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A smart energy monitoring system using ESP32 microcontroller

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ABSTRACT

Gaza's electrical deficit has resulted in the rise of new energy suppliers that sell power from private generators at higher prices. Consumers have challenges because they cannot tell whether their energy originates from the utility or private generators, resulting in unexpectedly large bills owing to a lack of an electronic monitoring system. This study fills this gap by developing a low-cost IoT energy monitoring system that provides real-time information on energy use (hourly, daily, and monthly) to assist consumers in managing their usage and expenditures. An ESP32 microcontroller is used in the system to gather data from energy meters, analyze it, and deliver updates to users via WhatsApp over a secure Wi-Fi connection via the Blynk platform. Experimental findings show that the system accurately captures voltage, current, active power, and cumulative power consumption and transmits this information to customers in real time.

1. Introduction

Real-time monitoring and analysis of power consumption is an important part of energy management, with applications ranging from electric car charging stations [1] to home energy usage [2]. The use of Internet of things (IoT) technology for real-time data analytics [2] and the creation of Android-based energy monitoring applications [3] have been presented as viable alternatives. These technologies allow consumers to analyze their usage trends, remotely regulate equipment, and view energy consumption in real time. In industrial contexts, microcontroller-based power meters have been proposed for monitoring specific devices and optimizing power consumption [4]. These studies demonstrate the necessity of real-time monitoring and analysis in a variety of energy usage scenarios.

The creation of low-power wireless sensor networks is critical to the optimal operation of smart energy monitoring systems [5]. The ESP32 microcontroller, known for its data processing capabilities, has been successfully used in a variety of applications, including smart home monitoring systems. Babiuch et al. [6] conducted a comprehensive analysis of this platform's possible uses in data monitoring and processing. Microcontrollers are frequently connected to IoT modules and other smart sensors, which send data to the central system. Babiuch and Postulka [7] reported an approach that utilized an organic light-emitting diode (OLED) display and the ESP32 Wrover development board with an integrated display. Its cheap cost, low power consumption, and highly integrated construction make it an excellent candidate for such systems [8].

Extensive research has been performed to create and deploy smart systems for real-time power consumption monitoring. These home systems use smart meters and the Arduino platform. Users may monitor and adjust their power use using a variety of devices, such as PCs, tablets, and smartphones.

An energy management system integrating networked energy harvesters, real-time monitoring, and intelligent distribution is proposed by El-Shaarawi and Ghoniemy [9]. The standby battery used in this system is charged using harvesters or centralized storage and is controlled by the push-pull hysteresis theory. It keeps an eye on and regulates sensor and harvest network power consumption at every phase of operation, from communication to startup.

Studies have indicated that substantial energy savings can result

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from the integration of Information and Communication Technologies (ICT) into Energy Management Systems (EMSs). ICT integration is essential for influencing energy economics, increasing resourcefulness, improving consumption efficiency, and guaranteeing grid stability, reliability, and scalability in power systems. [10,11]. This is especially true in the Middle East, where energy management has been demonstrated to benefit from ICT use [12]. Using ICT and AI methods for energy management in the residential sector can lead to more economical energy use [11]. The authors [11] suggest creating an intelligent energy management system that can regulate power flow within a networked grid in addition to controlling standalone microgrids. When time-of-use pricing is in effect, the system optimizes power flow, maintains system stability, and gives priority to load fulfillment and cost reduction.

The system efficiently regulates energy production and consumption by incorporating multiple renewable energy sources, including micro hydro, wind, photovoltaics, fuel cells, and batteries. Significant cost and energy savings under time-of-use pricing are highlighted, along with the possibility to bring in extra money by selling extra renewable energy to the grid [13].

Fig. 1 shows how the global market for energy management systems has grown significantly and how important it is. Forecasts indicate that by 2030, the market value will have surpassed US$ 153.62 billion. In 2021, it surged to an impressive US$ 45.11 billion. The estimated compound annual growth rate of 14.55% from 2022 to 2030 is the main driver of this noteworthy growth. These numbers highlight the growing importance of the industry and the worldwide trend toward the adoption of energy management systems. The increasing understanding of the vital role energy management plays in optimizing resource utilization, advancing sustainability initiatives, and satisfying the world's growing energy needs is reflected in this pattern. [14].

In order to maintain supply-demand balance and optimize energy source scheduling, an Energy Management System (EMS) is essential [15]. In order to ensure reliability, reference [16], highlights the critical role that power systems play in contemporary society as well as the significance of interconnected subsystems like computing, communication, and control. The operation, dependability, and efficiency of the grid are greatly impacted by the integration of these components. An Internet of Things (IoT) framework is proposed as a means of managing home energy in the study reported in [17]. Through an IoT dashboard, users can access insights about their daily power usage, thanks to this framework's monitoring and transmission of home energy consumption data to the IoT Cloud. The potential of Home Energy Management Systems to improve energy security and efficiency through the synchronization of multiple home devices, including entertainment and security systems, is emphasized in reference [18]. Technology for home automation is thought to be able to solve issues with power demand and enhance the performance of electricity.

The area of home energy management (HEM) has received a lot of attention because of its potential for resource conservation. Residential energy usage presently accounts for around 22% of total national energy demand [19]. Continuous technological advancements, such as lower costs for sensors, computation, and displays, as well as the widespread integration of device-level information processing and communications, have increased the market viability of HEM systems. This is bolstered by an increased interest in electric demand response and the use of smart utility meters. Over the last decade, a slew of goods and businesses have developed to capitalize on this burgeoning market. These range from smart thermostats and power strips to centralized home automation systems. Authors in [20] draw attention to the increasing challenge of rational energy use and environmental preservation. They highlight industrial systems, particularly production systems, as significant energy consumers. European regulations and environmental concerns are driving the adoption of energy-saving measures in industrial settings.

