

IoT-Driven Energy Monitoring Framework: Enhancing Efficiency, Sustainability, and Real-Time Optimization

¹M. Ajmal Khan

Department of Electrical and Computer Engineering

Ohio Northern University, USA

¹m-khan.2@onu.edu

²Gulnara Bektemyssova

Department of Computer Engineering and Information System, International

Information Technology University

Almaty Kazakhstan

²g.bektemisova@iitu.edu.kz

³Abdul Razaque*

Department of Cybersecurity International Information Technology

University, Almaty Kazakhstan

a.razaque@iitu.edu.kz

³Anar Beketova

Automation and Control Systems Department

Satbayev University

Almaty, Kazakhstan

³941001451133-D @

stud.satbayev.university

⁵Hari Mohan Rai

School of Computing

Gachon University

South Korea

⁵drhmrai@gachon.ac.kr

⁶Meer Jaro Khan

Department of Computer Engineering

International Information Technology

University, Almaty, Kazakhstan

⁴j.meer@iitu.edu.kz

Abstract—Energy waste is a critical issue, driving up utility costs and harming the environment. Traditional energy monitoring systems are passive, lacking real-time optimization, which leads to unattended energy consumption and inefficiency.

This article introduces IoT-based energy meters (IoT-EM) to provide a real-time approach to energy management, offering actionable insights and enabling immediate adjustments. By monitoring energy usage at the appliance level, these smart meters help users identify inefficiencies, reduce costs, and improve energy efficiency. Despite their benefits, IoT energy meters face challenges, such as data privacy concerns and the complexity of managing large-scale systems. This paper examines IoT energy metering systems, addressing their potential to improve energy management performance, modernizing outdated infrastructure, and reducing environmental impacts.

Keywords—Energy waste, IoT-based energy meters, real-time monitoring, smart meters, optimization.

I. INTRODUCTION

Businesses and consumers confront economic and environmental concerns from energy demand. Cost-saving and environmental protection necessitate energy monitoring. Passive meters reduce efficiency. However, IoT-enabled energy meters improve everyday management [1]. Outdated infrastructure hinders energy management. Traditional systems lack real-time optimization and analysis; therefore, energy usage trends are unknown until billing cycles. Many energy issues remain unresolved. Energy-intensive and inadvertent waste necessitate real-time monitoring and reporting [2]. Inefficiencies in finance and operations hurt businesses and people [3]. Cleaning PV panels and smart thermostats for home productivity and temperature management save waste. Cloud storage and machine learning for user data analysis and energy optimization are promising [4]. However, these systems rarely provide real-time energy use data. Energy meters with IoT work better. Active monitoring and real-time waste tracking save families and businesses energy using these meters. With adaptive optimization, energy waste, expenses, and resource use reduce. Real-time IoT energy usage assessments improve efficiency [5]. Outdated infrastructure causes energy waste and pollution. Monitoring slowly wastes money, energy, and resources [6]. Old infrastructure and data gaps increase these

inefficiencies, especially when residential and commercial buildings' energy demands strain systems to reliably manage complex processes. Ineffective energy monitoring raises peak demand, carbon footprints, outages, and network pressure [7]. Traditional energy management ignores inefficiencies, therefore proactive energy control is essential [8]. Waste reduction and inefficiency alarms are automated via IoT energy monitoring. Smart meters swiftly repair inefficient appliances and integrate renewable energy and energy-saving technologies into management systems. Scalable IoT predictive maintenance cuts household and company costs and errors [9]. The complexity of managing enormous data quantities, privacy concerns, and high initial expenses are IoT challenges. When deploying IoT in old infrastructure, consider cybersecurity. Data breaches can reveal personal usage patterns or affect business operations; thus, data protection is crucial. Since IoT integration into conventional systems is expensive and complicated, new solutions are needed. Data is secure and decentralized with edge and blockchain. The proposed IoT-based energy monitoring framework prioritizes data security, scalability, and real-time optimization. Architecture solves modern energy system problems while minimizing waste, prices, and environmental effects. This forward-looking energy management plan supports global resource efficiency and climate change with sustainable energy management.

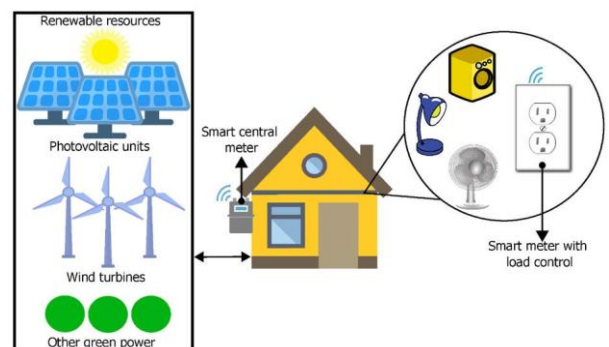


Fig. 1. IoT-Enabled smart energy management system integrating renewable energy and load control

A. Research Contribution

The main contributions of the article are summarized.

