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The development of real-time energy monitoring system using IoT base

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ABSTRACT

This paper aims to develop a real-time energy monitoring system based on smart metering to enhance energy efficiency in the single-phase residential sector. Based on the concept of low-cost IoT devices, this intelligent meter system is designed to monitor household energy consumption. It provides real-time information on a graphical Node-RED Dashboard, making it easy for households to track and manage their energy usage. The hardware of the power metering system included the Node MCU ESP8266, the PZEM-004T, and a cloud server built on the Raspberry Pi for storing electricity consumption data by using Node-RED to connect devices via an application programming interface system. This system can help analyze the electricity consumption behavior in the residential sector. It is a guideline for selecting the electricity rate between the TOD and TOU rates. The results found that in the electrical energy measurements of households 1 and 2, the mean deviations were 0.8758% and 0.5523%, respectively. The electricity cost-saving results when changing the electricity tariff from the TOD rate of households 1 and 2 to the TOU rate. It was found that electricity costs can be saved by 0.2807% and 1.0936%, respectively. The most critical variable is electricity consumption during peak periods. In the case study of household 1, if the electricity consumption during the peak period is less than 13%, it will be appropriate to select the Time of Use rate. In household 2, if there is electricity consumption during the peak period, less than 38% would be appropriate to choose the type of electricity user with a TOU rate.

Keywords: Energy monitoring system, Node-RED, IoT base, Residential sector, Smart metering

INTRODUCTION

Electricity is a critical factor in life and tends to use more energy. Due to the country's economic growth, it is growing steadily. Whether in the household, commercial, industry, transport, or agriculture sectors. Electric power is essential to various activities, including driving the country's economy, and all of these rely on electricity as the main factor. It is expected that the energy demand will continue to increase in the future. Efficient and sustainable energy use is an essential goal for both the public and private sectors. Many agencies have been continuously campaigning, especially the energy-saving efforts of the household sector. However, arousing public consciousness can save energy to a certain extent. Suppose technology is developed as a tool to help measure electrical energy. In that case, it can show the behavior of consumers using electricity daily to bring information to analyze the energy-saving results of each household. Each household will have different periods of electricity consumption. Some households may use less electricity during the day but more at night. It may give power users a way to adjust their electricity usage behavior in line with the time of use tariff, a government policy that encourages reducing peak demand and saving energy.

The Time of Use (TOU) tariff is a pricing structure for electricity consumption where electricity costs vary depending on the time of day. Instead of a flat rate for electricity throughout the day, TOU tariffs divide the day into different time blocks, typically categorized as on-peak and off-peak. Besides, the Time of Day (TOD) tariff is another term used to describe a pricing structure for electricity consumption, like the TOU tariff. Under a TOD rate, the cost of electricity varies depending on the time of day when it is consumed. Like TOU rates, TOD rates typically divide the day into different periods, such as on-peak and off-peak, each with its corresponding electricity rate. Peak Period: This is when electricity demand is highest, usually during daytime hours when businesses are operational and household energy usage is at its peak. Electricity rates during peak periods are typically higher, reflecting the higher cost of supplying electricity during high demand. Off-peak Period: This is when electricity demand is lowest, often during late-night or early morning hours when businesses are

