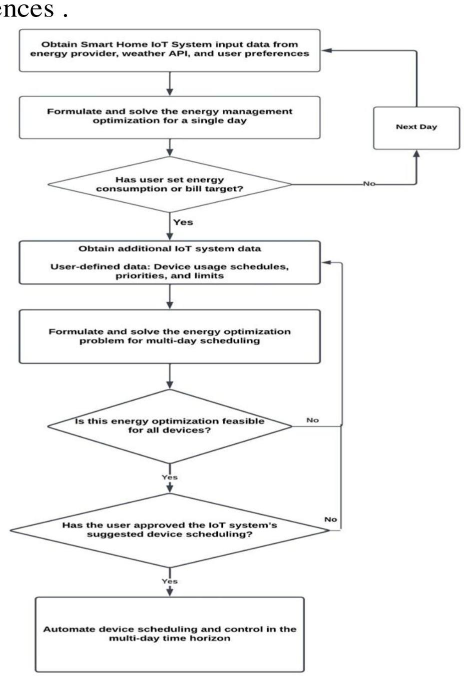

Fig. 8: Procedure of Optimal Household Appliance Scheduling Considering Consumer's Electricity Bill Target

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HEMS System Model: The system manages controllable and uncontrollable appli- ances in smart houses. Controllable appliances are classified into shiftable, e.g., washer, either interruptible or non-interruptible loads, and reducible, e.g., air conditioner. The scheduling system does not depend on the operation of uncontrollable appliances like lighting and refrigerators.

Dynamic Pricing Integration: The electricity price in the TOU pricing model varies at different time blocks throughout the day. When electricity demand is high, the price increases during peak hours, but the price drops to a lower rate during off-peak hours. Such a structure encourages consumers to shift their energy-intensive activities to off-peak periods, thus reducing the overall cost of electricity.

The TOU model is suitable for time-of-use energy management and is used in the proposed optimization framework to minimize household electricity. IBR pricing model uses a tiered structure where electricity prices increase with the amount of energy consumed.

The model is also meant to encourage energy conservation whereby it will charge a lower amount of the first block, increasing subsequent blocks as cumulative consumption continues to rise. The mechanism of pricing can thus be used to promote low-energy consumption, especially from the largest consumers in households; this therefore forms an integral component in the optimization model.

Multi-Household Coordination: The model supports trading of energy among houses. One house can buy surplus energy from another house at a cheaper rate than what is charged on the grid. This cooperative mechanism reduces the overall cost of electricity and fosters resource sharing.

Optimization Formulation: The MILP optimization problem is formu-lated to min- imize the total costs while satisfying constraints that include appliance operation durations, comfort preferences of the user, and monthly bill targets. A penalty func- tion is added to the formulation to relax thermal conditions; this will ensure feasibility when achieving bill goals without major user discomfort.

Equation 1, provides objective of the TOU and IBR appliance scheduling problem is to minimize the total cost J, which consists of two components: energy cost and user discomfort.

$$\min_{x} J = \sum_{u=1} \sum_{d=1} \pi_h \sum_{h=1} \left(P_u^{d,h,\text{net}} + P_u^{d,h,\text{trade}} \right) + \sum_{u=1} E_u \sum_{d=1} \sum_{h=1} \delta_u^{d,h} \quad (1)$$

where:

- J: The total cost to be minimized.
- J_1: The energy cost term,
  - π_h: Electricity price at hour h under the TOU tariff.
  - $P_u^{d,h,\text{net}}$: Net power consumption of user u at time h on day d.
  - $P_u^{d,h,\text{trade}}$: Power traded (e.g., from storage or renewables) by user u.
- J_2: The user discomfort term,
  - E_u: Weight associated with the discomfort tolerance of user u.
  - $\delta_u^{d,h}$: User discomfort for user u at time h on day d.

Thus, the optimization model balances cost savings and user comfort in a smart grid environment.

By balancing energy costs and consumer comfort, the optimization algorithm efficiently schedules appliance usage while adhering to monthly electricity bill targets. Simulations are performed for single and multiple households under TOU and IBR tariffs. The results from the simulations demonstrate the effectiveness of the approach in minimizing electricity costs and improving energy efficiency across different pricing schemes.

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Table 11: Components of Optimal Household Appliance Scheduling Considering Con- sumer's Electricity Bill Target

Category	Component	Description
Hardware	Smart Appliances	Includes controllable appliances (e.g., air con- ditioners, washers) and uncontrollable ones (e.g., refrigerators).
	Smart Meters	Monitors real-time energy consumption for integration with the HEMS framework.
	Distributed Energy Resources (DERs)	Rooftop solar photovoltaic (PV) systems and residential energy storage systems (ESS).
Software	MILP Optimization Framework	Formulated for appliance scheduling over a multi-day horizon under TOU and IBR tariffs.
	Penalty Function	Used to relax constraints on thermal comfort for achieving bill targets.
	Simulation Platform	Framework tested with synthetic datasets for multiple households.
	Dynamic Pricing Models	Supports Time of Use (TOU) and Inclining Block Rate (IBR) tariffs.
	Energy Trade Model	Algorithmic support for energy exchange among households.

Design and Implementation of Controller Boards to Monitor and Control Home Appliances for Future Smart Homes, focuses on developing cost-effective, ESP-based IoT control boards to retrofit traditional homes with smart capabilities [7]. The system uses open-source technologies and Wi-Fi communication to create an integrated home automation environment. Figure 9, shows the working diagram, which clearly explains the role of sensors, controllers, and cloud platforms in achieving real-time monitoring and efficient energy management.

1) Hardware Design: ESP-Based Modules: The system designs modules based on ESP8266 and ESP32 microcontrollers for a wide range of applications. The applica- tions include energy metering, environmental sensing such as temperature, humidity, and light intensity, and appliance control. Modules are specifically designed for tasks such as relay control for switching devices or DHT11 sensors for temperature and humidity monitoring.
2) LHAS: A Raspberry Pi running the open-source automation server called Has- sio, which is essentially a central hub for managing the device, supports easy communication, control, and monitoring through MQTT protocols.

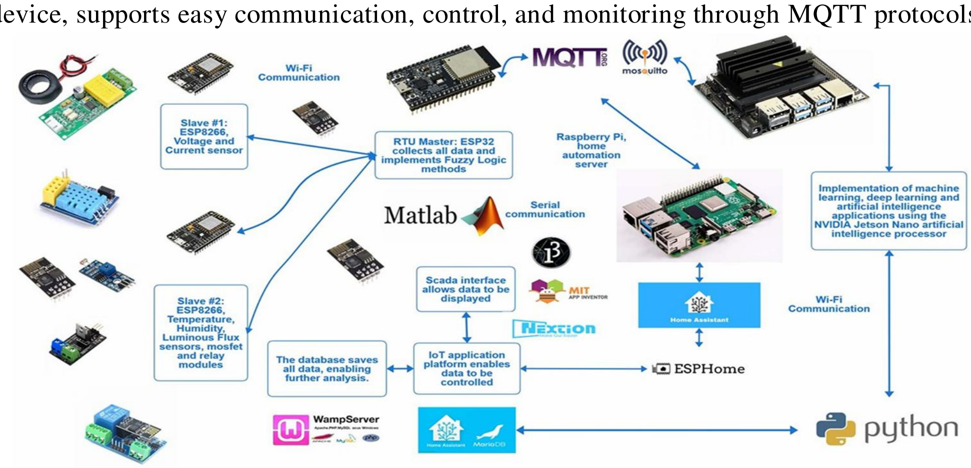

Fig. 9: Working principle of Design and Implementation of Controller Boards to Monitor and Control Home Appliances [7]