With its use of ESP32 technology, the Smart Energy Monitoring system provides a cutting-edge way to monitor and control energy use in a variety of settings. This system is essential for providing real-time data and insightful analysis to optimize energy usage, especially in light of the increasing demand for sustainability and energy efficiency. Its central component, the ESP32 microcontroller, is renowned for both its high performance and energy-saving qualities, guaranteeing a dependable and reasonably priced solution for both home and business use. Buildings consume a large amount of energy, frequently as a result of electrical appliances being used inefficiently. Consequently, increasing building energy efficiency has gained importance across a range of management tiers. Occupancy sensors were the mainstay of traditional methods but installing them in urban buildings presented significant challenges. To overcome this issue, IoT technology is used to monitor and manage power consumption depending on work schedules and occupancy patterns in the building [21].

This method is consistent with the overarching objective of encouraging sustainable and responsible energy use by improving energy efficiency while also simplifying energy management in urban contexts. [22] recommends Power Line Communication (PLC) technology for controlling and monitoring household electrical equipment that is powered by power lines. This enables appliances to be remotely controlled and monitored via the Internet using an integrated home server with a web-based user interface. According to [23], real-time data on energy use helps customers to take responsibility for their energy consumption, which aids in cost-cutting and sustainability efforts.

In [24], the authors utilized a smartphone app coupled with Blynk to

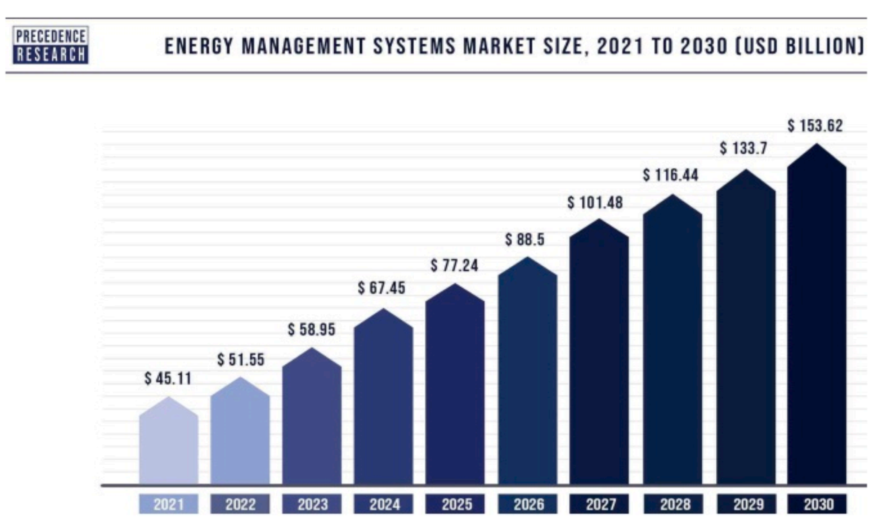

Fig. 1. The global energy management systems market size.

track energy use on a daily, weekly, and monthly basis. This technology also sends out reminders to encourage energy-saving activities. Reference [25] describes a configuration that uses the SCT-013–030 sensor and the ESP8266 NodeMCU V2 module to remotely monitor energy usage in smart homes. An artificial neural network built inside the ESP8266 NodeMCU module recognizes anomalous energy usage trends in appliances.

The Internet of Things (IoT) has a significant impact on the energy sector by offering enhanced metering and monitoring technologies. These systems integrate advanced control methods with smart meters, necessitating two-way communication, intelligent equipment control, and seamless network and user engagement. Utilizing IoT technology has the potential to transform the energy industry's efficiency and improve user control of energy resources [26].

Several research, including [27-30], have examined IoT for energy management. Aashik et al. [27] addressed better energy monitoring in India's urbanization and industrial expansion which resulted in increased energy demand. To address this, an IoT-based system using an ESP32 microcontroller was developed. It allows users to monitor individual appliance power consumption, troubleshoot issues, and save historical data via a web application. In [28], the authors employed IoT for energy analytics in contemporary companies, enabling thorough monitoring of power usage and performance. The authors employed Smart meters with IoT and Message Queuing Telemetry Transport (MQTT) protocols, an ESP32 microcontroller, and the Amazon Web Services (AWS) cloud to continuously measure three-phase voltage, current, and power. A web interface provides graphical data displays and downloadable reports, thereby lowering human error and providing a cost-effective solution for energy management.

Authors in [29] compares the power efficiency of two microcontrollers, the ESP32 (LX6 core) and the ESP32-S3 (LX7 core), running machine learning models. It focuses on the benefits of cache memory and vector instructions. The ESP32-S3 outperforms the ESP32 in power efficiency due to its advanced features. These findings are important for designing low-power embedded systems for applications like IoT, wearable devices, and edge computing.

Anush et al. [30] create an automated home system with the ESP32 microcontroller, which is well-known for its connection. The system uses sensors (motion, temperature, humidity, and light) and actuators (relays, servo motors, and light emitting diode (LEDs)) to control and monitor home gadgets. The ESP32 functions as the central hub, providing internet connectivity for remote access. Residents may control their homes, alter settings, schedule tasks, and get notifications via a smartphone app or web interface.

