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Embedded System

Home Electricity Cost Control System Based On Internet of Things

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A B S T R A C T

The increase in electricity consumption, especially in the household sector, is often not realized by users, resulting in uncontrolled increases in electricity bills due to the lack of transparency in real-time usage data. This study aims to design and implement an Internet of Things (IoT)-based electricity cost monitoring and control system for several electrical devices at home as a solution to overcome this problem. The method chosen based on the House of Quality (HoQ) analysis is an IoT system that uses an electrical energy sensor (then implemented as an ACS712 current sensor and a ZMPT101b voltage sensor) and an ESP32 microcontroller as a gateway. This system will measure the current and voltage values of the device in real-time, calculate power, accumulate electrical energy (kWh), and calculate cost estimates. The calculated data is sent wirelessly to the Firebase cloud database. Users can monitor this information, input the electricity price per kWh and the initial token, and control electrical devices through a website interface. In addition, the system can provide an estimate of the device's lifespan and automatically turn off the device if the token balance runs out. Test results show that this system is able to control the electricity costs of several devices in the home effectively, so it has the potential to be a significant solution in the efficiency of household electricity use.

INTRODUCTION

Electrical energy use is an integral part of daily life. Households, offices, and industries rely heavily on electricity to power various devices and equipment. However, users often lack awareness of wasteful energy use, which results in increased electricity bills. The inability to monitor electricity usage in real time and the lack of control over the use of electrical devices are among the main causes of energy waste.

On the other hand, electricity usage costs are generally only calculated after the bill is received, leaving users with no guidance for proactively controlling their usage. This is certainly problematic because people cannot anticipate and control their electricity costs. This is a common issue in society.

Electricity payments are difficult to predict because there are no clear figures and prices for each use of electricity in the home. This makes it difficult for people to estimate their electricity costs, resulting in uncontrolled monthly expenses. With this monitoring and control system, electricity users will receive real-time information about electricity consumption. Residents can manage their electricity usage, thereby addressing electricity waste and adjusting their electricity costs. Furthermore, electricity providers can easily monitor electricity usage at each location without having to check it in person. This problem is typically experienced by people who are rarely home, want to manage their expenses in detail, and have homes with an area of more than 60m^2.

According to a report from the International Energy Agency (IEA), global electricity consumption continues to increase in line

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with population growth and the increasing use of electronic devices, especially in urban areas. In Indonesia, data from PLN shows an annual increase in electricity consumption, particularly in the household sector. This increase is due to the increasing number of electrical devices used in daily life, such as air conditioners, televisions, washing machines, and smart home devices.[1]

In 2020, many residents in Singapore reported significant increases in electricity bills without clear explanation during the COVID-19 pandemic. Household electricity users complained that they only received bills with a sharp increase in total costs, but without a breakdown of usage per device or the time of use.[2]

Per capita electricity consumption in Indonesia in 2023 reached 1,285 kWh/capita, up from 1,173 kWh/capita in 2022. This increase was certainly influenced by various positive and negative factors. The positive factor is the increasing number of electronic devices, which require more electricity consumption, while the negative factor is electricity waste [3]
Based on PLN's annual report, electricity prices in Indonesia for July - September 2024 [4]

- S-1/TR class 450 VA: Rp 352 per kWh
- S-1/TR class 900 VA: Rp 455 per kWh
- R-1/TR class 900 VA: Rp 1,352 per kWh
- R-1/TR class 1,300 VA: Rp 1,444.70 per kWh
- R-1/TR class 2,200 VA: Rp 1,444.70 per kWh

Frequency: The electricity system in Indonesia operates at a frequency of 50 Hz. Voltage: For household use, the standard voltage is 220 Volts. For industrial sectors or large businesses, a higher voltage is used [5]

METHOD

The general design of the proposed system is illustrated in Figure. 1.

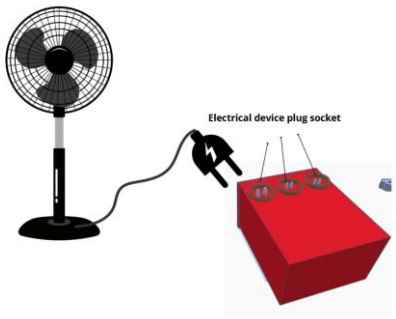


Figure 1. General System

The Figure 1 shows the layout of the electrical monitoring and control system, consisting of nodes and gateways. The rectangular enclosure is made of mica glass and is enclosed. For further details, see the following image.

