



Smart meter design for energy consumption monitoring of residential premises

Muhammad Mansattha¹, Hassan Dao^{2*} and Arfip Jikaraji²

¹Department of Electrical Engineering, Faculty of Engineering, Princess of Naradhiwas University, Narathiwat 96000, THAILAND

²Department of Computer Engineering, Faculty of Engineering, Princess of Naradhiwas University, Narathiwat 96000, THAILAND

*Corresponding author: hassan@pnu.ac.th

ABSTRACT

Electricity consumption is a crucial issue for economic development, especially in the residential sector. The number of households has increased significantly despite the declining availability of energy resources. There is a clear need for an efficient electricity consumption monitoring system that can provide accurate data on residential energy consumption. This paper proposes an Internet of Things (IoT)-based smart meter system design for monitoring household energy consumption. The system employs hardware and IoT technology, specifically the Node-MCU of ESP-32 and an ADE7757 power sensor module which runs on a 5(15) Amp of a single-phase meter. The energy consumption data is logged in cloud storage using the AppSheet platform hosted on Google Cloud. The system features digital displays and consumption analytics, allowing consumers to collect and transmit data about their energy usage. Energy usage data provides consumers accurate and timely information about their energy consumption. This information can help them better manage and reduce their energy usage. The system also offers the estimation of the energy consumption for individual appliances with a user-friendly monitoring experience for the energy sector. The proposed smart meter system has been evaluated using 1,080 data sets, with an average accuracy rate of 1.48% compared to a 5(15) Amp, single-phase meter. Additionally, the system can predict energy charges with an accuracy of 0.02% based on the schedule of residential electricity tariff regulated by the Provincial Electricity Agency (PEA), Thailand. These results show that the system is highly accurate and can promote positive user behavior towards better energy supply and demand management, reduced energy waste, and improved system reliability. The features of smart meter systems enable consumers and utilities to make more informed decisions about energy usage, promoting more efficient and sustainable energy practices.

Keywords: IoT, Smart meter, Energy consumption, Residential premises

INTRODUCTION

Inconsistency between demand and supply of electric energy is challenged in the context of sustainability. Energy shortage and rapid growing of electric energy consumption has become broadly studied throughout the world in terms of economic development [1-4].

Energy efficiency is prime concerned in two main aspects upon which issues can arise. On one hand, environmental awareness relates to management and prevention of consequences caused by energy wastage. On the other hand, economic aspect concerns cost reduction to achieve counterbalance [3, 5-7]. Since the energy cost tends to increase gradually, new technologies have been invented to reduce electric consumption. In this situation, energy efficiency of most types of appliances, electrical and control devices is continually sought to be improved in industrial, residential and business sector [8-10]. Many consumers intent to reduce their energy consumption.

According to International Energy Agency, 68% of energy consumption and greenhouse gas emission are mainly attributed to residential and commercial buildings. Reduction of energy consumption and emission in such sectors are crucial for long-term transition [11, 12]. Energy consumption statistics in Thailand between 2002 and 2018 recorded by Energy Policy and Planning office (EPPO), Ministry of Energy, Thailand found that residential sector is responsible for the second highest consumption as shown in figure 1.

Zhao et al. [1] developed an energy monitoring system for large public buildings. The system utilizes sensors to collect energy consumption data and displays the data on a user-friendly interface. The authors also highlight the importance of technical details, potential benefits of the system, sustainable practices, and energy efficiency in public buildings, emphasizing that the energy monitoring system can help achieve these goals by reducing energy costs and promoting more sustainable practices.

