

# IoT-Integrated Smart Energy Meter for Industrial Energy Monitoring

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**Abstract** - Electric energy monitoring in industrial loads like pressure die casting is extremely vital especially due to their energy handling requirements. This work details the conception and implementation of an Internet of Things based Smart Energy Meter designed specifically for Industrial purposes. The system can measure three-phase voltage, current (up to 100A) and furnace temperatures with the aid of Resistance Temperature detectors. Using the ESP32 microcontroller and the Blynk Internet of things platform, the meter enables the collection, storage, and displaying of the data on the Cloud in real time. In order to enhance accuracy, the hardware architecture combines ZMPT101B voltage sensors, SCT-013-000 current sensors and a MAX31865 Resistance Temperature detector module. The software part of the system uses the Open-Energy Monitor library which contains various algorithms for energy calculations and transfers data over Serial peripheral interface/Wi-Fi protocols. The system has been tested in an industrial setting and the results have shown an accuracy of measurement within a tolerance of 1% for electrical and thermal characteristics plus a normal operation for variable conditions. The presented results prove the possibility of intra- system energy optimization and the industrial prospects of its application. Promising research directions include the addition of predictive maintenance features based on machine learning as well as more efficient scaling to support many different industrial applications.

**Key Words:** Smart Energy Meter, IoT, ESP32, RTD Sensors, Energy Monitoring, Industrial Automation

## 1. INTRODUCTION

The growing demand for sustainable energy management in industrial settings has intensified the need for precise, reliable, and scalable energy monitoring systems. Traditional energy meters often fall short in meeting the evolving requirements of modern industries, where real-time data acquisition, remote monitoring, and actionable insights are paramount. The advent of the Internet of Things (IoT) has revolutionized energy management by enabling the integration of intelligent monitoring devices with cloud platforms, thereby facilitating real-time decision-making and predictive analytics. This study

presents the development of a Smart Energy Meter tailored for industrial applications, which addresses critical challenges such as high-frequency electrical noise, harsh environmental conditions, and fluctuating energy demands. The system leverages advanced hardware components, including Resistance Temperature Detectors (RTD), ZMPT101B voltage sensors and SCT-013-000 current sensors, to ensure precise measurement of energy parameters. Furthermore, the integration of an ESP32 microcontroller enables seamless data acquisition and communication with the Blynk IoT platform, allowing for real-time data visualization and remote control. The custom-designed printed circuit board (PCB) enhances reliability by incorporating robust power management circuits and protection mechanisms. The proposed design offers a platform for future advancements, including the incorporation of three-phase energy metering Integrated Circuits (IC), predictive maintenance algorithms, and a standalone data management system to enhance scalability, security, and operational efficiency. By combining IoT-based architectures with modular hardware and software frameworks, this work paves the way for innovative energy optimization solutions, empowering industries to achieve greater sustainability and cost-effectiveness in their operations

## 2. HARDWARE DESIGN

The hardware design of the smart energy meter that supports IoT applications is the main ingredient of the industrial design. This encompasses high-accuracy sensors, robust microcontroller unit, custom PCB layout and design, and sturdy casing. This design allows the energy parameters to be measured with precision and ensures accuracy under the industrial settings. For the three-phase voltage control, ZMPT101B voltage sensors are used. They give isolated voltage feedback, and they are also very accurate in terms of measurements with high sensitivity and a low error margin enabling them to be used in real-time voltage measurement. SCT-013-000 non-invasive AC current sensors are used for current monitoring which enables safe and precise measurement of up to 100A current. To interface the sensors with the Analog to Digital Converter (ADC) of the ESP32 microcontroller, a current to voltage conversion circuit is used.

For temperature measurement, PT100 and PT1000 RTDs which are capable of measuring temperature of up to 1000°C are used. These RTDs are connected with the MAX31865 RTD to DDC converter module which converts the data to ensure it is clear with no noises and can operate in challenging conditions.

