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Smart Energy Metering for Cost Comparative Analysis in Energy Management

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Abstract

A significant achievement in the precise and effective monitoring of electric energy is the development of an inexpensive wireless smart energy meter capable of measuring electricity consumption. This technology is essential for many applications, such as smart grids, in more complex and networked electric systems. It introduces a real-time energy monitoring system. Smart meters offer greater opportunities for effective and sustainable energy consumption and can enhance the utilization of energy sources. Sophisticated services offered by smart energy meters surpass those of conventional energy meters. These services include demand reduction, customer billing, time-based demand data analysis, outage management, distribution network analysis and planning, and remote connection. Additionally, two-way real-time communication between utility providers and smart energy meters is possible. In the framework of the study, an active energy evaluation technique was explored based on the dual components of instantaneous active and reactive power analysis. In addition, an application of electronic design and component fabrication for energy consumption monitoring and management through the concept of digital instrumentation and communication protocol was used for the realization of the physical project. The smart metering system developed was tested on three different households and the results show a decrease in the cost of electricity and the quantity of power delivered within a 24-hour timeframe.

Keywords: Smart Meter, Cost Analysis, Energy Management, Electricity, Real-Time, Communication.

Introduction

Access to energy is a fundamental aspect of our modern existence with the tendency for sustainable socio-economic development. To address challenges brought on by the continuously increasing energy demand and the negative environmental situation orchestrated by fossil fuel combustion fossil fuels, there must be integration of energy sources, energy tariffs and smart meters with reliable communication channels and effective control mechanisms. The integration of energy consumption and Information and Communication Technology (ICT) can increase the expected level of energy efficiency, functionality, security, stability and reduced cost in the energy business. The application of

ICT in energy involves some multifaceted and multidimensional perspectives such as the subject of smart energy, energy mix, automated metering infrastructure and energy management as part of the paradigm shift in the modern power sector. The concept of "smart energy" has been used in recent times to represent the exit from an inefficient perspective to a more robust, fast and reliable perspective. The block-level smart energy meter (SEM) design based on the existing technological concept is shown in Figure 1. The system design encapsulates different units with independent functionality. However, a smart meter is a blend of the sensing unit, hardware system and software components. The functionality of a smart meter majorly depends on the embedded IoT stack based on the communication commanding protocol (Braeken *et al.*, 2018).

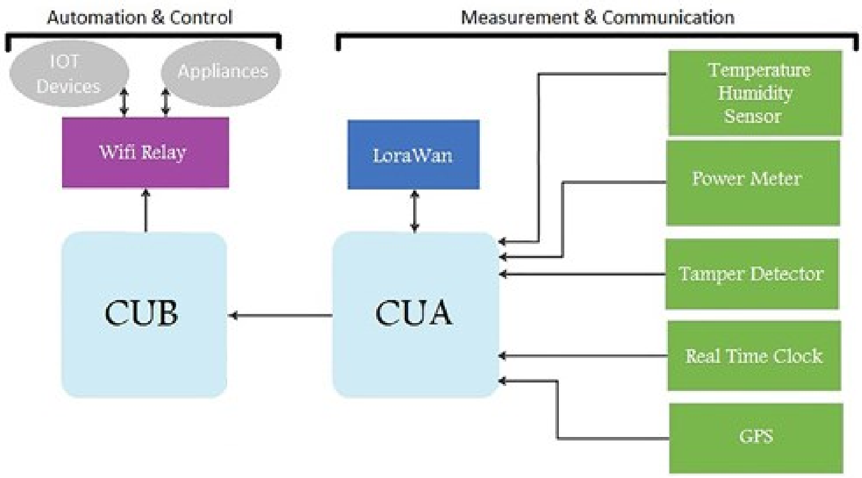

Figure 1: Block-level smart energy meter (SEM) design (Hseiki et al., 2024)