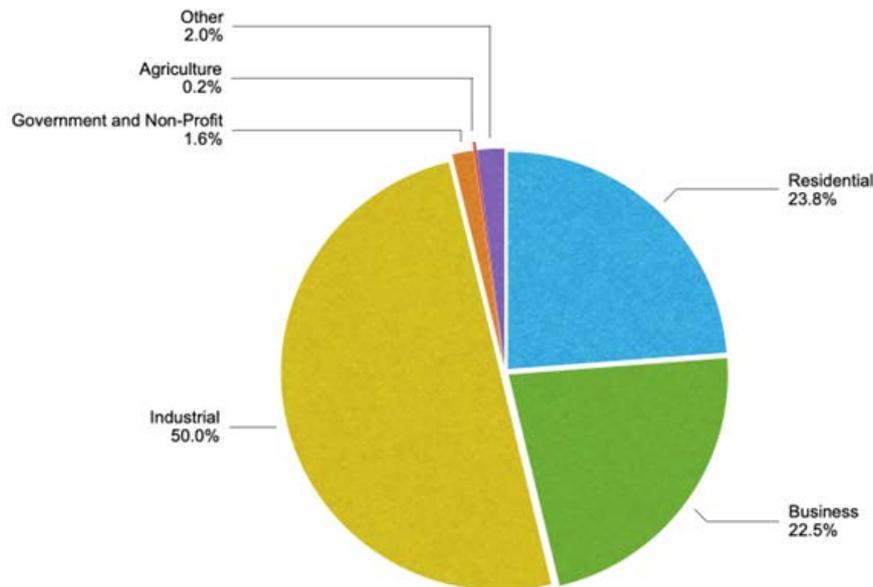


Figure 1 Electric consumption by sectors in Thailand between 2002 and 2018.

Marques and Pitarma [5] presented a wireless energy monitoring system designed to collect and display real-time energy consumption data in households and buildings. The authors describe the technical aspects of the system, including its hardware and software components, data processing methods, and visualization techniques. The article also emphasizes the potential benefits of the system, such as identifying areas of energy waste and promoting energy conservation. The authors conclude that the system has the potential to significantly reduce energy costs and promote sustainable practices in households and buildings.

Luan and Leng [10] presented a monitoring system that utilizes the Internet of Things (IoT) for smart energy management in a building. The system consists of wireless sensor nodes that monitor various parameters related to energy consumption, such as temperature, humidity, and light intensity. The data is collected and transmitted wirelessly to a central server, where it is analysed and used to optimize energy consumption. The authors provide a detailed description of the hardware and software components of the system and report on the system's performance in a real-world deployment. The study demonstrates the potential of IoT-based systems for effective energy management in buildings, with the ability to optimize energy consumption and reduce costs.

Sučić et al. [11] presented a study on the design and implementation of an energy monitoring system for residential buildings. The system is designed to monitor energy consumption in real-time and provide feedback to the occupants to encourage more efficient energy usage. The authors describe the hardware and software components of the system, which include a smart meter, sensors, and a user interface. The system is tested in a residential building, and the results indicate that it is effective in monitoring and analysing energy consumption patterns. The system provides feedback

to users through a user interface, which can be accessed via mobile devices or computers. The authors conclude that the system has the potential to significantly reduce energy consumption in residential buildings and contribute to the overall goal of sustainability.

Several studies have shown that energy consumption in buildings can be influenced by user behaviour, despite overall consumption being considered a dominant characteristic. However, traditional methods of measurement have been shown to be inefficient in changing consumer behavior [11, 13-15]. Therefore, an energy monitoring tool is essential to help manage energy and avoid wastage, allowing for more efficient decision-making and changes to consumption routines [16, 17].

The Provincial Electricity Agency (PEA), Thailand categorises electricity tariffs [18] into 8 schedules namely, residential, small general service, medium general service, large general service, specific business service, non-profit organization, agricultural pumping, and temporary service.

This paper presents the design of an electricity consumption monitoring system using a single-phase meter with a 5(15) Amp rating and energy charge prediction based on Thailand's PEA residential electrical tariff schedule. The system, which includes wireless communication for remote monitoring, is compared to a standard PEA meter and provides users with an easy way to monitor their electricity consumption and performance.