In the context of energy management systems, encryption is essential for protecting the confidentiality and integrity of sensitive data, such as energy consumption patterns, user preferences, and device configurations. Encryption ensures that unauthorized parties cannot intercept or tamper with communication between IoT devices, cloud servers, and mobile applications like Blynk, which are commonly used in energy management solutions. This helps prevent data breaches, unauthorized access, and manipulation of energy-related information [31,32].

When post-quantum cryptography replaces ECC (Elliptic Curve Cryptography) and RSA (Rivest-Shamir-Adleman) algorithms, it will cause a seismic change in cybersecurity. This transformation will have far-reaching consequences for a wide range of security applications, from common devices like smartphones to complex blockchain networks. The evolving cryptographic environment is being pushed by the imminent danger of quantum computers, which have enormous processing capacity and can break standard encryption techniques. Post-quantum encryption provides strong solutions to quantum assaults, protecting data secrecy and integrity in a quantum-powered future. This transformation necessitates substantial changes to current security infrastructures, cryptographic systems, and software implementations. While preparing for this paradigm change, works such as [33] offers insight on the complexities of post-quantum cryptography, driving the creation of safe and robust cryptographic systems appropriate for the quantum era.

In the context of internet-based energy management, it is critical to protect against side-channel attacks and choose between lightweight encryption and Advanced Encryption Standard (AES). Side-channel attacks take advantage of inadvertent information leakage from physical implementations, putting important energy data at risk. Mitigation options include careful cryptography design and countermeasures like as masking or randomization procedures. Lightweight cryptography, designed for resource-constrained IoT devices, provides efficiency and security, as opposed to AES, which delivers high security but may be less appropriate for such devices owing to complexity. The decision between them is based on application needs, hardware capabilities, and desired trade-offs. Overall, protecting energy management systems online necessitates paying attention to potential threats and selecting appropriate cryptographic algorithms based on unique requirements [34].

Consumption statistics through the Blynk platform's interface in the suggested system is presented, which streamlined data transfer and reception. This methodology is similar to that used in earlier studies [35,36], where the goal was to create models for tracking the amount of electricity used by end users. In these models, the data gathering device uses Internet of Things technology to send power usage statistics to the supplier's Blynk server. The authors acknowledged the possibility of human error when depending on data from traditional energy meters that are manually read by people. As a result, using IoT and the Blynk application was thought to be a worthwhile alternative. With this method, accuracy and convenience are increased as electrical power usage can be monitored online at any time and from almost any location.

In previous studies, the authors of this current study realized there are lack of studies that connected smartphones applications to the system to reach in real time to the users. Thus, this study presented a comprehensive study that enable end users to get reading in real times using phone applications that connected to AI system via platforms such as blynk. This study aims to reduce human error emerged from using traditional reading systems. Furthermore, it aims to help end user to control their daily, monthly, and yearly usage of private source of electricity.

2. Motivation for the system

The Gaza Strip has a serious electricity deficit, with the Gaza Electricity Distribution Company (GEDCO) providing just four hours of power each day. This shortage has resulted in the establishment of commercial energy suppliers charging much higher prices—eight times more than GEDCO's rates [37-41]. The cost of one kWh given by private owners of electricity generators is $1.05, but GEDCO charges just $0.13 [42]. Despite using these alternatives, customers complain about high costs, which are aggravated by a lack of tools for efficiently managing their energy use. To close this gap, this work provides an application for monitoring and managing energy use from private generators. Users get control over activation timings, which are often during GEDCO outages or certain time periods. The suggested system automates generator activation based on user choices and establishes a maximum bill limit to prevent overcharging.

3. Objectives of the work

a. Create a low-cost IoT energy-monitoring system to solve a major problem in monitoring two systems provided to the customers in Gaza.
b. Provide users with real-time energy consumption data (hourly, daily, and monthly).
c. Help consumers manage their energy usage and expenses more effectively.
d. Use an ESP32 microcontroller to collect data from energy meters, evaluate it, and provide updates.

e. Create a secure Wi-Fi connection to send data using the Blynk platform.
f. Accurately collect and transmit voltage, current, active power, and cumulative power consumption data in real time.

4. Proposed monitoring system

The envisioned system aims to efficiently oversee and relay details concerning energy usage within a client's home. Specifically tailored to oversee and regulate electricity usage at the client's premises, it integrates diverse elements to deliver instantaneous updates and enhance energy administration. This system epitomizes the practical integration of IoT into everyday living, addressing a critical issue in the local area.

4.1. Proposed system mechanism

Fig. 2 provides a visual depiction of the operational framework of the proposed system, delineating the sequential flow of information within it. The process unfolds as follows:

1. Integration of Energy Meter: The system's foundation lies in incorporating an energy meter within the client's residence. This device functions as the primary data source, capturing and quantifying electricity usage alongside other pertinent data. It draws information from two distinct sources: the utility company's electricity line (supplied by GEDCO) and the privately owned generators.
2. ESP32 Microcontroller: Facilitating data processing and communication, the energy meter interfaces with an ESP32 microcontroller. Acting as the central processing unit, the ESP32 undertakes tasks such as data collection, analysis, and transmission.
3. Establishment of Wi-Fi Connectivity: The ESP32 establishes a secure connection with the Blynk platform through a Wi-Fi network. This linkage enables the system to access external services and systems for the purposes of data analysis and generating notifications.
4. Notification Generation: Programmed within the ESP32, notifications are generated based on predefined criteria. These notifications encompass updates on energy consumption, alerts, and other pertinent information.
5. Integration with WhatsApp: Concluding the process, notifications are dispatched directly to the client's WhatsApp account. Leveraging the Blynk platform, the ESP32 ensures timely delivery of tailored messages pertaining to energy usage and system status.

