Progressive energy management technique for smart load control

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ABSTRACT

Electricity demand is rapidly increasing in many countries especially because of the increase in smart appliances, smart cities, and communities. The use of electricity ranges from agricultural load, to commercial and industrial load, and also residential load which account for the largest contributor to the increase in peak demand. Thus, residential consumers play a massive role in the national demand for electrical energy and power. The increased demand puts increasing pressure on the energy suppliers who force consumers to cope with short peaks. The need arises for an energy management technique to reduce energy consumption by allowing for consumer load control. The method explores using a Raspberry Pi to collect and evaluate the energy consumed over time and allow consumers access to directly control their home appliances. A more accurate load curve is deduced using the new readings gotten from the end-users. The data obtained from the proposed system is sent to a progressive web application that allows users manage their energy consumption.

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1. INTRODUCTION

With the increase in the adoption of renewable energy sources (RES), it is important to look more into demand-side management and load control. The study of load curves will enable microgrid management and reduce the operational cost and time of utility grids, and increase the dependency of smart homes on energy management [1]. The understanding of load curves and layout of controllable loads is necessary for home automation which improves consumers participation in energy management [2]. With the increased dependency on RES, energy storage systems are inevitable. The use of the storage systems are improved by access to the loads connected by the end-users so as to achieve power sharing and the control of the state of charge [3]. The goal of energy management scheme is to access the energy generation sources and more importantly schedule the available energy with minimal losses. Several optimization techniques have been used to achieve energy management especially as a demand-side management [4]. These methods of smart metering is common with demand-side management but there arises the need for it to be progressive and made available online [5], [6].

Smart energy meters are a game-changing breakthrough that private houses and businesses are beginning to employ in Africa to measure electricity consumed by end-users accurately [7], [8]. It is a source for a reliable information on utilized energy, minimizing the likelihood of errors to a bare minimum. The information gathered from these meters can optimize energy consumption and speed up the transition to sustainable energy by encouraging use when there is a surplus of clean energy and discouraging use when the grid is overburdened [9]. Demand side management (DSM) involves the reduction of energy wastage by monitoring and controlling the consumption behaviour of the consumer side of the unit to ensure more efficient system operation, lowering the electricity bill on the consumer side and reducing peak demand all day through [7], [10]-[12]. The DSM scheme has been identified by Ibrahim *et al*. [7] as the strategy to tackle the demand and supply balance problem, especially considering that limited fuel resources accompany increasing electricity demand. To help change the load profile and reshape the load curve, DSM techniques such as peak clipping, conservation, load building, valley filling, load shifting, and flexible load shape are used [13], as shown in Figure 1.

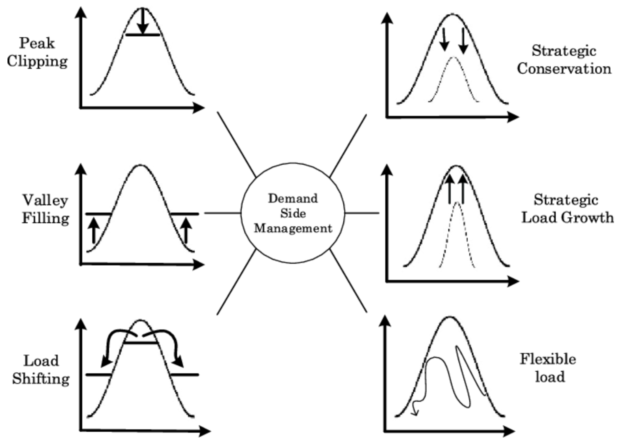

Figure 1. Demand side techniques [13]

A few advantages of demand-side management include cost reduction and environmental benefits by using energy-efficient appliances to significantly reduce peak demand, which diminishes greenhouse gas emissions [14]. Residential load management programs aim to reduce and shift consumption. An approach in this management scheme is direct load control (DLC). In DLC programs, the users can remotely manage the operations and energy consumption of selected household appliances based on a mutual agreement between the utility company and the consumers. It can regulate lighting, pumps, and refrigerators resulting in significant energy and cost savings [15]. In recent years, intelligent energy networks (IENs) have been rapidly created to meet expanding energy demand in a reliable, versatile, ecofriendly, and cost-effective manner. The most basic components in IENs are smart energy meters used to monitor or even operate home appliances in users homes [16], [17]. However, intelligent energy systems have altered the narrative of smart meters with internet of things (IoT) algorithms.