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closed, and overall energy consumption is reduced. Electricity rates during off-peak periods are usually lower to incentivize consumers to shift their energy usage away from peak times. The goal of TOD tariffs, like TOU tariffs, is to encourage consumers to adjust their electricity usage patterns to periods of lower demand, thereby helping to balance electricity supply and demand, reduce strain on the grid during peak periods, and potentially lower overall energy costs for consumers and utilities. The TOU tariff varies according to the time of use. The study was based on the electricity tariff rate (2023) of the Provincial Electricity Authority (PEA) [1]. Electricity rates during the day and night will be different. The TOU tariff varies according to the time of use. The study was based on the electricity tariff rate (2023) of the Provincial Electricity Authority (PEA) [1]. Electricity rates during the day and night will be different. The cost of electricity will be expensive during the period when the system has a high demand for electricity (on-peak) between 09.00 a.m. and 10.00 p.m. on working days (Monday-Friday), with an electricity rate of 5.1135 baht per unit (in the case of a voltage of 22-33 kV). The electricity rate equals 5.7982 baht per unit (in the case of a voltage lower than 22 kV) because electricity has to operate power plants that use all fuel types. Both cheap and expensive to produce enough electricity to meet demand, But when the system has low electricity demand (off-peak) between 10:00 p.m. and 9:00 a.m. on weekdays (Monday-Friday) and during the time between 00.00-24.00 on Saturday-Sunday, National Labor Day standard public holidays (excluding plowing day and substitution holidays) with an electricity rate of 2.6037 baht per unit (in the case of voltage 22-33 kV) and an electricity rate of 2.6369 baht per unit (in the case of voltage below 22 kV). Electricity costs will be cheaper because the utilities can operate power plants that use cheap fuel. The standard electricity tariff is calculated as a progressive rate; the more electricity used, the more expensive it will be. If comparing the standard electricity rate with the TOU electricity rate during the off-peak period, there will be a difference of about 40%, which means that the TOU electricity rate during the off-peak period is about 40% cheaper than the standard electricity rate. The possibility of an energy-saving effect and efficient energy use will result in the most value for the user. The electricity cost-saving chart changes from time of day (TOD) to time of use (TOU). It was based on the electricity tariff rate (2015) of the Provincial Electricity Authority (PEA). The customer can use this chart as a guideline to change the TOU rate by analyzing their electrical usage behavior parameter. The chart is plotted to evaluate the percentage of energy savings [2]. Nowadays, communication technology is more advanced and has been applied to various applications based on the IoT concept. It creates a network of connections between various devices via the wireless internet. The adoption of the IoT system is an additional function of energy management. It is one way to increase energy efficiency. We present a cutting-edge, real-time, low-cost, internet-of-things energy monitoring system developed in this work. The design and development of electrical energy monitoring systems are of various types, such as the IoT-based Smart Energy Meter for Home Appliances designed using an Arduino microcontroller. This innovative smart meter automatically measures energy consumption and calculates the bill with the help of IoT and GSM techniques. The energy consumption units are measured from the user's location to calculate the bill. The generated bill is sent to the user's smartphone through SMS [3]. They proposed electrical energy measurement and monitoring for an IoT home electrical load. The electrical energy measurement and monitoring application used an IoT system based on an ESP8266 microcontroller and a low-cost PZEM-004T current sensor. It measured such parameters by connecting it with a Node MCU ESP8266 unit, a board with built-in Wi-Fi capability. Electrical energy was displayed on a smartphone with the Blynk application, and the data was saved to a cloud system. Abnormal high-energy alerts were sent on a LINE application [4]. The IoT is based on intelligent energy meters for smart grids. The power meter is connected to the ESP8266 12E via an optocoupler. The system also has an OLED display. ULN2003 is used in the driver cycle to relay and shift loads. The current sensor is also installed to detect power theft [5]. An intelligent energy meter monitoring system. It consists of an Arduino, an energy meter, a WIFI module, a relay, and a transformer. An energy meter measures the live current, voltage, and power. The microcontroller reads these parameters and sends them to the cloud. Node MCU is a Wi-Fi device that has a microcontroller in it. This paper measures electricity consumption in home appliances and automatically generates its bill using IoT [6]. A prototype of an advanced meter based on the ESP8266 module with two-way communication over the MQTT protocol [7]. The intelligent energy monitoring systems for energy savings consist of the ZigBee module (IEEE 802.15.4), ESP-12 module, Blynk app, and cloud computing for interfacing the information between the meters and the consumer [8]. Schneider Industry installed an IoT-based energy monitoring system. It can read different electrical parameters. The computing system uses Raspbian, an open-source Linux-based operating system [9]. The hardware included PZEM-004T modules with non-invasive current transformer sensors, Arduino WeMos, and an ESP8266 microcontroller. The software unit, an algorithm using Matlab software, is developed to send measurement data to the ThingSpeak cloud. The proposed system can monitor and analyze the PQ parameters in real time, including frequency, root mean square (RMS) voltage, RMS current, active power, and the power factor of a low-voltage load [10]. The hardware included a Raspberry Pi 3, an Arduino Uno board, and

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an ESP8266 Wemos D1 mini to communicate with the PZEM-004T via RS-232. The software included Android Studio and the Raspbian operating system [11]. The hardware included the NodeMCU and sensor PZEM-004T microcontroller. The software included the ThingSpeak cloud server [12] and the Blynk application [13]. The controller, NB-IoT connection module, and cloud are the three main components of an IOT-based innovative energy meter system [14]. An energy consumption monitoring system based on IoT for residential rooftops uses the ESP8266 controller chipset to build the sensing peripheral node, which controls a relay and a PZEM-004T current sensor [15]. Besides, the energy is measured, and a product arrangement is given to create a bill for energy consumption and implement it in LabVIEW software. An IOT-based platform is created to monitor the metering infrastructure in real-time [16] remotely. Overall, Energy monitoring systems promote energy-conscious behavior by raising awareness of energy usage habits. Homeowners can visualize their energy consumption data, set energy-saving goals, reduce energy waste, and contribute to a more sustainable future.

The primary objective of our research is to enhance energy efficiency in the residential sector by developing a household energy monitoring system. This system, which displays real-time information on a graphical Node-RED Dashboard, is connected to a cloud server on the Raspberry Pi for storing electricity consumption data. The system uses Node-RED to connect devices via APIs (Application Programming Interface) system, and the electrical data obtained from the electrical energy measurement system is used to analyze the variables on the behavior of electricity consumption of each household. This analysis is a guideline for selecting the electricity rate between the TOD and TOU rates. Using the relationship equation of the base electricity rate and the variables on electricity consumption behavior, we can calculate the result of saving electricity bills when changing the electricity tariff from the TOD to the TOU rate. The research materials and methods, results and discussions, and conclusions are presented in the following sections.

MATERIALS AND METHODS

This paper aims to 1) develop an energy monitoring system for the residential sector. The data were real-time on a graphic with a Node-RED Dashboard, 2) Building a cloud server on the Raspberry Pi for storing electricity consumption data by using Node-RED to connect devices through Application Programming Interface (APIs, and 3) analyzing variables on electricity consumption behavior in the household. It will guide the selection of electricity tariffs between the TOD and TOU rates.

The functional structure design of the real-time electrical energy monitoring system consists of three parts.

A. The design of a real-time electrical energy monitoring system

The real-time data display system is designed with a Node-RED Dashboard on the graphic. The purpose of MQTT is to make our systems send and receive data more efficiently, including wasting the device's energy. In the IOT system, we want to send real-time data and want our devices to use only a little energy unnecessarily. The hardware includes a microcontroller and electrical data measurement sensors such as voltage, current, power, energy, frequency, and power factor. The microcontroller will receive various values from the sensor, which processes and transmits data to Node-Red over a wireless Internet network. Display graphical data on the Node-RED Dashboard and use the data to analyze the variables affecting the electricity consumption behavior of each household. To be a guideline for selecting the electricity tariff between the standard rate and the time of use (TOU) rate. The working process of the system as shown in Figure 1.