In summation, the proposed system adeptly manages and disseminates energy-related data through the amalgamation of an energy meter with an ESP32 microcontroller. By establishing a Wi-Fi connection to the Blynk platform and delivering customized notifications to clients via WhatsApp, this comprehensive mechanism empowers informed decision-making regarding energy consumption while keeping users abreast of system-related developments. events.

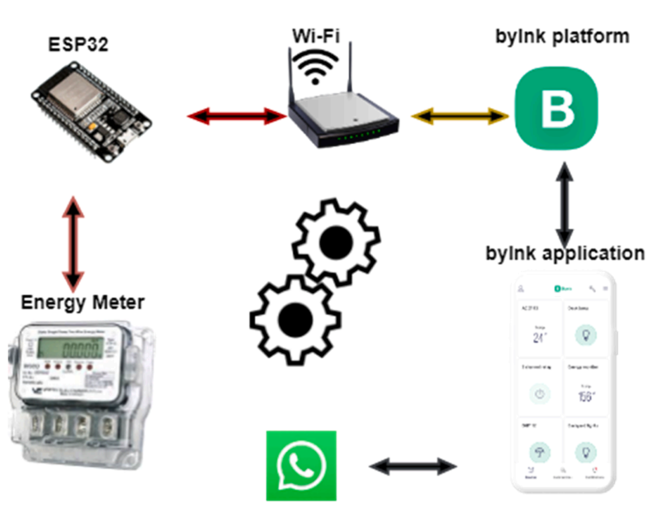

Fig 2. Mechanism of the proposed system and its components.

4.2. System taxonomy

4.2.1. Limitation in using Blynk

While the Blynk platform provides a robust and user-friendly interface for energy management systems, several limitations need to be addressed:

a. Scalability: Blynk is primarily designed for small to medium-sized projects. As the scale of the energy management system increases, such as in large industrial settings or urban infrastructure, the platform may face performance and stability challenges. The infrastructure required to support a large number of devices and the associated data traffic may exceed the platform's current capabilities.
b. Security Concerns: Although Blynk offers basic security features such as SSL encryption, it may not meet the stringent security requirements needed for critical infrastructure. Energy management systems are often targets for cyber-attacks, and the platform's security measures may need to be augmented with additional layers of protection to safeguard against sophisticated threats.
c. Integration with Existing Systems: Integrating Blynk with existing energy management and automation systems can be complex. Legacy systems may use different protocols and standards that are not natively supported by Blynk, necessitating the development of custom interfaces or middleware, which can be both time-consuming and costly.
d. Real-Time Data Processing: While Blynk provides real-time monitoring capabilities, the speed and efficiency of data processing can be a limitation for applications requiring instantaneous responses. High-frequency data streams might encounter latency issues, impacting the effectiveness of real-time decision-making processes in energy management.
e. Limited Customization for Advanced Users: Blynk's interface is designed to be user-friendly, which sometimes limits the extent of customization available for advanced users. Advanced features or complex algorithms required for sophisticated energy management solutions might be difficult to implement within the platform's predefined structure.
f. Dependency on Internet Connectivity: The Blynk platform relies heavily on stable internet connectivity. In environments where internet access is unreliable or intermittent, the performance of the energy management system can be severely impacted. This dependency poses a significant risk for continuous monitoring and control in remote or infrastructure-poor areas.
g. Cost Considerations: For large-scale implementations, the costs associated with using Blynk, including cloud services and subscription fees, can become substantial. This could limit the feasibility of adopting Blynk for extensive energy management systems, particularly in cost-sensitive sectors.

Addressing these limitations requires a careful assessment of the specific requirements and constraints of the energy management project. Future research and development could focus on enhancing the scalability, security, and integration capabilities of platforms like Blynk to better support comprehensive energy management solutions.

4.2.2. ESP32 important features

The ESP32 microcontroller presents a number of noteworthy benefits for creating an intelligent energy system monitoring system.

1. Built-in Wi-Fi and Bluetooth connectivity: These features are crucial for real-time data transmission and remote monitoring, and they are included with the ESP32 microcontroller. The smart energy system's integrated connectivity facilitates smooth communication with other systems and devices, allowing for effective data collection and analysis.
2. Minimal Power Consumption: Power efficiency is a vital component of any monitoring system. Multiple sleep modes, one of the low-power features built into the ESP32′s design, drastically cut down on power usage when the device is not actively transmitting data. It is therefore perfect for uses where energy efficiency is crucial.
3. High Processing Power: The dual-core processor of the ESP32 has enough processing capacity to manage intricate algorithms and data processing jobs. Accurately tracking and analyzing energy usage patterns, spotting anomalies, and making real-time adjustments to optimize energy consumption all depend on this capability. Flexible Peripheral Interfaces:
4. The ESP32 is compatible with a wide range of peripheral interfaces, including I2C, SPI, UART, DAC (Digital-to-Analog Converter), and ADC (Analog-to-Digital Converter). By connecting the microcontroller to various sensors and parts of the energy monitoring system, these interfaces increase the microcontroller's adaptability and scalability.
5. Cost-Effectiveness: The ESP32 is a viable option for broad implementation in smart energy systems due to its lower cost when compared to other microcontrollers with comparable capabilities. It offers a high return on investment because its low cost does not degrade its performance.
6. Sturdy Development Ecosystem: The ESP32 boasts a robust development ecosystem that consists of an active community, a large selection of libraries, and thorough documentation. The deployment of the smart energy system is accelerated by this strong support, which speeds up development and simplifies troubleshooting.
7. Security Features: One of the main issues with smart systems is security. Data integrity and confidentiality are safeguarded during transmission and processing by the ESP32 thanks to its hardware encryption and secure boot features.