In the early phase of electricity consumption technology, delivery of electricity is completely dependent on traditional energy meters. Traditionally, electric meters play a fundamental role in the measurement and control of energy consumption in households or commercial centers. The usage of traditional analog electric meters has been slowly decreasing with the incursion of new technologies due to the rapid transformation in ICT and smart communication technologies. Energy customers are usually unaware of their electricity consumption behaviors due to the one-end communication scheme is the usage of analog electricity meters. Thus, the monthly feedback given to the consumers is not sufficient to determine the actual cost of energy consumed by the individual appliances. To overcome the problems of traditional electricity meters, smart energy meters were developed and deployed in the last few decades. With the use of smart meter, energy alerts will be provided to the consumers based on hourly utilization of energy (Sun *et al.*, 2015; Islam *et al.*, 2017; Gopinath *et al.*, 2019). The principal objective of using a smart meter is to reduce energy consumption based on the concept of energy management. With the help of Internet of Things (IoTs) technologies, the accurate measurement, control, and monitoring of energy consumption by consumers can be achieved with ease, thereby providing energy users with direct access to their energy usage data through a web-based platform. Based on the users' access to their energy data, informed decisions such as reduction in energy consumption level and usage of energy-efficient appliances can be made. In this study, an efficient localized energy meter was developed with the consideration of high-performance analytics for energy data. Real-time experimental data using an IoT platform were collected to measure the performance of the energy meter based on cost-comparative analysis for different households.

Problem Statement

There are serious challenges concerning the increasing level of energy consumption brought on by population expansion. The use of new technology orchestrated the problems of cost sustainability and energy management (Avancini *et al.*, 2021). With the present increasing advancement in modern power systems, the need for integrated smart network technology for energy measurement in the context of reliable cost framework is quite important for bidirectional communication that enables effective measurements of energy consumption.

Objectives of the Study

The key objectives of this study are to develop a new smart meter system using an IoT model for measuring and analyzing the power consumption of some selected households in a real-time environment. The development of energy meters with smart features is essential to the economy about the global commercialization of the power sector, particularly for the achievement of effective measurement of energy use in kWh and the corresponding cost. The anticipated interest in sustainable energy management and consumption is aided by this objective.

Scope of the Study

This work is limited to the development of smart metering systems using IoT technology. A case study will be conducted on the standard data obtained for three sets of households based on comparative analysis for the making of reliable judgment on the efficient performance of the smart meter developed.

Literature Review

As electricity became more widely used and distributed, there was a need for more accurate and reliable electricity meters. This led to the development of electronic meters that used electronic sensors to measure electricity usage. These meters were smaller, more accurate, and easier to read than their analog counterparts. The electronic meter comes in various forms which are categorized into traditional meters, modular meters, and pre-pay electricity meters. pre-pay electricity meters are electric-base designed with a single module and a seal that gives no room for embedded component upgrades. The seal was added as a protective measure to prevent any form of tampering. For future upgrading, the device undergoes a complete replacement of all the components irrespective of any identified outdated components. Patented electricity was first rolled out in the late 19th century. With the persistence of time, the development of smart meters using ICT and advanced electronic technologies emerged in the 20th century. A smart meter is an environmentally friendly energy meter that is used for measuring electrical energy in terms of kWh (Weranga et al., 2012; Dahunsi *et al.*, 2021). It is simply a device that affords a direct benefit to consumers who want to save money on their electricity bill. They belong to a division of Advanced Metering Infrastructure (AMI) and are responsible for sending meter readings automatically to the energy supplier. A smart metering system could be described as an energy system that executes the precise measurement of the consumption of energy, data collection, data creation and energy billing activities (Makanjuola *et al.*, 2019; Somefun *et al.*, 2019). In the work conducted by Khan et al. (2020), it was stated that a smart meter is a device built and installed around a home or business center to measure the real-time consumption rate of electrical energy to envisage the improvement required for accuracy, reliability and efficiency enhancement of the outdated electrical meter system.

In Nigeria, as electricity became more widely used and distributed due to increasing socio-economic activities in the country, the need for more accurate and reliable electricity meters arose. This substantially led to the research and development of electronic meters that used electronic sensors to measure electricity usage. Smart meters are characteristically smaller, more accurate, and easier to read than their mechanical counterparts. With the widespread adoption of digital technology, digital electricity meters have become more prevalent. These meters use digital sensors to measure electricity usage and transmit data electronically, allowing for more accurate and efficient measurement of electricity consumption. The field of electricity metering has undergone rapid development, thanks to the contributions of numerous research and development. This progress has led to the emergence of varieties of smart meters, a new generation of electronic meters that offer a range of advanced features (Okafor et al., 2017; Srinivasan *et al.*, 2019). In Nigeria, the National Electricity Regulatory Commission (NERC) has stipulated policies and regulations to achieve smart metering in the electricity distribution system. Pilot studies have been carried out by some distribution companies to experiment with the use of smart meters in Nigeria. This is done to understand what it will take to achieve the transition from prepaid meters to smart meters. Presently, electricity usage data obtained is only used for billing purposes. The implementation of this NERC policy will result in a smart grid that delivers electricity to consumers using digital technology for continuous monitoring and optimization of the distribution system (Hartman *et al.*, 2018).