- Combines real-time monitoring, adaptive algorithms, and secure data management to make energy use more efficient.
- Functions in residential, commercial, and industrial environments while also providing support for legacy systems and renewable energy sources.
- Uses encryption and secure connection to keep important energy data safe.

II. RELATED WORK

This section analyzes current advancements in IoT-enabled energy monitoring systems. Ali et al. [10] examined the role of IoT-enabled technologies in facilitating real-time energy monitoring and management inside smart grids. Their research emphasizes that improved data collecting, and analysis could mitigate energy loss, although it also recognizes that scalability in extensive networks poses a considerable barrier. Kumar et al. [11] concentrated on the advantages of long-term energy analytics and remote monitoring through cloud-integrated IoT devices. Nonetheless, due to the technique's need for stable internet access, they identified a considerable drawback in regions with inadequate network infrastructure. Nikpour et al. [12] developed an innovative IoT system for smart cities that enhances energy management with machine learning techniques. This approach, while successful, is less appropriate for resource-constrained applications due to its substantial processing requirements. Shivaraman et al. [13] examined IoT-enabled mobile devices for real-time energy monitoring to enhance user control and transparency. They acknowledged that connecting IoT devices to conventional infrastructure presents specific obstacles. Giordano et al. [14] proposed adaptive sampling algorithms for IoT devices to enhance energy efficiency in limited settings. This approach's scalability is constrained by substantial initial installation expenses, despite its potential.

III. PROPOSED ENERGY MONITORING MODEL

Intelligent energy optimization is attained by the application of sophisticated predictive models and reinforcement of learning algorithms in energy monitoring. The cloud gathers energy meter data from both wired and wireless edge nodes. Our objective is to eradicate energy waste, enhance efficiency and sustainability, and empower consumers to make choices. Wired energy meters at energy points deliver accurate data, while wireless meters in various industrial assets and processes offer consumption patterns. Hybrid industrial methodologies are present. Edge layer processing reduces latency and enhances efficiency following data acquisition. The edge rule engine produces nine energy indicators from raw data to identify inefficiencies and consumption trends. Edge database servers momentarily retain filtered and processed data. Cloud data filtration and transmission necessitate more processing power and bandwidth. Users can track consumption patterns, assess statistics, and make energy-efficient choices using an interactive interface. It facilitates real-time edge decision-making and cloud-based energy efficiency, sustainability, and management reporting. The system consists of an edge layer and a cloud platform,

forming an energy metering system (Figure 2). It oversees 19 industrial assets or processes utilizing connected and wireless energy meters. Wireless energy meters transmit data to a gateway, whereas wired meters aggregate data from many locations. These elements utilize MQTT. This layer processes data locally utilizing an edge device. The edge rule engine computes nine innovative energy parameters, while the database server retains the data. The edge machine utilizes gRPC to transmit only pertinent data to the cloud platform, enhancing data transmission efficiency. The cloud platform utilizes a tailored user interface to store, analyze, and engage with processed data. This arrangement facilitates data management, real-time energy monitoring, and enhanced operational decision-making.

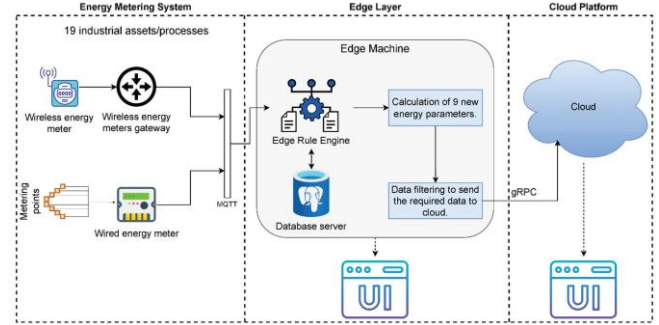


Fig 2: Overview of the energy metering system architecture

Lemma 1: The proposed IoT-based energy monitoring system can reduce energy wastage by at least $E_w\%$. where E_w depends on the accuracy of real-time data aggregation and optimization.

Proof: The energy wastage reduction E_w is expressed as a function of real-time data aggregation D_a and the optimization efficiency E_o .

$$E_w = \gamma \cdot D_a + \beta \cdot E_o \quad (1)$$

Where γ and β denote the weighting coefficients that reflect the relative impact of data suggestion and optimization on reducing energy wastage.