3) Software Implementation MQTT Communication: Through an MQTT broker, it supports data exchange between the server and devices. Devices operate as publish- ers (transmitter of data) and subscriber commands to have real-time interactions with the server.
4) Data Logging and Analysis: The LHAS database holds the logged data from sen- sors in regard to energy consumption and environmental conditions. It can also present these data in the user-friendly interface to perform complex analysis like load profiling.
5) System Applications: Energy Management: Smart plugs installed with PZEM sen- sors are connected to real-time measurement of parameters like voltage, current, and power consumption. The data allows easy identification of usage patterns for better appliance control.
6) Environmental Control: Modules like NeoPixel LED drivers regulate the intensity of light in a fuzzy logic controller by considering ambient light. Temperature and humidity measurements are utilized in the case of automation scenarios.
7) Testing and Verification: The system was actually tested in a real home for five months, during which its energy consumption was observed along with control- ling appliances. Its results verified efficiency, reliability, and suitability to meet the requirements of the smart grid.

In conclusion, the methodology successfully demonstrates the design and implementa- tion of cost-effective IoT-based controller boards for smart home energy management. By leveraging open-source platforms like Hassio, ESP-based modules, and the MQTT protocol, the system enables seamless integration of smart devices with efficient mon- itoring and control capabilities. The incorporation of fuzzy logic for environmental automation further enhances system intelligence, providing adaptable solutions for lighting and energy usage.

Table 12: Components of Design and Implementation of Controller Boards to Monitor and Control Home Appliances for Future Smart Homes

Category	Component	Description
Software	Hassio (LHAS)	Open-source automation server installed on Raspberry Pi for device management.
	MQTT Protocol	Facilitates communication between devices and the central server.
	ESP-Home Framework	Creates configurations for ESP modules to integrate them with the LHAS.
	Fuzzy Logic Controller	Controls lighting conditions based on environ- mental data like ambient light intensity.
	MySQL Database	Stores sensor data, energy usage, and appli- ance performance metrics.
	User Interface	Web browser and Android/iOS applications for monitoring and controlling devices.
Hardwar e	ESP Modules	ESP8266 and ESP32 microcontrollers used for smart plug, sensor, and control module devel- opment.
	Raspberry Pi	Acts as the LHAS to connect all devices and store data.
	Sensors	DHT11 (temperature and humidity), light intensity sensors, NeoPixel LEDs for ambient control.
	Smart Plugs	NodeMCU-based modules with PZEM-004T v3.0 sensors for measuring AC power, voltage, and current.
	Relay Modules	Used for ON/OFF control of connected home appliances.

D. Methodologies on Energy Monitoring and Load Control

IoT Application for Energy Management in Smart Homes, involves designing and developing an IoT-based energy management system designed to monitor, control, and optimize energy usage in smart homes. Here, the system architecture has considered all the important hardware devices like ESP8266 microcontrollers, ACS712 current sen- sor, ZMPT101B voltage sensor, and also relay module for controlling appliances. The ESP8266 microcontroller is programmed to collect real-time data from the current and voltage sensors, which measure the electrical parameters of connected appliances [8]. Figure 10, includes current, voltage, and power consumption, which are transmitted wirelessly to a cloud server using MQTT protocol.

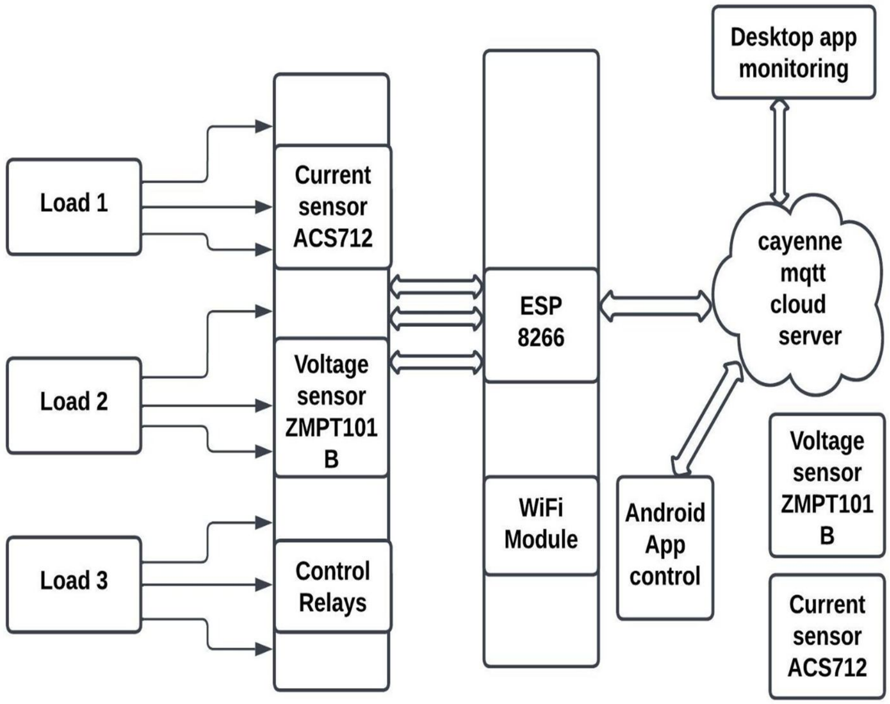

Fig. 10: Working Diagram of Energy Management in Smart Homes

The system allows users to control the appliances remotely using mobile or desk- top applications, which serve as the human-machine interface (HMI). The sensors are interfaced with ESP8266, which processes raw analog data into usable digital form. The cloud server acts as a storage and processing hub, which enables the user to mon- itor real-time as well as historical data in daily, weekly, or yearly periods. Control functionality for the system is achieved using relays, where appliances get switched on or off based upon user input or based on predetermined automation rules like over- load detection. The circuit design ensures that data from each appliance is collected sequentially using ACS712 and ZMPT101B sensors and processed by the ESP8266 microcontroller. These values are sent to the cloud server for visualization, decision- making, and control with a desktop or mobile app to interact with the user. Overload detection is implemented by continuously monitoring the total power drawn by all connected appliances.

In the event that the sum load surpasses a defined threshold (300W in the proto- type), the system gives preference to appliances based on their priority. For example, lower-priority loads like washing machines are automatically turned off so that higher- priority appliances like air conditioning or lighting continue running. In the event that the system cannot keep the load within safe limits, it turns off all appliances to safe- guard the infrastructure. This is through the programmable logic of the ESP8266, which processes the power readings in real-time and commands the relays for instant action. Validations were conducted using case studies with three appliances of power ratings at 65W, 100W, and 120W, respectively.