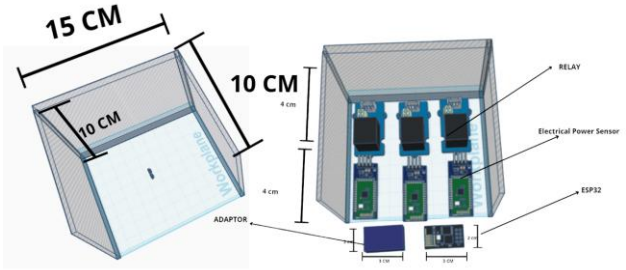


Figure 2. General System Design

In this design in figure 2, the author uses 3 ACS712 current sensors and an AMPT101b voltage sensor used on each contact to measure the voltage and current of the device. Next, there will be sensor data processing to obtain power and electrical energy values. This processing is carried out by esp32. Device control is done by placing a relay in parallel for each contact, so that the relay can disconnect the current for each contact without disturbing the other contacts. For more clarity, see the schematic circuit below.

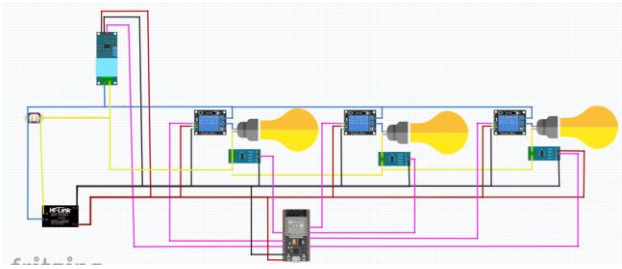


Figure 3. Circuit schematic

The circuit schematic can be seen in Figure 3. The AC current source will be made in parallel with two paths. The first path is connected to the adapter which will power the DC components, while the second path will be connected to the electrical load which will later be measured with a voltage sensor connected in parallel and a current sensor connected in series. The first path will enter the adapter and become the power source for the ESP32. The relay will be connected in series with the load path, while its control pin will be connected to the ESP32.

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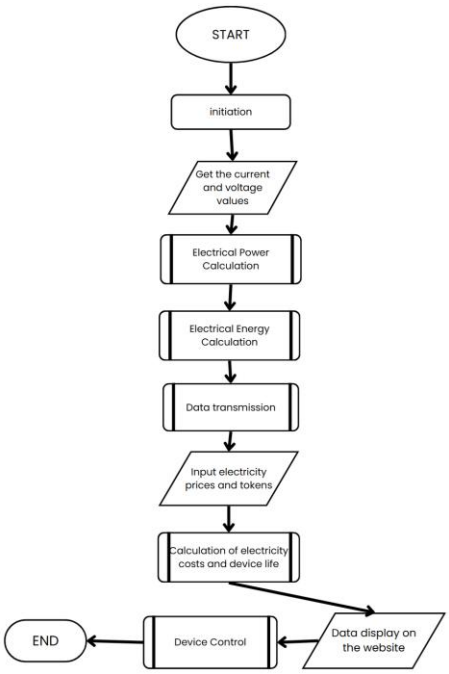


Figure 4. Flowchart of Process Design

The general flowchart of the system can be described as follows: The process begins with the initialization of all hardware components, including the sensor, microcontroller, and internet connection. Then the sensor capturing current and voltage values. Next, the electrical power calculation is performed, divided by the device's operating time to generate electrical energy. The results are sent to a database, which then processes them to generate an estimated operating time and calculate electricity costs based on the user's input price per kWh. The data is then displayed on the website, allowing users to monitor and control the device's operation. The control carried out is when electricity usage reaches the tolerance limit, a notification will appear informing that the token has run out and giving the user the option to add a token or turn off the device. The website will display how long the device can last based on the token entered, the current power of the device, the accumulated electrical energy of the device, and how much electricity the device has used.

The device energy accumulation formula is used to calculate the total electrical energy consumed by the device over a certain period of time. This calculation is based on the basic principle of electrical energy. The device energy accumulation formula is used to calculate the total electrical energy consumed by a device over a given period of time. This calculation is based on the basic principles of electrical energy. The basic formula for calculating electrical energy is as follows:

$$E = V \times I \times t \qquad (6)$$

E : Electrical Energy (Wh)

V : Voltage (V)

I : Curret power (A)

t : time (s)

In the Arduino code, power is obtained from the results of current and voltage measurements, then multiplied by the difference in measurement time (in hours, called deltaHour). The energy value generated at each reading is added (cumulative sum) to the energy_kWh variable, so that each time the loop runs, the total energy continues to increase according to device usage. The following are the details of the electrical energy accumulation formula:

$$Ei(t) = Ei(t-1) + \frac{Pi(t)\ x\ \Delta t}{1000} \qquad (6)$$

Ei(t): Total energy of device i at time t

Ei(t-1): Previous energy (kWh)