The brain of the system is the ESP32 microcontroller, a dual core processor with Wi-Fi and lots of GPIO. The ESP32 is responsible for real time data acquisition, calculation of critical energy parameters (power factor and real power) and cloud connectivity through the Blynk IoT platform. This allows for data visualization and remote monitoring and hence improves operational efficiency and energy optimization. A custom-designed PCB serves as the backbone of the system, ensuring efficient integration of sensors and modules while maintaining robust performance in industrial environments. The PCB incorporates low-dropout (LDO) voltage regulators to provide stable power to the sensors and micro- controller, as well as overcurrent and overvoltage protection circuits to safeguard the system against electrical anomalies.

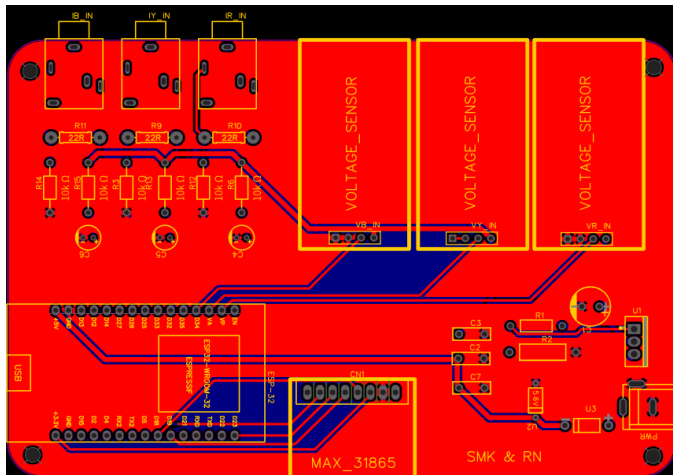


Fig -1: PCB Layout

The PCB layout has been optimized at great length for size and reliability, allowing for easy installation and maintenance. For the hardware design, Figure 1 is the PCB layout which shows how close you can place the components and the routing.

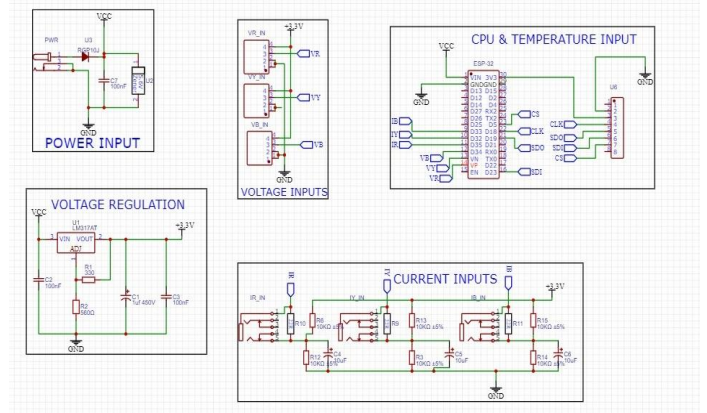


Fig -2: Circuit Diagram

The circuit diagram which shows how to connect the sensors with the microcontroller and modules is shown in Figure 2. It builds on an in-house 3D-printed enclosure constructed from industrial-grade materials and houses these hardware components. It’s a solid enclosure that helps prevent damage from heat, dust, and mechanical wear, which is especially helpful because these systems live in industrial settings, where conditions can get harsh. Thanks to its modular design, sensors are easy to install and maintain in different operating environments, and the compact form factor makes deployment in space-constrained environments possible.