In summary, the ESP32 microcontroller is an excellent choice for a smart energy system monitoring solution due to its connectivity options, low power consumption, processing power, peripheral interface support, cost-effectiveness, robust development ecosystem, and built-in security features. These characteristics make it well-suited for creating an efficient, reliable, and secure energy monitoring system [45].

4.3. System design

The proposed system is divided into two distinct components: the software part, elucidated in section 3.2.1, and the hardware part, comprehensively detailed in section 3.2.2.

4.3.1. Software design (Mobile application interface)

A complete solution for the creation and administration of networked hardware systems is provided by Blynk. Numerous features are included in this solution, such as easy device setup, real-time alerts, simplified automation procedures, firmware updates over-the-air, remote control via mobile and web interfaces, sensor data visualization, strong cloud security measures, advanced data analysis capabilities, and efficient user and access management. Blynk is a flexible IoT platform that runs on iOS and Android and is especially made to work with online-connected devices such as Arduino, Raspberry Pi, and NodeMCU. By configuring and linking appropriate addresses to various available widgets, it essentially acts as a Human-Machine Interface (HMI) and streamlines the creation of graphical user interfaces.

The flexible range of widgets offered by Blynk to create interfaces within the suggested system is utilized. To ensure smooth and effective operation, the Blynk Server plays a crucial role in coordinating communication between smartphones and the system's hardware components. The application's interfaces are shown in (Fig. 3).

The proposed system's interfaces can be divided into four main sections:

a. Reading Section:
   - Presenting pulse and energy readings on a daily and monthly basis.
   - Date and time in real time.
   - Emphasizing the particular date in the month where the cost is to be calculated.
   - Monitoring the total energy and pulses since the start of the monitoring.
   - Displaying the power usage as of right now.
   - Displaying the price per KWh and the monthly energy expenditure.
   - Providing the network name that is connected.
b. Control Section:
   - Including sliders for limiting daily and monthly energy use.
   - Using toggle buttons to enable or disable monthly and daily energy consumption caps.
c. Visualization Section: putting charts of daily and monthly energy use on display.
d. Status Indicators Section:
   - Making use of LED indicators to display the generator source's status (on or off).
   - Using LED indicators to display the electric utility source's status (on/off).
   - Using LED indicators to show the system output's status (on or off).
   - Offering gauges that show the daily and monthly energy consumption.

For a detailed overview of the control statuses, please refer to (Table 2).

In Table 2, when the line from the utility is on, the output is off. When utility and private generator are off, the output is off. The output is on in the cases where utility is off, the private generator is on and the consumption does not exceed the limits identify by the customer.

4.3.2. Hardware design

The hardware of the current design consists of three key components: the PCB (Printed Circuit Board) as shown in Fig. 4, the energy meter, and the battery as displayed in the final project design in Fig. 5. The PCB (Fig. 4) has a variety of components, including the ESP32 microcontroller, relays, a buzzer, optocouplers, capacitors, resistors, diodes, transistors, and a 16×2 LCD screen, each of which serves a distinct role within the system. Below is a breakdown of the roles of these components:

- ESP32 Microcontroller: This serves as the central processing unit of the system, responsible for numerous tasks. It handles communication with the Blynk application, performs read and write operations, issues commands to control loads, LEDs, and buzzers. Additionally, it reads pulses from the energy meter for energy calculation (for both sources), sends data to the Blynk application via Wi-Fi, calculates energy usage, displays readings on the LCD screen, and sends notifications to WhatsApp, among other functions.
- Relays: These components are used to control the activation and deactivation of electrical loads. Two relays are employed to accommodate the two sources.
- Buzzer: The buzzer provides audio feedback for various system events, including startup, changes in the status of the electric utility source, generator source, and Wi-Fi connection loss.
- LEDs: LEDs are used to visually indicate the status of various system components, such as pulses, power supply levels (5 V and 12 V), relay status, the status of the electric utility source, and the generator source.