The results showed the potential of the system to monitor actual power usage, gen- erate alerts in overloading conditions, and execute automated prioritization of loads. Live graphs related to voltage, current, and power were displayed, with data being stored in the cloud for later analysis. This data was downloadable in whatever format is preferred by the end user for easy management. This robust approach is modular, which then allows the system to scale from being integrated into larger smart city frameworks or advanced energy management systems.

Table 13: Components of IoT Application for Energy Management in Smart Homes

Category	Component	Description
Hardware	ESP8266 Wi-Fi Controller	A low-cost, programmable Wi-Fi module for wireless communication and control.
	ACS712 Current Sensor	Measures the current flowing through the appliances.
	ZMPT101B Voltage Sensor	Detects the voltage levels of connected appliances.
	Relays	Enables switching appliances on/off remotely based on user-defined conditions.
	Load Devices	Appliances used for testing the system (e.g., lamps, resistive loads).
	Power Supply	Provides electricity to the ESP8266 and other components.
	4-Channel Relay Board	Allows control of multiple loads simultaneously.
Software	MQTT Protocol	A lightweight messaging protocol for commu- nication with the cloud server.
	Cloud Server Interface	Stores real-time data and provides access for monitoring and controlling loads.
	Desktop and Mobile App	User interface for data visualization and appliance control.

Optimization of Three-Phase Feeder Load Balancing Using Smart Meters develops a systematic approach to reduce power losses in three-phase distribution feeders by implementing a load-balancing technique using smart meters and advanced algorithms. The methodology begins with real-time data acquisition from smart meters installed at various points in the distribution network [9]. These meters capture parameters such as voltage, current, and load consumption at individual customer connection points. The collected data feeds into a mathematical model designed to calculate load imbalances and identify opportunities for redistribution.

This architecture is designed for seamless integration and efficient data handling and is adaptable to various configurations of smart homes. The sequential mechanism of data collection ensures effective monitoring of individual appliances while maintaining a centralized control framework. The ESP8266 microcontroller is low-cost and widely supported and enables wireless communication over Wi-Fi, thus eliminating the need for additional hardware like gateways. This improves efficiency as the MQTT protocol enables lightweight and secure communication between devices and the cloud server, and this makes data flow unintermitted even with multiple users simultaneously accessing the system. User-friendly mobile and desktop applications enable users to monitor energy consumption, set automation rules, and make informed decisions about appliance usage. Figure 11 provides a schematic of the distribution feeder, illustrating how dynamic load balancing is achieved through phase reconfiguration and heuristic optimization.

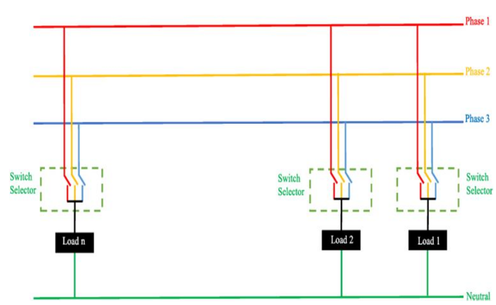

Fig. 11: Schematic of distribution feeder with switch selector [9]

To optimize load balancing, heuristic optimization techniques and an ONN algo- rithm are used. These tools analyze the data for prediction and recommendation of an optimal switching configuration for feeder nodes.The ONN algorithm used in this paper plays a pivotal role in improving the load-balancing process within a three-phase distribution system. ONN leverages the capabilities of neural networks to analyze, predict, and optimize the switching configurations for feeder nodes, ensuring a more balanced distribution of loads across all three phases. The network is trained using real-time data collected from smart meters, including electrical parameters like volt- age, current, and load consumption. The CYME load flow software is used to model the distribution system and simulate effects from different load reconfiguration scenar- ios. MATLAB/Simulink provides additional computational power for implementing and testing the optimization algorithms. The optimization process involves feeder topology by changing the open/closed position of phase switches or through the swapping of customers between the phases. The method maintains an equal load on all three phases, which further reduces loss, minimizes voltage fluctuations, and improves the system.
The error (ϵ) is calculated as the absolute deviation of the current loads (I_1, I_2, I_3) from the ideal current (I_{ideal}):

$$\epsilon = \sum I_1 - I_{ideal} + \sum I_2 - I_{ideal} + \sum I_3 - I_{ideal} \quad (2)$$

where:
I_1, I_2, I_3 represent the total current loads assigned to the three phases.
I_{ideal} is the ideal current load for each phase.

Equation 2, error calculation formula determines the deviation of the current load distribution across the three phases from an ideal balanced state. Here, the errors expressed as the absolute summation of the differences between the actual phase loads and the ideal load This ensures that the system evaluates load imbalance across phases by quantifying the deviation, allowing for adjustments to achieve optimal load balancing.
Figure 12, outlines a step-by-step process for analyzing load currents using a vector of 27 inputs. The procedure begins by initializing the output, summing all loads, and calculating the average ideal current. Phase 1 and Phase 2 currents are computed, and the output is updated. Remaining currents are marked as Phase 3, after which phase currents are determined using output sequences and load values. Finally, the process calculates the differences between phase currents and returns these as the output.

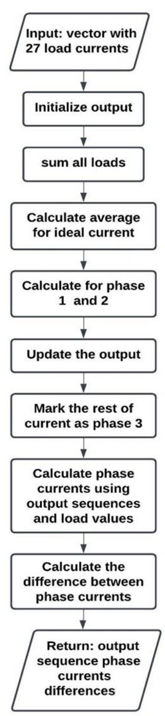

Fig. 12: Flow Chart of Phase Current Balancing

A case study of this methodology is as follows based on the Irbid District Electricity Company, in which, through real-time load balancing, technical loss reduction was significant, and network stability improved. It further contains measures to deal with fault occurrences, thus enabling the speedy reconfiguration to ensure continuity in power supply.

Table 14: Components of Optimization of Three-Phase Feeder Load Balancing Using Smart Meters

Category	Component	Description
Hardware	Smart Meters	Devices used to measure real-time voltage, cur- rent, and load consumption at different feeder points.
	Feeder Nodes	Points in the power distribution network where load measurements are collected.
	Phase Switch Selector	Mechanism for dynamically switching loads between phases to balance feeder loads.
	Distribution Transformer	Supplies power to the feeders; monitored and analyzed for load balancing effectiveness.
	Customer Connections	Points where consumers are connected to the feeder for load reconfiguration.
Software	CYME Load Flow Software	Used for modeling the feeder network and sim- ulating load reconfiguration scenarios.
	MATLAB/Simulink	Simulates optimization algorithms (e.g., heuristic techniques, ONN) and visualizes results.
	C Programming Language	Implements mathematical models and opti- mization algorithms for load balancing.

The methodology in the paper titled ”Design and Development of an IoT Smart Meter with Load Control for Home Energy Management Systems” involves developing and validating a smart meter systematically, which can monitor and control appliance loads to enhance energy efficiency.

The process starts with the identification of the problem, which is the rising energy demand and the inadequacy of the existing grid infrastructure. The paper stresses that efficient energy management systems at the household level are required, especially during peak usage periods, to avoid energy wastage and power outages. The proposed solution is the design of an IoT-based Smart Meter with Load Control (SMLC) that can monitor electrical parameters and manage energy consumption through real-time manual and automatic load control.

