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Smart Metering System Design and Field Validation for Electricity Theft Detection

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Abstract

Electricity is one of the basic supports required for human existence in our modern society. It is required for the existence of different sectors of modern development. Electricity supply needs to be secured, reliable and sustainable for any anticipated socioeconomic development. Electricity theft is a serious problem for utility companies, especially in underdeveloped countries, where it leads to financial losses, inefficient technology, and safety risks. In Nigeria, like other developing countries such as India, there has been some documented and published evidence of electricity theft. Numerous efforts have also been put forward to combat electricity theft among the scientific communities and energy experts. One of such is the deployment of Smart Energy Metering Infrastructure (SEMI). A SEMI uses a wireless communication protocol with an integrated electronic system with the capability to measure the amount of electricity consumed and possibly detect electricity theft via automated actions. Therefore, this study presents the design and implementation of a smart meter system through the use of an Arduino microcontroller, a voltage sensor, a current sensor, and a relay for the evaluation of energy consumption and tamper detection by sending a Short Message Service (SMS) to the utility company and the electricity users. The study further embarks on field experimentation for the testing of the functionality of the realized electronic device to determine its functional efficacy.

Keywords: Smart Meter, Energy, Electricity Theft, Detection, Energy Billing.

Introduction

Many developing countries are currently battling the curtailment of electricity theft due to its negative impact on economic investment in the power sector. Energy theft usually affects the utility companies such that either the expected revenues are not met or it takes a longer time than expected to recover the investment costs. On this account, there are tendencies for poor investment by the potential investors and future expansion of the sector may be practically jeopardized due to financial instability (Shokoya and Raji, 2019). There are reports that billions of dollars are lost annually to energy theft (Akinwole and Akinyemi, 2024; Onyimadu, 2018; Sibiya et al., 2024). Unfortunately, electricity tariffs in many developing countries have been constantly rising due to the passing of the financial burden to the paying customers, with substantial negative impacts. Electricity theft in Nigeria, electricity theft is a major economic crisis to the power sector because of the absence of smart metering for measurement of energy consumption, especially in rural and semi-urban communities. The problem of energy theft is a multifaceted issue that requires a comprehensive understanding of various factors as shown in Fig. 1.

Fig. 1: Socio-economic determinants of electricity theft (Wabukala et al., 2023)

In some countries, electricity tariffs are subsidized to benefit economically disadvantaged citizens. In the absence of the subsidies, the incidence of energy theft may be rampant and thus affect the expected revenue drive of the investment. Apart from the economic implications, many developing countries with a history of electricity theft also encounter technical and safety challenges. Energy theft crimes are usually committed with poor knowledge of the consequences to most individuals who are directly involved in the theft. The use of technological solutions to combat energy theft is presently gaining tremendous momentum in our modern technological space. Designing and implementing a smart energy metering system that can precisely track electricity consumers' real-time energy consumption is the main goal of this project. Therefore, to improve the overall security of energy distribution by a utility company, the system will also take into account having an effective theft detection mechanism that can instantly send tampering notifications to the appropriate authority in real-time. In order to ascertain the smart meter's operational dependability and scalability, this effort also attempts to do a practical test of the device.

Objectives of the Study

The focal objectives of this study are highlighted as follows:

- To design and implement a system for the mitigation against energy theft.
- To compare the performance of the system with the existing design based on its functional characteristics.

Problem Statement

Energy theft usually encompasses several integrated issues covering economic, social and technical perceptions. There are a lot of key variables that are involved, such as poor customer satisfaction, level of income, and expensive electricity tariffs. An electricity customer is most likely to pay their electricity billing conveniently without default or engagement in energy theft when the energy tariff is affordable based on reasonable prices. On the other hand, people are more prone to use illegal means to steal electricity from the utility and consume electricity when it is unaffordable (Wabukala et al., 2023). The stability, reliability and security of the entire power sector are threatened by power theft in multiple folds, such as load instabilities, heavy financial losses and poor power quality. From this perspective, the use of technological solutions is to fight against unauthorized use of electricity from the distribution system.