MATERIALS AND METHODS

The proposed energy monitoring system design comprises three primary components: Cloud of Things (CoT), Smart meter nodes, and Software design, as illustrated in figure 2. The smart meter node serves as a mediator between an AC power source and an

electrical appliance. It is equipped with voltage and current sensors (ADE7757) that accurately measure energy consumption.

The embedded Node-MCU within the smart meter then transmits this information to the cloud platform every ten minutes, allowing easy access and data analysis from each meter node. The data obtained from the smart meter nodes enables users to identify areas of high energy consumption and compare energy usage across different nodes.

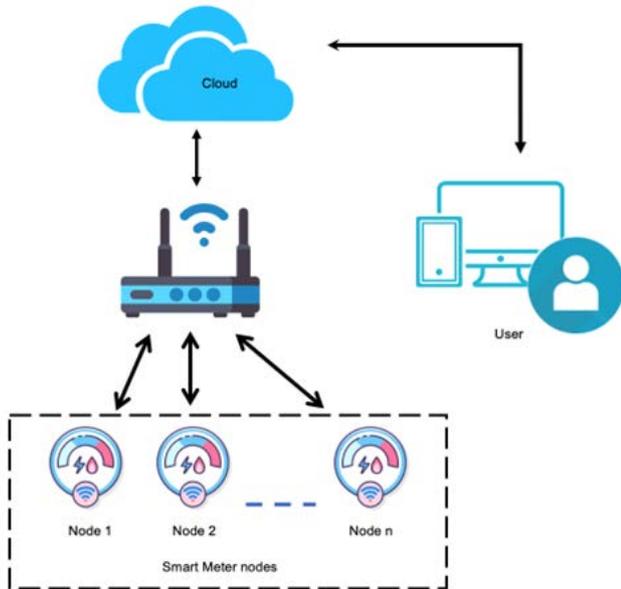


Figure 2 Designed overview of proposed electricity consumption monitoring system.

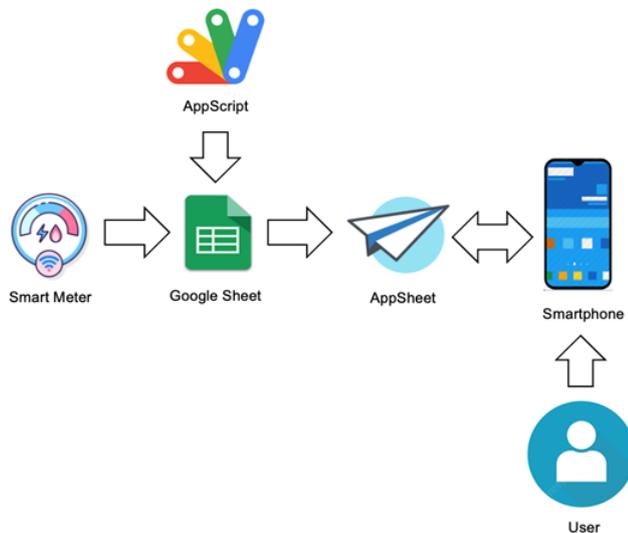


Figure 3 Data-driven application for Smart meter monitoring system.

Cloud of Things (CoT)

CoT is a combination of Cloud and Internet of Things (IoT), which enables the transfer of computer functionalities from local computers to the cloud [19]. This technology can be applied in various optimal solutions where users no longer need to worry about

resource maintenance, local storage, or application installation. AppSheet platform is an example of a cloud-based platform that supports both mobile operating systems and web platforms. AppSheet apps provide on-premise data integration with several data sources [20, 21].

Data-driven applications are essential for effective communication and data exchange. Figure 3 illustrates the framework of the energy monitoring system. Smart meter nodes initially acquire the energy consumption data, which are then updated and transferred to a spreadsheet using Appscript. The collected data are visualised in application using Appsheet.