Pi(t): Current power (watts)

Δt: Time difference in hours

Divide by 1000 to convert from watt-hours (Wh) to kilowatt-hours (kWh)

The calculation of electricity costs can be done after obtaining the total energy which will then be multiplied by the costs that have been previously inputted and then the data will be saved. Next, the system compares the energy used with the electricity price per kWh entered by the user to obtain the total usage cost. Based on the initial cost (initial_token) entered, the remaining cost is calculated (remaining_cost = initial_token – total_cost). Finally, the device's lifespan is estimated by dividing the remaining charge by the current cost per second of power usage, resulting in an estimate of how long the device can remain on before the balance runs out.

A rule-based device control mechanism in an electricity monitoring system. The process begins with device control and checking the remaining token condition. If the remaining token is greater than zero, the device remains operational and the system immediately updates the energy history. However, if the remaining token is ≤ 0, a notification appears stating that the token has run out. At this stage, the user is given the option to turn off the device or add a new token. If the user chooses to turn off the device, the relay is turned off and the system continues updating the energy history. Conversely, if the user adds a new token, the system updates the remaining token value before proceeding to the energy history update process.

RESULTS AND DISCUSSION

Hardware Implementation

The implementation of the hardware circuit will be placed in a box measuring 21 cm x 14 cm x 8 cm, which has undergone slight design changes, as shown in Figure 5 below.

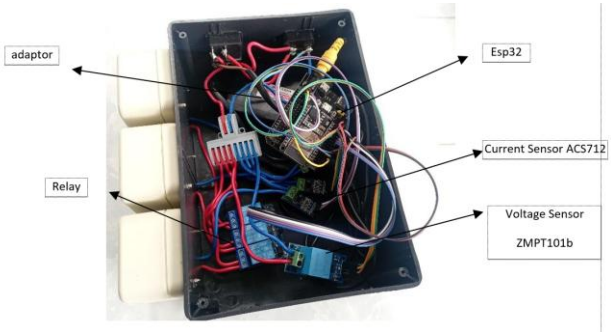


Figure 5. Hardware Implementation

The hardware design changes include:

- The contact position, originally at the top, is now at the side for easier checking of the thick single AC cable.
- The box size has been changed from 15cm x 10cm x 10cm to 21cm x 14cm x 8cm. This is because the components require more cables and cannot fit in the previous size.
- The energy sensor has been replaced with a voltage and current sensor because the large sensor and its induction current calculation require a spacious location, making it unsuitable for the initial box design.

The hardware components consist of:

- ESP32: Functions as a microcontroller connected to each sensor, providing input, output in the form of a relay, and processing that calculates the power from the input and sends the output to the database.
- The ACS712 current sensor measures current at each contact up to 10 Amperes.
- The ZMPT101b Voltage Sensor measures voltage in the circuit up to 280 volts.
- The 3-Channel Relay regulates the current at each contact.
- The 12V adapter supplies power to the DC components.

The final result of the tool implementation can be seen below.

Software Implementation

The software used in the system is a website, accessible at https://monitoring-listrik-tes.web.app. Data and readings from each sensor and module will be sent to Firebase and displayed on the website connected to the ESP32 or the system being built.

The website displays the price per kWh, power, kWh used, lifespan, usage history, and estimated lifespan of the device. Users can input the price per kWh and token, and can also control the device's on and off. Data retrieved from Firebase includes power, energy, device status, lifespan, and remaining tokens.

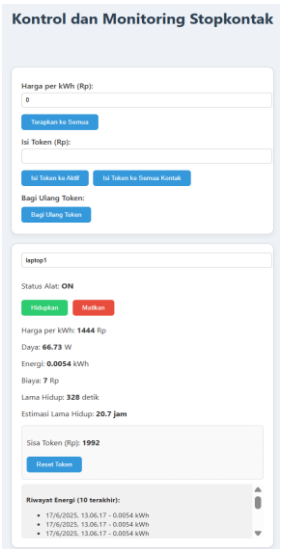


Figure 6. Software Implementation

Figure 6 shows the website display. The website displays the price per kWh, power, kWh used, lifespan, usage history, and estimated lifespan of the device. Users can input the price per kWh and token, and can also control the device's on and off. Data retrieved from Firebase includes power, energy, device status, lifespan, and remaining tokens.