Literature Review

The theft of electricity can occur in various forms, such as tampering with the metering system to secure billing irregularities, illegal connection and unpaid electricity bills (Smith, 2004). Many studies have been conducted about energy theft considering its potential negative impacts on the socio-economic status of human societies. For example, Smith (2004) examined the motives behind power theft and concluded in the framework of the study that higher rates of electricity theft transpire in nations with poor financial accountability, unstable political environments, inefficient operational systems of governance, and corruption. Experience from Pakistan revealed that the economic gap between the price of electricity and the consumer's income created a favourable atmosphere for electricity theft. It was disclosed in the findings that as the income of the electricity customers increases, so does electricity theft. In another study, the electricity theft was said to be more perpetuated among the lower-income classes in Pakistan (Mirza and Hashmi, 2015). The impact of electricity theft on power quality was investigated, and it was discovered that electricity theft has potential impacts on quality problems, considering the fact that energy theft consumers have a tendency to consume more energy. In India, it was reported that due to widespread energy theft, almost 20% of the electricity is lost, thereby affecting the electric power sector from the technical and non-technical perspectives (Gaur and Gupta, 2016). According to Ahmed et al. (2022), one of the core problems in emerging nations that hampers their economic progression is electricity theft and the problem is increasingly complex, particularly with the advent of new technology.

In the study conducted using a case study of Lagos in Nigeria, it was presented that corruption and weak implementation of anti-electricity theft laws were the major reasons for energy theft (Obafemi, 2021). The study concluded that to lessen the issue, it is advised that institutions for the implementation and enforcement of anti-electricity theft regulations be strengthened. Detecting and preventing electricity theft using technology-based models was studied by Kgaphola et al. (2024). They presented that electricity theft continues to be a big concern despite many efforts taken to identify and prevent it. The study validates the use of technological solutions to combat energy theft. An overview of energy theft in developing nations, with a primary focus on Sub-Saharan Africa (SSA), is presented by Sibiya et al. (2024). It also seeks to acknowledge how electricity theft affects towns, utilities in the region of SSA from an economic perspective. Depuru et al. (2010) conducted a study on the prevention and management of electricity theft. It was stated that non-technical losses due to energy theft create significant losses for the majority of utility companies in developing nations. It argued that the inadequate infrastructure in developing nations makes it exceedingly challenging to identify and manage potential sources of energy theft. Additionally, a study focusing on electricity theft investigated illegal connections in KwaXimba, South Africa (Mbanjwa et al., 2023). The goal of the study was to pinpoint the underlying reasons for illegal connections and investigate viable ways to lessen their occurrence.

From a technical perspective, modern electronic-based technologies have been deployed for combating unauthorized tapping of electricity from the utility distribution networks. A study on the design and implementation and analysis of a smart prepaid energy metering system has been carried out in many studies (Abbas et al., 2018; Nicolas, 2024; Paul et al., 2023; Varshney et al., 2024). A pre-paid single-phase smart electricity meter for multi-tenant electricity management was studied by Kyaluzi (2024). Findings revealed that the system will keep track of each tenant's energy usage in real time, and instantly disconnect tenants whose units have run out of power, but allow access to electricity to the customer with functional energy units. In Dimbar et al. (2024), a smart prepaid-postpaid electricity meter strategy and simulation with an alarm and anti-theft controller was presented. According to the result obtained, it was concluded that the smart meter application was effective in terms of measuring electricity parameters such as output voltage, current, and monitoring of energy usage. In this present study, the project accomplishment focuses on the design and implementation of a smart metering system through the use of an automated SMS notification system based on real-time monitoring of electricity consumption for transparent electricity consumption and prevention of energy theft. The operational accuracy of the system was also tested through real-time experiments.

Causes of Electricity Theft

Electricity theft is a type of corruption, which is defined as any fraudulent usage of electricity in which utility employees and customers conspire for their benefit, resulting in losses for the utility (Jamil and Ahmad, 2019). The rates of electricity theft in developed and developing nations vary significantly. The United States and Western Europe have fairly low rates of theft, ranging from 1% to 2%. The average for the Organization for Economic Co-operation and Development (OECD) is roughly 7% (Yurtseven, 2015). The extent of the loss is much greater in developing nations like Bangladesh, Malaysia, India, and Turkey

(Bhattacharyya, 2005). Electricity theft is caused by multiple factors. Prominent among the causes are the social capital, absence of accountability, irregularities in the billing system, ineffective enforcement system of penalties for energy theft, political protection of influential customers, education, social capital and unemployment.