IoT monitoring system has offered a solution to improve the process of automation and control [10], [18], [19]. Samson *et al*. [16] designed and developed an IoT monitoring system to provide real-time tracking of energy assessment for consumers on an andriod application. The suggested system was divided into the electricity board (EB) and the end-user side. The latter had the app loaded on their phones, whereas the former communicated via the website. The Raspberry Pi’s Wi-Fi module was used to allow easy communication with the cloud, and power calculations were performed using data from both sensors (voltage and current). They utilized a 10-bit 8-channel MCP3008 IC analogue to digital converter (ADC) converter to convert continuous-time current and voltage readings to discrete-time by sampling and quantization and further displayed the power readings to the consumer via an liquid crystal display (LCD) [20], [21]. Notably, use universal asynchronous receiver/transmitter (UART) to implement their smart monitoring [16], [22], [23].

Chandra *et al*. [22] in automated an energy meter that used a Raspberry Pi to record the number of pulses detected by a light sensor system installed on the smart meter. These counted pulses were calculated into energy consumption by the meter on the Raspberry Pi, and then its data was sent to Google Spreadsheets using Google API. For accurate data delivery from the Spreadsheets, serial communication was utilized to send raw data to the global system for mobile communication (GSM) module, and a UART was used for parallel communication between the GSM and Raspberry Pi. Initially, the project was designed to use Zigbee technology because it carried small amounts of data while consuming less power. However, Chandra *et al*. [22] preferred Wi-Fi over Zigbee since the distance constraint was low; once linked to the Internet, Google Docs preserved the data acquired at intervals. The final display of the android app’s web page was achieved using a web view class and a load uniform resource locator (URL) command, but internet access posed a major constraint to accessing these data readings. As an outcome, could effectively develop a low-cost, easy-to-install metering system utilizing Pi 3 in India, reducing the requirement for human involvement and the costs associated with manual labour [22]. This research might be aided by using data analytics on the Internet to predict future energy use trends and electricity costs.

Energy information going in and out of the building via the smart meter can be routed through a home energy management system (HEMS), which can simply be accessed on laptops or mobile devices. A software based HEMS in a web application would be integrated into this project to allow users to access, monitor data or track energy usage details for effective savings [8], [24]. The application is protected since it is hosted through hypertext transfer protocol secure (HTTPS) and can be accessed using a simple URL. This paper aims to develop a new approach to smart energy metering for energy management by providing device-based real-time data to the householder.

2. ENERGY MANAGEMENT ALGORITHM AND DESIGN

The Raspberry Pi with an active Wi-Fi connection act as a smart system control in the energy management model. This system uses an embedded algorithm as stated in Figure 2 to make intelligent decisions to either turn off an appliance or let it run. It collects data such as the total energy requirement of various appliances which culminates into the overall consumption per hour from the installed smart meter. The data collected is used to determine the energy limit for the hour and check if it exceeds the estimated boundary. The next action is communicated to the smart meter to determine the operation of the appliance based on the primary need. The priority is classified broadly into two; high-end need and low-end need, depending on the time of the day. Figure 2 shows the flow chart or conceptual framework of the process involved in this particular project.

