IoT-Based Residential Energy Efficiency System

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***Abstract*— This project aims to develop an IoT-based AC monitoring, energy monitoring and decision support system that helps users manage their energy consumption habits more consciously. With the help of the ACS712 current sensor and ESP32 microcontroller in the project, the average energy consumption of the devices is measured in the most optimum and precise way, this data is processed and used in real time, analog signals are converted to digital and presented to the user wirelessly (Wi-Fi). The system analyzes the energy consumption statistics of the users and offers optimization recommendations to the users (OpenAI API). In addition, it provides a feedback mechanism to the user by detecting abnormal situations that may occur in consumption. It offers a user-friendly interface thanks to the mobile application and aims to promote a sustainable lifestyle. It offers graphing, historical analysis and notification support of energy data through the mobile application. This project offers a solution both individually and industrially with its low-cost, flexible and scalable structure.**

***Keywords*— Keywords: IoT, AC monitoring, energy efficiency, sustainability, real-time data, ESP32, ACS712.**

I. Introduction

Energy efficiency is becoming increasingly important for both environmental sustainability and economic savings. However, the deficiencies in current energy monitoring systems for households and industries pose a significant global challenge. Households cannot adequately track the causes of their electricity bills, which prevents them from becoming informed and conscious consumers. Moreover, current energy monitoring systems are often inaccessible due to their high costs, inflexible designs, and lack of user-friendly interfaces. This creates a substantial gap, particularly in meeting the need for precise monitoring and management of energy consumption for energy-intensive devices. The inability to obtain real-time energy consumption data also hinders analyzing and optimizing usage patterns. These shortcomings make it difficult for users to understand their energy consumption and make informed, energy-saving decisions. As a result, there is a growing need for a cost-effective, user-friendly, and scalable real-time energy monitoring system. IoT (Internet of Things) systems are emerging as an effective solution to address this need. With their flexibility, IoT systems can be tailored to various requirements and applied across different domains. Particularly, IoT systems play a critical role in improving energy efficiency in both residential and industrial contexts. By monitoring, analyzing, and presenting energy data in a meaningful way to users, IoT systems contribute significantly to changing consumption habits and raising user awareness. To maximize the effectiveness of these systems, it is essential to develop and implement the most suitable applications and solutions for specific use cases.

II. Objective

For the reasons stated in the introduction, this project was carried out to address this deficiency. This project aims to provide a cost-effective, user-friendly and scalable IoT-based solution for real-time energy consumption monitoring and analysis. A simple visualization of this system is shown in Figure 1.

Figure 1 A Simple Visualization of System

The project criteria and objectives in this IoT-based solution are listed as follows:

- To develop a sensitive AC current measurement system for real-time monitoring of the energy consumption of household appliances using the city grid voltage and to verify its accuracy.
- To provide real-time and uninterrupted monitoring of the input data and output coming through the microcontroller and to visualize this data using a user-friendly interface.
- To identify inefficiencies through the AI plugin for the optimization of the energy used and to provide a forward-looking view in the suggestion to the user to reduce their costs. Thus,
- To design a low-cost, forward-looking, simple and compact structure for the use of the product in both residential and industrial applications. (SDG 7)(Figure 2) Thus, to ensure that users make informed, energy-efficient decisions and to encourage responsible energy use. In this way, achieving the SDG 11 (Figure 3) target of sustainable cities and communities.
- Increasing its functionality and integrating IoT technology using cloud-based and remote monitoring management.

Figure 2 SDG 7

Figure 3 SDG 11

III. System

This project is designed to instantly monitor users' energy consumption, analyze incoming data, and optimize data in the most appropriate way by using IoT technologies. While the ACS712 current sensor measures the current data of the devices used, the ESP32 microcontroller processes this data and transmits it to the server wirelessly (Wi-Fi). The analog signals received from the sensor are converted to digital form with the ADC unit thanks to ESP32 and transferred to a server in JSON format. Data is stored and analyzed using PostgreSQL on the server. This project makes energy management more efficient and accessible with its low-cost, user-friendly interface and scalable structure, and is a tool capable of meeting the needs for sustainable energy use.