Research Method

Smart Meter Design

Nigeria is continuously battling with the incidence of electricity theft and the advent of technological advancement is expected to boost the mitigation efforts against fraudulent activities. Poor technological development in Nigeria has paved the way for easy manipulation of the metering system and line tapping for electricity theft. In Fig. 2, the circuit design of the smart metering system is shown, while Fig. 3 shows the hardware implementation of the smart meter system. Smart meters have the potential capability to identify variations in current measurements during tampering or a faulty situation. This characteristic of a smart meter can be employed to combat energy theft in electrical circuits. Smart meters employ current transformers to compare the current passing through the main lines with the user's load system for theft detection through a tamper detection sensor. The design of the meter was carried out in a Proteus environment using an Arduino controller with a Liquid Crystal Display (LCD) system, voltage sensor, current sensor, integrated circuit and other electronic components. The system operating voltage is designed with a step-down regulated capacity of from 220 V to 5V; the constructed hardware of the smart meter is shown in Fig. 3. An LCD system that can modulate and transmit light was used in the construction. The PIC16f877A microcontroller is used in the suggested design. The controller includes enough I/O lines to effectively enable all internal communication.

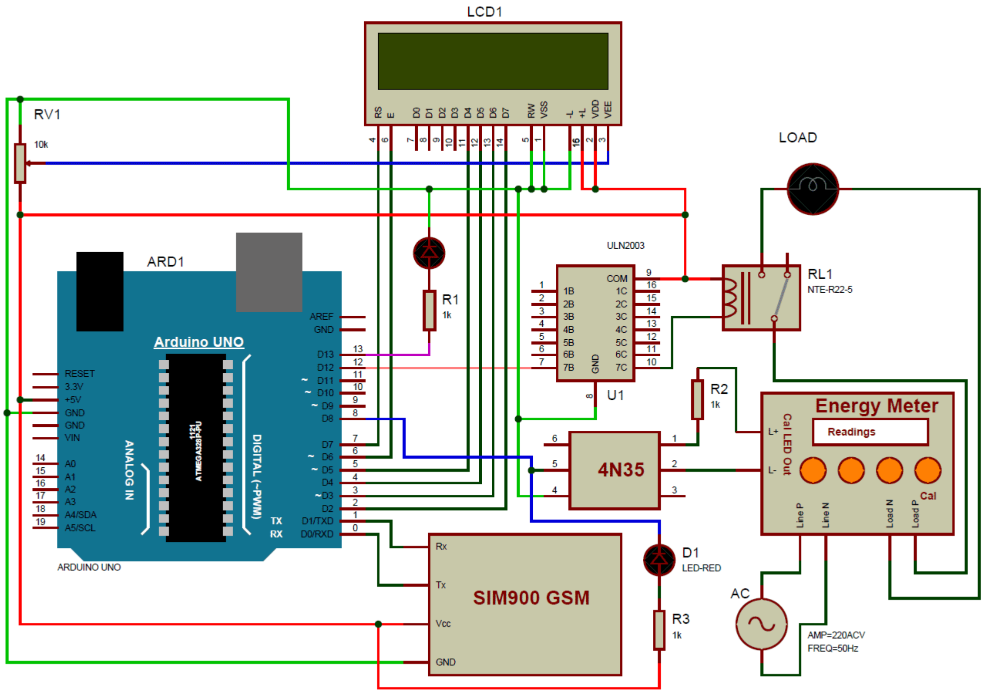

Fig. 2: Circuit design for the smart metering system

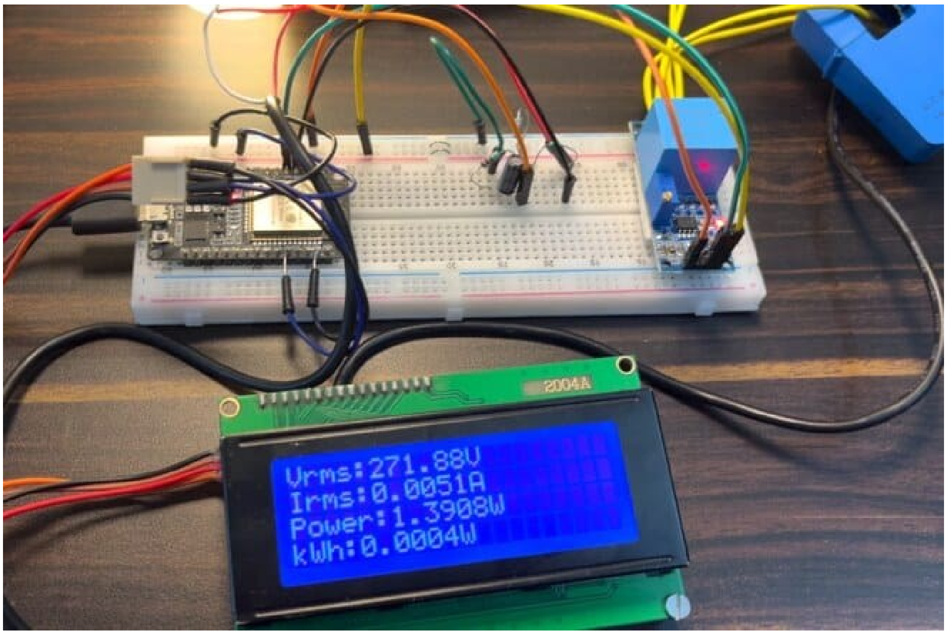

Fig. 3: Hardware implementation of the smart meter system