Testing And Analisys

Testing 1 ACS712 Current Sensor

In this first test, the ACS712 current sensor was tested, the test will be carried out using an experimental method, where the sensor will be tested to calculate the current and later the reading results will be compared with the calculations by the multimeter as can be seen in the following table. In this test, the tool will be tested using an experimental method where the sensor will be tested to calculate the current and later the reading results will be compared with the calculations by the multimeter, this test is carried out to determine the accuracy of the sensor calculations, the error calculation is carried out with the following formula.

Table 1 ACS712 Current Sensor Test Results

Data	Device	Device Current (A)	Watt meter Current(A)	Error Value	Error percentage
1	None	0	0	0	0 %
2		0	0	0	0 %
3		0	0	0	0 %
4		0	0	0	0 %
5		0	0	0	0 %
6	Refrigerator	1.93	1.92	0.005	0.52 %
7		1.94	1.92	0.010	1.04 %
8		1.93	1.92	0.005	0.52 %
9		1.96	1.92	0.020	2.08 %
10		1.95	1.92	0.015	1.56 %
11	Rice	1.63	1.61	0.012	1.24 %
12	Cooker	1.58	1.61	0.018	1.86 %
13		1.53	1.60	0.0125	1.25 %
14		1.68	1.61	0.043	4.34 %
15		1.62	1.61	0.006	0.62 %
16	AC	1.8	1.8	0	0%
17		3.31	3.31	0	0 %
18		3.27	3.30	0.009	0.90 %
19		3.28	3.30	0.006	0.60 %
20		3.25	3.30	0.015	1.56 %
		Avarage			**1.30 %**

In presenting your tables, please follow Table 1 Test results show that the ACS712 current sensor can calculate the current value in the device with an average error of 1.30%, which is quite accurate when compared to multimeter calculations. This result is quite consistent with the initial specifications with an accuracy of >85%.

Testing 2. ZMPT101b Voltage Sensor

The ZMPT101b voltage sensor test aims to calculate the sensor's accuracy. This test is performed by comparing the sensor readings with those of a multimeter. In this test, the device will be tested using an experimental method, where the sensor will be tested to calculate the current and then the readings will be compared with

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the calculations made by the multimeter. This test is carried out to determine the accuracy of the sensor's calculations. The results obtained from the test are as can be seen in the following table.

Table 2 ZMPT101b Voltage Sensor Test Results

Data to	Tegangan Device (V)	Voltage watmeter (V)	Error Value	Error percentage
1	227	227	0	0 %
2	228	228	0	0 %
3	227	228	0.004	0.43 %
4	228	228	0	0 %
5	227	227	0	0 %
6	228	228	0	0 %
7	227	228	0.004	0.43 %
8	228	228	0	0 %
9	227	227	0	0 %
10	228	228	0	0 %
11	227	228	0.004	0.43 %
12	228	228	0	0 %
13	227	227	0	0 %
14	228	228	0	0 %
15	227	228	0.004	0.43 %
16	228	228	0	0 %
17	227	227	0	0 %
18	228	228	0	0 %
19	227	228	0.004	0.43 %
20	228	228	0	0 %
21	227	227	0	0 %
22	228	228	0	0 %
23	227	228	0.004	0.43 %
24	228	228	0	0 %
25	227	227	0	0 %
		Avarage		0.69 %

From the test results in table 2, it can be seen that the ZMPT101b voltage sensor is able to calculate the current value in the device with an average error of 0.69%, which is quite accurate when compared to multimeter calculations. This result is quite in accordance with the initial specifications with an accuracy of >85%.

Testing 3 Mikrokontroler ESP32

In this esp32 test, the tester conducted a test using an experimental method where the esp32 will be tested to calculate power and send it to firebase, this test is done to determine the use of Flash and heap memory (SRAM) when the program is run in real-time. The test is done by loading the program into esp32 and then compiling it to see the initial allocation of flash memory and SRAM, the system is run for 1 full hour to see if there is a memory leak or increased memory usage, memory usage data will be recorded every 10 minutes

Table 3. Mikrokontroler ESP32 Test Result

Memory	Total Capacity	Early Use	Use While Running	Note
Flash	4 MB	± 250 KB	Tetap	Doesn't change after upload
SRAM	520 KB	± 280 KB	Stabil di 270–285 KB	No Memory Leaks
PSRAM	-	Not Use	-	Not enabled in testing

Based on the test results in table 3, it can be concluded that the ESP32 is capable of running the electricity monitoring program efficiently, both in terms of Flash memory and RAM. During the 60-minute test, heap memory usage was very stable and showed no signs of memory leaks, meaning memory allocation was proceeding smoothly and no data accumulated over time. Flash memory usage is also relatively small compared to the ESP32's total capacity, allowing for optimal calculation performance.