A. Hardware

1. ACS712 Current Sensor

The hardware part of the system is designed to precisely measure and process AC data. The ACS712 current sensor is an important device in power calculation and management applications. It measures the current through a device or circuit and produces an appropriate analog signal proportional to the measured current. The ACS712 Current Sensor is an Allegro MicroSystems product that can be used for precise measurement of AC. This sensor is based on Hall Effect and has an integrated Hall Effect device IC. Current measurements can generally be made between -30A and +30A. It varies depending on the model.(Figure 4)

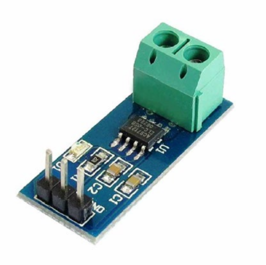

Figure 4 ACS712 Current Sensor

In this project, measurements are made between -5A and +5A. It provides an analog voltage output, which varies according to the magnitude of the current. In addition, thanks to electrical isolation, there is no physical connection between the circuit where the sensor measures and the control circuit.

2. ESP32 Microcontroller

ESP32; Bluetooth (both classic Bluetooth and Bluetooth Low Energy - BLE and Wi-Fi (802.11 b/g/n) is a low-cost and low-power microcontroller system. ESP32 has a dual-core processor, so it has the capacity to perform parallel processing and fast processing. The cores are usually based on Ten silica LX6 microprocessors. ESP32 has 34 GPIO pins. These pins can read and write digital signals and also have ADC (Analog-to-Digital Converter) features that can read analog signals. It supports many communication protocols such as SPI, I2C, UART, CAN. As a result, it can easily communicate with external sensors. ESP32 is efficient in terms of low power consumption and energy efficiency can be increased by using deep sleep mode. (Figure 5)

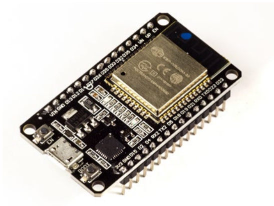

Figure 5 ESP32 Microcontroller

In this project, an IoT project is carried out by using the ESP32 microcontroller to collect data from the ACS712 current sensor and send this data to the server via Wi-Fi network. Data from the current sensor connected to the GPIO34 pin of ESP32 was collected. The collected data was converted to voltage to be used in power calculation. Then, the collected data was structured in JSON format after the ADC conversion process was performed and prepared to be sent to the server. The data sending process to the server was done with the HTTP POST process and the data sent to the server was written to the serial monitor. In addition, the data collection process of the sensors was organized by adding a 3-second delay at the end of each cycle.

3. 220V-5V Transformer

The AC220V-DC5V converter converts alternating current 220 volts to direct current 5 volts and 0.7 ampere current. It can be used in LED lighting, low voltage electronic devices, microcontroller projects and applications requiring low power. The converter first reveals the alternating current. Then, it converts AC to DC with a rectifier circuit. It performs filtering and regulation processes to obtain a smooth DC output. (Figure 6)

Figure 6 AC220V-DC5V Transformer

The reason we use a transformer in this project is that instead of feeding the ESP32 microcontroller and ACS712 with any external power source, it converts the AC coming from the phase line to DC, creating a system with less material, low cost and compactness.

4. Capacitor

Capacitors are basic electrical and electronic circuit elements created by placing an insulating material between two metal layers, taking advantage of the ability of electrons to polarize and store electrical charge within the electric field. (Figure 7)

Figure 7 Capacitor

In this project, 2 22uF capacitors and 2 33uF capacitors were used, each with a capacity of 110uF. The reason for this is to filter and prevent signal distortions that may occur at the output of both the ESP32 microcontroller and the ACS712 current sensor, and to ensure that the system operates optimally. The reason for using + capacitors is to filter different frequency components and to provide stability in a wide frequency range.

The connections in the project were made as follows: First, the phase, ground and neutral lines coming from the triple socket were determined. Then, the phase and neutral cables were connected to the transformer and the input of this converter. This converter converts high voltage 220V AC electricity to 5V DC and provides 5 volts of power for the circuit. The 5V required for the ACS712 and ESP32 microcontrollers to operate was obtained from the output of the transformer. The connections of the ACS712 are connected to the phase cable and the phase cable of the socket where the measurement is made is connected to its input. In this way, the current value is obtained by observing the voltage arc. The outputs of the current sensor are ground, voltage and an output that sends the signal to the microcontroller. This output is connected to the GPIO34 pin of the ESP32. In addition, the 5 V required for the operation of the ESP32 was provided from the transformer. Finally, the filtering process was performed with the help of capacitors in order to transfer both the ACS712 and ESP32 signals properly. The ground and 5V line of the entire system are combined into a single line. In this way, both the cable crowd is reduced, and the possible pollution is prevented. The simulation of the circuit is in Figure 8 below and the real picture of the circuit is in Figure 9.