By transmitting usage data, smart meters assist the utility in efficiently controlling energy consumption. In addition to enabling efficient meter reading, smart meters also avoid disconnection, eliminate billing inefficiencies. The digital energy meter system is coordinated by the Arduino microcontroller, which also connects the system to a WiFi network provided by the Internet. To identify any unauthorised changes to the metering system, a passive infrared sensor is integrated into the system. In such a scenario, the system will automatically disconnect and reconnect the power supply and send an alarm to the server. The suggested system can track and notify the energy source and user of the quantity of units used continuously. An Internet of Things network is used to automatically calculate energy consumption. The block diagram of the implemented system is shown in Fig. 4.

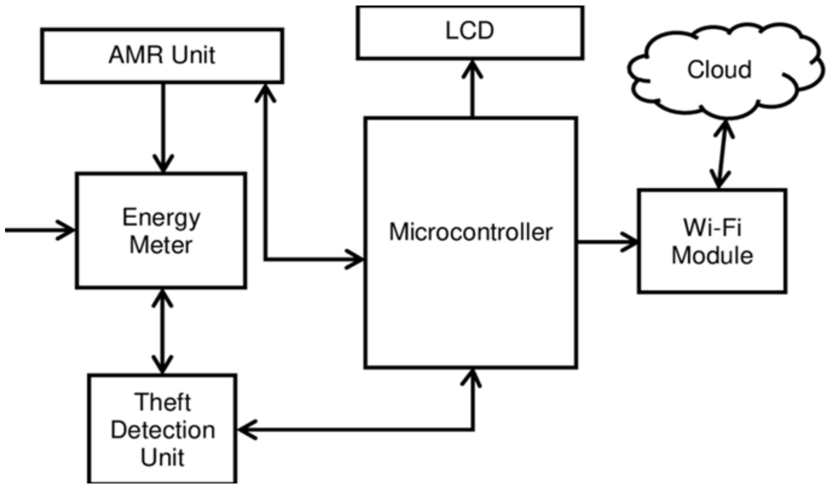

Fig. 4: Block diagram of the IoT-based smart energy meter reading and monitoring system (Mufassirin and Hanees, 2018)

Case Study

For experimental purposes, four houses with different energy consumption potentials were chosen for the desired practical experimentations. The selected houses are domestic household electricity customers and the experiments were set up at the houses selected for the energy theft investigations. The constructed smart meter was installed at the consumers' premises for energy theft monitoring. The experimental goal is to find out how well the system detects electricity theft and how it leads to energy usage disparity between the honest and fraudulent consumption of electricity among the energy users. The experiments were conducted on the same day in two separate weeks for normal electricity consumption of the selected households and fraudulent electricity consumption by the same electricity customers under the approval of the Abuja Electric Distribution Company (AEDC) in Keffi Zone in Nasarawa State, Nigeria. The first day of the first week of the experiment was conducted with regard to the honest consumption of each of the selected households, while the second phase of the experiment is such that consumers are allowed to be involved in energy theft for 24 hours to ascertain the electricity theft capability of the meter.