Model efficiency is of paramount significance. Thus, model efficiency M_e can be calculated as follows:

$$M_e = \left(\frac{E_t - E_w}{E_t} \times 100\% \right) \quad (2)$$

Where E_t denotes total consumed energy, and E_w is the total wastage energy.

Corollary 1: IoT-driven energy monitoring frameworks change energy management with real-time optimization, operational efficiency, and sustainability. This system tracks, analyzes, and adjusts energy use to reduce waste, costs, and environmental impact. Modern IoT technologies like adaptive algorithms and edge computing allow residential and industrial customers to create scalable and sustainable energy solutions while addressing infrastructure restrictions and data security.

Proof: The relationship can be captured between real-time monitoring, edge computing, adaptive technologies in reducing energy waste and achieving energy usage. Thus, optimized energy usage E_o can be calculated as follows:

$$E_o = f(E_m + A_a + C_e + T_{rt}) - E_w \quad (3)$$

Where E_m denotes optimized energy usage, A_a is the adaptive algorithms enabling dynamic adjustments, C_e is the

edge computing capabilities for localized processing and real data analysis, and T_{rt} is the real-time optimization processes.

IV. EXPERIMENTAL SETUP AND RESULTS

The proposed intelligent energy monitoring system is outfitted with sophisticated hardware and software for optimal performance. The experimental setup comprises a high-performance computational environment capable of managing a substantial volume of intricate activities associated with energy data processing. The system incorporates both edge devices and cloud infrastructure, facilitating real-time monitoring and processing capabilities. Edge devices, encompassing both wireless and cable energy meters, aggregate unprocessed energy data from many sources. These devices locally preprocess data utilizing rule engines to calculate significant metrics. The analyzed data is subsequently consolidated and transmitted to a cloud platform for additional analysis and optimization. This hybrid methodology guarantees scalability and reduces latency in decision-making processes. The system's software stack utilizes Python (version 3.12.1, 64-bit) as the principal programming language. PyCharm functions as the integrated development environment (IDE), facilitating real-time code execution and debugging. Machine learning libraries, including Scikit-Learn, NumPy, and TensorFlow, are utilized to execute predictive and reinforcement learning algorithms for energy optimization. Table-1 summarizes the used tools.

TABLE I
TOOLS AND THEIR DESCRIPTION FOR CONDUCTING THE EXPERIMENTS

Tools	Description
Programming Language	Python (version 3.12.1, 64-bit)
Development Environment	PyCharm
Machine Learning Libraries	Scikit-Learn, NumPy, TensorFlow

A. Energy Efficiency

Figure 3 compares the energy efficiency of the proposed IoTEM framework to a strategy that does not employ the IoTEM framework. The y-axis denotes the relevant energy efficiency as a percentage, while the x-axis signifies the total number of IoT devices (up to 1000). The energy efficiency of the proposed IoTEM architecture is markedly superior, starting at nearly 100% and gradually decreasing to a minimum of 82% efficiency with 1000 devices. This performance is attributed to the framework's intelligent energy management and resource allocation. The energy efficiency of the technique without the IoTEM framework, on the other hand, decreases markedly, reaching only 56% at 1,000 devices. The lack of a defined architecture leads to inefficient power use and increased energy waste as the network grows. The results highlight the necessity of including the IoTEM framework into large-scale IoT deployments, ensuring energy efficiency amid the growing quantity of connected devices. The considerable performance disparity between the two methods underscores the need to develop an effective energy management strategy to improve system dependability and durability.

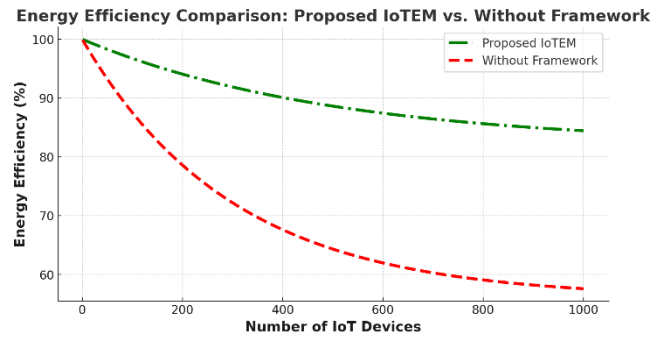


Figure 3: Energy efficiency of the proposed IoTEM and without IoTEM framework

B. Sustainability

Figure 4 compares the sustainability of the proposed IoTEM framework to the framework without IoTEM across 1000 IoT devices. The proposed IoTEM architecture produces a high level of sustainability, which starts with 100% and remains over 90% despite an increase in the number of devices. This indicates that the IoTEM framework effectively manages resources and improves system performance. In contrast, the framework without IoTEM starts at about 80% sustainability but quickly deteriorates as the number of IoT devices increases, dropping to around 60% at 1000 devices. The lack of a systematic optimization procedure causes an increase in deterioration rate, which makes the system less sustainable over time.

