Modelling and Designing an IoT based energy meter for hybrid energy consumption Monitoring and Transmission- Heterogeneous Hybrid Environment (HEE), a Case Study

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Abstract- Developing nations grapple with insufficient electricity supply, often due to a lack of comprehensive planning and coordinated energy management. This research addresses the critical need for accurate and real-time energy consumption data in heterogeneous hybrid environments (HEE), where populations utilize both grid and alternative energy sources. To this end, the study aims to model and design an Internet of Things (IoT)-based energy meter capable of monitoring and transmitting the total energy consumption, irrespective of the source, along with location data. The research first reviews existing energy monitoring systems and then develops a mathematical model to characterize energy consumption in HEE. Subsequently, it proposes an IoT-based energy meter design for hybrid energy measurement and transmission. A comprehensive framework is then developed as a roadmap for energy consumption monitoring and storage in such environments. Finally, a proof-of-concept (PoC) is designed and prototyped, demonstrating the feasibility of the proposed framework with two customers in different locations. The prototype encompasses a physical layer sensor node for real-time hybrid energy data acquisition, a Firebase-based back-end layer for secure data storage, and a front-end layer for authorized user access and visualization. The successful development and validation of this IoT-based system offer a pathway towards informed energy planning, management, and forecasting in developing nations like Nigeria, ultimately contributing to improved electricity supply and resource allocation.

Index Terms- Heterageneous hybrid Environment, Internet of Thimgs, Transmission.

I. INTRODUCTION

In sufficient energy in terms of electricity supply has been identified as one of the major challenges of developing countries. Several strategies and methods have been adopted in recent times to ameliorate the identified problem. A proposal to integrate photo voltaic systems into natural grids has been suggested by some researchers. This approach has the potential to improve the availability of the power supply to the customers. One of the major challenges facing this method is the ability to synchronise the photo voltaic system with the grid supply. Also, there is a danger of overloading the infrastructure as the number of customers connected to the grid increases. Another approach to solving the energy problem that is widely accepted is the development of independent alternative energy sources including biogas, solar farms, and wind turbines among many other methods. All these approaches will lead to improved electricity supply if proper planning is put in place before the installation of such energy sources.

The research shall Design an IoT based meter that can monitor energy consumption data customers develop a prototype back-end IoT system that can measure and transmit the energy consumption data of customers to a centralised front-end system. The energy measurement shall not be limited to public power supply alone, instead total energy consumption of the customer shall be measured irrespective of what supplies the energy. The location of the customer shall also be transmitted. Being a virgin project, two customers in two different locations shall be used to demonstrate the proof of concept (PoC)

Aims and Objectives

This research aims to develop an IoT model for exact energy consumption in a heterogeneous hybrid environment. The specific objectives are listed below.

1. To Review the existing energy consumption monitoring and storage systems.
2. To model and characterise the energy equation for energy consumption monitoring and transmission in HEE.
3. To design an IoT-based energy meter for hybrid energy measurement and transmission in HEE

II. LITERATURE REVIEW

Conceptual review

Overview of the Heterogeneous Hybrid Energy Consumers

In this section, a clear understanding of the phrase "Heterogeneous Hybrid Energy Consumers" is established. In the context of this research, the word heterogeneous defines the set of electrical energy consumers who apply electrical energy generated, in different ways. This includes residential use, business Use, Industrial Use, commercial use and government Use. The word hybrid defines the set of electrical energy consumers who utilize electrical energy generated from different sources including the power grid and personal power sources like renewable sources (solar, biogas, wind, etc.) and non-renewable sources like fuel generators. Essentially, this Research work will develop an IoT model for characterising and monitoring the energy consumption data of consumers who fall under the set defined by "heterogeneous hybrid energy consumers". That is, consumers who use electricity generated from the power utility and their generators in different ways.

Background of IoT Technology

The IoT concept was born out of a need to remotely monitor and control processes through enhanced connectivity using the combination of several advancements in technology. This need was solved out of curiosity at Carnegie Mellon University (Press, 2014) by some Graduate students. The first literature on the topic was published by (Schoenberger, 2002) which was published in regard to the mass industrial adoption and potential of IoT technology. At the beginning stages of the technology, few achievements were recorded but as the number of devices increased coupled with the presence of the internet, it became increasingly necessary and feasible to interconnect devices for seamless communication, data exchange, and intelligent decision-making.

The primary driving force behind IoT's adoption was the vision of an inter-connected world, where objects, like household appliances and industrial machinery, could communicate and collaborate with their environment and humans. This vision promised increased efficiency, automation, and improved quality of life across various domains.

Review of General Architecture of IoT Technology

An Architecture is simply a defined structure by which a particular system works. The IoT general architecture was developed to address factors like scalability, interoperability, reliability, QoS, etc as this technology is projected to expand exponentially (Rafiullah, Sarmad Ullah, Rifaqat, & Shahid, 2012). This is particularly necessary as more industrial systems are being automated and more smart objects are being invented.