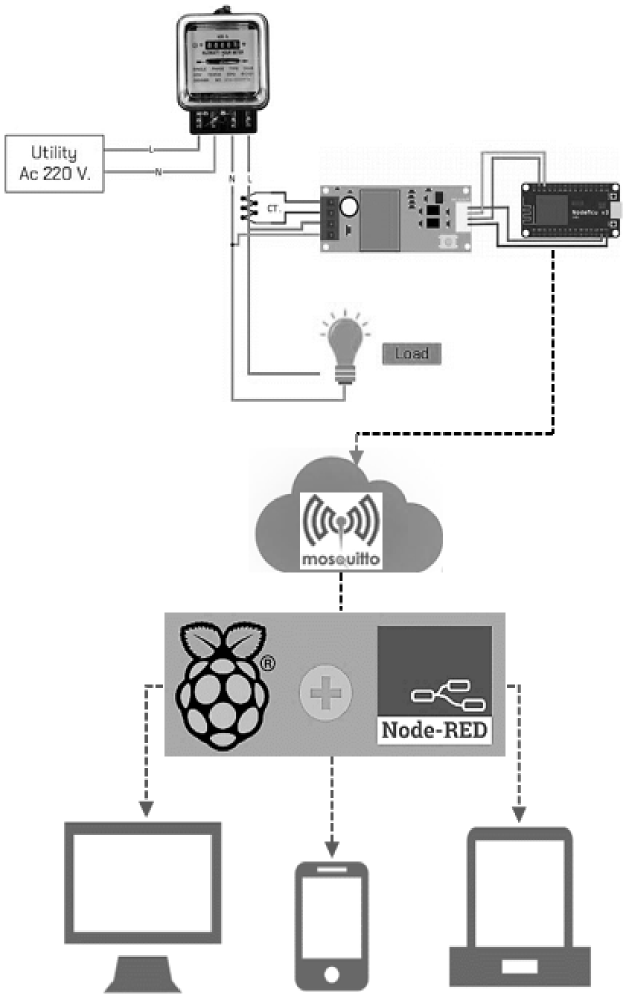

Figure 1 The proposed real-time electrical energy monitoring system design with Node-RED Dashboard.

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B. The creating a cloud server on Raspberry Pi

The creation of a cloud server on Raspberry Pi for storing electricity consumption data using Node-RED connects devices via APIs, as shown in Figure 2.

Figure 2 Node-RED uses the cloud server on Raspberry Pi.

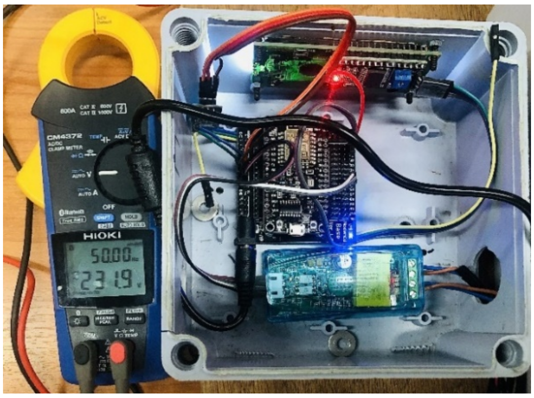

Figure 3 Installation of the proposed system for the experiment.

Data protection protocols and measures can be implemented to ensure user information confidentiality in energy monitoring systems. Encryption: All data transmitted between the energy monitoring system and any external devices or servers should be encrypted using robust encryption algorithms. This prevents unauthorized access to the data during transmission. Access Control: Implement access control mechanisms to restrict access to sensitive user information. Only authorized users should have access to the data, and different access privileges can be assigned based on roles and responsibilities.

C. The installing an electrical energy metering system for the experiment

The hardware includes NodeMCU ESP8266-V3 and AC Digital Power Energy Meter Module PZEM-004T. The software consists of storing and displaying data with the cloud server on Raspberry Pi using Node-RED. The real-time data of power measurement can be transmitted via a wireless system of devices based on the smart meter concept, as shown in Figure 3.

D. The analysis of electricity cost savings

The relationship equation of the base electricity cost with the behavioral variables of electricity usage type 1 residential house considered the TOD of the group of electrical energy consumers not exceeding 150 units per month as in equation (1).

$$\begin{aligned}\mathrm{Base_{TOD}} = {} & 2.3488 + 0.6394 - \left(\frac{9.5910}{\mathrm{kWh_{Total}}}\right) \\ & + 0.2523 - \left(\frac{6.3075}{\mathrm{kWh_{Total}}}\right) \\ & + 0.3832 - \left(\frac{13.4120}{\mathrm{kWh_{Total}}}\right) \\ & + 0.0934 - \left(\frac{9.3400}{\mathrm{kWh_{Total}}}\right) \\ & + 0.5047 - \left(\frac{75.7050}{\mathrm{kWh_{Total}}}\right) \\ & + 0.1999 - \left(\frac{79.9600}{\mathrm{kWh_{Total}}}\right)\end{aligned} \tag{1}$$

The group of electrical energy consumers exceeds 150 units per month, as shown in equation (2).

$$\begin{aligned}\mathrm{Base_{TOD}} = {} & 3.2484 + 0.9734 - \left(\frac{146.01}{\mathrm{kWh_{Total}}}\right) \\ & + 0.1999 - \left(\frac{79.96}{\mathrm{kWh_{Total}}}\right)\end{aligned} \tag{2}$$