### 3. SOFTWARE ARCHITECTURE

The software aims to strike a balance between precision and usability while integrating with existing smart IoT platforms. Our architecture is supported by smart computational frameworks, reliable communication protocols, and human-centric inter- faces to accurately monitor energy and take real-time decisions in industrial settings. The Open-Energy Monitor library is the basis of the software at the heart of the application, designed specifically for high precision energy monitor applications. This allows for the calculation of RMS (for voltage and current) so that the values measured meet the real-life electrical demands. The library also computes important power metrics such as real power, apparent power, and power factor using sophisticated mathematical models and algorithms. Analysis of these metrics contributes significantly to mastering the energy consumption behavior of a production process, which is key to industrial energy management. It then combines with a temperature data processing module which uses MAX31865 RTD-to-digital converter. The EmonLib library is a popular open-source library for energy monitoring. It has tools to measure voltage, current, and calculate power.

$$V = ADC_{Reading} \times \left( \frac{V_{ref}}{ADC_{Resolution}} \right) \times Calibration_{Factor} \quad [1]$$

To measure voltage, a voltage divider circuit along with an ADC (Analog-to-Digital Converter) is used. Formula [1] is used to calculate the actual voltage. Where, ADC\_Reading is the value read from the ADC, Vref is the reference voltage for the ADC (typically 5V or 3.3V), ADC\_Resolution is the resolution of the ADC (e.g., 1024 for a 10-bit ADC) and Calibration\_Factor is a factor derived experimentally to account for circuit tolerances.

$$I = ADC_{Reading} \times \left( \frac{ADC_{Resolution}}{V_{ref}} \right) \times Burden_{Resistor} \times CT_{Ratio} \times Calibration_{Factor} \quad [2]$$

Current is measured using a current transformer (CT) sensor. The output of the CT sensor to actual current is converted using the formula [2]. Where, Burden-Resistor is the resistor used in the CT circuit and CT-Ratio is the ratio of the CT sensor (e.g., 1000:1).

$$V_{rms} = \sqrt{\left( \frac{\sum V_i^2}{N} \right)} \quad [3]$$

$$I_{rms} = \sqrt{\left( \frac{\sum I_i^2}{N} \right)} \quad [4]$$

Formulas [3] and [4] are used to get the Root Mean Square values (rms) of Voltage and Current. Where,  $V_i$  and  $I_i$  are instantaneous voltage and current samples, and N is the number of samples.

The IoT-based system for real-time monitoring of sensors, specifically for the Smart Energy Meter is fundamentally driven by the architecture of how the ESP32 microcontroller interacts with external devices like current transformers, gas sensors, and temperature probes to form a high-utility data acquisition network. Data is collected and processed locally by ESP32, which securely sends it to the cloud through the router, employing authentication tokens for high-level security.



Fig -3: System Architecture

As illustrated in Figure 3, this architecture integrates IoT devices, cloud platforms, and user interfaces, with processed data transmitted to the Blynk cloud platform for accessibility through an internet-enabled dashboard. This dashboard provides real-time insights and visual analytics, enabling operators to monitor parameters efficiently and make informed decisions. The architecture exemplifies the potential of IoT to streamline sensor-based applications, ensuring both scalability and reliability in industrial environments.

To facilitate remote monitoring and control, the system leverages the Wi-Fi connectivity capabilities of the ESP32 microcontroller. This connectivity enables seamless data transmission to the Blynk IoT platform, a versatile and user-friendly tool for IoT-based data visualization and management. Through the Blynk platform, the system provides real-time access to monitored parameters, such as phase voltages, currents, power parameters, and furnace temperatures. The platform's cloud integration allows for data logging and historical analysis, giving plant operators actionable insights for optimizing energy consumption and scheduling maintenance activities. The system features highly customized dashboards within the Blynk platform, designed to cater specifically to industrial users. These dashboards offer an intuitive interface for visualizing critical data in real-time, enabling operators to track performance metrics at a glance. Users can set alerts for anomalies,

generate reports, and remotely control the system's functionality, thereby enhancing operational efficiency and reducing downtime. To ensure adaptability and scalability, the software is designed with a modular architecture. This modularity allows for seamless integration of additional features in future iterations. For example, machine learning algorithms can be incorporated into the system to enable predictive maintenance.