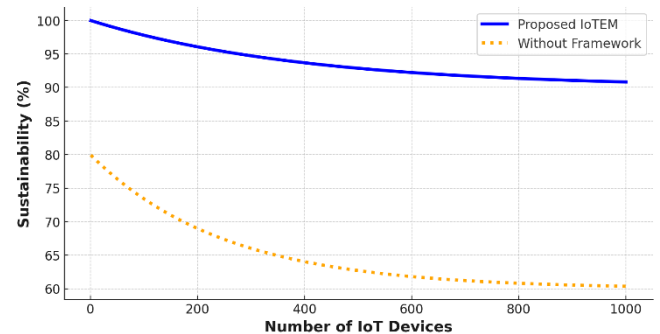


Figure 4: Sustainability of the proposed IoTEM and without IoTEM

C. Real Time Optimization

Figure 5 depicts the real-time optimization efficacy of the proposed IoTEM framework in comparison to a method lacking a framework across 1000 IoT devices. The suggested IoTEM framework, indicated by the solid purple line, has a high degree of optimization, commencing at almost 100% and remaining over 95% despite the increase in the number of IoT devices. This performance demonstrates the framework's efficacy in dynamically allocating resources and guaranteeing optimized system responsiveness under real-time settings. Conversely, the framework-less strategy, represented by the dotted brown line, initiates at nearly 90% but undergoes a gradual fall, ultimately achieving around 70% with 1000 IoT devices. The absence of an optimization mechanism leads to diminished performance as the system expands.

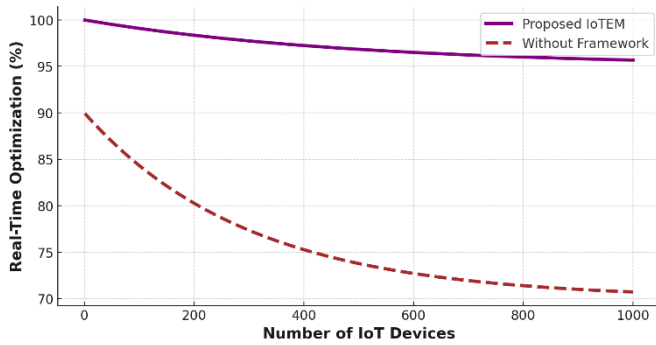


Figure 4: Real-time optimization of the proposed IoTEM and without IoTEM

V. DISCUSSION OF RESULTS

IoT-Driven Energy Monitoring Framework experiments show better energy efficiency, sustainability, and real-time optimization than standard systems. Energy waste, resource allocation inefficiencies, and traditional infrastructure's lack of adaptive energy management can be reduced using the framework. Studies demonstrate the IoTEM framework outperforms current energy efficiency strategies. IoTEM framework is 100% efficient at first but 82% at 1000 IoT devices. This loss is small compared to the non-IoTEM approach, which drops efficiency to 56% without adaptive optimization. These results show that real-time monitoring and intelligent energy management reduce residential, commercial, and industrial energy waste and electricity costs. Sustainability assessment highlights IoTEM's benefits. As IoT devices grow, sustainability stays over 90%, demonstrating resource management. Sustainability lowers from 80% to 60% without IoTEM for the same equipment. The non-IoTEM architecture falls quickly due to poor energy allocation and higher operational costs due to lack of systematic optimization. In large-scale IoT installations, IoT-based real-time monitoring may increase energy management system lifespan and reliability, ensuring sustainable resource utilization. The IoTEM framework optimizes about 100% and over 95% with more IoT devices. This remarkable performance shows the framework's capacity to dynamically distribute energy and respond to operational situations. However, non-IoTEM optimization starts at 90% and drops to 70% as the system scales. Traditional energy allocation without adaptive energy management is inefficient and slows systems.

VI. CONCLUSION AND FUTURE WORK

IoT-based energy-efficient meters are introduced. Internet of Things provides a breakthrough technique for controlling energy by eliminating waste, enhancing efficiency, and guaranteeing sustainable operations. The framework that has been offered gives a solution that can be altered and scaled for residential, commercial, and industrial environments. It shows that it can upgrade infrastructure that is no longer up to date while reducing the negative effects on the environment. Based on the results, the proposed methodology IoTEM obtained improved energy efficiency, real-time optimization, and sustainability as compared with technique without IoTEM framework. Future work should concentrate

on strengthening data security, cutting implementation costs, and enhancing predictive analytics to achieve even higher optimization and operational robustness.

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