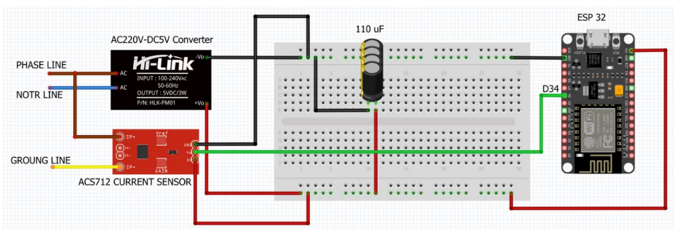

Figure 8 Simulation

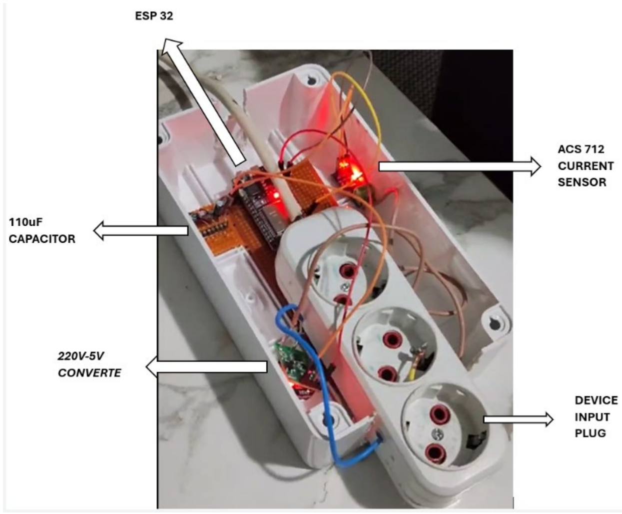

Figure 9 Real Circuit

B. Software

In this project, the software part collects, stores, processes and shares all the data coming from the ESP32 microcontroller with the user in real time. The system has been developed with various technologies for innovative energy methods and analysis. The data is stored in the PostgreSQL database and made useful by both mobile applications and web applications via the RESTful API. Socket.IO is used to transmit data instantly and OpenAI integration has been made for analysis with the incoming data.

Data transfer is one of the main building blocks of the system and is set in the most optimum way in terms of both speed and reliability. Here, the IEEE 802.11 standard is used, allowing high-speed data transfer thanks to Wi-Fi technology. Thanks to this communication protocol, it allows uninterrupted and fast transfer of energy consumption data with its wide-band capacity and high-speed transfer time. In this way, data from IoT devices can be transported securely and effectively on the network. In addition, the system has a platform-independent communication infrastructure. Thanks to the RESTful API, data from the device is transformed into a format that can be easily accessed by clients. The JSON format is chosen for data transmission here. JSON offers a data structure that can be easily understood and parsed by both clients and programs. Thanks to this, the system allows it to work without any problems between different operating systems or devices. The mobile application designed here receives data in JSON format via the RESTful API and can process this incoming data according to its own needs. In addition, the simple structure of JSON helps in fast data processing and transmission. It provides maximum efficiency with minimum processing load even in high amounts of data. This provides suitable infrastructure for the analysis of this project. The system helps users to obtain energy consumption data quickly and effectively by providing a reliable connection and using modern data formats.

The system is designed with low energy consumption requirements in mind, in order to analyze and instantly monitor energy consumption. This process ensures long-term and sustainable operation of IoT devices, which is critical for energy efficiency. This process not only extends the life of devices but also contributes to environmental sustainability by preventing energy waste. It directly contributes to SDG 7 within the scope of the Sustainable Development Goals (SDG). Real-time monitoring of energy consumption data helps individuals and organizations increase energy efficiency. It also provides sustainable solutions for energy management in cities and communities in line with SDG 11. Working together with IoT devices, this system can optimize cities' energy infrastructure and reduce their carbon footprint.

Security is one of the most important components for such systems. Various layered approaches were adopted to both protect data security and provide system integrity. The system is equipped with advanced security measures both in wireless communication and on the server side. WPA2 (Wi-Fi Protected Access 2) protocol was used to ensure the security of data during wireless communication. WPA2 protects data against unauthorized external access and manipulation using a modern encryption method. An additional secure authentication mechanism ensures that only authorized devices connect to the system. Server security is provided by firewall rules and port management. The firewall allows only requests from specific protocols and IP addresses to access the server. This forms the first line of defense against malicious attacks and unauthorized access. In addition, only the required ports are left open, and all other ports are closed to access.