At the stage of system design and development, there is a selection of essential hardware components that ensure precision and proper performance. The energy mea- surement unit-ADE7758-is designed for measurements of electrical parameters in form of rms current and rms voltage, active and reactive power, and power factor. The ESP32 microcontroller has been chosen because of the built-in Wi-Fi ability; this eliminates the gateway for direct communication with the cloud. The non-invasive current sensing was carried out using a current transformer, CST-1020. The voltage attenuation circuit was also applied to measure the voltage safely. For load con- trol, SRA-05VDC-CL relays were applied so that appliances can be turned on or off manually or automatically. The entire system was mounted on a custom-designed two- layer printed circuit board that is enclosed in a standard 4 × 4 electrical box, which allows the device to be scaled and integrated into conventional home electrical instal- lations. Figure 13, details the architecture, highlighting how ESP32 microcontrollers and energy measurement ICs enable precise energy tracking and load prioritization for enhanced efficiency.

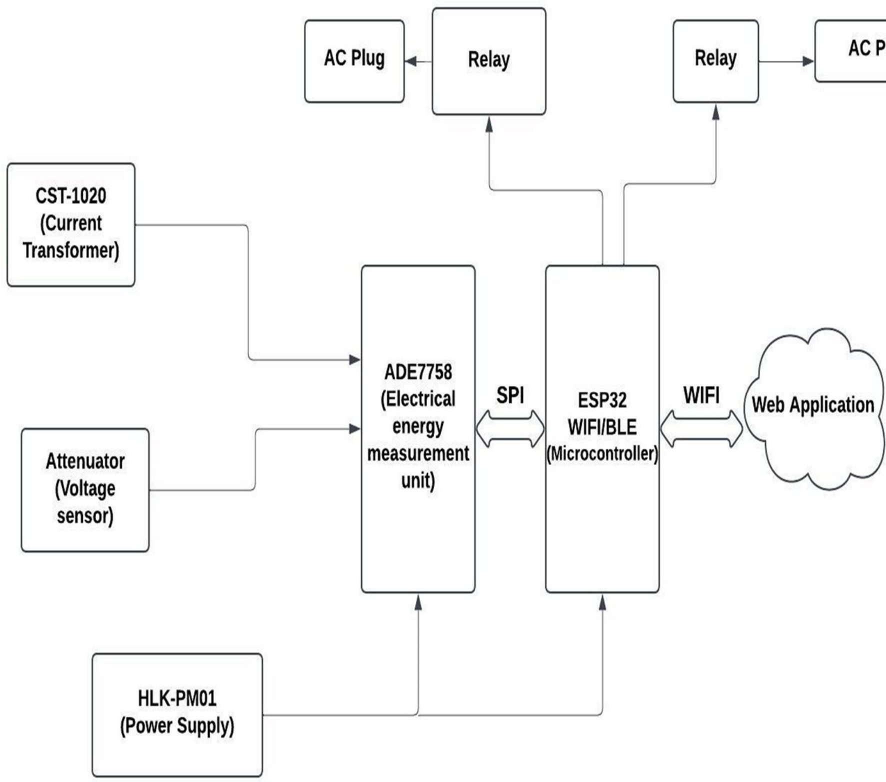

Fig. 13: Architecture of the smart meter with load control

The subsequent process carried out was calibration for ensuring precise measure- ments. The ADE7758 IC was calibrated by configuring offsets and gains through both nominal and test load conditions with respect to voltage and current measure- ments. Power calibration was further provided for active, apparent, and reactive power for refining its accuracy. Furthermore, a phase calibration was conducted in correcting the phase errors that affected the power factor measurements and ensuring that power offset calibration solved the errors during the time of low power measurement conditions.

The SMLC was integrated with IoT using the ESP32 microcontroller through MQTT protocol for efficient data transmission. The measurements were sent to a MongoDB Atlas cloud database in real time. A web application was also developed using Node.js and deployed on Heroku. The application was made available to the users, who could monitor electrical parameters in real time and also control connected devices manually or automatically. To minimize latency, data from the SMLC was transferred directly to the cloud interface via MQTT over WebSockets, achieving a response time of less than 500 ms.

The system was validated through extensive testing in both controlled laboratory conditions and real-life scenarios. In the laboratory, the SMLC's measurements were compared with a reference device (HIOKI PW3360-20) under various load conditions, including unity and non-unity power factors. The results indicated a Mean Absolute

Percentage Error of less than 1% for all measured parameters, thus proving the accu- racy of the system. Furthermore, a real-world implementation was performed in a household environment, where the SMLC successfully monitored and controlled appli- ances such as an electric heater and a coffee maker. Both manual control through the web application and automatic control, which was triggered when predefined power thresholds were exceeded, were demonstrated effectively.

In summary, the paper develops a comprehensive methodology for building an IoT-based smart meter with real-time monitoring, accurate energy measurement, and automated load control.

The scalability, precision, and user-friendly interface make it an effective tool for improving energy efficiency in home energy management systems.

Table 15: Components of Design and Development of an IoT Smart Meter with Load Control for Home Energy Management Systems

Category	Component	Description
Hardware	ESP32 Microcontroller	Manages data acquisition, processing, and communication over Wi-Fi.
	ADE7758 Energy IC	High-accuracy chip for measuring electrical parameters like power, voltage, and current.
	CST-1020 Current Transformer	Measures current non-invasively with high accuracy and safety.
	Voltage Divider Network	Reduces input voltage to a safe level for the ADE7758.
	SRA-05VDC-CL Relays	Controls the switching of loads for manual or automatic operations.
	Integrated Power Supply	HLK-PM01 module for powering the circuit components.
	Electrical Load Appliances	Household devices tested in the lab, such as lamps and heaters.
Software	Web Application	Provides user access to monitor and control the smart meter's operation.
	Wi-Fi Protocols	Facilitates communication between the ESP32 and the cloud/server.
	ADE7758 Configuration	Firmware implemented for setting up the IC to measure electrical parameters.

IV. RESULTS AND DISCUSSIONS

Performance analysis of the different energy monitoring and management systems shows that there is a wide range of capabilities and trade-offs depending on the design, scalability, and intended use of the system. The comparative assessment indicates that while some systems have superiority in real-time energy monitoring and cost efficiency, others focus on advanced features for renewable energy integration and optimization. The adaptability of these systems to different energy sources, ease of user interaction, and real-time responsiveness have to be considered in making choices for specific applications.

But these developments notwithstanding, there exist common challenges facing these systems, such as scalability limitation, hardware complexity, and non- smart devices, that hinder their full utilization. The results from the performance indicate which systems have strengths and weaknesses in areas where they should improve, giving a basis for further improvement in energy management technology.

A. Performance Analysis

The performance analysis of these energy monitoring and management systems high- lights the strengths and weaknesses in each, depending upon their design, application, and scale.

In summary, these systems perform with relative excellence in various perspectives: real-time monitoring, cost efficiency, integration with any energy source, and ease of use. Most are designed for small applications on residential or commercial lines with cost-effective and easy solutions that offer real-time data and basic control operations. However, there are also more complex systems of bigger scales that aim at adding more sophisticated elements like optimization of renewable energies, environ- mental metrics, or better analytics. Although the precision of all these systems and reliability in their scope of activity are quite excellent, selection among them basically depends on user needs in the respective application, scalabilities, and desired degree of complexity.