Smart meter node

Smart meter nodes are strategically placed based on the monitoring requirements and comprise two main components: the Node-MCU of ESP32 and the ADE7757 Power sensor. The smart meter nodes are installed between the AC source and the electrical appliance or socket requiring monitoring. ESP32 features an open-source microcontroller and a WiFi microchip. The ADE7757 sensor is considered a precise electrical energy measurement tool. After receiving the voltage and current outputs from the load through the power sensor, the data is transmitted to the ESP32, which calculates the energy consumption parameters and energy charges, displaying them on an LCD and transmitting the data via WiFi to the server. The smart meter node diagram in figure 4 depicts this process.

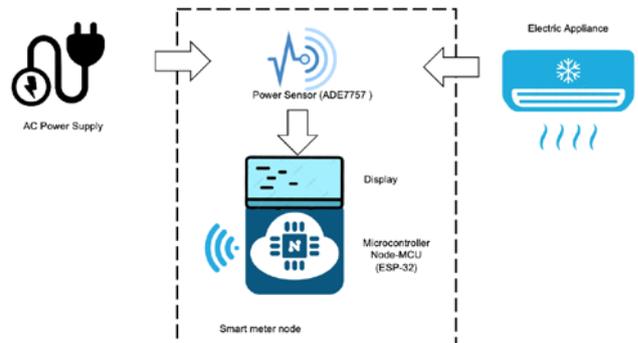


Figure 4 Design of proposed smart meter node.

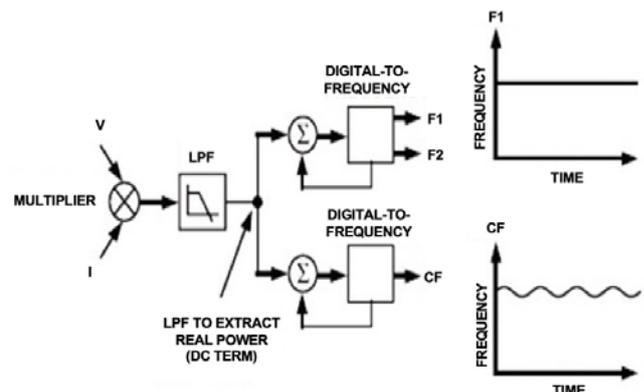


Figure 5 Real Power-to-Frequency Conversion process.

Figure 5 shows the signal process diagram of ADE7757 [22, 23], which outlines the process of digitizing the voltage signal input using voltage and current sensors. Initially, the DC component of the instantaneous power signals is removed using a high-pass filter as the IC is intended to operate with AC input. Subsequently, the instantaneous power signal is multiplied directly by the current and voltage signals, which yields the instantaneous real power component from the previous signal of the low-pass filter.

The digital-to-frequency converter generates an output frequency based on the real power component. This output frequency is then processed in the digital domain and connected to a counter in the microcontroller. The counter calculates the number of pulses for a specific

interval, enabling the expression of the average power as a proportion to the average frequency using equation (1) [22-24]:

$$F_{avg} = P_{avg} = \frac{Counter}{Time} \tag{1}$$

where F_{avg} is Average frequency and P_{avg} is Average power.

The relationship between energy and counter is defined by (2).

$$Energy = P_{avg} \times Time \\ = \frac{Counter}{Time} \times Time = Counter \tag{2}$$

Table 1 Number of PPM at steady currents and voltages.

