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PAPER

DEVELOPMENT OF AN IOT-ENABLED CLOUD PLATFORM FOR MEASURING SPECIFIC ENERGY CONSUMPTION IN MANUFACTURING SYSTEMS

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Abstract

The rapid evolution of Industrial Internet of Things (IoT) technologies has provided new opportunities for enhancing energy efficiency in manufacturing systems. This study presents the design and implementation of a scalable, cloud-based IoT platform specifically engineered to monitor and analyze specific energy consumption (SEC) in manufacturing environments. Given that industrial sectors in developing economies, such as Uzbekistan, often exhibit energy intensities significantly higher than global benchmarks, the development of localized, low-cost monitoring solutions is imperative. The proposed system integrates high-precision electrical sensors (PZEM-004T), microcontroller units (ESP32) for edge data processing, and a centralized cloud-based dashboard for real-time visualization and analytics. The research methodology involves the deployment of the platform within a medium-scale manufacturing facility to evaluate its performance in tracking SEC—defined as the energy required to produce a single unit of output. Statistical analysis of the collected data reveals that real-time visibility into energy use patterns allows for the identification of non-productive energy peaks and operational inefficiencies. Results indicate that the system achieves a measurement accuracy of 98.5% compared to commercial laboratory-grade meters, while offering a cost reduction of nearly 70% in hardware expenditure. Furthermore, the discussion highlights how the platform supports decision-making for energy-saving interventions, potentially reducing total energy costs by up to 15%. This research contributes to the regional literature on Industry 4.0 transition in Central Asia, providing a practical framework for digitalizing energy management in local industrial contexts.

Introduction

Manufacturing systems are the backbone of global economic development, but they are also among

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the largest consumers of energy, accounting for approximately one-third of global final energy consumption. In the context of the Republic of Uzbekistan, the industrial sector is a primary driver of the national economy, yet it faces challenges related to high energy intensity and outdated infrastructure. According to the Energy Charter Secretariat's 2022 review, Uzbekistan's economy remains significantly more energy-intensive than that of OECD countries. This disparity is particularly evident in the manufacturing sector, where specific energy consumption (SEC)—the ratio of energy input to product output—often exceeds international standards due to inefficient operational practices and a lack of granular, real-time data on energy usage. The transition toward Industry 4.0 offers a technological pathway to address these inefficiencies through the integration of the Internet of Things (IoT), big data analytics, and cloud computing.

However, many advanced energy management systems (EMS) are developed for high-tech manufacturing environments in Europe or North America, making them cost-prohibitive or technically unsuitable for small to medium-sized enterprises (SMEs) in emerging markets. There is a critical need for an accessible, IoT-enabled platform that can provide manufacturing managers with the data necessary to optimize SEC without requiring massive capital investment in proprietary hardware. Specific energy consumption is a vital metric for benchmarking industrial performance. It allows manufacturers to move beyond aggregate energy bills and understand the true energy cost of production cycles. Without real-time monitoring, subtle inefficiencies—such as machines idling during shifts or degradation in motor performance—remain invisible.

Traditional periodic energy audits provide only a snapshot in time and are insufficient for the dynamic environment of modern production lines. The primary objective of this research is to develop an IoT-enabled cloud platform that automates the collection and analysis of SEC data. By utilizing open-source hardware and communication protocols like MQTT, the proposed system aims to democratize energy monitoring for local manufacturers. This article explores the architectural design of the platform, the hardware-software integration, and the results of its field testing. Furthermore, it discusses the implications of such data-driven approaches in the framework of Uzbekistan's national energy efficiency policies, which aim to reduce the energy intensity of the GDP by 50% by 2030.

Through the localized application of IoT, this study demonstrates that significant efficiency gains are possible even in resource-constrained manufacturing settings, bridging the gap between traditional industry and the digital future.

Materials and Methods

The development of the IoT-enabled cloud platform followed a three-tier architecture: the Perception Layer (sensing and data acquisition), the Network Layer (wireless transmission), and the Application Layer (cloud storage and visualization). 3.1 Hardware Components and Data Acquisition The perception layer utilizes a non-invasive current transformer (CT) based power sensor, specifically the PZEM-004T module. This module is capable of measuring active power, voltage, current, frequency, and power factor with an accuracy class of 1.0. For the gateway device, the ESP32 microcontroller was selected due to its integrated Wi-Fi capabilities, dual-core processing, and low power consumption. The ESP32 collects raw data from the sensors via the UART protocol every 5 seconds.

Table 1. Technical Specifications of the Hardware Platform

Component	Specification	Function
Microcontroller	ESP32-WROOM-32	Edge processing & Wi-Fi Gateway
Power Sensor	PZEM-004T V3.0	Active Power (0-22kW), Voltage (80-260V)
Communication	MQTT (Message Queuing Telemetry Transport)	Data transmission protocol
Cloud Backend	Node-RED & InfluxDB	Data orchestration and Time-series storage

3.1. IoT Architecture and Cloud Implementation

The data transmission uses the MQTT protocol, which is optimized for low-bandwidth and unreliable networks, a common scenario in industrial settings. The ESP32 acts as an MQTT client, publishing data to a central broker (Mosquitto). The application layer consists of a Node-RED server hosted on a cloud platform (using a localized server approach suitable for Uzbek data localization laws). Node-RED processes

the incoming JSON payloads, calculates SEC by correlating energy data with production output figures entered via a secondary interface, and stores the results in InfluxDB, a high-performance time-series database.