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The following sections will give detailed breakdowns of the performance of each system across the categories of energy monitoring, remote control, scheduling, and load management.

1) Performance Analysis on Energy Monitoring

The comparison of the two systems based on performance analysis presented in ”A Smart Energy Monitoring System Using ESP32 Microcontroller” and ”An IoT-Based Intelligent Smart Energy Monitoring System for Solar PV Power Generation” shows great differences between them in terms of functionality and application. The sys- tem based on ESP32 offers an economical and easy-to-use system for real-time energy monitoring in residential and small commercial installations. It provides seamless inte- gration to utility and private generator power sources focusing on affordability and simplicity, while the solar PV monitoring system focuses on optimizing renewable energy management by integrating environmental metrics into temperature and sun- light intensity. Therefore, this system offers finer data and advanced features in its solar energy generation but higher hardware complexity and larger upfront investment. Both systems provide high accuracy for their respective monitoring task; however, the choice would lie between them based on application requirements, whether it would need simplicity and cost-effectiveness or advanced renewable energy management [1, 2].

Figure 14, displays such features as real-time monitoring, cost efficiency, and scalability in a simple pictorial representation.

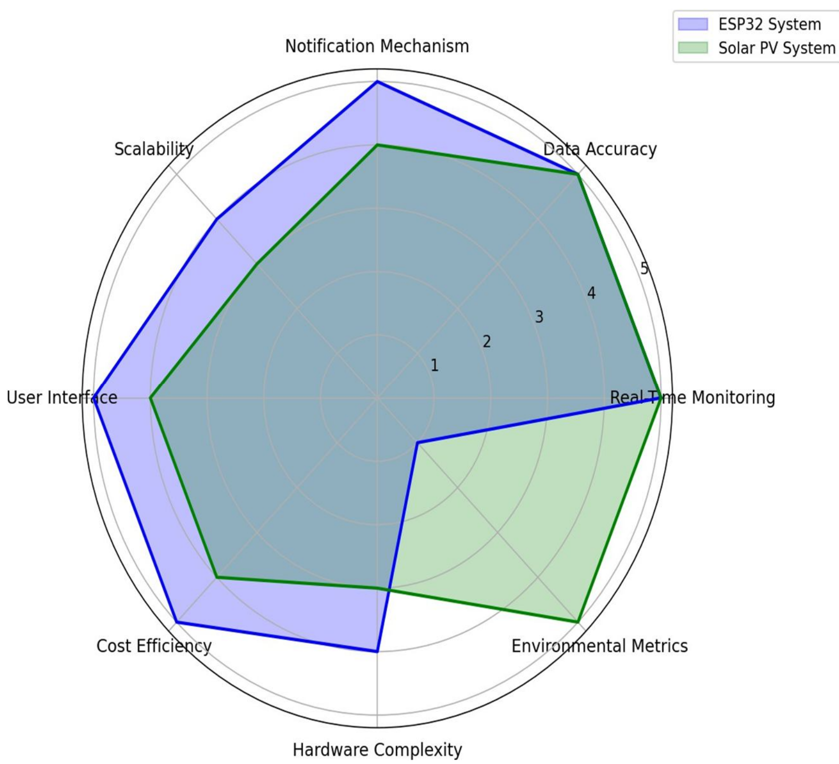

Fig. 14: Radar Chart on Energy Monitoring Systems

The radar chart clearly depicts each system’s strengths in various categories. ESP32-based system excelled in affordability and ease of integration, while the solar PV monitoring system excelled with regard to environmental data collection and optimization of solar energy.

Table 16, then gives more detailed performance data of systems in multiple per- spectives. Here, it compares and contrasts on metrics such as energy source integration, user interface, and hardware complexity, enabling a good distinction between suit- ability for certain use cases through the two systems. Again, its cost-effectiveness and simple nature make ESP32 suited for applications which require those features, with the Solar PV monitoring system being targeted as a far more elaborate system for applications under solar energy that require more data inputs.

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Table 16: Comparison of Smart Energy Monitoring Systems

Criteria	A Smart Energy Monitoring System Using ESP32 Microcontroller [1]	An IoT-Based Intelligent Smart Energy Monitoring System for Solar PV Power Generation [2]
Real-Time Monitoring	Provides real-time monitoring of energy consumption from utility and generator sources.	Monitors solar PV parameters (voltage, current, temperature, sunlight intensity) in real time.
Data Accuracy	High accuracy in monitoring using pulse-based energy meters.	High accuracy in solar energy monitoring with environmental parameters like sunlight and temperature.
Scalability	Suitable for small to medium-scale applications (residential/commercial).	Focused on solar energy applications; not easily scalable to large installations.
Energy Source	Monitors energy from utility power and private generators.	Primarily designed for solar PV energy generation monitoring.
User Interface	Uses Blynk platform for mobile/web-based data visualization and user interaction.	Uses ThingSpeak for cloud-based monitoring and data storage with graphical representation.
Cost Efficiency	Low-cost solution with minimal hardware requirements (ESP32 and basic components).	More complex, with additional components (Arduino, NodeMCU, sensors), making it costlier.
Notification Mechanism	Alerts and notifications sent via WhatsApp when energy consumption exceeds thresholds.	Relies on cloud-based visualization on ThingSpeak; lacks direct alert system.
Hardware Complexity	Simplified hardware setup with ESP32 as central processing unit.	More complex setup with Arduino for processing and NodeMCU for communication.
Environmental Metrics	Does not measure environmental factors (e.g., temperature, sunlight intensity).	Measures environmental factors like temperature and sunlight intensity to assess solar panel efficiency.

2) Performance Analysis on Energy Monitoring and Remote Control

The studies show some great contributions to energy management in smart home environments by focusing on optimization of energy consumption, enhancing user interaction, and providing scalable solutions. Scalability with advanced analytics is highly effective in large-scale implementations such as utilities or HVAC systems, emphasizing the use of IoT and Big Data for actionable insights. The other is practical and cost-effective in design and allows integration of both smart and non-smart appli- ances, especially very beneficial for the purpose of catering to different user groups in low-income regions. They achieve real-time responsiveness due to the effectiveness of the communication protocols used with differing analytics depth and adaptability. Collectively, the approaches point to the rising trend towards user-centric designs, affordability, and scalable architectures for smart energy systems [2, 4]. Figure 15, highlights key performance differences between the two systems.

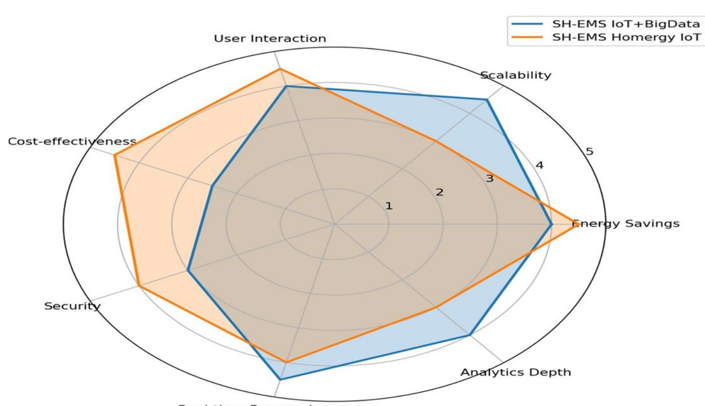

Fig. 15: Radar Chart on Energy Monitoring Systems and Remote Control

One system is scalable and analytics deep, making it ideal for large-scale imple- mentations, such as utility-level applications or advanced energy management. It provides high responsiveness and substantial energy savings through HVAC opti- mization. The other solution performs well in user interaction, cost-effectiveness, and real-time responsiveness, thus making it accessible to low-income households and environments with mixed appliance types. The visualization clearly shows how each of the approaches caters to a different need while performing very well in its respective area of focus.