The time of use rate (TOU) with a voltage of 22-33 kV, as in equation (3), and a voltage lower than 22 kV, as in equation (4).

$$\mathrm{Base_{TOU}} = 2.6037 + 2.5098\left(\frac{\mathrm{kWh_{Peak}}}{\mathrm{kWh_{Total}}}\right) \tag{3}$$

$$\mathrm{Base_{TOU}} = 2.6369 + 3.1613\left(\frac{\mathrm{kWh_{Peak}}}{\mathrm{kWh_{Total}}}\right) \tag{4}$$

According to the equation for saving electricity costs from TOD rates to change TOU rates for electricity tariff type 1 residential home can be created, as in equation (5).

$$\varphi = \frac{\mathrm{Base_{TOD}} - \mathrm{Base_{TOU}}}{\mathrm{Base_{TOD}}} \times 100 \tag{5}$$

The result of saving electricity costs found that changing the electricity consumption rate depends on the variables of electricity consumption behavior that differ according to the type of electricity users. The electricity consumers who want to change their electricity usage rate can analyze their electricity consumption behavior and calculate the result from equation (5). It will inform us of the savings in electricity

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costs when changing to the TOU rate. kWh_{Peak} is the electricity consumed for the whole month during the peak period (kWh). kWh_{Total} is the total electricity consumed for the whole month (kWh). $Base_{TOD}$ is the base electricity cost per unit of TOD rate (Baht/kWh). $Base_{TOU}$ is the base electricity cost per unit of TOU rate (Baht/kWh), and ϕ is the percentage of saving electricity costs. The calculation of the error between a measurement from a clamp meter and the proposed system for the experiment. The results were displayed and compared to determine the percentage difference, as in equation (6) [2].

$$\text{Error} = \frac{\text{Measuring}_{Real} - \text{Measuring}_{\text{Exp}}}{\text{Measuring}_{Real}} \times 100 \quad (6)$$

RESULTS AND DISCUSSION

Energy management in the residential sector involves various practices and technologies to optimize energy usage, reduce energy waste, and promote energy efficiency in homes. A vital component is using Home Energy Management Systems (HEMS). These systems, integrated with our IoT-based energy monitoring system, utilize smart devices, sensors, and software to monitor and control energy usage in real-time. By providing insights into energy consumption patterns, HEMS enables homeowners to make informed decisions that can significantly reduce energy waste, thereby promoting energy efficiency in the residential sector. This section presents the results obtained from the proposed system for the experiment with an electrical energy metering system, including Node MCU ESP8266 and AC Digital Power Energy Meter Module PZEM-004T that power energy meter module. It is utilized for voltage (V), current (A), power (W), energy (kWh), frequency (Hz), and power factor measurement of household electricity.

A. The results of the voltage and current measurement

There were two households in the experiment. The energy monitoring system is tested with a randomized measurement process for voltage and current values that test 30 cycles simultaneously. As shown in Table 1, the energy monitoring system tested the household 1. It can store the voltage and current values using an AC digital power energy meter module PZEM-004T and the CM4372 AC/DC clamp meter every 15 minutes. The minimum and maximum voltages were measured with the PZEM-004T module. They were 224.1 V and 235.4 V, respectively, while the CM4372 clamp meter measured voltages 222 V and 236 V, respectively. Moreover, the minimum and maximum current measured with the AC digital power energy meter module PZEM-004T were 1.06 A and 7.85 A, respectively, while the minimum and maximum current measured with the CM4372 AC/DC clamp meter were 1.05 A and 8.5 A, respectively. As shown in Table 2, the household 2 was tested by the energy monitoring system. It can store the voltage and current values using an AC digital power energy meter module PZEM-004T and the CM4372 AC/DC clamp meter every 15 minutes. The minimum and maximum voltages were measured with the PZEM-004T module. They were 225.6 V and 235.4 V, respectively, while the CM4372 clamp meter measured voltages 227 V and 234 V, respectively. Moreover, the minimum and maximum current measured with the AC digital power energy meter module PZEM-004T were 5.26 A and 15.89 A, respectively, while the minimum and maximum current measured with the CM4372 AC/DC clamp meter were 5.6 A and 16.25 A, respectively. The results illustrated that both measuring tools were highly reliable.

Table 1 The voltage and current measurement of household 1.

No.	Power Energy Meter Module PZEM-004T		The CM4372 AC/DC Clamp Meter		No.	Power Energy Meter Module PZEM-004T		The CM4372 AC/DC Clamp Meter	
	V	I	V	I		V	I	V	I
1	234.3	4.35	233	4.10	16	234.5	1.25	233	1.2
2	230.1	1.08	228	1.05	17	232.9	1.15	234	1.1
3	228.9	1.35	226	1.24	18	233.7	1.37	234	1.2
4	227.8	4.32	224	4.10	19	234.2	1.18	234	1.1
5	227.3	1.36	229	1.30	20	235.4	1.36	236	1.2
6	230.7	1.60	231	1.50	21	230.6	1.24	231	1.1
7	224.1	5.42	222	5.80	22	229.7	1.25	230	1.1
8	230.7	1.23	231	1.30	23	228.5	3.89	229	3.7
9	234.9	1.06	236	1.15	24	229.1	1.30	230	1.2
10	233.4	1.85	233	1.70	25	228.3	3.54	229	3.2
11	232.7	1.51	231	1.61	26	230.5	7.85	232	8.5
12	231.2	1.14	230	1.13	27	231.4	2.14	230	1.9
13	230.8	1.53	231	1.40	28	235.1	3.76	234	3.4
14	231.6	1.84	232	1.70	29	234.8	5.40	233	5.1
15	230.2	1.28	229	1.20	30	228.5	1.26	229	1.1