Testing 4 The Power Of Tool Components

This component power test was performed to calculate the power consumption of all components in the system: the ESP32, the ZMPT101b voltage sensor, the ACS712 current sensor, and the relay module. This test aims to ensure that the total power consumption of all components does not overload the system when used continuously, which would affect future electricity costs. The system runs as usual in three states: when the system is not connected to Wi-Fi, when the system is connected to Wi-Fi but the relay is off, and when the system is connected to Wi-Fi with the relay on. The overall component power is calculated by measuring the current flowing from the DC adapter to the ESP32 and the input voltage on the ESP32. The average power is then calculated based on the product of the current and voltage.

Table 4. The Power Of Tool Components Test Result

Skenario	Voltage Supply (V)	Average Current (mA)	Average Powet (W)
Idle, Relay OFF	5	127	0.635 W
Wi-Fi TX, Relay OFF	5	300	1.5 W
Wi-Fi TX, Relay ON	5	367	1.8W

From the test results shown in Table 4, it was found that the total power consumption of the components when the system was running was only 1.8 watts. From these results, it can be concluded that the components in this system do not consume much electrical power, so they do not significantly affect the calculation of electricity costs.

Testing 5 Kwh Calculation

The kWh calculation in the system will be compared with the kWh calculation on the home's electricity meter. This aims to evaluate the accuracy of the electrical energy calculations performed by the monitoring system and the calculations on the PLN electricity meter. The testing process involves running the system for approximately one hour to calculate the kWh of a device. The results are compared with those displayed by the home's electricity meter. The difference between the two is used to determine the accuracy level.

Table 5. Kwh Calculation Test Result

Previous kwh meter value (Kwh)	KWh meter value after that (Kwh)	Total Kwh meteran (Kwh)	Previous system Kwh value (Kwh)	System Kwh value after that (Kwh)	Total Kwh meteran (Kwh)	difference (%)
23.33	23,22	0.11	23.33	23,22	0.117	0.7 %
15.37	15,06	0.31	15.37	15,05	0.315	0. %
15.31	15.26	0.05	15.31	15.26	0.050	0%

Based on table 5, test results show that the monitoring system's kWh calculations closely match the kWh values on home electricity meters, with an average difference of less than 6.33%. This difference could be due to decimal rounding in the price per kWh or the home meter's specific rounding method. Overall, it can be concluded that the system has excellent accuracy in calculating electrical energy (kWh).

Testing 6 Whole System Testing

Overall system testing was conducted to ensure the integration between the hardware (ACS712 current sensor, ZMPT101B voltage sensor, and ESP32 module) and software (Firebase, Node-RED, and website monitoring) ran as designed. This testing covered the flow from sensor readings, power and energy calculations, electricity token input, device lifespan estimation, to monitoring and notification displays on the website. Overall system testing was conducted by connecting the monitoring device to an electrical load, then entering the initial token amount via the website application. After that, the system would calculate the estimated lifespan of the device based on the load power value and the available token balance. The calculation results in the form of power, kWh energy, and estimated lifespan were recorded on the website display, then the load was operated for the estimated duration. Next, it was observed whether the actual lifespan matched the estimate and whether a notification appeared when the token balance was depleted, thus determining system performance.

Table 6. Overall System Test Results

Test	Load (Watt)	Initial token (Rp)	Pricek Wh (Rp)	Estimated length of on (Hour)	Real Length of on (Hour)	difference (%)	Notification Status
1	±100	500	1444	3,5	3,4	2,94%	Appear
2	±150	500	1444	2,3	2,2	4,55%	Appear
3	±370	500	1444	0,9	0,95	5,26 %	Appear
4	±500	500	1444	0,7	0,73	4,1%	Appear
5	±600	500	1444	0,6	0,62	3.2%	Appear

Based on Table 6, the system shows results for the estimated lifespan calculation that are very close to the actual conditions, with an average difference of 4%. This indicates that the integration of the sensor, microcontroller, and token calculation is running well. This difference arises due to unstable power from the load, which does not quite match the estimated lifespan. Furthermore, the notification feature when the balance/token runs out functions correctly on each test sample.

CONCLUSIONS

The designed electricity monitoring system exhibits good accuracy, with average reading errors of 1.41% for current and 0.69% for voltage. The system is capable of operating on AC power, automatically calculating power and costs, and displaying the results—including electricity usage information and estimated tariffs for a specific time period—on the website as programmed. Furthermore, with a relatively low power consumption of only 1.8 watts for its own components, the system does not significantly impact the electricity costs of the device being monitored.

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