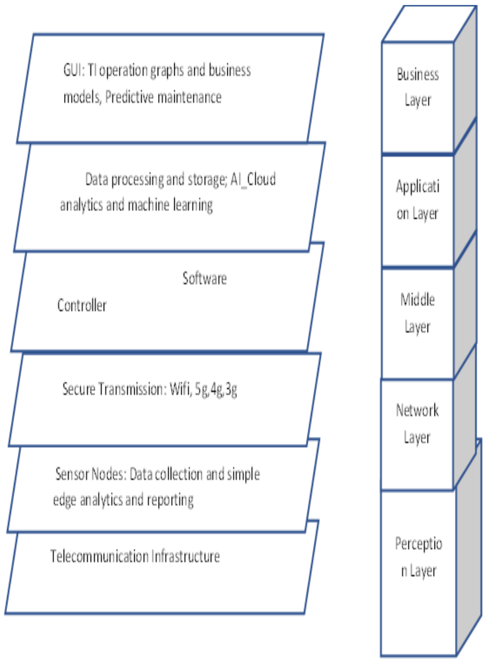

Figure 2.2 : Five layer IoT architecture (Khan, Khan, Zaheer, & S, 2012) (SIDDIOUI, 2022) (Okafor & Longe, Integrating Resilient Tier N+1 Networks with Distributed Non-Recursive Cloud Model for Cyber-Physical Applications, 2022).

Theoretical Review

The integration of IoT technologies into energy monitoring systems has been pivotal in managing hybrid energy sources. For instance, Thulasingam et al. (2024) developed an IoT-based system for monitoring grid-connected hybrid systems, incorporating photovoltaic sources and utilizing Programmable Logic Controllers (PLCs) for load control. The system employed MQTT protocols for data transmission and demonstrated effective energy management over a three-month period. (Thulasingam M. et al, 2024)

Similarly, a study conducted in Morocco implemented an AI-based IoT-enabled Home Energy Management System (HEMS) that integrated renewable energy sources and storage devices. The system optimized energy consumption by dynamically scheduling power dispatch among generation, consumption, and storage agents, resulting in improved energy efficiency in residential buildings. (Felipe Condon et al 2022)

The design of smart energy meters has evolved to incorporate IoT capabilities for real-time monitoring and control. Ruslan et al. (2023) proposed a cost-effective energy meter monitoring system using NodeMCU ESP8266 and PZEM-004T current sensors. The system provided real-time energy consumption data and remote-control capabilities, making it suitable for smart home applications. (Eliyanna Ruslan et al 2024)

In another study, Ahmad Hisham and Abd Wahab (2023) developed an electrical energy meter monitoring system utilizing the MQTT dashboard application. The system employed the ESP8266 NodeMCU microcontroller and ACS712 current sensors to monitor energy consumption, offering a user-friendly interface for tracking electricity usage. (Mohamad Iqmal et al 2023)

Efficient data transmission is crucial in IoT-based energy monitoring systems. The MQTT protocol has been widely adopted due to its lightweight nature and suitability for constrained environments. For example, in the Wahaha production base in Guiyang, China, an IoT energy consumption monitoring project utilized MQTT for real-time data collection from various meters, enabling effective energy management across multiple plants. (EMQ Technologies. 2023)

Additionally, the use of CoAP (Constrained Application Protocol) has been explored for its efficiency in low-power and lossy networks. A study in Turkey implemented a secure smart monitoring network for hybrid energy systems using both MQTT and CoAP protocols, facilitating real-time monitoring and control of energy production and consumption. (Ali M. et al 2021)

Real-world implementations of IoT-based energy monitoring systems in heterogeneous hybrid environments have demonstrated their effectiveness. For instance, a study conducted on a smart campus in Saudi Arabia proposed an IoT-based architecture for a hybrid renewable energy system comprising wind turbines, photovoltaic systems, battery storage, and diesel generators. The system employed the IEC 61850 standard for communication and demonstrated efficient energy management across the campus. (Feras N. et al 2021)

Furthermore, the integration of cloud computing with IoT has enhanced the scalability and accessibility of energy monitoring systems. A study by Rodríguez et al. (2023) designed and implemented a cloud-IoT-based HEMS that collected and stored energy consumption data from appliances and the main load of a home. The system provided real-time monitoring and control, contributing to energy efficiency in residential settings. (Nabaa Ali et al 2022)

III. MATERIALS AND METHODS

3.2 Materials

The following hardware and software resources were used in this research work.