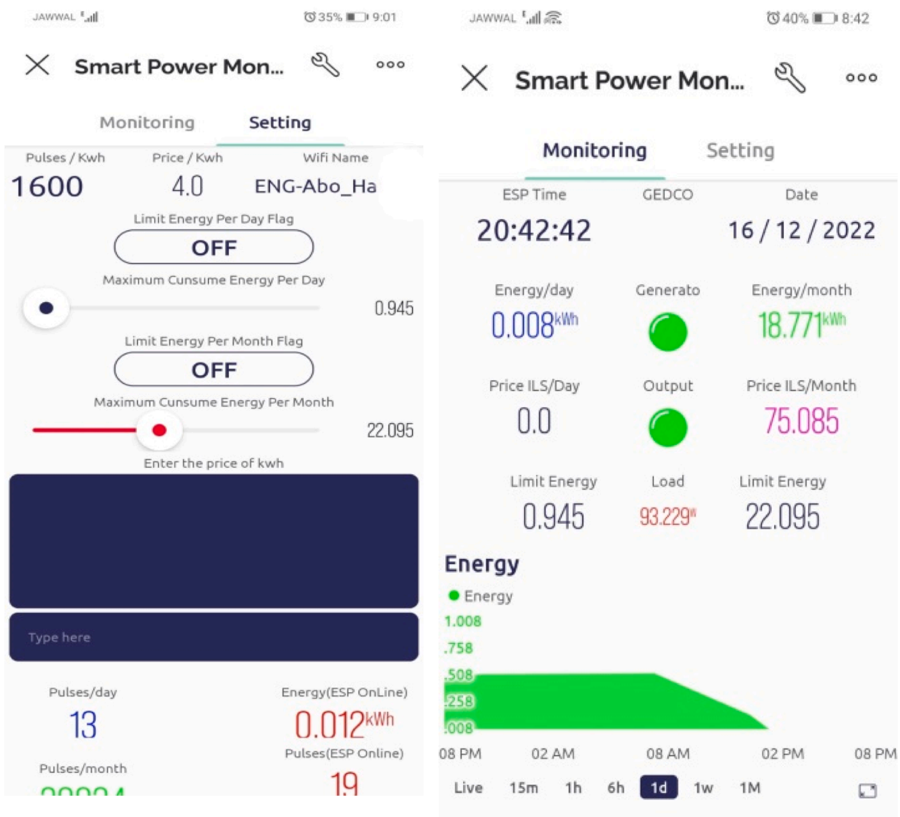

Fig 3. Interfaces of blynk application for proposed IoT monitoring system.

Fig 4. PCB components for proposed monitoring system.

- Optocouplers: Optocouplers are employed to isolate different circuits, ensuring signal separation and protection.
- LCD 16 $\times$ 2: The LCD screen displays monthly energy consumption in KWh and the associated cost in shekels. It serves as a backup display in case of issues accessing data from the application.
- T Blocks: These connectors allow the connection of multiple wires to the circuit board, with two pins for inputs (pulses from the meter, power supply (5v, 12 v)), for the electric line form the utility company and form private generator. And three pins to hold wires for the relay connections.
- Capacitors: Capacitors are used for voltage stabilization.
- Resistors: Resistors are employed to limit the flow of current.
- Diodes: Diodes function as one-way switches for current, allowing it to flow in one direction while restricting reverse flow.
- Transistors: Transistors act as switches in controlling the relays. A voltages source that exists in the designed circuit.

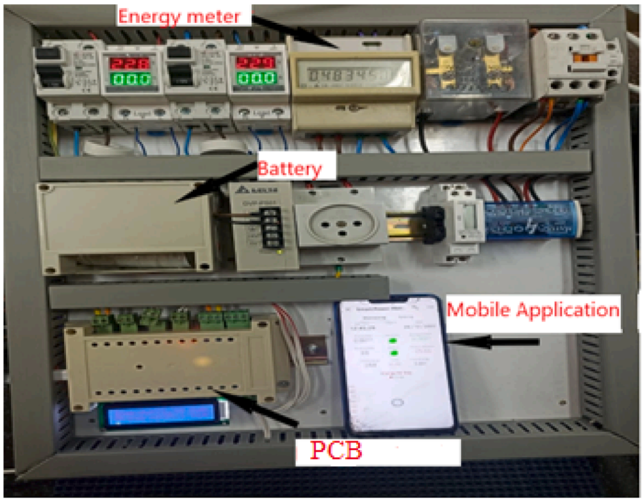

Fig 5. Hardware components for proposed IoT monitoring system.

- 5 V DC: The circuit is powered by a 5 V DC voltage source, which supplies power to most of the components in the system, including the ESP32, optocouplers, buzzer, LCD, and more.

Fig. 5 the energy meter kit of the proposed IoT monitoring system. The energy meter kit consists of the following components:

a. PCB and its components.
b. circuit breakers.
c. Contactors connected with relays to withstand high current.
d. Two digital energy meters to produce pulses to calculate energy.
e. Two digital volt current meter to show reading of current and voltage.
f. Electrical sockets.
g. Battery 5v.
h. Automatic electric changeover switch.

Mobile is added to Fig. 5 just to clarify that part of the project is mobile communication.

5. Real time monitoring

In this discussion, the significance of real-time data processing and analysis in ensuring the effectiveness of energy monitoring initiatives employing devices such as the ESP32 microcontroller and mobile applications will delve. Real-time data processing holds paramount significance in energy monitoring applications for a multitude of reasons:

1. Timely Decision Making: Real-time processing furnishes immediate insights into energy consumption trends, empowering users to make informed decisions promptly, thereby optimizing energy usage and cutting down costs.
2. Early Anomaly Detection: Swift data processing facilitates early identification of abnormal energy consumption patterns, aiding in the timely detection of potential issues such as equipment malfunctions or leaks.
3. Immediate Alerts: The capability for real-time processing allows for the system to promptly issue alerts and notifications to users upon surpassing predefined thresholds, facilitating rapid responses to prevent waste or emergencies.
4. Environmental Impact: Real-time monitoring enables organizations to mitigate their carbon footprint by pinpointing areas where enhancements in energy efficiency can be implemented, thereby directly contributing to environmental sustainability.
5. Participation in Demand Response Programs: Through real-time monitoring, organizations can participate in demand response initiatives, adjusting energy usage in response to grid conditions. This not only leads to financial incentives but also enhances grid stability.
6. Cost Savings: Real-time tracking of energy usage enables organizations to pinpoint opportunities for reducing waste and optimizing consumption, resulting in substantial cost savings over time.