Results and Discussion

From initialisation to energy monitoring, electricity theft detection, and power management, there is a logical flow of information in the smart meter during a technical operational sequence of the system. When the smart energy meter is connected to an alternating current power system, it starts to function. In order to track consumption, electricity flows into the smart meter during operation, updating the LCD system to show the energy units. To notify the user of any changes in decision-making, the system has a *Global System Mobile (*GSM) alert system. The meter uses a position sensor to continuously check for tampering during operation. An SMS notice is issued to the utility company for action when tampering is discovered. The system's ability to save information and function depends on the usage of a tiny, portable lithium battery, which allows it to function continuously even in the event of a power loss from the utility supply system. A digital sensor attached to the meter cover is used in the tampering detection process. Through a mobile phone interface network system, the Arduino receives a digital signal from the sensor when the cover is removed, causing an SMS alarm to be sent. The system uses predefined SMS codes to distinguish between authorised and unauthorised access.

The data obtained from the physical experiments conducted for the honest consumption by the selected households labelled as A, B, C and D are shown in Fig. 5. It was observed that the energy consumption by the households is different in terms of energy demand. It was observed that in B, the energy consumption is greater than the others based on the size of the family in the house. The total normal and honest energy consumption obtained was 66.2 kWh, compared to A, C and D, which are 17.4 kWh, 25 kWh and 32 kWh, respectively, for the 24 hours of the experiment were conducted. In Fig. 6, the electricity consumption of the same set of customers is shown. The total illegal energy consumption with the period of 24 hours by each of the household are 21.4 kWh, 79.2 kWh, 31.2 kWh and 42.2 kWh respectively for A, B, C and D. from the numerical comparative analysis, it was observed that energy theft scenario attracts more energy consumption by the consumers as shown by the primary data obtained from the smart meter readings as analyzed. This indicated that in a legitimate consumption, electricity users tend to be prudent with their energy usage capacity to save money, while their consumption behaviours are entirely different in the case of theft. This is an indication that an energy theft scenario has a great economic loss to utility companies and, subsequently, may inflict serious technical havoc on the normal operations of the entire power system.

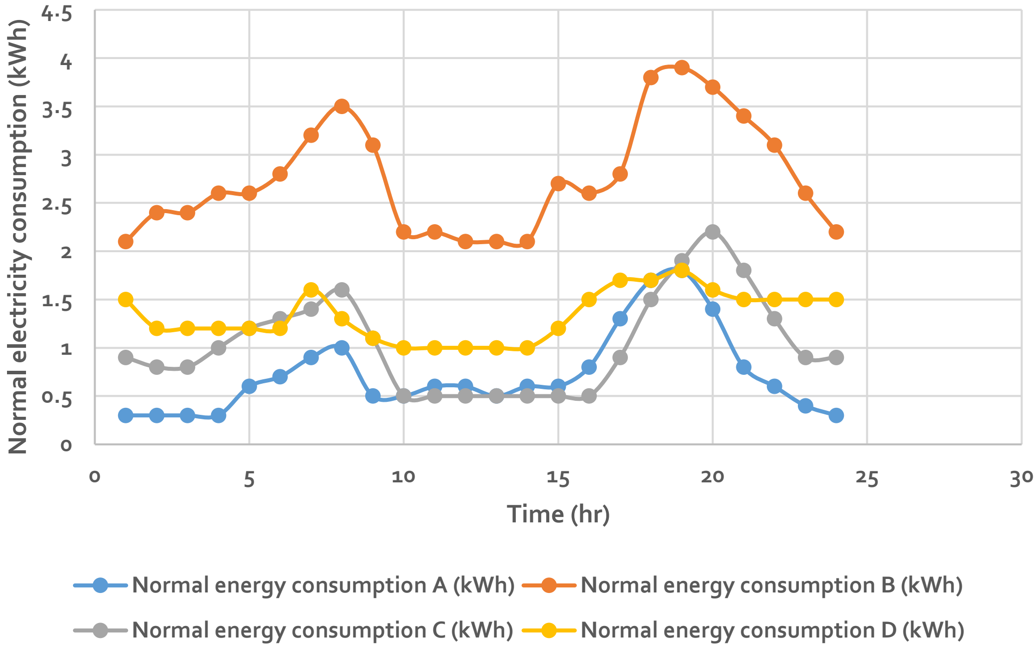

Fig. 5: Normal energy consumption of the case study households based on honest electricity usage