Hardware Resources:

1.Current transformer

2.Integrated voltage, frequency, power factor, power and energy sensor

3.Node MCU

4.IoT gateway

Software Resources:

1.Arduino integrated development environment (IDE)

2.MATLAB

3.Firebase and Firestore

4.Vergel

5.React

6.Chakra UI

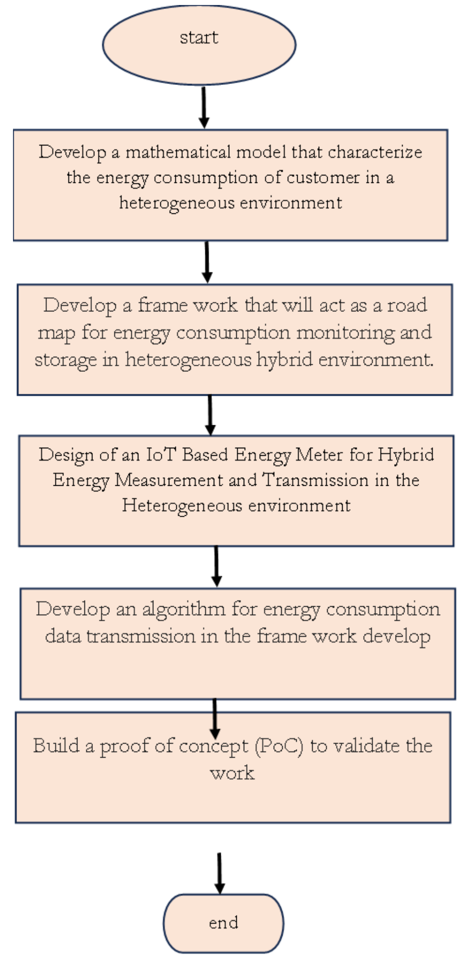

Figure 3.1: Methodology flow chart

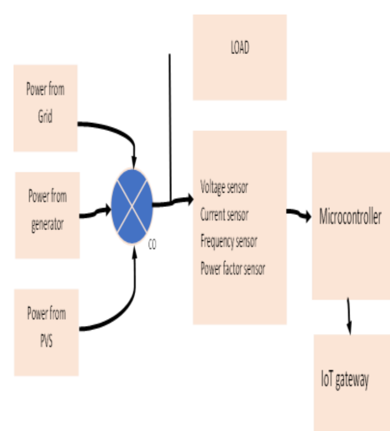

Figure 3.2: High-level block diagram of design and implementation of an IoT-based energy meter for hybrid energy measurement and transmission in the heterogeneous customer's environment

3.2.2 Hardware Requirement

The design of the IoT-based energy meter for HEM&T-in-HE is divided into three sections: Physical Layer Design (PLD), Back-End Layer Design (BLD), and Front-End Layer Design (FLD).

Physical Layer Design

Figure 3.3 shows a high-level block diagram for the design and implementation of the IoT-based energy meter for hybrid energy measurement and transmission in the heterogeneous customer's environment at the physical layer. As shown in Figure 3.2, the input to the meter can come from either a public power supply (grid), generator, or solar PVs. The changeover (CO) system is used to select the choice input to the meter per time.

The Hardware Design

The Sensing Block

The standard formula for instantaneous AC voltage is given by equation 3.9.

$$V_{ins} = V_{max} \sin (2\pi f t + \theta) \qquad 3.9$$

Where is the maximum amplitude of the AC signal, f is the frequency while is the phase angle. It therefore follows that at least four parameters must be measured to calculate the energy consumption of a customer. These four parameters are:

1.Instantaneous AC voltage
2.Instantaneous AC drawn by the connected loads
3.The frequency of the AC signal
4.Power factor of the AC signal

Choice of Sensors

At least four sensors are required to implement the energy meter proposed in this work. a 4-in-1 sensor, PZEM-400T which can measure the voltage, current, frequency, and power factor of an AC signal. One of the major interesting things about the sensor is that it has serial communication outputs that can be interfaced directly to a microcontroller making it ideal for IoT applications.

Choice of Microcontroller

ATMEGA 2560 microcontroller shown in Figure 3.5 is considered in this work because it is compatible with the sensor PZEM-400T. It can also be interfaced with the sim808 IoT gateway for the transmission of energy consumption to the cloud. It has inbuilt WIFI for easy connection to the internet besides being smaller in size.

Choice of IoT GateWay

Sim808 is a complete quad-band GSM/GPRS module that combines GPS technology for satellite navigation. It is considered in this work because it is not only compatible with the selected microcontroller but also has a wide area of network coverage. It can be used in remote areas. ESP 8266 can be used in areas that have WIFI. It has the advantage of fast connections to the Internet.