Socket.IO is used to provide instant data sharing. Socket.IO provides two-way and high-speed communication between the server and the clients. In the first connection, Socket.IO automatically triggers the connection event. During this connection, it queries all energy consumption data in the database. This data is sent to the client via an event called "initial_data". As a result of this process, the client has access to all available data. Sharing of New Data ("new_data") When new data comes and is recorded in the system, it instantly transmits this data to all clients. Data is sent to the server and recorded in the database through the REST API. The server transmits this new data recorded in the database to all clients connected to Socket.IO via the "new_data" event. In this way, it is always possible to work with up-to-date data and allows instant monitoring.

The system uses OpenAI API integration for efficient analysis and optimization of energy consumption data. This integration provides AI-based solutions for energy management and allows users to make informed decisions. For example, it analyzes whether certain devices consume more energy than expected and guides the user on how to optimize which devices can be optimized for energy saving. Here, the data analysis and the values collected in the system are transferred to OpenAI API. OpenAI API generates user-specific recommendations using machine learning algorithms with existing data. It transfers these recommendations to the user through a user-friendly interface and helps users become aware of energy efficiency.

Ngrok, thanks to internet access with ngrok, although it works on a local server, the internet becomes open. Normally, a local server can only be accessed from devices on the same network. However, Ngrok eliminates this limit. The working principle is that Ngrok creates a tunnel between the local server and the internet connection. This tunnel can be accessed with a URL connection. In addition, for security reasons, all data transfers passing through the tunnel are sent encrypted. This ensures that the connection established between users and the server communicates securely (Figure 11).

To summarize the project, the project is configured by creating a package.json file with the npm init command. All necessary dependencies are installed with the npm install command. In this way, all packages required for the project to work are installed. Nodemon detects file changes and automatically restarts the server. This saves time in a development process where frequent changes are made. The type: module setting allows modular coding with import and export keywords. This increases the readability and reusability of the code.

To support different functions in the system

- express: To create servers and develop RESTful APIs
- body-parser: To parse and process JSON data sent in API requests
- pg: To connect to the PostgreSQL database and perform data operations
- socket.io: To provide real-time data sharing
- cors: Allows access to the API from different platforms by allowing cross-source requests.
- openai: To create AI-based analysis and energy efficiency recommendations

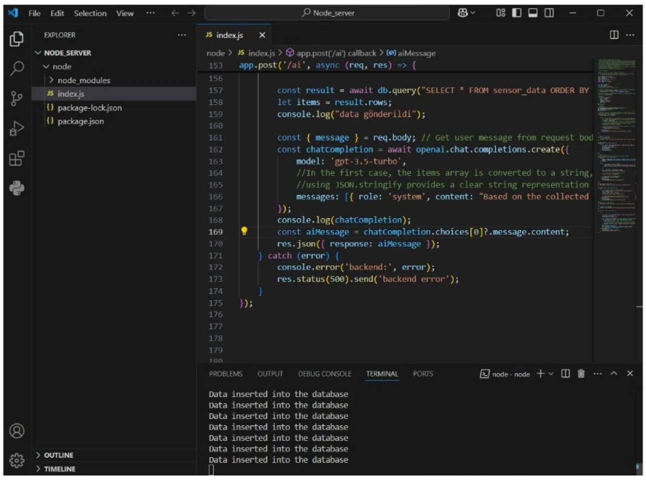

Figure 10 Server to App Data Transmission

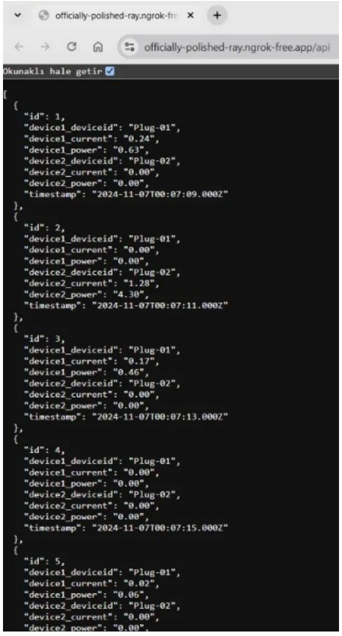

Figure 11 Ngrok

C. *Mobil Application*

Data Visualization and Processing Module (Mobile Application)

In the project, data visualization is required to create meaningful information for the user. Therefore, we have implemented a mobile application to transfer the data on the server to the screen and present it to the user. The details of our module are explained under 4 main headings:

1. Data Retrieval and Management

Data is retrieved from our server in real-time using Socket.IO. The data received is converted to the DataModel class. At the same time, this data is managed through a central structure. Cost calculation is also made here according to the power data received every 7 seconds and the kWh price determined in Turkey.