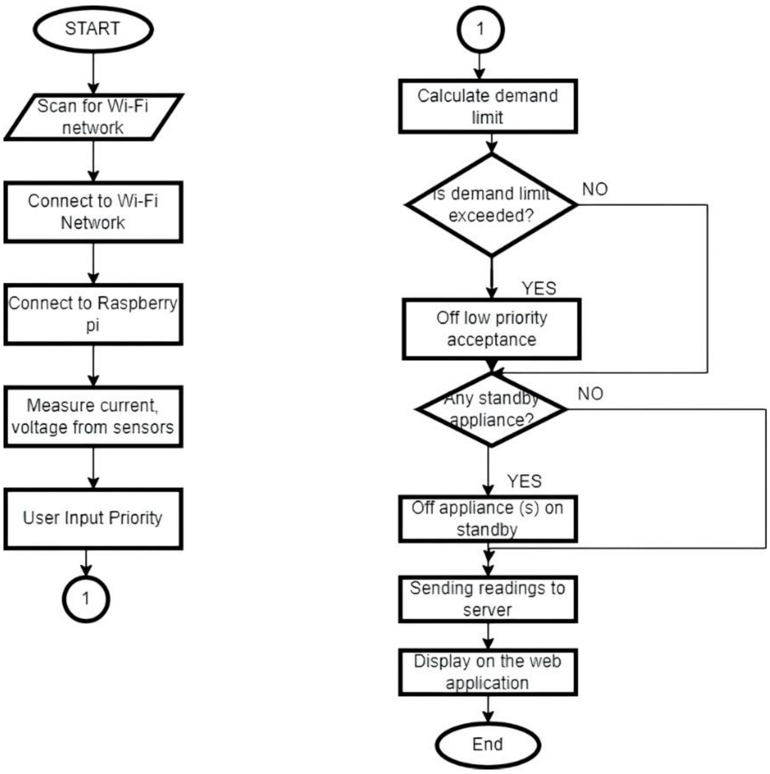

Figure 2. Design flowchart

2.1. System implementation

The connection of the devices is as shown in Figure 3 describing the layout for the circuit layout for the proposed management technique. Tests are carried on the system at every point to ensure communication among the devices to achieve the design requirement. The specifications for the key hardware components are given as, Raspberry Pi 3 model A+, current sensor (ACS712ELC-20A), voltage sensor (ZMPT101B), ATmega 328 ADC, and HF3FF-009-1ZST-5 pin power relay.

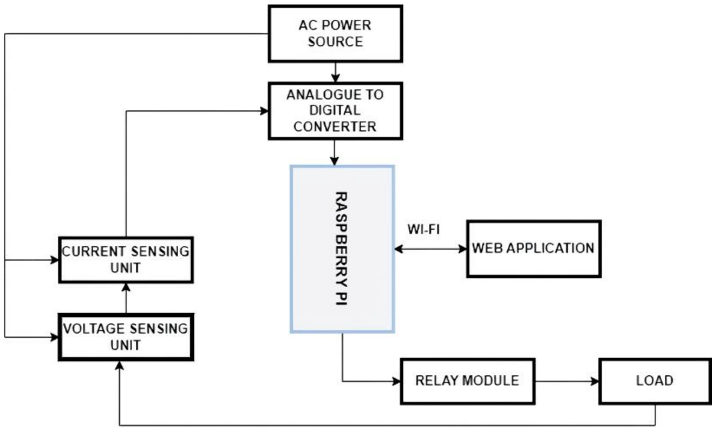

Figure 3. Block diagram of the proposed smart energy load control

The proposed system uses a Raspberry Pi 3 microprocessor to collect current readings from a current sensing unit and voltage readings from a voltage sensing unit. The ATMega328P served as an alternative ADC to calculate power in watts by multiplying the current and voltage. For the ATMega and Pi to interact seamlessly, the UART is employed as a communications protocol to enable direct communication between the two microcontrollers through a physical connection. The data readings collected by the sensor nodes are processed and transmitted through the ATMega. The data is transmitted serially through the receiver (Rx) and transmitter (Tx) pins to the Pi and stored in the database of Raspberry.