By analyzing historical energy and temperature data, such algorithms could identify patterns indicative of potential equipment failures, providing operators with timely recommendations to prevent breakdowns. Furthermore, the software incorporates error-handling mechanisms to address challenges commonly faced in industrial environments, such as high-frequency noise and fluctuating network conditions. Advanced filtering techniques are employed to mitigate the impact of electrical noise on measurement accuracy, while robust retry and failover strategies ensure uninterrupted data transmission even in the event of Wi-Fi connectivity issues. The integration of advanced hardware and software components makes the Smart Energy Meter a comprehensive solution for industrial energy management. Its precision in measurement, reliability in operation, and adaptability for future enhancements make it a valuable tool for industries aiming to optimize their energy consumption while embracing digital transformation.

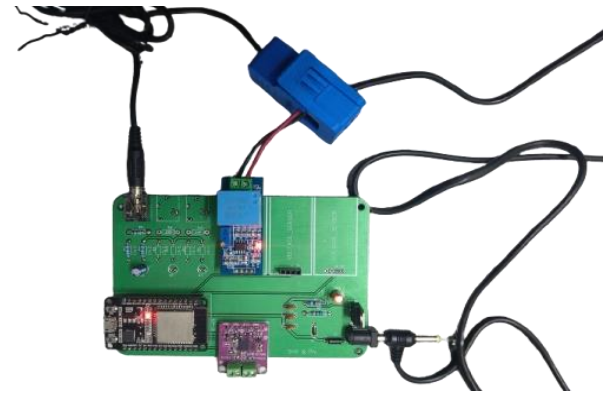
#### 4. TESTING AND DEPLOYMENT

##### 4.1 Calibration and Validation

Volt-Power Analysers validated the system's voltage, current, and temperature measurements for industrial applications. The ZMPT101B voltage sensors were tested under industrial three-phase conditions, with calibration adjustments made using a high-precision reference voltmeter. This process ensured consistent sensor output, reducing real-time monitoring errors. For current calibration, SCT-013-000 sensors were tested with resistive loads to verify accuracy up to 100A. Various load conditions were applied, minimizing phase shift errors. Additional tests assessed sensor stability under varying ambient temperatures, with results cross-checked against a precision ammeter.

The RTD temperature system, using PT100 and PT1000 sensors with a MAX31865 module, was calibrated in a temperature bath from 0°C to 1000°C. Calibration data was logged and analysed to refine measurement algorithms. A multi-point calibration method enhanced accuracy across the temperature range. Long-term stability tests ensured reliability, with

periodic recalibration and software corrections maintaining accuracy in demanding industrial environments.



**Fig -4:** Hardware Implementation and Testing Setup

The hardware implementation of the Smart Energy Meter, as shown in the Figure 4, integrates various sensor modules and processing units. The ZMPT101B voltage sensor, SCT-013-000 current sensor, and MAX31865 RTD interface module are mounted on a custom-designed PCB. An ESP32 microcontroller serves as the core processing unit, responsible for data acquisition, signal processing, and communication with the cloud platform. The testing setup involved connecting the hardware to industrial-grade equipment to simulate real-world conditions. The system was powered through a stable DC source, and the sensors were interfaced with industrial three-phase power supplies and calibrated resistive loads. The compact and modular design of the PCB ensures ease of integration into existing systems and allows for scalability for future enhancements. The testing procedure included measuring sensor outputs under varying environmental and electrical conditions. The robust performance of the system under high-noise environments validated its suitability for industrial applications. The modular design also facilitates quick replacements and upgrades, making the system a cost-effective solution for energy monitoring and management.