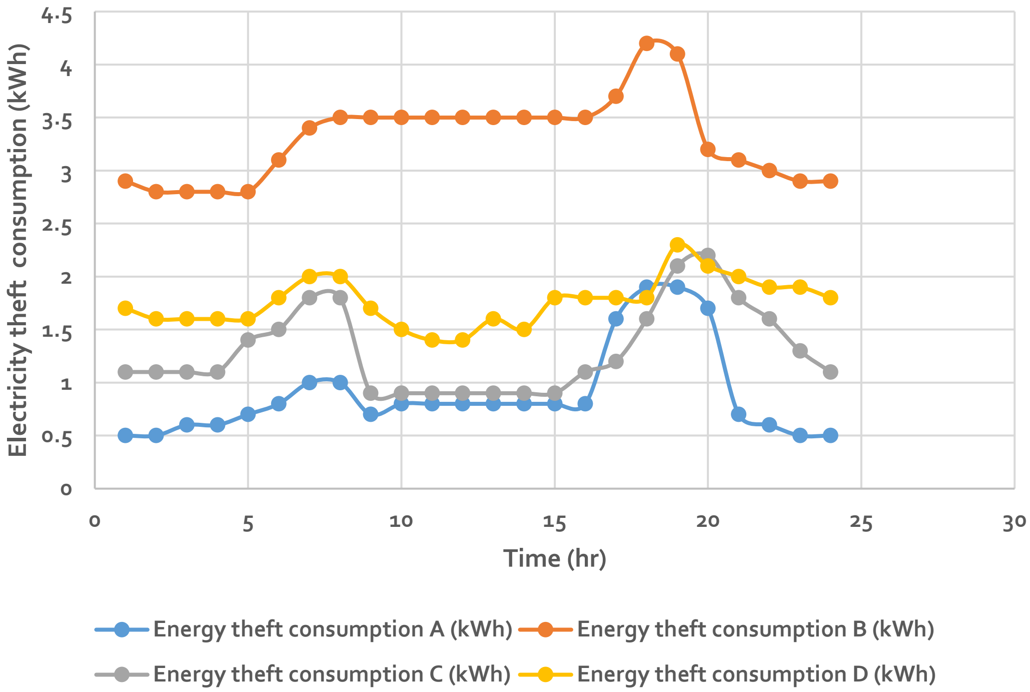

Fig. 6: Fraudulent energy consumption of the case study households based on electricity theft

Furthermore, in Figs 7 – 10, the comparative analyses are shown for both the energy theft and the normal energy consumption. The quantity of energy theft is higher than the honest consumption within the timeframe of the 24 hours of the observation due to the fact that the electricity consumers use more appliances when there is an opportunity to steal energy from the utility company, as revealed by the smart metering system. It was also discovered that electricity consumption generally increases during energy theft situations in all the households, as seen from the experimental results and their interpretation. The increase in the percentage of energy consumption from honest electricity usage by consumers is very conspicuous. For example, in House A, the total energy consumption based on honest usage of electricity, in line with the billing tariff, increased from 17.4 kWh to 21.4 kWh due to electricity theft, accounting for approximately a 19% increment in the consumption level. Similarly, in house B, there is a percentage increase of 16.4% of the total electricity consumption.