The voltage sensing unit is a sensing module <1000 V alternating current (AC) with a voltage divider configuration at its core to scale down input voltages. 240 V AC mains is stepped down by a power adapter, rectified, filtered, regulated and fed with an output voltage of 12 V direct current (DC) to power the PCB. Next, a current sensing unit is made up of hall-effect sensors that detect current flowing through its magnetic field and also help to measure the current values that the ATMega can read. The voltage and current values received through its analogue input pins are converted to digital forms with its inbuilt 10-bit analogue to a digital controller to perform mathematical operations. Readings from the input analogue pins are used to calculate power in watts and are later converted to kilowatt-hours on the app front. The Arduino Uno is programmed in C++, and the Raspberry Pi is programmed in python language.

2.2. Design components specification

The design specification discusses each component and how they are interconnected to ensure the system works properly. In this project, proper research on the voltage ratings of hardware components was carried out to determine the voltage at which these components were designed to work and the current consumption at that voltage. Table 1 shows the components that make up the hardware system and their voltage ratings. The Raspberry Pi is a small-sized computer that runs on linux and is designed and manufactured by the Raspberry Pi foundation [25]. It has a set of general purpose input/output (GPIO) pins that allow easy connection of control electronic components for physical computing.

Table 1. Specification for Raspberry-Pi based home energy management

S/N	Electronic components	Voltage specifications (V)
1	Raspberry Pi 3 model A+	4.75-5.25
2	Voltage sensor module (ZMPT101B)	5-30
3	Current sensor module (ACS712)	4.5-5.5
4	ATMega 328 ADC	1.8-5.5
5	8 channel solid state relay (SSR) module	5

The Pi 3, as displayed in Figure 4, is globally used to amp up programming skills, to develop hardware projects, and in industrial settings for automated control systems. The Pi, released in 2019, has unique features such as a 64-bit quad-core processor and a dual-band 2.4 GHz and 5 GHz wireless local area network (WLAN). Most generations of the Raspberry Pi have both models A and B, but model A was chosen to build the smart energy meter because it is less expensive, use lesser ports and tends to have reduced RAM [26]. The sensing unit uses ACS712 as in Figure 5, to measure current up to 30A based on the Hall effect principle [8]. Because hall effect sensors are disconnected from the voltage being measured, they face no safety risk. Furthermore, they have low insertion impedance and can accurately monitor AC and DC power. These features make the suggested energy meter's use of ACS712, a hall effect-based sensor desirable [27]. Figure 6 shows an ACS712 current sensor.

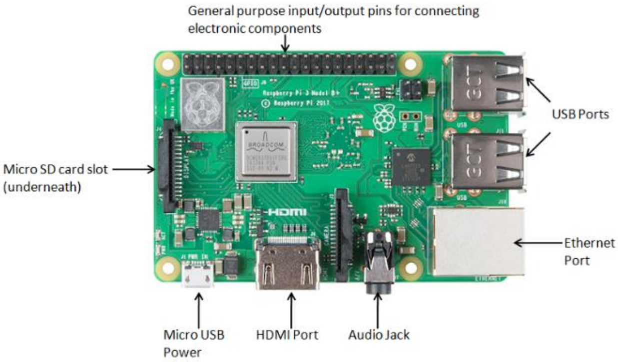

Figure 4. Raspberry Pi 3

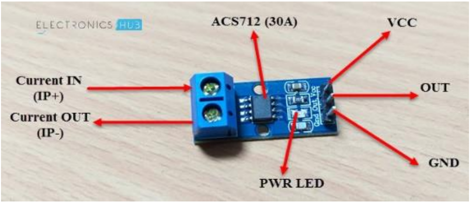

Figure 5. Current sensing unit (ACS712)

Figure 6. ZMPT101B voltage sensor

The ZMPT101B voltage transformer is used to develop a voltage sensor. It measures voltage up to 250 V AC with high precision and consistency. It is simple and includes a multi-turn potentiometer for modifying the ADC output [16]. Figure 6 shows the ZMPT101B voltage sensor module. Easy computer aided design (EasyEDA) is a robust web-based PCB design software tool that assists electronics hardware engineers, students, and enthusiasts in designing, simulating, and sharing project schematics. This software application synchronizes with the component catalogue from LCSC electronics and the JLCPCB service to help users turn their design concepts into actual products. Figure 7 shows the brain box of the smart energy load control.