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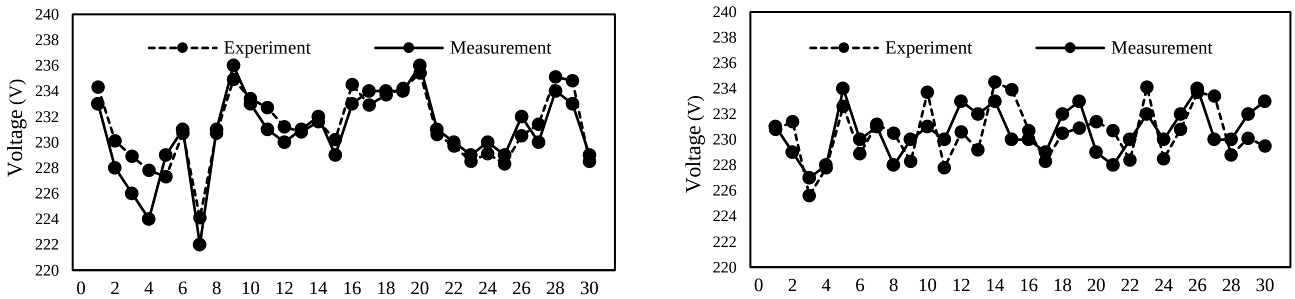
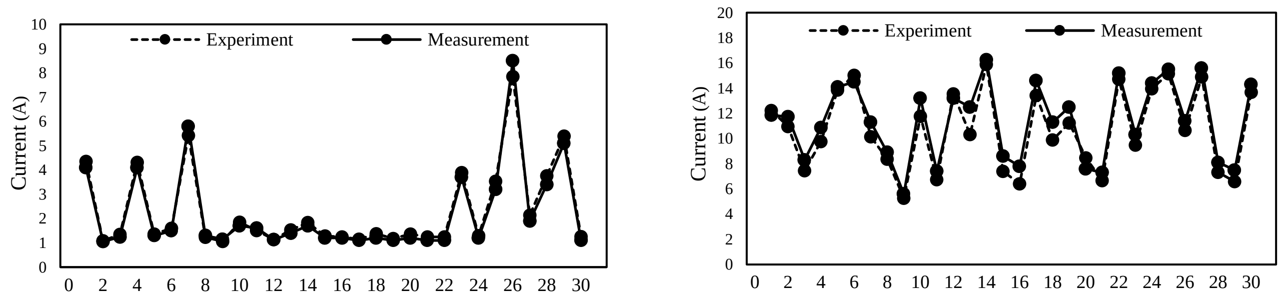
Table 2 The voltage and current measurement of household 2.

No.	Power Energy Meter Module PZEM-004T		The CM4372 AC/DC Clamp Meter		No.	Power Energy Meter Module PZEM-004T		The CM4372 AC/DC Clamp Meter	
	V	I	V	I		V	I	V	I
1	230.8	12.24	231	11.86	16	230.7	6.42	230	7.8
2	231.4	10.95	229	11.74	17	228.3	13.43	229	14.6
3	225.6	7.46	227	8.31	18	230.5	9.88	232	11.3
4	227.8	9.76	228	10.87	19	230.9	11.25	233	12.5
5	232.6	13.85	234	14.10	20	231.4	8.47	229	7.6
6	228.9	15.02	230	14.50	21	230.7	6.65	228	7.3
7	231.2	10.14	231	11.30	22	228.4	14.73	230	15.2
8	230.5	8.36	228	8.90	23	234.1	9.48	232	10.3
9	228.3	5.26	230	5.60	24	228.5	13.96	230	14.4
10	233.7	11.78	231	13.20	25	230.8	15.14	232	15.5
11	227.8	6.75	230	7.40	26	233.7	10.65	234	11.4
12	230.6	13.56	233	13.20	27	233.4	14.89	230	15.6
13	229.2	10.32	232	12.50	28	228.8	7.32	230	8.1
14	234.5	15.89	233	16.25	29	230.1	6.58	232	7.5
15	233.9	7.41	230	8.60	30	229.5	13.67	233	14.3



a) Household 1 b) Household 2

Figure 4 Comparison of voltage measurements between the developed energy monitoring system of experiment and measuring instrument.



a) Household 1 b) Household 2

Figure 5 Comparison of current measurements between the developed energy monitoring system of experiment and measuring instrument.

The comparison of voltage and current values measured between the power energy meter module PZEM-004T of the experiment and the CM4372 AC/DC clamp meter is shown in Figure 4 and Figure 5. It was found that voltage and current measurements can be made by various factors affecting measurement accuracy, whether it is surrounding environmental conditions such as temperature, humidity, or atmospheric pressure. It can affect measurement error and sensor operation, which can cause the error. One of the key findings of this research is the importance of regular sensor maintenance for ensuring long-term measurement accuracy. The correct and careful use of current and voltage sensors can significantly reduce measurement error. However, it is crucial to emphasize the need for regular updates and maintenance to keep the sensors performing at their best, thereby ensuring the long-term accuracy of the measurements.