Methodology

Active Energy Calculations

In the computation of the active energy, rate of energy flow was considered based on the formulation expressed mathematically in Equation (1):

$$P(t) = \frac{dE}{dt} \quad (1)$$

Where, P denotes the power and E denotes the energy flow in the system. The active power within the time domain is expressed as;

$$E = \int_0^t p(t)\, dt \quad (2)$$

Where T denotes the period considered. In most energy measurement electronic interface system, the discrete accumulation time is used for the active energy calculation as shown in Equation (3).

$$E_D = \sum_{n=0}^{N} p(nt) * t \quad (3)$$

E_D denotes the obtained discrete time accumulated; t denotes the sampled period for a ddiscrete-time n denotes the nth sample point, and N is the number of sampled points. When the discrete-time sample period tends to zero, the expression for the energy is shown in Equation (4):

$$\int_0^t p(t)\, dt = \lim_{t=0} \sum_{n=0}^{N} p(nt) * t \quad (4)$$

The Equation (5) represent the expression for the reactive energy of the system:

$$E_R = \int_0^{t_1} q(t)\, dt \quad (5)$$

Where E_R denotes the reactive energy, $q(t)$ denotes the instantaneous reactive power, and t_1 denotes the considered period. However, reactive energy measured uses discrete time accumulation for reactive energy calculation. The formula employed in computing the reactive energy can be expressed as:

$$E_R = \lim_{t=0} \sum_{n=0}^{N} q(nt) * t \quad (6)$$

Where t denotes the discrete time sample period, n denotes the nth sample point, and N is the number of sample points. Since the sample period cannot be kept at zero, a system with low reactive energy measurement errors is expected to keep the value small.

Modeling of IoTs for Energy Monitoring System

The modeling conducted for the development of the smart energy system was accomplished for energy monitoring using electronic devices for centralized management, digital instrumentation and communication networks. The system is based on the browser and server mode structure which can be seen as an improvement from the client and server mode of internet technology. A three-layer structural scheme is used in browser and server mode. The user's interaction with the entire system is provided by the first-tier client. The customer's application is reduced to a generic browser program. The browser would convert the Hypertext Machine Language (HTML) code into an illustrated Web page. The Web page would contain an interactive feature that allows users up to 20-50 people to send information to the backend via the Web application form, as well as make processing requests. The response process would start with the second-tier Web server, which dynamically generates a string of HTML code that embeds the processing results and sends it to the client's browser. When a client requests data access, the server must work together with the database server to accomplish the procedure. The third-tier server's job is similar to that of the client and server mode, which is in charge of coordinating requests given by different Web servers and managing the database. The monitoring system manages the browser and electricity meters.

Results and Discussions

Three case study households were used for data collection over 24 hours. The comparison of energy consumption of the selected households is shown in Figure 2.