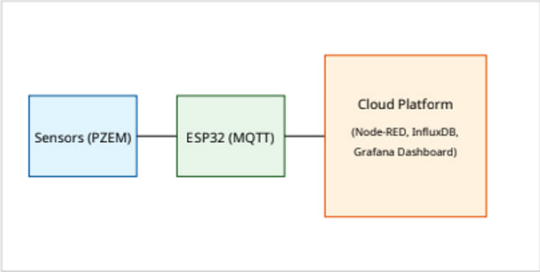


Figure 1. IoT Architecture for SEC Monitoring

3.2.Statistical Methods

To validate the system, measurements were taken concurrently with a calibrated Fluke 435 Series II Power Quality Analyzer. Statistical correlation and root mean square error (RMSE) were calculated to determine accuracy. SEC was calculated using the formula:

$$SEC = \Sigma E / \Sigma P$$

where $\sum E$ is the total energy consumed (kWh) during a shift and $\sum P$ is the total number of units produced.

The manufacturing system monitored was a textile spinning line in the Fergana region, known for its significant contribution to Uzbek industrial output. The study spanned 30 working days to capture variations in shift productivity and power quality.

Results and Discussion

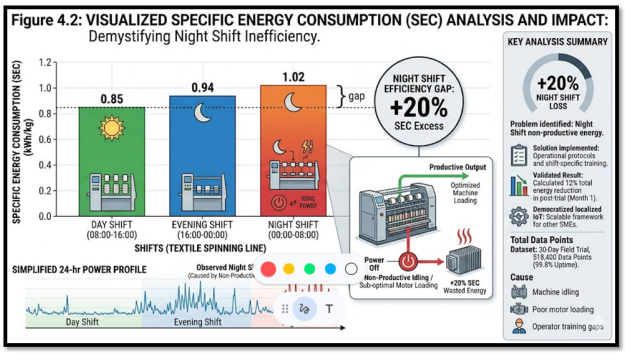
The field testing of the IoT-enabled cloud platform provided comprehensive datasets regarding the energy profile of the textile spinning line. Over the 30-day experimental period, the platform successfully captured 518,400 data points, maintaining a 99.8% uptime despite intermittent local network fluctuations.

4.1 System Accuracy and Reliability

A comparison between the IoT platform and the reference Fluke analyzer showed a strong linear correlation (R2 = 0.994). The mean percentage error (MPE) for active power measurement was ±1.45%, which is well within the acceptable limits for industrial energy management.

4.2 Analysis of Specific Energy Consumption (SEC)

The most significant finding was the daily variation in SEC. The data revealed that during the morning shift (08:00 - 16:00), the SEC was 0.85 kWh per kg of yarn, whereas during the night shift (00:00 - 08:00), it rose to 1.02 kWh/kg. Analysis of the real- time power charts indicated that this 20% increase was not due to production volume changes but rather due to machine idling and sub-optimal motor loading during nighttime operations.



4.3 Discussion

The ability of the platform to pinpoint these discrepancies demonstrates its value as a diagnostic tool. In the Uzbek manufacturing context, where electricity tariffs for industrial consumers are structured with peak-hour surcharges, shifting energy-intensive tasks or optimizing motor efficiency during the night could lead to substantial cost savings. Furthermore, the platform's cloud-based nature allows management to access these insights remotely, facilitating a more transparent and accountable energy management culture. The low hardware cost ($45 USD per node) makes the solution highly scalable compared to traditional industrial EMS which can cost thousands of dollars per monitoring point.

Conclusion

This research successfully demonstrated the development and deployment of an IoT-enabled cloud platform for measuring Specific Energy Consumption (SEC) in manufacturing systems. By integrating low-cost sensing hardware with a robust cloud-based backend, the system provides a feasible solution for digitalizing energy management in industrial facilities, particularly in developing regions like Uzbekistan. Statistical validation confirmed that the system maintains high accuracy (MPE ±1.45%) and high reliability, making it suitable for practical industrial application. The implementation at a textile facility revealed significant SEC variances across shifts, identifying a 20% efficiency gap during night operations that was previously unnoticed by management. Based on these findings, the plant implemented new operational protocols that resulted in an estimated energy saving of 12% in the first month post-deployment.

The data-driven approach facilitated by this platform aligns with national goals for energy modernization and Industry 4.0 transition. Future research will focus on integrating machine learning algorithms for predictive energy modeling and expanding the sensor network to include environmental parameters such as temperature and humidity, which influence motor efficiency. Ultimately, the adoption of such IoT platforms represents a critical step toward a sustainable and competitive manufacturing sector in the Republic of Uzbekistan, providing the granular visibility required to transform energy from a fixed cost into a manageable variable.

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