Table 3 shows the voltage and current error percentage compared to the measured value and 30

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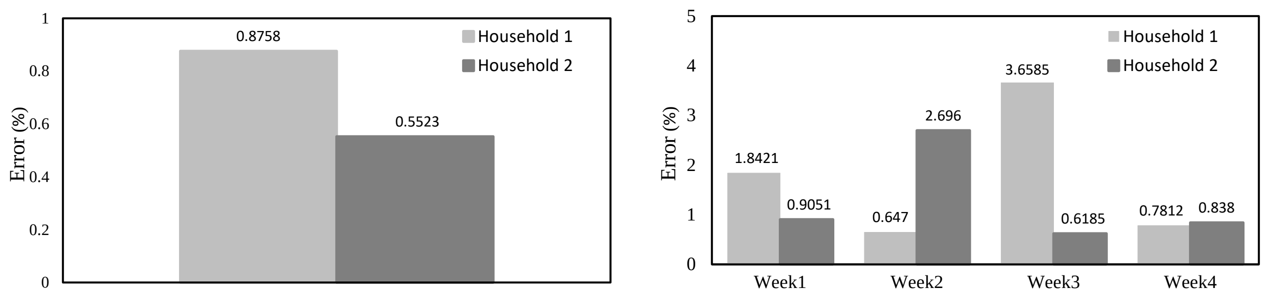
data collection systems. Household 1 was found to have an average voltage error of 0.487 V, and an average current error of 7.987 A. Household 2 has an average voltage error percentage of 0.773 V and an average current error percentage of 7.880 A.

Table 3 An error of voltage and current for household 1 and household 2.

No.	Household 1		Household 2		No.	Household 1		Household 2	
	%Error		% Error			% Error		% Error	
	V	I	V	I		V	I	V	I
1	0.56	6.10	0.09	3.20	16	0.64	4.17	0.30	17.69
2	0.92	2.86	1.05	6.73	17	0.47	4.55	0.31	8.01
3	1.28	8.87	0.62	10.23	18	0.13	14.17	0.65	12.57
4	1.70	5.37	0.09	10.21	19	0.09	7.27	0.90	10.00
5	0.74	4.62	0.60	1.77	20	0.25	13.33	1.05	11.45
6	0.13	6.67	0.48	3.59	21	0.17	12.73	1.18	8.90
7	0.95	6.55	0.09	10.27	22	0.13	13.64	0.70	3.09
8	0.13	5.38	1.10	6.07	23	0.22	5.14	0.91	7.96
9	0.47	7.83	0.74	6.07	24	0.39	8.33	0.65	3.06
10	0.17	8.82	1.17	10.76	25	0.31	10.63	0.52	2.32
11	0.74	6.21	0.96	8.78	26	0.65	7.65	0.13	6.58
12	0.52	0.88	1.03	2.73	27	0.61	12.63	1.48	4.55
13	0.09	9.29	1.21	17.44	28	0.47	10.59	0.52	9.63
14	0.17	8.24	0.64	2.22	29	0.77	5.88	0.82	12.27
15	0.52	6.67	1.70	13.84	30	0.22	14.55	1.50	4.41

Table 4 Comparison of electrical energy measurements between the developed energy monitoring system of experiment and measuring instrument.

Week	Household 1			Week	Household 2		
	Experiment (kWh)	Measurement (kWh)	Error (%)		Experiment (kWh)	Measurement (kWh)	Error (%)
1	37.3000	38.0000	1.8421	1	117.0500	116.0000	0.9051
2	34.2200	34.0000	0.6470	2	104.7500	102.0000	2.6960
3	42.5000	41.0000	3.6585	3	96.4000	97.0000	0.6185
4	32.2500	32.0000	0.7812	4	104.1200	105.0000	0.8380
Total	146.2700	145.0000	0.8758	Total	422.3200	420.0000	0.5523



a) Weekly average b) Monthly average

Figure 6 The error of electrical energy measurements between the experiment and measuring instrument.

B. The results of measuring energy consumption

Each household's monthly electricity consumption is measured using the electrical energy measurement system developed for the experiment. To verify the accuracy of the information and test the system's performance by measuring the energy value from the prototype measurement system compared with the measuring instrument. This test aims to compare the system's performance to see if it can accurately measure wireless power with acceptable tolerances. From Table 4, which shows the monthly electric energy consumption of household 1, it was found that the electric energy measured by the developed energy monitoring system was 146.27 kWh/month, and the measuring instrument measured it as 145.00 kWh/month. An error equals 0.8758%. The monthly electric energy consumption of household 2, it was found that the

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electric energy value measured by the developed energy monitoring system was 422.32 kWh/month and measured by the measuring instrument was 420.00 kWh/month. An error equals 0.5523%. The error of electrical energy measurements between the experiment and measuring instrument as shown in Figure 6.

Table 5 The result of electricity cost savings in the household sector.

Household	kWh_{Total} (kWh)	kWh_{Peak} (kWh)	$Base_{TOD}$ (Baht/kWh)	$Base_{TOU}$ (Baht/kWh)	kWh_{Peak}/kWh_{Total}	ϕ (%)
1	145.0000	20.0000	3.0816	3.0729	0.1379	0.2807
2	420.0000	160.0000	3.8837	3.8412	0.3809	1.0936

Table 6 The result of electricity cost savings of electrical energy consumers not exceeding 150 kWh/month.

Electricity consumption	kWh_{Total} (kWh)	kWh_{Peak} (kWh)	$Base_{TOD}$ (Baht/kWh)	$Base_{TOU}$ (Baht/kWh)	kWh_{Peak}/kWh_{Total}	ϕ (%)
<150	80.0000	0.0000	1.9927	2.6369	0.0000	-32.3242
kWh/month	90.0000	0.0000	2.2626	2.6369	0.0000	-16.5409
	100.0000	0.0000	2.4785	2.6369	0.0000	-6.3890
	110.0000	0.0000	2.6551	2.6369	0.0000	0.6890
	120.0000	6.0000	2.8024	2.7949	0.0500	0.2654
	130.0000	11.0000	2.9269	2.9043	0.0846	0.7711
	140.0000	17.0000	3.0337	3.0207	0.1214	0.4271
	149.0000	22.0000	3.1175	3.1036	0.1476	0.4458

Table 7 The result of electricity cost savings of electrical energy consumers exceeding 150 kWh/month.