##### 4.2 Industrial Deployment

Following laboratory validation, the system was installed at a pressure die-casting facility to evaluate its performance in real-world industrial conditions. The deployment site presented a range of environmental challenges, including high temperatures, electrical noise from large motors, and mechanical vibrations. The 3D-printed enclosure proved effective in protecting the

hardware components from heat, dust, and mechanical wear, while the PCB's integrated protection circuits mitigated electrical surges. During installation, the system monitored three-phase voltage, current, and furnace temperatures, transmitting data in real time to the Blynk IoT platform. The deployment highlighted the system's ability to adapt to fluctuating load conditions typical of die-casting operations. The use of Wi-Fi connectivity ensured uninterrupted data transmission despite the presence of industrial electromagnetic interference. Operators at the facility utilized the Blynk dashboard to monitor critical parameters, enabling timely interventions and improved energy management.



**Fig -5:** Final Prototype enclosed in a 3D-printed case

The final prototype, housed in a durable 3D-printed enclosure, was meticulously designed to withstand harsh industrial conditions while ensuring reliable performance. Its compact and ventilated design provides protection against heat, dust, and vibrations, maintaining optimal functionality even in challenging environments. As illustrated in Figure 5, the enclosure features ventilated holes specifically for the ESP32 to prevent overheating, alongside precise openings for ports, including a Micro USB Type-B pin for programming and power supply, and a dedicated provision for current sensor jack ports, ensuring seamless connectivity. The modularity of the enclosure facilitates easy maintenance and upgrades, allowing components to be accessed and replaced with minimal effort. Additionally, the design includes mounting provisions for wall installation, enabling secure and space-efficient deployment in industrial settings. These features collectively make the enclosure robust, adaptable, and highly suitable for real-world applications.

### 4.3 Performance Evaluation

The performance evaluation focused on both the accuracy of measurements and the reliability of the

system under continuous operation. Voltage and current measurements demonstrated an accuracy of  $\pm 1\%$ , as verified against precision instruments during calibration and industrial testing. The RTD-based temperature monitoring system achieved a similar level of precision, with errors consistently below  $\pm 1^\circ\text{C}$  when compared to reference measurements from a calibrated thermometer. Reliability metrics were assessed over a continuous operation period of 30 days. The system recorded consistent data transmission with zero packet loss, confirming the robustness of its Wi-Fi-based communication. Additionally, the energy meter maintained stable operation despite temperature fluctuations, electrical noise, and high humidity levels within the facility. These results underscore the system's capability to function effectively in demanding industrial environments, providing accurate and actionable data for energy management and optimization. By successfully addressing calibration, deployment, and performance challenges, the Smart Energy Meter has demonstrated its potential as a reliable solution for industrial energy monitoring and management.



**Fig -6:** Blynk dashboard displaying real-time data.

The system's integration with the Blynk IoT platform and JSON-based logging further enhanced its utility for industrial energy management. The Blynk dashboard (Figure 6) provided a user-friendly interface for real-time visualization of critical parameters, including voltage, current, and furnace temperatures. Operators could easily monitor trends, set alerts, and analyze performance metrics, enabling proactive decision-making and swift response to potential inefficiencies.



Fig -7: JSON log data for performance analysis

The JSON log data (Figure 7) offered a detailed record of system performance, capturing time-stamped measurements for comprehensive analysis. This structured data format facilitated seamless integration with analytics tools, allowing for advanced energy usage insights and optimization strategies.

### 5. RESULTS

The evaluation of the Smart Energy Meter under both controlled laboratory conditions and real-world industrial deployment yielded significant insights into its performance, accuracy, and reliability. The results highlight the system’s potential as a robust and practical solution for industrial energy management. The Smart Energy Meter demonstrated high accuracy in measuring all key parameters. Voltage measurements using the ZMPT101B sensor exhibited a margin of error of  $\pm 0.08\%$ , while current measurements obtained via the SCT-013-000 sensor showed a margin of  $\pm 3\%$ . Temperature monitoring using PT100 and PT1000 RTDs interfaced with the MAX31865 module achieved a precision of  $\pm 5^\circ\text{C}$  over the tested range. These accuracy levels align with industrial standards, ensuring reliable monitoring for energy optimization and process control. Under industrial conditions, the system exhibited remarkable stability and reliability.