Current (A)	Voltage (V)						
	200	205	210	215	220	225	230
1.43	19.2	19.7	20.2	20.6	21.1	21.6	22.1
2.08	26.2	26.9	27.5	28.2	28.8	29.5	30.2
2.45	32.5	33.3	34.1	34.9	35.7	36.5	37.3
3.02	39.0	39.9	40.9	41.9	42.9	43.8	44.8
3.5	45.5	46.6	47.7	48.9	50.0	51.1	52.3
4.05	52.4	53.8	55.1	56.4	57.7	59.0	60.3
4.53	59.3	60.8	62.2	63.7	65.2	66.7	68.2
5.08	65.1	66.7	68.3	70.0	71.6	73.2	74.9

The calibration process is crucial to guarantee the precise accumulation of pulses and eliminate any ripple frequency. To perform calibration, the pulse frequency is manually measured using an oscilloscope, ranging from 0.4 to 5.08 V. Under steady load conditions and at a voltage of 220 V, ten different current levels are measured, resulting in 1,080 data set. The corresponding number of pulses per minute (PPM) is then recorded and summarized in table 1.

$$F = 13.685I + 2.084 \tag{3}$$

The relationship between the number of PPM and current is described by equation (3). The linear relationship between the number of PPM and the current levels is determined by fitting a straight line to the measured PPM values for current levels ranging between 0.4 - 5.08 A at 220 V as shown in figure 6.

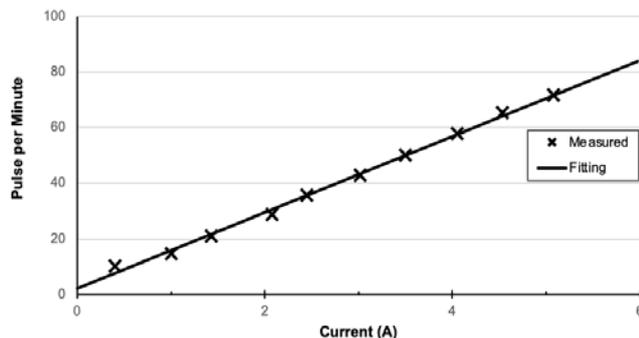


Figure 6 Relationship between number of PPM for given currents at 220 V.

Figure 7 demonstrates a linear increase in the number of PPM with the voltage, ranging from 200-230 V at a current of 5.08 A. Specifically, the number of PPM increases linearly between 65 and 75 PPM.

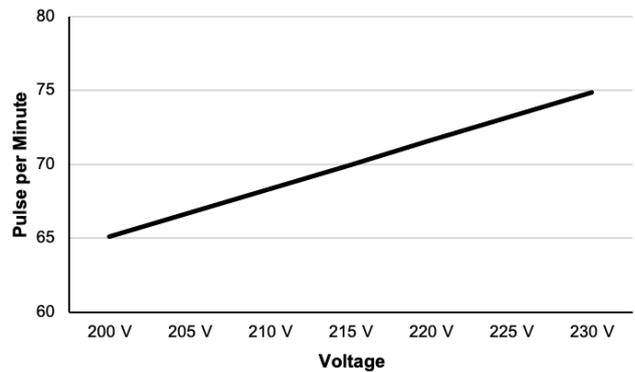


Figure 7 Measurement of number of PPM at 5.08 A for given voltages.

Software design

The flowchart diagram used in the design of smart meter node is shown in figure 8.

Initially, the power signal is acquired from the line using the power sensor, followed by the calculation of electricity consumption by the microcontroller. The energy charge is then determined based on the residential electricity tariff schedule in table 2, measured in baht per kilowatt-hour (kWh). Additionally, a service charge of 8.19 baht per month is applied [25].