Electricity consumption	kWh_{Total} (kWh)	kWh_{Peak} (kWh)	$Base_{TOD}$ (Baht/kWh)	$Base_{TOU}$ (Baht/kWh)	kWh_{Peak}/kWh_{Total}	ϕ (%)
>150	180.0000	25.0000	3.1663	3.0759	0.1388	2.8532
kWh/month	200.0000	35.0000	3.2918	3.1901	0.1750	3.0901
	220.0000	50.0000	3.3945	3.3553	0.2272	1.1543
	250.0000	65.0000	3.5178	3.4588	0.2600	1.6766
	280.0000	85.0000	3.6146	3.5965	0.3035	0.5003
	300.0000	95.0000	3.6684	3.6379	0.3166	0.8311
	320.0000	105.0000	3.7155	3.6742	0.3281	1.1126
	350.0000	125.0000	3.7760	3.7659	0.3571	0.2684
	380.0000	140.0000	3.8270	3.8015	0.3684	0.6650
	400.0000	150.0000	3.8567	3.8223	0.3750	0.8916
	450.0000	180.0000	3.9195	3.9014	0.4000	0.4624
	500.0000	210.0000	3.9697	3.9646	0.4200	0.1288
	550.0000	235.0000	4.0108	3.9876	0.4272	0.5786
	600.0000	265.0000	4.0450	4.0331	0.4416	0.2952
	650.0000	270.0000	4.0740	3.9500	0.4153	3.0436
	700.0000	280.0000	4.0988	3.9014	0.4000	4.8175

C. The results of the electricity cost savings

The electricity cost savings effect depends on the amount of electrical units, including the month and the proportion of electricity usage. The analysis of saving electricity when changing the TOU rate of household 1. The rate for general households receiving electricity at 220 volts and using electricity is less than 150 kWh/month.

From Table 5, it was found that it consumed 145 kWh/month. During peak time, 20 kWh/month. The proportion of electricity consumption (kWh_{Peak}/kWh_{Total}) is 0.1379. The percentage of electricity costs saved is 0.2807%. It is possible to reduce electricity bills by changing to the TOU rate.

The electricity cost analysis is saved when changing the TOU rate of household 2. The rate for general households receiving electricity is 220 volts and uses more than 150 kWh/month. From Table 5, it was found that it consumed 420 kWh/month. During peak time, 160 kWh/month. The proportion of electricity consumption (kWh_{Peak}/kWh_{Total}) is 0.3809. The percentage of electricity costs saved is 1.0936%. It is possible to reduce electricity bills by changing to the TOU rate.

Table 6 shows the results of electricity cost savings. In the case study of general households receiving electricity voltage of 220 volts and having electrical

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energy consumers not exceeding 150 kWh/month, if considering the total monthly electric energy (kWh) that is in the range of 80 - 100 kWh/month and without energy consumption Electricity during the peak was found not to affect saving electricity bills when changing to the TOU rate. Considering the total monthly electric energy equal to 110 kWh/month and without using electric power during the peak period, it was found that the effect on saving electricity was 0.6890% when changing to the TOU rate. Considering the total monthly electricity consumption in the range of 120 - 149 kWh/month, it was found that electricity costs could be saved. The electricity consumption during the peak period must be more than 5 percent of the total electricity.

Table 7 shows the results of electricity cost savings. In the case study of a typical household receiving an electricity voltage of 220 V and having electrical energy consumers exceeding 150 kWh/month, if considering the total monthly electricity consumption, it is 180 kWh/month, and the electricity consumption in the peak period is 25 kWh/month. It is about 13% of all units of electricity. It was found that an effect on saving electricity equals 2.8532% when changing to the TOU rate. If the electricity used during the peak period was less than 13% of all units of electricity, it was found that the results in an increase in electricity bill savings of up to 15%.

Electricity cost savings in the household sector can be achieved through various strategies and practices to reduce energy consumption and optimize energy efficiency. Here are some practical ways to save on electricity costs: 1. Install an energy monitoring system to track and analyze household energy consumption in real-time. This visibility helps identify energy-intensive appliances and behaviors to make informed decisions to reduce energy use. 2. Time of Use (TOU) Tariffs: If available, consider switching to a TOU electricity tariff that offers lower rates during off-peak hours. Adjusting energy use to take advantage of lower rates can lead to significant savings, especially for running appliances and charging electric vehicles. 3. Behavioral Changes: Adopt energy-saving habits such as turning off lights when leaving a room, using energy-efficient settings on appliances, and washing clothes in cold water. Implementing these strategies can help households reduce their electricity consumption, lower utility bills, and contribute to a more sustainable environment by reducing energy demand.

D. The comparison of electricity bills as TOD and TOU

Considering the total monthly electrical energy is 700 kWh/month, and the electrical energy consumption during the peak is 280 kWh/month or about 40% of the total electrical unit, it was found that the effect on saving electricity is 4.8175% when changing to the TOU rate. Suppose the electricity consumption during the peak period is less than 40% of the total electricity unit. In this case, it will increase electricity cost savings by up to 35%, as shown in Figure 7.