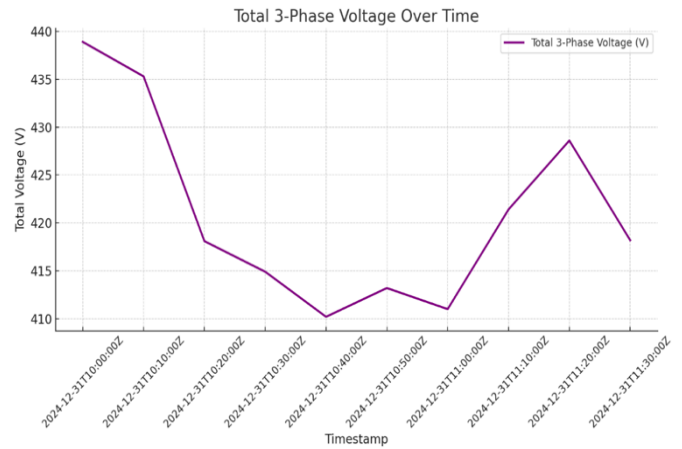


Chart -1: Line Voltage variation over Time

The total 3-phase voltage was continuously monitored to evaluate the system’s ability to capture variations in voltage over time. Chart 1 illustrates the recorded voltage fluctuations, ranging from 410V to 440V, over the evaluation period. These variations are consistent with typical industrial load cycles and reflect the system’s capability to monitor real-time voltage changes accurately. Voltage dips observed during specific intervals likely correspond to load surges or operational transitions in connected machinery. This accurate voltage tracking ensures operational stability and facilitates the early detection of anomalies, which is critical in preventing potential equipment failures or production downtime.

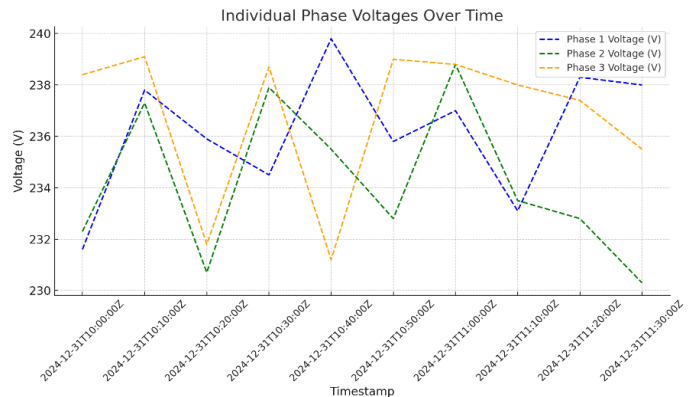


Chart -2: Phase Voltages variation over Time.

To assess phase-specific voltage variations and identify potential imbalances, individual phase voltages were tracked. As shown in Chart 2, the voltage levels for Phase 1, Phase 2, and Phase 3 ranged from 230V to 240V. The graph highlights periodic fluctuations that reflect

dynamic load conditions inherent to industrial operations. Despite these fluctuations, the system maintained a high degree of accuracy, demonstrating its reliability in capturing phase-specific data. Monitoring individual phases provides essential insights into load distribution and power quality, enabling industrial operators to address imbalances proactively and optimize energy usage.

utility by enabling real-time monitoring and cloud-based data logging. This combination of features not only improves real-time decision-making but also facilitates long-term energy optimization and predictive maintenance. The Smart Energy Meter's performance under real-world conditions highlights its capability to deliver reliable and actionable insights, paving the way for more efficient and sustainable industrial operations.