In this way, the device or devices are allowed to continuously update the current, calculated Power and cost information at certain periods. Similarly, current and power are recorded regularly with time information.

2. Graphing

Graphing is a system that provides a visual way to interpret raw data. This system offers suitable visuals for the user to interpret the data. The user can see which hours the energy consumption is higher more easily than the line graph and reduces complexity. Similarly, the ability to pan and zoom over the graph in our application allows the user to focus on the details. In the graph, using different colors for different devices and their current and power information would avoid confusion. Similarly, labeling the title and axes of each graph would serve the same purpose. The graph can also filter the data hourly, daily, weekly, and monthly. The Syncfusion Flutter Charts library was used for the use of all these mentioned features. (Figure 12)

Figure 12 Graphing & Cost

3. Excel Output

If the user wants to examine or export the historical data specifically, it is possible to do this again from the application interface. To do this, the data is saved in Excel format thanks to the Dart Excel library. Choosing a format like Excel is both user-friendly due to the familiarity of the users and allows IoT data to work smoothly and harmoniously in different sectors.(Figure 13)

On the other hand, it allows users to easily store, share, and analyze their own data. It also allows users to interact with the data more efficiently.

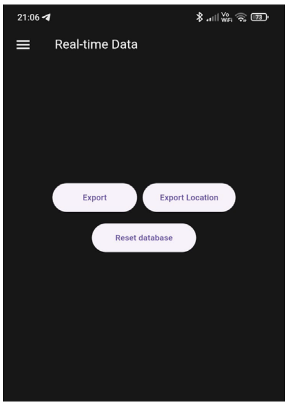

Figure 13 Export Data & Export Location & Reset Database

4. User-Friendly Design

The interface is designed to adapt to different devices. Users can easily switch between different pages within the application and quickly access the data they need. At the same time, the calculated variable electricity usage fee can be easily read both for each device and for the total price(Figure 12). An interface has been added to track data without pulling it out of the application, which allows the user to easily track current and past values on the screen (Figure 14). The interface is designed to adapt to different devices. Importance has been given to purifying the interface from complex menus and unnecessary details, where simple technical information is used less. Thus, the goal of learning and adapting to the application in a shorter time has been achieved. As stated in the system section, OpenAI API can provide information, suggestions, and ideas that the user wants to reach from our data to the users in line with their wishes (Figure 15). This has been realized as an important feature that shows that our project is a user-friendly application.

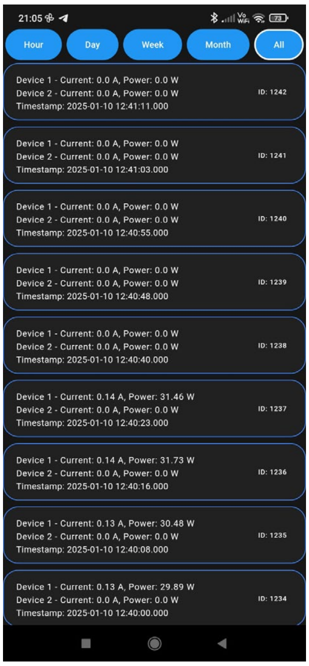

Figure 14 Target Page

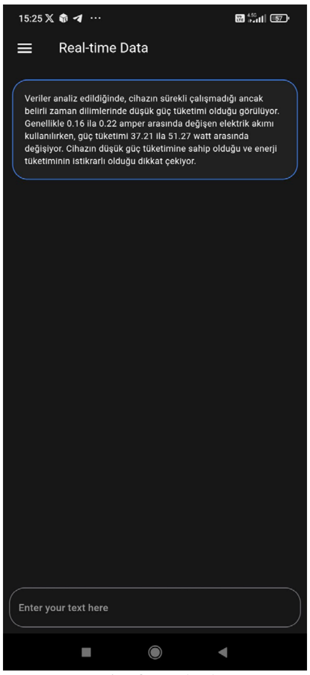

Figure 15 OpenAI API

IV. Result & Discussion

As a result of our project, the current received from our sensor and all the data we took by the multimeter and transferred to the application matched. The data we took was realized by the IoT-based energy monitoring system, real-time energy data, and accurate monitoring. Power consumption, cost calculation, real-time calculation, and visualization were completed. The system completed the presentation of real-time data to the user using a user-friendly interface. Our IoT device made remote monitoring possible, increased convenience, and ensured the applicability of the system. Simple and understandable graphics and tables were created from the data obtained by the users, and they were specifically allowed to share and store the data. Thus, the aim of increasing domestic energy efficiency was achieved.