In the proposed system, real-time monitoring was realized through continuous daily and monthly consumption readings, alongside alerts regarding shifts in energy sources, notifications on monthly bill costs, and warnings if consumption limits were exceeded.

6. Calculation of the consumption

In the calculation, variables are presented to express targeted values such as number of pulses pass the power counter is defined as pulsCount as stated in Table 3:

Energy calculation:

The energy calculations here are based on the pulses emitted by the energy meter, with the following parameters:

$$pulses\,KWh = 1600 \tag{1}$$

This means that the energy meter generates 1600 pulses when 1 kWh of energy is consumed.

$$energy\,PerPulse = 1/1600 = 0.00025W\ of energyusage. \tag{2}$$

If you want to calculate the energy consumption based on the number of pulses received by the meter, you can use the formula:

$$energy\,Comsumed\,PerDay = pulse\,Count\,PerDay * energy\,PerPulse \tag{3}$$

For example, if the energy meter receives 4800 pulses:

$$Energyperday(kWh) = 4800pulses/1600pulses/kWh = 3kWh$$

So, the energy consumption would be 3 kWh based on the received pulses. Similarly, energy consumed per month can be obtain as follows:

$$energy\,Comsumed\,Per\,Month = pulse\,Count\,Per\,Month * energy\,PerPulse \tag{4}$$

and total energy consumed given as follows:

$$total\,Energy\,Comsumed = total\,Pulse\,Count * energy\,PerPulse \tag{5}$$

//from starting work of system

$$energy\,Comsumed = pulse\,Count * energy\,PerPulse; \tag{6}$$

Price calculation:

To calculate the monthly and daily costs based on the energy consumed, the price of kWh is utilize as determined by the owners of the generators. Therefore, the prices are denoted as follows:

$$Price\_KWH = 4ILS(Shekel)perkWh \tag{7}$$

Then, the formulas to calculate the monthly and daily costs are as follows:

$$Monthlycost : price = energy\,Comsumed\,PerMonth * Price\_KWH; \tag{8}$$

$$Dailycost : price\,Day = energy\,Comsumed\,PerDay * Price\_KWH; \tag{9}$$

These formulas allow us to determine the monthly and daily costs based on the energy consumed and the price per kWh.

7. Challenges and solutions

- **Communication and data transfer issues**:

Communication and data transfer challenges: Encountering intermittent internet connectivity issues posed a hurdle, where loss of connection sometimes persisted despite attempts to reconnect. To address this, a code is developed that systematically checks the internet connection at regular intervals, facilitating automatic reconnection without necessitating system restarts.

- **Energy efficiency and battery management**:

In instances of battery depletion, system functionality halts, leading to communication loss and inaccuracies in power consumption calculations and data transmission to the microcontroller. To mitigate this, an electronic circuit capable of converting alternating voltage into a continuous one is devised, ensuring uninterrupted system operation until the battery is recharged. Consequently, data integrity is preserved, with error occurrences minimized to negligible levels.

8. Limitations

During the development and implementation of the energy management system using the Blynk platform, several significant limitations were encountered:

1. Financial Coverage Constraints: The project was primarily funded by a group with limited financial resources. This financial constraint restricted the scope of the system's development and implementation. For instance, the ability to invest in more advanced hardware, additional sensors, or enhanced data storage solutions was limited. Consequently, the system's performance and capability may not fully reflect what could be achieved with more substantial financial backing.
2. Transition of Blynk from Free to Paid Services: At the inception of the project, Blynk offered a free tier that was sufficient for the initial development and testing phases. However, during the course of the project, Blynk transitioned to a paid service model for certain features that were previously free. This unexpected change posed a significant challenge:
   a. Budget Overruns: The transition necessitated additional, unplanned expenditures to maintain access to essential features and capabilities of the Blynk platform. This resulted in budget overruns, as the project had not allocated funds for software subscriptions or additional service fees.
   b. Feature Limitations: Some advanced features that became part of the paid tier were critical for the optimal functioning of the energy management system. The need to either pay for these features or find alternative solutions led to delays and compromises in the system's functionality and efficiency.
   c. Disruption in Workflow: The sudden change disrupted the project's workflow, as the team had to reallocate time and resources to address the financial implications of the new payment model. This also led to a temporary halt in the project's progress as alternative funding and cost-effective solutions were sought.
3. Impact of the Siege on Gaza: The geopolitical situation, specifically the ongoing siege on Gaza, significantly increased the burden on the project group:
   a. Resource Limitations: The siege resulted in severe restrictions on the availability of essential resources, including hardware components, reliable internet access, and electricity. These shortages directly impacted the ability to procure necessary materials and maintain continuous operation of the energy management system.
   b. Operational Challenges: Frequent power outages and unstable internet connections disrupted the development and real-time monitoring capabilities of the system. This instability required the team to devise alternative strategies to ensure minimal downtime and maintain data integrity.
   c. Increased Costs: The scarcity of resources and the need to import components at higher costs due to the blockade significantly increased the financial strain on the project. The additional costs further exacerbated the existing budget constraints, limiting the ability to expand or enhance the system.
4. Reliance on Free or Low-Cost Tools: Given the financial constraints, the project heavily relied on free or low-cost tools and platforms. While Blynk offered a user-friendly and accessible interface, the reliance on free services often meant dealing with limitations in terms of scalability, data storage, and advanced analytics capabilities. This reliance restricted the ability to fully explore and implement more sophisticated energy management solutions.