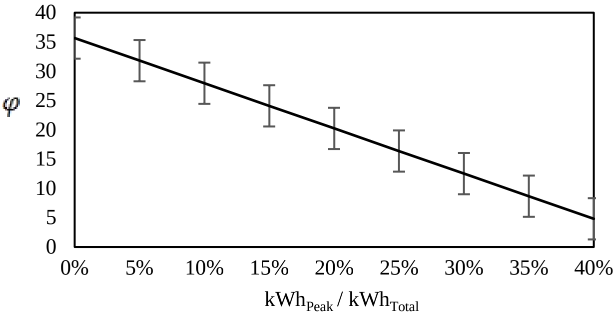

Figure 7 The electricity bills saved by electrical energy consumers are 700 kWh/month.

Table 8 Comparison of electricity bills as TOD and TOU of electrical energy consumers 700 kWh/month.

kWh_{Peak}/kWh_{Total}	TOD (Baht)	TOU (Baht)	Error (Baht)
35/700	2869.22	1956.48	912.74
70/700	2869.22	2067.12	802.10
105/700	2869.22	2177.77	691.45
140/700	2869.22	2288.41	580.81
175/700	2869.22	2399.06	470.16
210/700	2869.22	2509.70	359.52
245/700	2869.22	2620.35	248.87
280/700	2869.22	2730.99	138.23

Table 8 compares electricity bills as TOD and TOU of 700 kWh/month electrical energy consumers. Considering the ratio (kWh_{Peak}/kWh_{Total}) of 0.1, it means that kWh_{Peak} is 10% of kWh_{Total}, the TOD electricity bill is 2869.22 Baht and the TOU electricity bill is 2067.12 Baht. Therefore, TOU electricity bills are more economical than TOD electricity bills by 802.10 baht or savings of about 28%. Considering the ratio (kWh_{Peak}/kWh_{Total}) of 0.2, it means that kWh_{Peak} is 20% of kWh_{Total}, the TOD electricity bill is 2869.22 Baht and the TOU electricity bill is 2288.41 Baht. Therefore, TOU electricity bills are more economical than TOD bills by 580.81 baht, or savings of about 20%. Considering the ratio (kWh_{Peak}/kWh_{Total}) of 0.3, it means that kWh_{Peak} is 30% of kWh_{Total}, the TOD electricity bill is 2869.22 Baht and the TOU electricity bill is 2509.70 Baht. Therefore, TOU electricity bills are more economical than TOD electricity bills by 359.52 baht or savings of about 13%.

E. The display of the real-time data on Node-RED Dashboard

The software consists of storing and displaying data with the cloud server on Raspberry Pi by using Node-RED. The real-time data of power measurement can be transmitted via a wireless system of devices based on the IoT concept. Display of the real-time data on the Node-RED dashboard, including voltage (V),

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current (A), power (W), Electricity consumption (kWh), frequency (Hz), and power factor, as shown in Figure 8 and Figure 9.

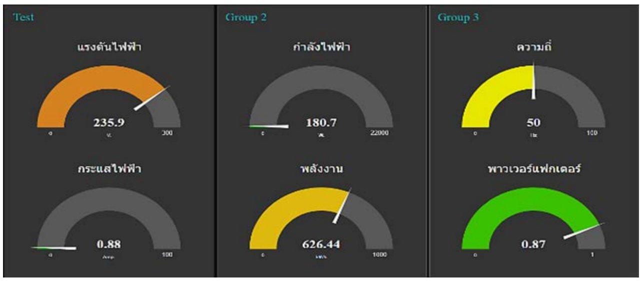

Figure 8 The data is shown in a graphical output on the dashboard.

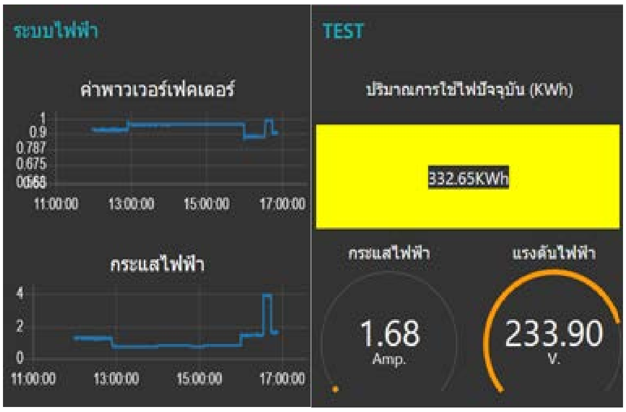

Figure 9 Display of the real-time data on Node-RED.

CONCLUSIONS

To develop a real-time energy monitoring system based on smart metering to enhance energy efficiency in the single-phase residential sector. Based on the concept of low-cost IoT devices, this intelligent meter system is designed to monitor household energy consumption. It provides real-time information on a graphical Node-RED Dashboard, making it easy for households to track and manage their energy usage. The research results presented measurements and recorded voltages and currents. This technique employed a facile design and development using a simple and inexpensive IoT configuration. The results found that the system can measure electrical energy by transmitting real-time data through a wireless network. That can store data in the database system and efficiently measure electrical energy. In the electrical energy measurements of households 1 and 2, the mean deviations were 0.8758% and 0.5523 %, respectively. The electricity cost-saving results when changing the electricity tariff from the TOD rate of households 1 and 2 to the TOU rate. It was found that electricity costs can be saved by 0.2807 % and 1.0936 %, respectively. Future research should develop a system that is more compact and user-friendly. Moreover, it would allow users to monitor their homes for theft prevention as if they were bright houses. Standards for all types of electrical devices in the home can be developed. Also, over a long period, monitoring electric power usage can be used to predict future energy consumption and user behavior.

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