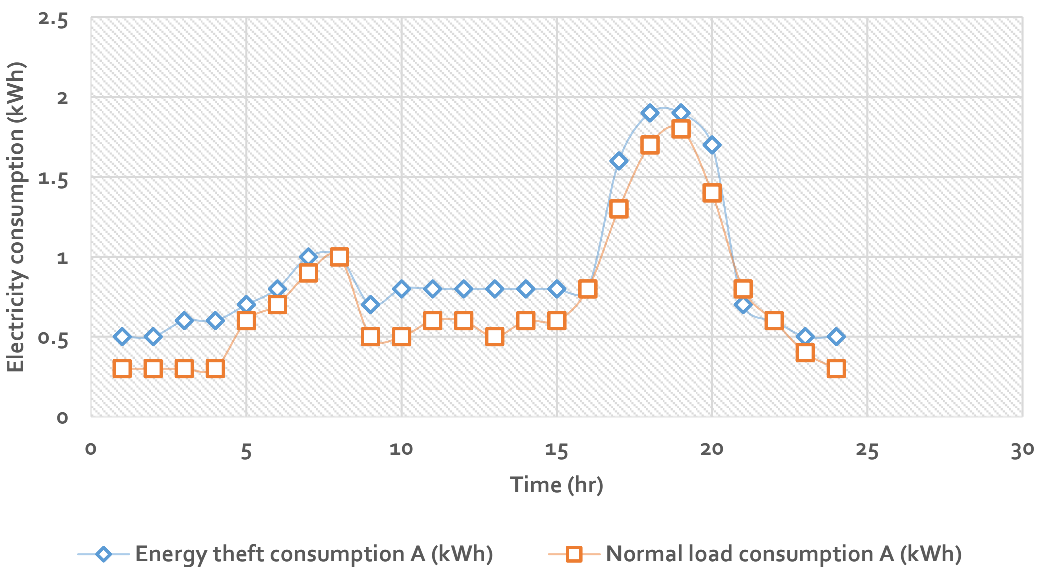

Fig. 7: Comparison of normal electricity and theft consumption of household A

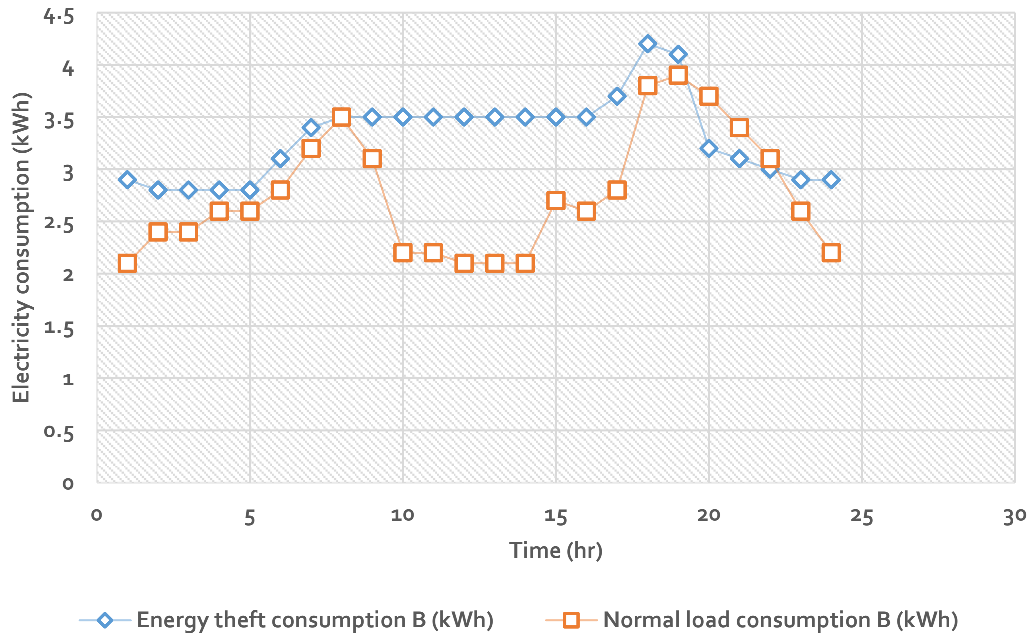

Fig. 8: Comparison of normal electricity and theft consumption of household B

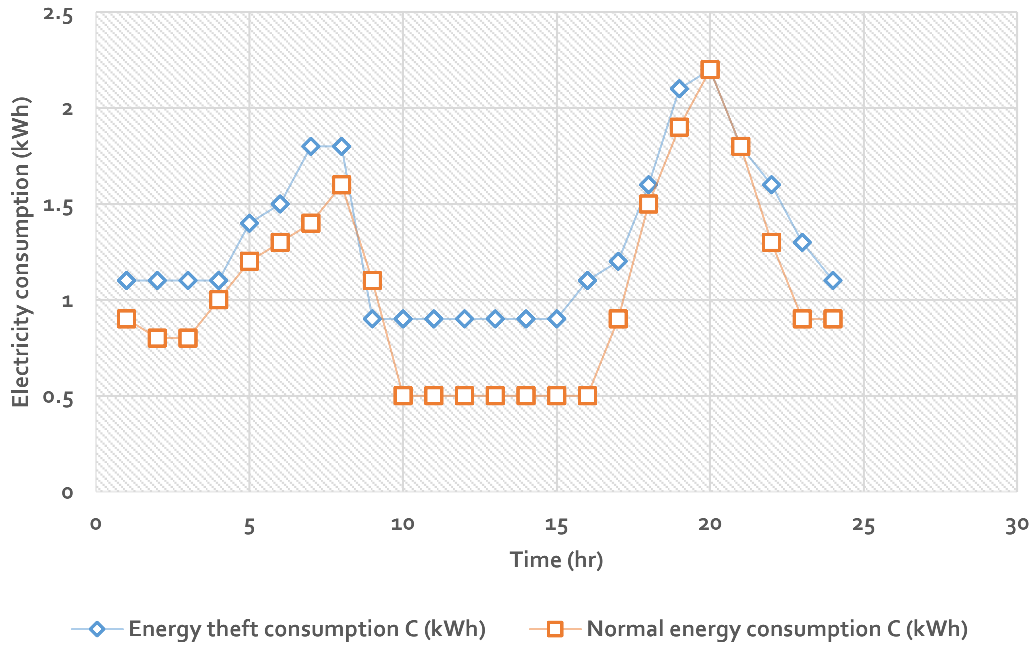

Fig. 9: Comparison of normal electricity and theft consumption of household C

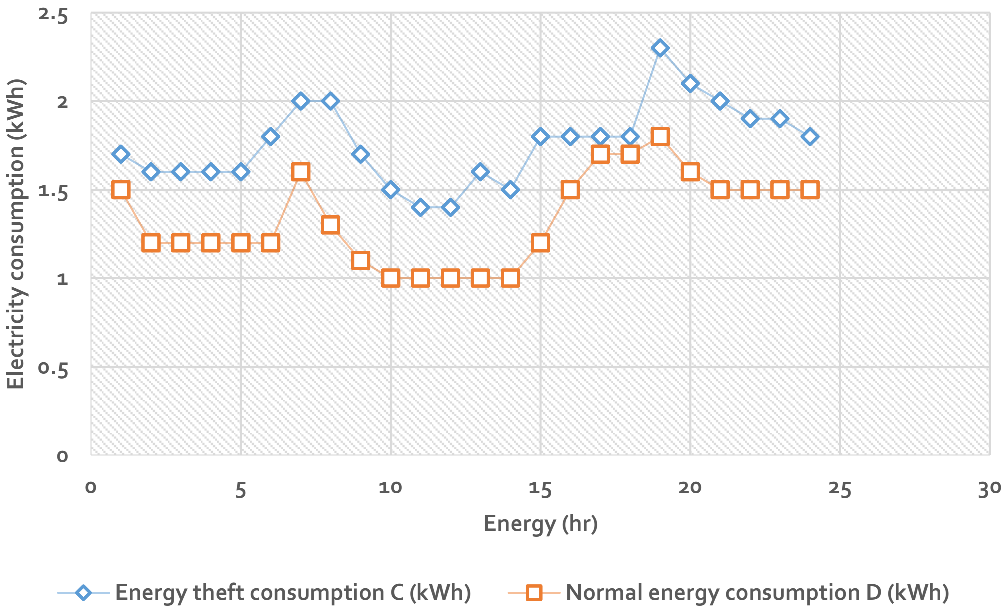

Fig. 10: Comparison of normal electricity and theft consumption of household D

Conclusion and Recommendations

In order to improve accuracy and precision, the suggested smart meter design basically integrates a new digital advanced technology. The smart principles needed by IEEE standards are incorporated into the design of the metering system. Because of its ability to notify customers of any new electrical device connections while it is working for load curtailment, it has the qualities to assist consumers in wisely managing their energy consumption. The issue of data storage can be resolved since the system has a battery storage system, guaranteeing dynamic, dependable, and constant data storage. By adding and integrating energy limitations, including energy consumption, current, voltage, and power quality, the code in the microcontroller's embedded system is in charge of calculating the data parameters. In case of an unpredictable power consumption, the system has the potential to handle it due to its system circuitry and structural design concepts for both power injection and theft. It can quickly detect electricity theft caused by a change in energy flow since it can detect the injection of a new device connection link. It is strongly recommended that more advanced technologies, such as the application of cloud storage of measurement data with growing artificial intelligence systems and a lot of potential for billing and tampering detection, be integrated into the meter's future design and implementation. Future technical developments in the system could do away with the requirement for human interaction, improve measurement accuracy, and provide customers with electricity bills that include due dates.

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