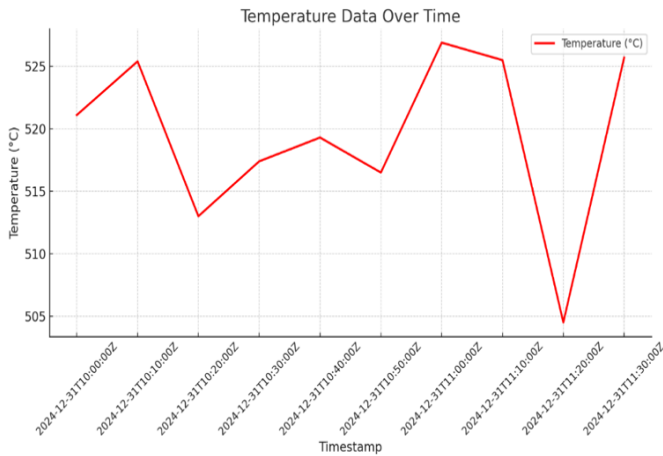


Chart -3: Temperature Variation Over Time (°C)

Temperature data from furnace operations was analyzed to evaluate the system's precision in capturing thermal variations. Chart 3 depicts the temperature fluctuations recorded during the evaluation period, ranging from 505°C to 525°C. Significant variations in temperature were observed during furnace cycles or operational changes, underscoring the dynamic nature of industrial processes. The system maintained a precision of  $\pm 1^\circ\text{C}$ , aligning with industrial-grade standards. Accurate temperature monitoring is vital for ensuring effective process control, enhancing energy efficiency, and supporting predictive maintenance strategies. This level of precision enables operators to maintain optimal operating conditions, thereby improving overall productivity.

### 5.1 Discussion

The graphical analysis underscores the Smart Energy Meter's high accuracy and reliability across multiple parameters: total voltage, individual phase voltages, and temperature. These findings confirm the system's potential to serve as a robust tool for industrial energy management. The system demonstrated exceptional resilience in harsh industrial environments, including its ability to withstand electrical noise, mechanical vibrations, and high ambient temperatures. Its IoT-enabled features further enhance its

### 5.2 Advantages

The Smart Energy Meter incorporates several advantages that make it well-suited for industrial applications. The use of non-invasive SCT-013-000 current sensors ensures safe and straightforward installation without the need for interrupting live circuits. The system's reliance on the ESP32 microcontroller, with its integrated Wi-Fi capability, provides seamless cloud connectivity for remote monitoring. The custom PCB, designed with integrated power management and protection circuits, enhances the system's reliability and robustness in high-stress environments. Additionally, the industrial-grade 3D-printed enclosure protects against dust, heat, and vibrations, ensuring durability in harsh conditions. The IoT-enabled architecture introduces significant value by enabling cloud-based data logging. This feature provides users with historical and real-time data, helping identify patterns, optimize energy consumption, and enhance operational efficiency. The system's modular design and flexibility to integrate additional sensors further extend its applicability to other industrial domains.

### 5.3 Challenges Faced

Despite its advantages, the system faced challenges during development and deployment. One major issue was mitigating high-frequency electrical noise, particularly during temperature measurement with RTD sensors. This was addressed by careful calibration and the implementation of hardware-based noise filtering techniques in the PCB design. Another challenge was maintaining stable Wi-Fi connectivity in an environment with significant electromagnetic interference from heavy industrial equipment. Strategic placement of the ESP32 module and the use of a high-gain external antenna ensured reliable communication, even in the presence of interference. By addressing these challenges, the Smart Energy Meter has proven to be a resilient and versatile solution. Its performance under real-world conditions underscores its potential to enhance industrial energy management, paving the way for more efficient and sustainable operations.