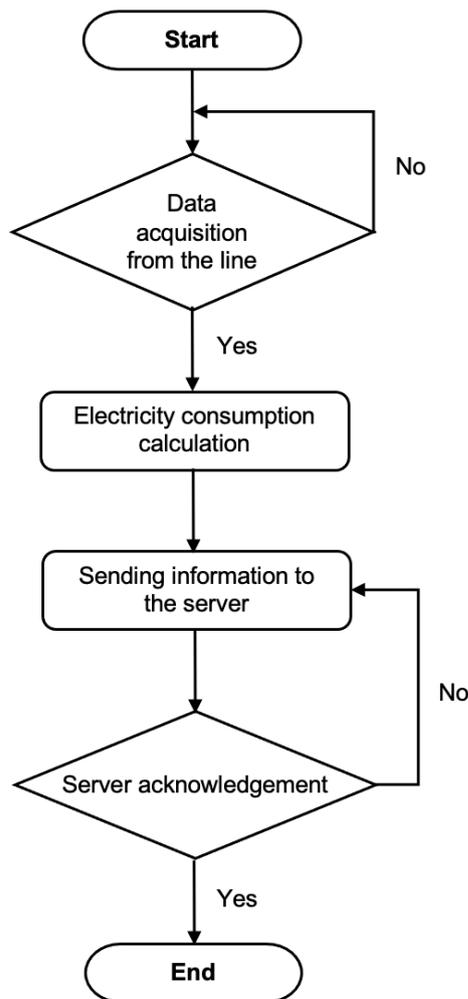


Figure 8 Process diagram of a smart meter node.

Once the smart meter node calculates electricity consumption and determines the energy charge, it transmits this information to the server and awaits confirmation. In case no acknowledgement is received from the server, the microcontroller is programmed to

re-send the information after every ten-minute interval until a response is received.

Calculating the percentage difference between a measurement and from a meter is crucial to compare and assess the accuracy of the smart measure node and the PEA meter. The percentage difference can determine by equation (4) [26].

$$|(PEM - SMN)/SMN| \times 100\% \quad (4)$$

Where PEM is PEA meter and SMN is the smart meter node.

Table 2 Schedule of residential electricity tariff.

Unit charge(kWh)	Energy Charge(baht/kWh)
0-15 th	2.3488
16 th -25 th	2.9883
26 th – 35 th	3.2405
36 th – 100 th	3.6237
101 st – 150 th	4.2218
151 st – 400 th	4.4217

RESULTS AND DISCUSSION

The energy consumption is measured and compared between the standard PEA meter and the smart meter node at 220 V. The energy charge is also computed for given steady currents based on residential tariff, using table 2. In addition, the results are recorded in table 3, which compares the electricity unit consumption and energy charge between the standard consumer meter (PEM) and smart meter node (SMN). The findings show that the smart meter has an average accuracy of 1.48% in measuring energy consumption and can predict energy charges with a high precision, with only a 0.02% deviation.

Table 3 Comparison of standard consumer meter of PEA and smart meter node for given currents and interval times.

Current (A)	Time (Minute)	Electricity Unit		Electricity Charge (Baht)	
		SMN	PEM	SMN	PEM
3.5	4	0.05	0.06	8.31	8.32
	6	0.08	0.08	8.38	8.38
	8	0.11	0.11	8.45	8.45
	10	0.14	0.14	8.52	8.52
4.0	4	0.06	0.06	8.33	8.33
	6	0.10	0.10	8.42	8.42
	8	0.13	0.13	8.50	8.50
	10	0.17	0.16	8.59	8.57
4.5	4	0.06	0.07	8.35	8.35
	6	0.11	0.11	8.45	8.45
	8	0.14	0.14	8.52	8.52
	10	0.18	0.18	8.61	8.61
5.0	4	0.08	0.08	8.38	8.38
	6	0.12	0.12	8.47	8.47
	8	0.17	0.16	8.59	8.56
	10	0.21	0.20	8.68	8.66

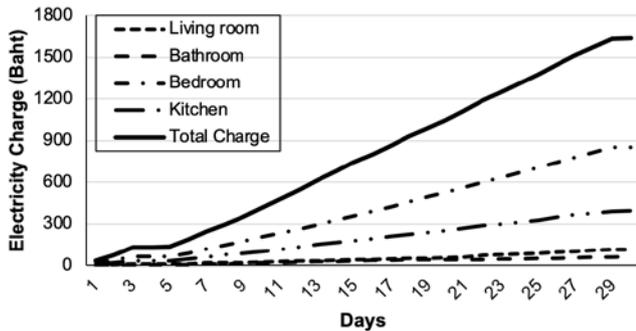


Figure 9 Electricity charge of different nodes for 30 days.