Table 17, gives a structured comparison over the key parameters of energy savings, scalability, user interaction, and security. While one of the systems shows excellent performance in large-scale settings using high-end hardware and software, its cost and complexity are not feasible for larger usage. The second solution is more balanced in terms of affordability and functionality because of modular components that will be easy to adopt even in a household with multiple incomes and capabilities of devices.

The table clearly depicts how each system puts its unique strengths in priority, thus providing complementary solutions for smart energy management.

Table 17: Performance Analysis Comparison on Energy Monitoring Systems and Remote Control

Criteria	A Smart Home Energy Manage- ment System Using IoT and Big Data Analytics Approach [3]	Smart Home Energy Manage- ment System Based on IoT [4]
Energy Savings	Focuses primarily on HVAC systems; optimization of energy usage poten- tially up to 60%.	Measurable energy savings: Low-consuming house: 0.5 kWh/week, Single-user office: 0.35 kWh/week, High-consuming house: 13 kWh/week.
Scalability	Tested for scalability to support up to 1,000 concurrent users for large-scale deployment, such as utility-level.	Primarily designed for small to medium-scale households, with no extensive scalability testing for larger deployments.
User Interaction	Provides mobile app with remote appliance control, usage visualization, and energy consumption insights.	Mobile app enables easy control of appliances, with additional features like a rewards system for energy-efficient behaviors.
Cost-effectiveness	More expensive due to high-end hard- ware (SoC, sensors, and servers), lim- iting deployment in low-cost environ- ments.	Affordable setup using components like Arduino Mega and NodeMCU, making it suitable for low-income households.
Security	Basic security using HTTPS for secure communication but lacks advanced user authentication mechanisms.	Uses encrypted QR codes and access codes for secure appliance control, along with email-password authentica- tion for user access.
Real-time Responsiveness	High responsiveness with minimal latency, suitable for real-time data pro- cessing and control, using MQTT pro- tocol.	Real-time updates enabled through Firebase and WebSocket protocols, ensuring timely appliance control and monitoring.
Analytics Depth	Utilizes Big Data analytics and Busi- ness Intelligence tools for deep insights into energy consumption patterns and optimization strategies.	Basic analytics for device-level usage monitoring; lacks predictive or in- depth trend analysis.

3) Performance Analysis on Energy Monitoring and Control via Scheduling

A comparative performance analysis of the three studies about energy monitoring and control systems, it can be concluded that there is a prominent concentration on cost-cutting measures, energy efficiency, and user-centric design. In both systems, the advanced technological approaches are well-balanced with practical implementation. The TPC-aware energy management framework features a strong mechanism of cost savings in optimization of source selection and scheduling tasks on time and user preference basis.

The optimization framework for home energy management excels in convergence to user-defined bill targets under dynamic pricing schemes, where con- sumer satisfaction is of major importance.

Meanwhile, the controller boards based on IoT have real-world applicability; they allow for the smooth integration of smart devices through low-cost solutions and fuzzy logic-based automation for environmental control [5–7].

Figure 16, illustrates a comprehensive visual comparison of the systems across multiple performance criteria including cost reduction, energy consumption, scalability, and real-world implementation.

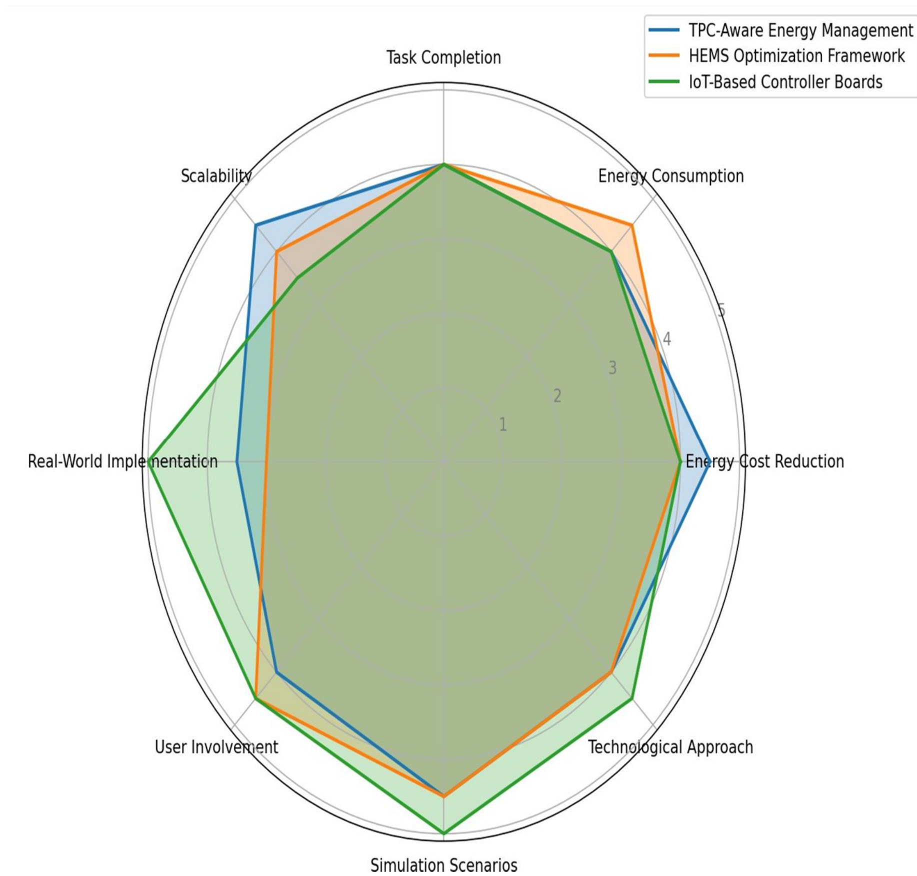

Fig. 16: Radar Chart on Energy Monitoring Systems and Control via Scheduling

The IoT-based controller boards showed excellent performance in the real-world testing and user involvement, which depicts the merits of their practical deployment. The TPC-aware framework depicted a well-balanced performance across all the criteria by focusing on cost reduction and scalability through energy source optimization. The optimization framework for energy management showed excellent performance in simulation scenarios and user-centric design while keeping the focus on consumer com- fort and dynamic pricing adaptation. These visual insights underscore the strengths and weaknesses of each approach to address energy management challenges.