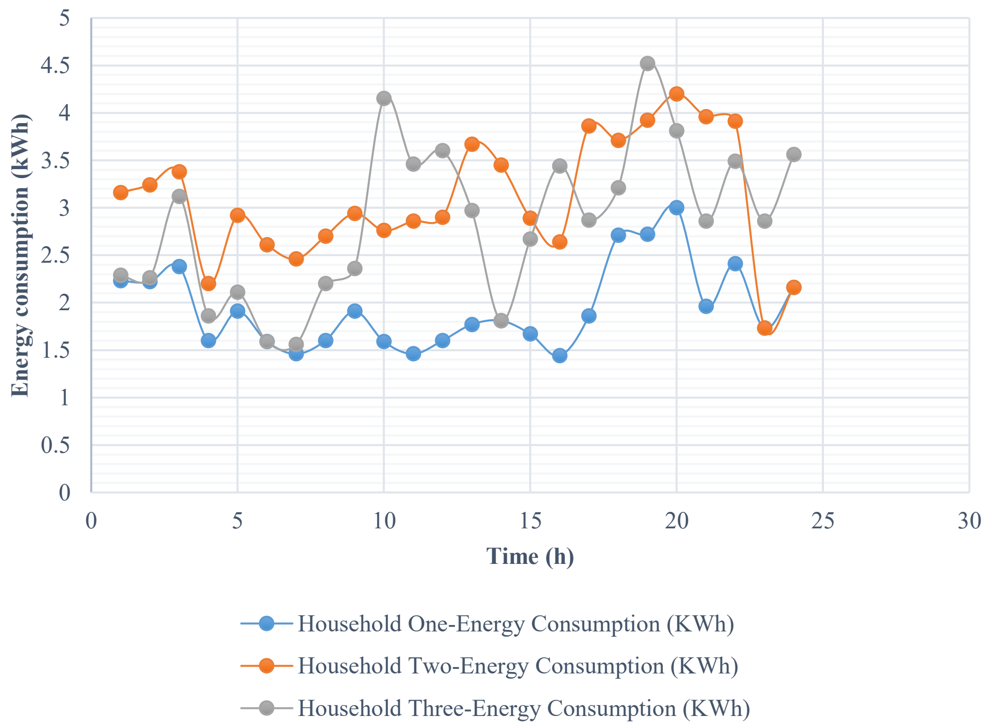

Figure 2: Comparison of energy consumption for all the households over 24 hours

There is variation in the quantity of energy usage by the households as expected. However, the comparative analysis of the cumulative cost for all three households from 1:00 to 24:00

hours was compared with the existing conventional metering system obtained from Behm et al., (2023) as presented in Table 1. Based on the sensitivity result analyzed from the smart metering cumulative cost factor. The result obtained justified that the cumulative cost of convectional metering is generally high compared to the smart metering system designed, developed, and tested. Thus, this occurs due to too much energy consumption by the conventional metering system and energy losses from the consumer at both the peak and off-peak periods. At the hours of 2:00, 3:00 and 13:00, the cumulative cost of N521.950, N1393.804, and N5348.562 decreases based on the convergence point at which the energy loss is mitigated. Conventional energy metering is inefficient, laborious and cost ineffective compared to the smart metering system. Hence, the conventional metering system consumed maximum power compared to other households using a smart metering system.

Table 1: Comparison of smart metering cumulative cost of the households with a convectional meter system

Time	Household One-Cumulative Cost	Household Two-Cumulative Cost	Household Three-Cumulative Cost	Behm et al. Cumulative Cost
1:00	531.7435	753.597	546.119	693.628
2:00	1018.621	1402.208	984.575	**521.950**
3:00	1471.516	2106.585	1593.443	**1393.804**
4:00	1919.239	1728.056	1871.406	4997.980
5:00	2372.086	2964.825	2363.735	5644.181
6:00	2831.715	3242.250	2739.139	5473.747
7:00	3306.619	3436.076	2951.197	6403.909
8:00	3642.972	4540.752	3571.638	6756.341
9:00	4055.093	5709.276	4175.149	6621.061
10:00	4413.176	6215.789	5292.435	6644.825
11:00	4731.033	6849.1609	5869.462	7480.550
12:00	5077.401	7533.504	6615.629	8576.838
13:00	5437.153	9697.064	6814.973	**5348.562**
14:00	5783.949	9254.279	6771.144	9218.664
15:00	6086.253	7847.220	6880.570	12567.324
16:00	6336.122	7329.488	7192.405	8975.800
17:00	6652.787	11171.805	7545.480	8908.865
18:00	7128.527	11723.238	8343.892	8919.028
19:00	7691.186	15406.929	10767.063	10500.580
20:00	8351.726	18495.120	12299.255	12904.105
21:00	8797.646	18919.719	13359.388	14467.555
22:00	9337.655	19274.508	13939.395	16261.943
23:00	9713.6874	8648.759	14143.615	18061.570
24:00	10171.369	10984.392	14542.011	19092.416

Furthermore, Table 2 shows the cumulative cost computed for the original and flattened values of Household 1, household 2, and Household 3 respectively. The values are relatively compared to demonstrate evidence of when hourly prices are advantageous or disadvantageous for consumers. From Table 2, the values in the hours of 9:00, 10:00, 20:00 and 21:00 of household one (1), 9:00 to 12:00 of household two (2) and 9:00 to 11:00 and 21:00 of household three (3) corresponds to peak price hours obtained from the household. Lastly, the improved variations help consumers gain knowledge and encourage them to achieve immediate savings with benefits. From the consumption analytical scenario, consumption varies at peaks from 9:00 to 10:00 hours and from 20:00 to 21:00 hours. So, the average of corresponding consumption in a 4-hour duration is performed at two instances of time.