The cost of our IoT device was determined as 400 Turkish Liras, but since this was the first product, such a price came out. It was calculated that the price would decrease by 65 percent if this product was intended to be produced for commercial purposes.

Future work will focus on integrating machine learning for predictive energy analysis, increasing data security, and expanding the scalability of the system to support more devices. Incorporating renewable energy tracking, such as solar panels, could expand its application and align it with sustainability goals. While the project addresses the limitations of traditional systems, ensuring long-term reliability and optimizing hardware dependencies remain areas for improvement. These advancements will improve the user experience and support broader adoption in residential and industrial environments.

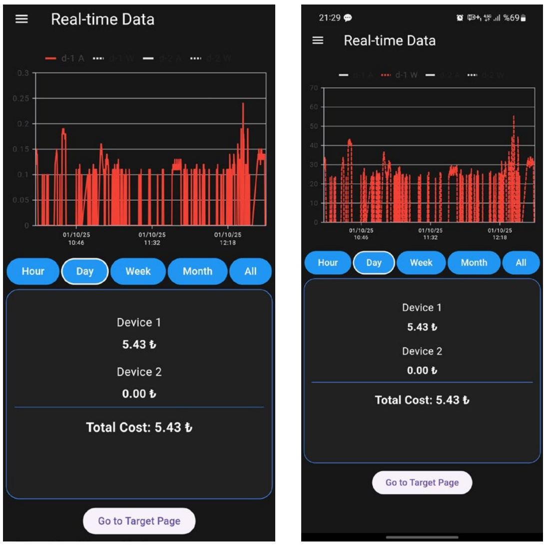

Figure 16 Current & Power Results

V. Conculison

This project, as an IoT-based energy monitoring and decision support system, offers an innovative solution to significant deficiencies in individual and industrial energy management. With the use of the ESP32 microcontroller and ACS712 current sensor, the energy consumption of the devices was measured in the most accurate and optimum way and presented to the user in real time. Converting the data to ADC (Analog to Digital) and transferring it via wireless communication with Wi-Fi made the energy consumption monitoring process both user-friendly and increased its efficiency. This project supports energy saving by analyzing users' energy consumption data and offers artificial intelligence extension suggestions for this, guiding them to a sustainable lifestyle.

This system, which is a suitable solution for both individual users and industrial applications with its low-cost, scalable and flexible structure, directly contributes to the SDG 7 (Accessible and Clean Energy) and SDG 11 (Sustainable Cities and Communities) targets of the Sustainable Development Goals.

Being able to track and analyze real-time energy consumption data allows users to make more conscious decisions in energy management. In addition, the system is cloud-based and remotely controlled, which optimizes the infrastructure of cities or residences and provides an important step towards reducing the carbon footprint.

The PostgreSQL database in the project ensures the security of incoming data and makes historical analysis easier; It helps users easily access data through mobile and web applications using the RESTful API. Thanks to Socket.IO, it enables instant data sharing and synchronous operation. It allows users to observe current data every time.

In addition, OpenAI API integration has made it possible to analyze energy consumption data with artificial intelligence and create personalized suggestions for energy saving.

In terms of security, the system is equipped with both WPA2 encryption protocol in wireless communication and measures such as firewall and port management on the server side. This both protected the confidentiality of the data and ensured the integrity of the system. In addition, thanks to Ngrok integration, the system has been made securely accessible worldwide even if it runs on a local server.

On the mobile application side, users were able to benefit from features such as visualizing energy consumption data, performing historical analysis and exporting in Excel format. With a simple and user-friendly interface design, users have been provided with easy access to data and more efficient management of energy consumption.

As a result, this project has contributed to both environmental sustainability and economic savings by providing a comprehensive solution for energy monitoring, analysis and optimization. With its innovative and versatile features, it sets a new standard in energy management for users.

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