Table 18, reflects the different approaches and results of the experiments, demon- strating their specific contributions to energy monitoring and control. The TPC-aware system's scheduling algorithm optimizes the use of energy sources with significant sav- ings in terms of cost and energy while having minor losses in terms of dropped tasks. The optimization framework includes advanced mathematical models that balance comfort and cost efficiency towards meeting monthly electricity bill targets. The IoT- based control boards, with their cheap hardware and open-source software, prove to be viable in the practical application in smart homes. This comparison, therefore, brings home the point that customized implementations are needed for different conditions to be energy-efficient.

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Table 18: Performance Analysis Comparison of Energy Monitoring Systems and Control via Scheduling

Criteria	TPC-Aware Energy Management [5]	HEMS Optimization Framework [6]	IoT-Based Controller Boards [7]
Energy Cost Reduction	Achieved up to 33% cost reduction by prioritizing renewable sources and optimizing task scheduling.	Successfully converged electricity costs to user-defined monthly bill targets under TOU and IBR pricing.	Cost reduction achieved by using low-cost IoT modules for smart home conversion and energy monitoring.
Energy Consumption	Reduced total energy consumption slightly by optimizing task scheduling.	Maintained energy efficiency while achieving desired bill targets.	Enabled monitoring of energy usage patterns, supporting demand-side management in smart grids.
Task Completion	Increased task execution on higher-priority energy sources but observed a slight increase in dropped tasks.	Effectively scheduled controllable appliances while maintaining user comfort.	Successfully controlled appliances through smart modules with reliable ON/OFF operations.
Scalability	Designed for multi-source energy systems; supports cloud integration for aggregated energy management.	Simulated multi-household energy trading scenarios with cooperative optimization.	Scaled for small to medium smart homes; limited testing for large-scale deployments.
Real-World Implementation	Simulation-based evaluation with realistic energy source constraints.	Simulation-based results; no physical implementation.	Successfully deployed in a residential setting for five months with stable performance.
User Involvement	Allowed users to modify suggested schedules while maintaining automated optimization.	Incorporated user-defined bill targets and comfort levels into the optimization process.	Provided a user-friendly interface for monitoring and controlling devices.
Simulation Scenarios	Simulated one-month energy usage for manual and automated scheduling to compare cost savings.	Evaluated single and multi-household setups under TOU and IBR pricing schemes.	Tested in real-time with data logging for energy, temperature, and humidity measurements.
Technological Approach	ZigBee-based communication and TPC-aware algorithm for scheduling.	MILP optimization for multi-day scheduling under dynamic pricing.	ESP-based IoT modules integrated with an open-source automation server using MQTT protocols. Also incorporated fuzzy logic for light intensity control, enhancing automation based on environmental conditions.

4) Performance Analysis on Energy Monitoring and Load Control

In terms of performance, the three studies collectively show significant improvements in energy monitoring and load control systems. These systems excel in achieving energy efficiency by using IoT technologies, smart metering, and advanced algorithms.

The solutions exhibit scalability and adaptability to various environments, such as residential, commercial, and industrial settings, while providing users with real-time monitoring capabilities. Effective load management is another common advantage.

Features such as load balancing, prioritization of critical loads, and dynamic schedul- ing ensure optimal energy use. One focuses on managing appliances at the household level, while the other centers its focus on feeder level load balancing in power grids.

The third integrates monitoring real-time parameters with smart energy meters. Together these emphasize the importance of the technology in improving energy efficiency and reliability [8–10].

Figure 17, compares the relative strengths of the three systems in different perfor- mance metrics like scalability, real-time monitoring, accuracy, and automation. All the systems possess strong strengths in real-time monitoring and web and mobile-based user interfaces make the system accessible.

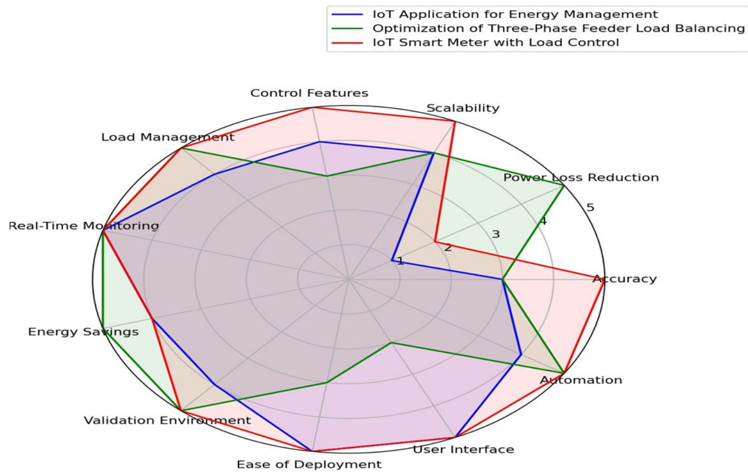

Fig. 17: Radar Chart on Energy Monitoring Systems and Load Control

Table 19 provides a detailed breakdown of the systems, offering insights into their practical applications and contributions to energy efficiency. Key metrics such as power loss reduction, control features, and energy savings are distinctly analyzed.

Table 19: Performance Analysis Comparison of Energy Monitoring Systems and Load Control

Criteria	IoT Application for Energy Management in Smart Homes [8]	Optimization of Three-Phase Feeder Load Balancing Using Smart Meters [9]	Design and Development of an IoT Smart Meter with Load Control [10]
Accuracy	Not explicitly mentioned.	Not explicitly mentioned but validates improvements in load balancing and voltage stability.	Measurement error of less than 1%.
Power Loss Reduction	Not applicable (focus is on household appliance management).	Reduced annual power losses by 253 IDs in the Irbid District Electricity Company case study.	Not directly addressed (focus on efficient load management and energy monitoring).
Scalability	System supports integration with additional devices and smart city frameworks.	Suitable for distribution networks and can scale with more feeders/customers.	Modular design adaptable to residential, commercial, and industrial applications.
Control Features	Remote control of appliances using mobile/desktop apps.	Automatic reconfiguration of feeder topology for load balancing and fault handling.	Manual and automated control of appliances with load prioritization and scheduling.
Load Management	Real-time monitoring and control of individual appliances, overload detection.	Redistribution of loads across three phases to maintain balance and reduce losses.	Load prioritization, scheduling, and anomaly detection.
Real-Time Monitoring	Voltage, current, and power consumption displayed via a cloud-based app.	Real-time data acquisition of voltage, current, and power using smart meters.	Real-time monitoring of multiple electrical parameters via a web interface.
Energy Savings	Focus on reducing energy wastage by controlling less critical appliances during peaks.	Achieved energy efficiency by minimizing technical losses.	Energy savings through load scheduling and deferred non-essential usage.
Validation Environment	Tested on three appliances with power ratings of 65W, 100W, and 120W under different scenarios.	Case study conducted on a three-phase feeder with 27 customers in a radial network.	Calibrated and validated in a laboratory environment with diverse appliance loads.
Ease of Deployment	Utilizes ESP8266 for cost-effective and straightforward integration.	Requires CYME software and MATLAB/Simulink for optimization; dependent on smart meters.	Simple IoT architecture without additional gateways, reducing deployment complexity.
User Interface	Mobile/desktop app for monitoring and control.	Not user-centric; focuses on grid optimization.	Web-based application for monitoring and controlling loads remotely.
Automation	Overload detection and automatic disconnection of lower-priority appliances.	Automated reconfiguration of feeder topology based on optimization results.	Automated load prioritization and scheduling.