## 6. CONCLUSION

The proposed Smart Energy Meter demonstrates a comprehensive solution for industrial energy management, addressing key challenges such as precision measurement, robust operation under harsh conditions, and real-time data monitoring. The system's integration of advanced hardware components, including ZMPT101B voltage sensors, SCT-013-000 current sensors, and PT100/1000 resistance temperature detectors (RTDs), ensures high accuracy in measuring critical energy parameters. Coupled with the ESP32 microcontroller's computational capabilities and its seamless connectivity with the Blynk IoT platform, the design enables real-time visualization, cloud-based data logging, and remote control. The custom-designed printed circuit board (PCB) enhances system reliability by incorporating robust power regulation and protection mechanisms, while the modular design facilitates easy installation, maintenance, and scalability for diverse industrial environments. Testing under industrial conditions validated the system's ability to withstand electrical noise, mechanical wear, and fluctuating environmental factors, proving its reliability and suitability for demanding applications.

The Smart Energy Meter's IoT-enabled architecture not only enhances operational efficiency but also paves the way for future advancements, such as predictive maintenance through machine learning algorithms, standalone data management systems, and the integration of industry-grade components for enhanced durability. These features position the system as a scalable and forward-looking solution capable of supporting energy optimization and sustainability goals in modern industries. By providing actionable insights through real-time and historical data analysis, the Smart Energy Meter empowers industries to achieve greater energy efficiency, reduce operational costs, and embrace digital transformation. Its robust design and innovative features underscore its potential to revolutionize industrial energy management practices.

## 7. FUTURE SCOPE

While the Smart Energy Meter addresses the immediate needs of industrial energy monitoring, its design provides a platform for future advancements and scalability. Several potential enhancements can further elevate its utility and extend its applicability to a broader range of industries.

### 7.1 Integration of 3-Phase Energy Metering IC with Opto-Isolator Circuit

In future iterations, the system will utilize a 3-phase energy metering IC coupled with an opto-isolator circuit, replacing the individual sensors currently in use. This upgrade will enhance the accuracy and reliability of the system, providing more efficient and comprehensive energy monitoring. The integration of these components will simplify the design while ensuring more precise measurement of energy consumption across three-phase systems, which are commonly used in industrial applications.

### 7.2 Custom Platform for Data Collection and Storage

To improve security, reliability, and real-time performance, a custom platform will be developed for data collection and storage, moving away from the Blynk cloud. This new platform will be a standalone setup, locally deployed to provide a higher level of security and control over data management. By eliminating the reliance on cloud services, the system will reduce the potential vulnerabilities associated with external cloud storage, ensuring that sensitive industrial data is stored securely within the local network. This approach will also improve system performance by minimizing latency and providing more direct access to data.

### 7.3 Use of Industry-Grade Components and Circuits

The system will incorporate industry-grade components and circuits to ensure durability and resilience in demanding industrial environments. These high-quality components will help the system withstand harsh conditions, such as extreme temperatures, electrical noise, and mechanical vibrations, ensuring long-term reliability and minimizing the risk of failure. The use of these components will further enhance the system's performance, making it suitable for deployment in a wide range of industrial settings.

### 7.4 Predictive Maintenance with Prediction Models

The system will feature prediction models designed to detect potential breakdowns before they occur. By analyzing historical data, these models will identify patterns indicative of impending failures, allowing the system to raise alarms and trigger pre-emptive maintenance actions. This predictive capability will help minimize downtime, reduce operational costs, and extend the lifespan of industrial equipment. The integration of machine learning or advanced analytics will further refine the accuracy of these predictions, ensuring timely interventions.



## 7.5 Configurable I/O for External Devices and Sensor Interfacing

To increase flexibility and adaptability, the system will include configurable I/O (Input/Output) for seamless interfacing with not only external sensors but also external devices. This feature will allow the system to be customized based on the specific requirements of different industrial applications, making it suitable for a variety of environments. The system will be capable of connecting to and interacting with a wide range of external devices, such as actuators, alarms, or additional monitoring equipment, thereby extending its functionality. This flexibility will enable the system to provide more comprehensive insights into energy usage, equipment health, and overall system performance. These future enhancements will solidify the Smart Energy Meter's role as a versatile, scalable, and reliable solution for industrial energy management, with advanced predictive maintenance, improved security, and broader applicability across diverse industries.

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