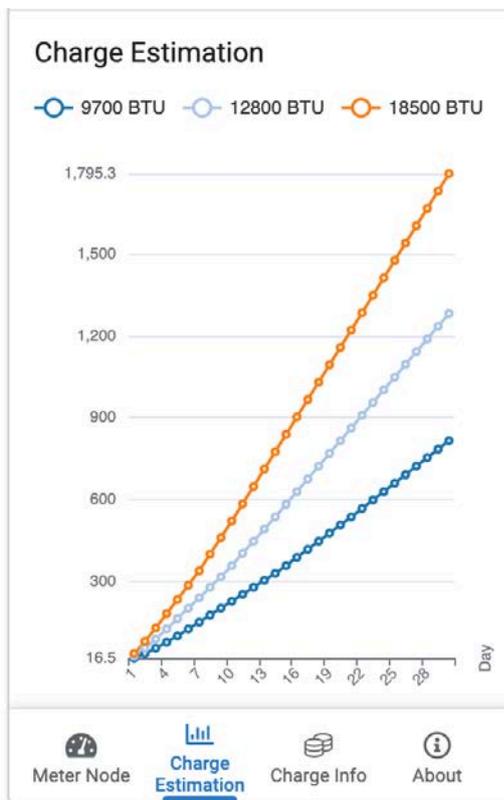


Figure 10 Estimation of electricity charges for air conditioners with varying BTU provided by the smart meter application.

The monitoring system performance is tested using variety of appliance installed in different home partitions. The smart meter has potential to measure energy consumption which depends on the load on devices. The series of collected data are converted to electricity charge and then visualize in the application. figure 9 exemplifies the electricity charge of five different rooms in a house, namely the kitchen, bedroom, bathroom, living room and total charge for thirty days.

Furthermore, the smart meter has the capability to estimate the electricity charges for individual appliances by considering their power consumption and daily usage time. Figure 10 demonstrates this feature by showing the electricity charge for an air conditioner over a period of 30 days, calculated based

on three different British Thermal Units (BTU). This valuable tool allows users to make informed decisions about which appliances to purchase, as they can estimate the potential electricity costs associated with their usage beforehand. Overall, the smart meter provides a convenient and helpful solution for monitoring and managing electricity usage, empowering users to make more informed decisions about their energy consumption.

CONCLUSION

The design of energy consumption monitoring system is presented in this paper based on residential tariff. CoT is capable to communicate and update the smart meter nodes in real-time. Thus, the users unnecessary require local storage and resource maintenance.

The energy consumption and energy charge are presented and compared between standard PEA meter and smart meter node at 220 V for given currents. The results show that the smart meter can measure the energy consumption and charge accurately compared to the standard meter. The findings show that the smart meter has an average accuracy of 1.48% in measuring energy consumption and can predict energy charges with high precision, with only a 0.02% deviation.

The proposed smart meter system is a well-designed integration of cloud-based technology and IoT for efficient energy consumption monitoring and accurate charge prediction. The system features digital displays and consumption analytics, allowing consumers to collect and transmit data about their energy usage. The energy usage data is used to provide consumers with accurate and timely information about their energy consumption. Additionally, the system also offers the estimation of the energy consumption for individual appliances with a user-friendly monitoring experience for the energy sector.

It is recommended to extend the electricity charge computation for 15(45) Amp meter or larger, as there are different schedules of electricity tariff for such meters. Overall, this system can be beneficial for both residential and commercial applications, as it enables remote monitoring and comparison of energy consumption across multiple nodes. The implementation of this system can not only improve energy efficiency but also increase awareness and promote more sustainable energy practices. Thus, identifying opportunities for potential energy savings.

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