These limitations highlight the critical impact of financial planning, geopolitical factors, and platform stability on the development of technology projects. Future endeavors should consider securing more robust funding, evaluating the long-term viability of platform choices, and developing contingency plans to mitigate risks associated with geopolitical instability and resource limitations.

9. Conclusion

In this study, the traditional electricity meter is enhanced by interfacing it with an ESP32 microcontroller, allowing for the calculation of energy consumption based on the received pulses. Each pulse, equivalent to one kilowatt-hour, is meticulously tallied to determine daily and monthly energy usage, adhering to user-defined thresholds. Upon surpassing these limits, an alarm is triggered, and electricity supply to the house is automatically disconnected. Continuous monitoring of consumption is achieved, with data visualized through graphical representations.

Future enhancements could involve incorporating multiple electric meters and integrating both utility and generator power sources. Presently, each user is equipped with a dedicated device, which might be cost-prohibitive for individual users. A potential future strategy involves scaling up the system to accommodate more than 10 users, facilitating centralized installations in residential complexes, thus optimizing costs and simplifying system maintenance in the event of technical issues. Furthermore, leveraging a GSM module in place of a WhatsApp server could enhance alert mechanisms in case of system failures. Table 1

10. Recommendations for future work

For further studies and future work:

1. Each user in the system is assigned a unique gadget, potentially increasing prices for individual users. With over ten active users, extending the user base is recommended for cost savings, expedited installation processes for residential buildings, and simpler system maintenance during technical challenges.
2. The next phase comprises implementing an automated mechanism for salespeople to manage power distribution based on specific user requirements.
3. Emphasizing careful analysis of security concerns is critical for future research and development.

CRediT authorship contribution statement

Hala Jarallah El-Khozondar: Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Conceptualization. **Shady Y. Mtair:** Validation, Software, Investigation, Data curation. **Khaled O. Qoffa:** Writing – original draft, Project administration, Formal analysis. **Omer I. Qasem:** Writing – original draft, Validation, Resources, Data curation. **Ahmad H. Munyarawi:** Writing – original draft, Methodology, Formal analysis. **Yasser F. Nassar:** Writing – review & editing, Validation, Resources, Formal analysis,

Table 1
present the current System Taxonomy.

Category	Component	Current project Description	ESP32 Based Electric Energy Consumption Meter [43]	Automatic Energy Meter Using IoT [44]
Hardware	ESP32	A low-cost, low-power system on a chip with integrated Wi-Fi and Bluetooth used to connect sensors and other hardware components to the internet.	Used ESP32 as the core processing unit, indicating reliability and effectiveness in energy management applications.	Used arduino uno to process data from sensors and send it to Blynk, showing common use for IoT projects .
	Sensor	Devices that detect and measure physical properties (e.g., voltage, current, energy consumption) and send this information to the ESP32 for processing.	Uses SCT-013 current sensors and ZMPT101B voltage sensors for accurate measurement of electrical parameters.	Employs SCT-013 current sensor and ZMPT101B voltage sensor, standard in energy management systems.
	Energy Meter	An electronic device that measures the amount of electrical energy consumed by a residence, business, or electrically powered device.	Integrates an energy meter setup using voltage and current sensors to compute energy.	Measures and displays energy consumption in real-time using similar sensor setup.
Software	Blynk	An Internet of Things (IoT) platform with iOS and Android apps to control Arduino, Raspberry Pi, and the likes over the Internet. Used for the user interface and remote monitoring.	Utilizes Blynk to create a dashboard for real-time monitoring of electrical parameters.	Implements Blynk for visualizing data from the energy meter.
Devices	iPhone	A smartphone used to run the Blynk app, providing a user interface for monitoring and controlling the energy management system.	Not specified, but Blynk app is compatible with both iOS and Android devices.	Not specified, but Blynk app is compatible with both iOS and Android devices.
Communication	WhatsApp	A messaging platform used for notifications and alerts related to the energy management system.	Not mentioned.	Not mentioned.

Table 2
Output status.

GEDCO line Status (utility company)	Private Generator line Status	Limit switch/ day	Limit switch/ month	Consumed per day greater than Limit	Consumed per month greater than Limit	Output Status
ON	-	-	-	-	-	OFF
OFF	OFF	-	-	-	-	OFF
OFF	ON	OFF	OFF	-	-	ON
OFF	ON	ON	OFF	Yes	-	OFF
OFF	ON	ON	OFF	No	-	ON
OFF	ON	OFF	ON	-	Yes	OFF
OFF	ON	OFF	ON	-	No	ON
OFF	ON	ON	ON	Yes	Yes	OFF
OFF	ON	ON	ON	Yes	No	OFF
OFF	ON	ON	ON	No	Yes	OFF
OFF	ON	ON	ON	No	No	ON

Table 3
variables and their representations.

variable	Stands for
pulseCount	Number of pulses pass the power counter
pulseCountPerDay	Number of pulses pass the power counter/day
pulseCountPerMonth	Number of pulses pass the power counter/ month
energyPerPulse	The energy obtained per plus
totalEnergyComsumed	Total energy consumed from the starting of the system
energyConsumedPerDay	the energy consumption in kWh per day.
energyConsumedPerMonth	the total energy consumption in kWh over a month
Price_KWH	Cost of 1 kWh in Shekel
price	The energy cost for one month
priceDay	The energy cost for one day

Conceptualization. **Ehab H.E. Bayoumi:** Writing – review & editing, Software, Formal analysis. **Ahmed Abd El Baset Abd El Halim:** Writing – review & editing, Resources, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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