B. Challenges and Limitations

The most important limitations that hinder the efficiency and scalability of energy monitoring and management systems, and, consequently, their adoption are related to scalability. These systems perform excellently at small-scale or controlled levels but are incapable of managing large-scale applications, including industrial and household levels where there is diversity in the energy sources. Internet dependency also poses a significant challenge as stable connectivity is required to ensure real-time monitoring and control, which can be an issue in remote or underdeveloped areas. Incorpora- tion of non-smart devices into energy management systems is also a persistent issue, mainly in areas that lack advanced technologies. The gap between smart and conventional devices in many systems creates a void that reduces their overall efficiency. In addition, hardware complexity in systems that integrate sensors, microcontrollers, and communication modules increases the cost of setup, maintenance requirements, and the possibility of errors in operation. Security and privacy issues also complicate adop- tion, as IoT-based systems often rely on cloud platforms, which expose sensitive user data without proper encryption and authentication mechanisms. In addition, a lack of interoperability standards among devices and platforms prevents these various energy sources-from renewables to grid power-from seamlessly integrating into the system, leading to inefficiencies in communication and control. Other major challenges include high upfront costs, which limit access to these systems, especially in poorer regions where affordability is an important concern. Lastly, achieving a balance between user comfort and automation while considering diverse consumer behaviors remains an unresolved issue, as many systems struggle to provide both adaptability and effi- cient automation simultaneously. These challenges highlight the need for innovative, scalable, and user-centric solutions that address system integration, accessibility, and real-time energy optimization across varied environments.

V. CONCLUSION AND FUTURE WORK

The survey emphasizes the crucial role of energy monitoring and control systems in optimizing energy consumption, enhancing efficiency, and fostering sustainability. Advanced IoT technologies allow these systems to monitor in real-time, prioritize loads, and integrate with renewable energy sources. Some of the most important inno- vations include smart scheduling, adaptive frameworks for energy management, and cost-effective retrofitting options for existing infrastructure. Although significant, some challenges persist with these systems: scalability, integration complexity, offline func- tionality, and data security, which means the development is still not mature enough to tackle different application scenarios. Overall, the surveyed systems indicate the transformational potential of intelligent energy management in cost reduction, over- load avoidance, and empowerment of users. These systems are crucial for achieving the goals of global energy sustainability and to meet the rising demand for smarter, more user-friendly, and adaptive solutions.

Future work in energy monitoring and control systems may focus on scalabil- ity, interoperability, and user-centric designs. One important application area is the design of scalable load balancing systems that manage energy distribution effectively while still accommodating user-defined priorities. Such features would help in smooth interfacing from individual home implementations to large-scale commercial/industrial applications. Other factors include the integration of advanced scheduling algorithms and dynamic pricing models, which can help optimize energy usage, reduce costs, and enhance overall system efficiency. Security measures should also be improved, such that the energy data is protected through robust encryption, secure communication proto- cols, and user authentication mechanisms. Affordability is another factor in increasing the adoption of these systems, especially in low-resource environments. More specif- ically, it should research cost-effective options like modular hardware designs and optimized software that would maintain the level of performance without sacrificing accessibility. Ultimately, development of more intuitive, more user-configurable user interfaces would let technical and non-technical users alike monitor and manage their energy consumption effectively, and it would make the system even more user-friendly for people to adopt. By addressing these challenges, future systems will be able to deliver more efficient, secure, and accessible energy management solutions.

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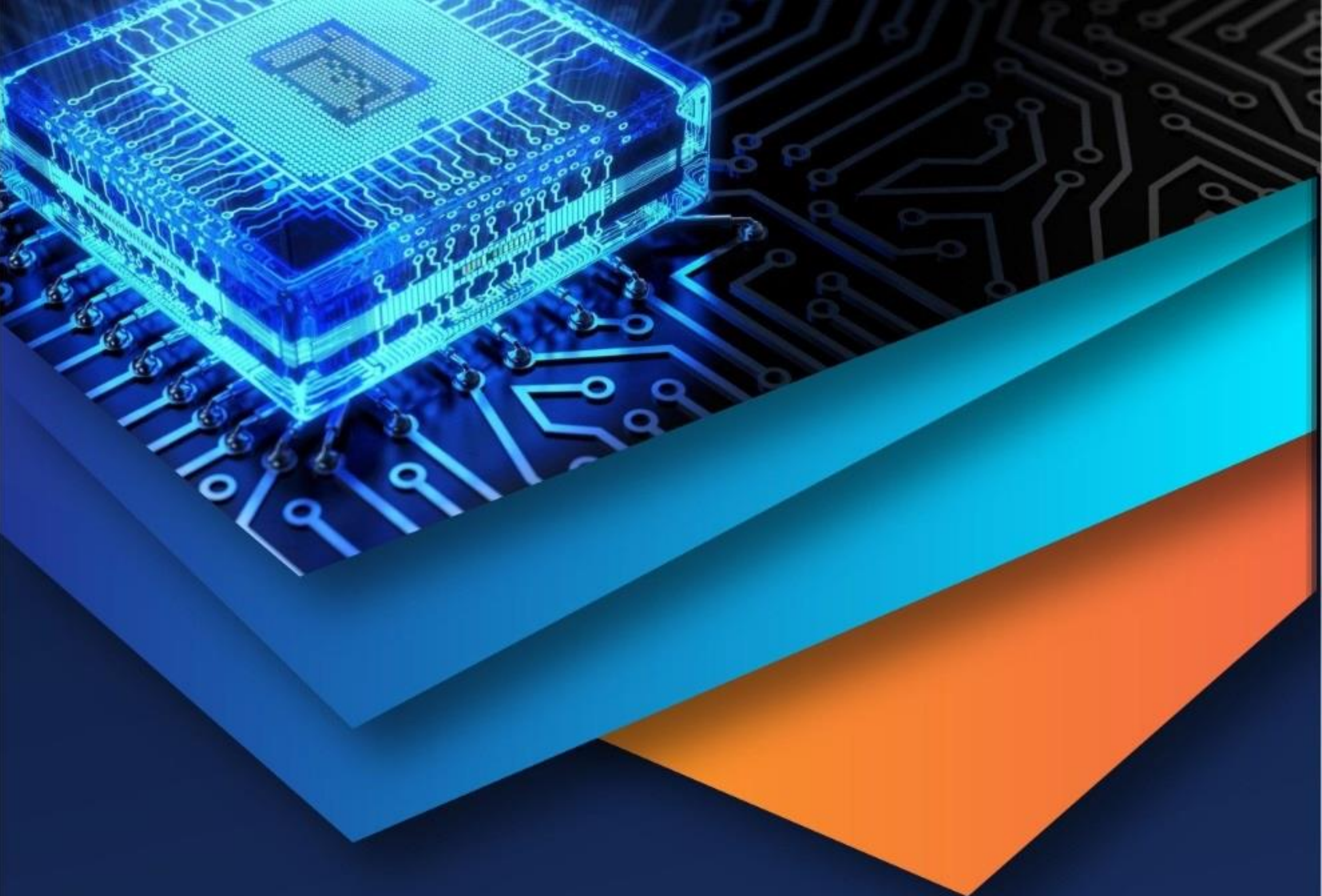

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