Table 2: Flattened and non-flattened cumulative cost of households

Time	Household one-cum cost	Household one-flattened cum cost	Household two-cum cost	Household two-flattened cum cost	Household three-cum cost	Household three-flattened cum cost
1:00	531.7435	531.7435	753.597	753.597	546.119	546.119
2:00	1018.621	1018.621	1402.208	1402.208	984.575	984.575
3:00	1471.516	1471.516	2106.585	2106.585	1593.443	1593.443
4:00	1919.239	1919.239	1728.056	1728.056	1871.406	1871.406
5:00	2372.086	2372.086	2964.825	2964.825	2363.735	2363.735
6:00	2831.715	2831.715	3242.250	3242.250	2739.139	2739.139
7:00	3306.619	3306.619	3436.076	3436.076	2951.197	2951.197
8:00	3642.972	3642.972	4540.752	4540.752	3571.638	3571.638
9:00	4055.093	3942.193	5709.276	5330.296	4175.149	3887.227
10:00	4413.176	4042.333	6215.789	5943.880	5292.435	4979.400
11:00	4731.033	4731.033	6849.161	6982.322	5869.462	6008.504
12:00	5077.401	5077.401	7533.504	7102.502	6615.629	6615.629
13:00	5437.153	5437.153	9697.064	9697.064	6814.973	6814.973
14:00	5783.949	5783.949	9254.279	9254.279	6771.144	6814.973
15:00	6086.253	6086.253	7847.220	7847.220	6880.570	6771.144
16:00	6336.122	6336.122	7329.488	7329.488	7192.405	6880.570
17:00	6652.787	6652.787	11171.805	11171.805	7545.480	7192.405
18:00	7128.527	7128.527	11723.238	11723.238	8343.892	7545.480
19:00	7691.186	7691.186	15406.929	15406.929	10767.063	8343.892
20:00	8351.726	7962.653	18495.120	18495.120	12299.255	10767.063
21:00	8797.646	8390.746	18919.719	18919.719	13359.388	12778.555
22:00	9337.655	9337.655	19274.508	19274.508	13939.395	13359.388
23:00	9713.6874	9713.6874	8648.759	8648.759	14143.615	13939.395
24:00	10171.369	10171.369	10984.392	10984.392	14542.011	14143.615

Conclusion and Recommendations

In the context of the commercialization of electricity for sustainable consumption, the emergence and development of smart energy metering systems represent a crucial technology. Unlike conventional energy meters, smart energy meters consume less energy with characteristics but both have the same functionality of measurement of energy use in kWh. Energy consumption measurement through the kWh meter. Conventional electricity energy meters are used in traditional energy networks to monitor the entire consumption of electricity in households or business centers used by consumers. There is an absence of data transmission between the utility provider and the energy consumers thereby creating a problem with dynamic pricing systems, electric power load shifting, programmed invoicing, and the implementation of other automatic services thus limiting the energy management portfolio. In conventional energy meters, the measurement of consumption is executed manually. Therefore, the smart energy meter design, developed and tested in this work is such that allows for bi-directional communication between the energy consumers and the utility through the processes of data exchange using the consumer's home area network. Demand reduction, customer billing, two-way real-time communication between smart meters and utility providers, time-based demand data analysis, service quality measurement, outage management, distribution network analysis and planning, and remote connection are some of the more sophisticated features that smart meters offer over traditional meters. The developed energy metering system presented in this study and tested on three different households consists of a multiple sensors-connected processing unit, power supply, timing module, control, and wireless communication infrastructure. The significance of the designed smart meter based on the tests conducted revealed that the cost of energy consumption can be reduced through the application of smart metering system for energy measurement compared to a traditional energy meter. The following recommendations are thus necessary based on the study conducted:

- It is important to research cyberattack prevention strategies to safeguard the system's integrity, data security, and service interruption.
- Enhancement of operational reliability of the system to protect data integrity and prevent denial-of-service attacks.

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