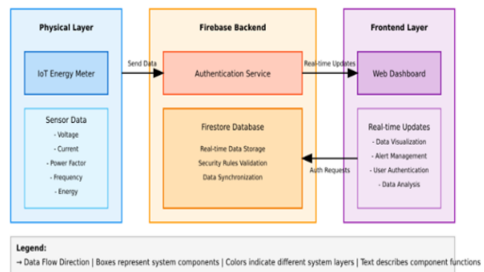

Figure 3.3: the complete circuit diagram of the physical layer

The Software Architecture of the Entire System

The diagram in Figure 3.4 shows the overall software architecture for Energy Consumption Monitoring and Storage in Heterogeneous Hybrid Environment. It reveals at a high level the interaction between different components. The system is organized into four main sections: the Frontend Web Application, Firebase Backend, Energy Data Collections, and Energy Data Sources. The front-end handles user interactions through components like authentication and visualization using Recharts. The Firebase Backend manages authentication and data storage through Firestore, which maintains separate collections for each region's energy data. Data flow from energy sensors through the backend and ultimately to the dashboard, where they are processed and displayed via charts. This architecture ensures secure access control while enabling efficient real-time energy monitoring.

IV. RESULTS

Data integrity Across the Three Layers

Figure 4.6 shows the plot of energy consumption data as transmitted from the physical layer. While Figure 4.6 shows the graph of 100 samples of the data transmitted, the analytics shows a window of 50 samples per time. From the online dashboard, region 1 has an energy consumption of 4.92KWh while Regions 2 and 3 have 3.12KWh and 2.18KWh respectively. They represent the last data transmitted from the physical layer to the back-end, and then to the front end. From Table 3.3, the physical layer data transmitted are: region 1 = 4.917966KWh, region 2 = 3.122796KWh, and region 3 = 2.180503KWh. These when approximated to 2 decimal places correspond exactly to the values shown on the front-end dashboard.

The 99th set of data transmitted from the physical layer are: region 1: 4.837627KWh; region 2: .080243KWh; region 3: 2.144804kWh. The percentage changes in the 99th and 100th data as computed from Table 3.3 are 1.66% for Region 1; 1.38% for Region 2; 1.66% for Region 3. These percentage changes in energy consumption per time are computed automatically in the online dashboard. What it means is that there is no loss or modification of data transmitted from the physical layer to the front-end layer via the back-end layer. So, it can be said that 100% data integrity is achieved in the design.

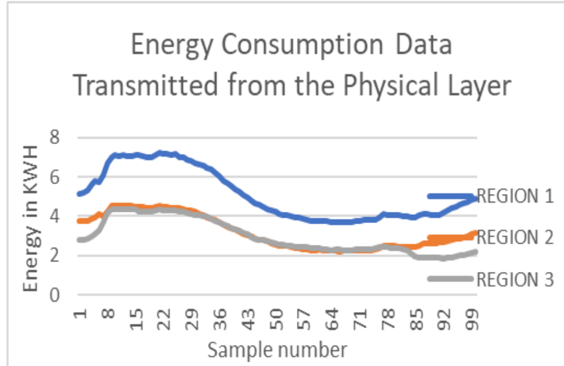

Figure 4.1: Energy consumption data at the physical layer

Comparison with Standard Measuring Instruments

At this point, it was important to compare the physical layer readings of the consolidated energy meter with those of standard instruments. A multimeter and frequency meter were used to validate the selected readings of the energy meter. Table 4.1 shows the summary of the validation readings. From Table 4.1, the error in voltage readings was consistently 0.8v. That of current is 0.009A while the frequency reading has zero error. If a resistive load is considered, it means that the error in power measurement will be 0.0072W. This is clearly insignificant.

s/n	Loads plugin	Instantaneous current (A) measured by the energy meter at the physical layer	Instantaneous voltage (V)measured by the energy meter at the physical layer	Instantaneous frequency (Hz) measured by energy meter at the physical layer	Instantaneous current (A) measured by ammeter	Instantaneous voltage (V)measured by a voltmeter	Instantaneous frequency (Hz) measured by a frequency meter
1	Fan	0.40	217.4	49.9	0.391	218.2	50
2	Fan + laptop	0.43	216.5	50	0.421	217.3	50
3	Fan + laptop + power bank	0.54	216.7	50	0.531	217.5	50

Table 4.1: Validation of the selected parameters of the consolidated energy meter readings

CONCLUSION

This work first developed a mathematical model that characterizes the energy consumption of customers in a heterogeneous environment before proposing a framework for the deployment of the model developed. To demonstrate the concept of the framework practically, an IoT-based energy meter for hybrid energy measurement and transmission in a heterogeneous environment was designed and prototyped. The design and prototyping were done in three separate layers: the physical, back-end, and front-end layers. At the physical layer, a sensor node was designed to measure the current, voltage, frequency, power factor, and energy consumption of a customer in a heterogeneous way while transmitting the energy consumption data (ECD) to the back-end layer. At the back-end layer (BEL), the data received are stored using Firebase software tools. On request from the front-end layer (FEL), the data stored at the BEL are sent to FEL. Only registered users can view the energy consumption data online. .

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