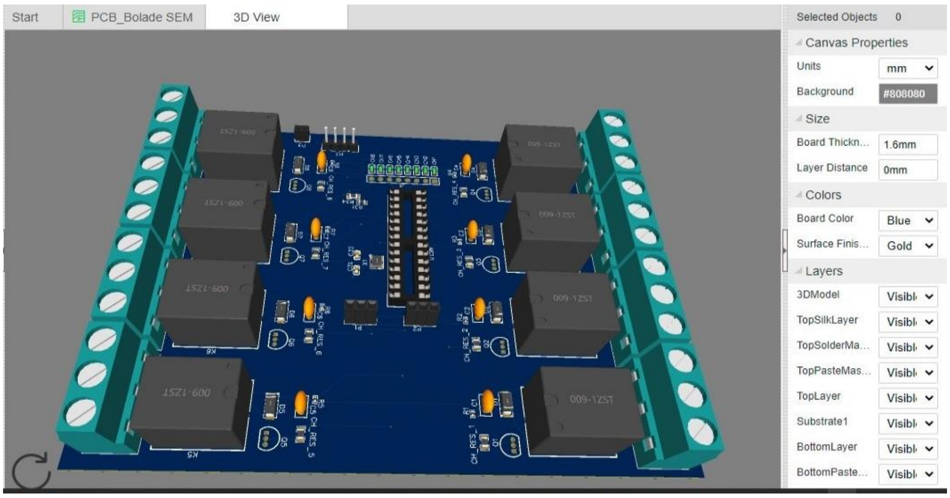

Figure 7. EasyEDA 3D view PCB connection

3. RESULTS AND DISCUSSION

Several hardware components were connected to the Raspberry Pi at various points during the project's development. As seen in Figure 8, testing the simulated circuit on a breadboard, mounting and soldering the design on a PCB and the final packaging of the system was achieved. The circuit was simulated with the EASYEDA software tool for electronic design and automation. The voltage and current sensing units connected to the ATMega and the relays were tested on the software, with the load monitored. This was done to ensure the practical workability of the designed circuit.

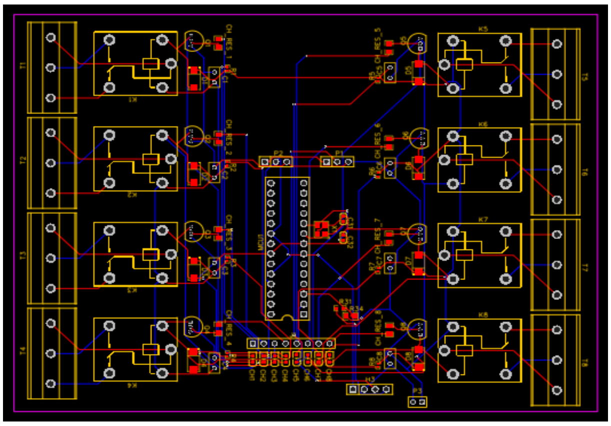

Figure 8. EasyEDA PCB layout diagram

3.1. Software implementation

The ATMega32 microcontroller chip was embedded into the smart energy load control system. The sole purpose of the ATMega32 microcontroller chip was to obtain current and voltage sensor data and use the Rx and Tx pins to transmit the data to the Raspberry Pi. An open-source Arduino IDE was used to upload instructions onto the microcontroller chip. The codes in Figure 9 were written in C++ and Python and easily uploaded onto the web server. API testing was done using the Postman API to validate the web application's programming interface. The testing was done to ensure the program's interface's reliability, performance and security. Figure 10 depicts the system in testing with a Raspberry Pi to send the measured readings to an online database. Also, the system is designed to allow consumers turn off the devices easily. The Visual Studio Code, text editor, is made solely to edit a list of commands that will be executed into a computer program.

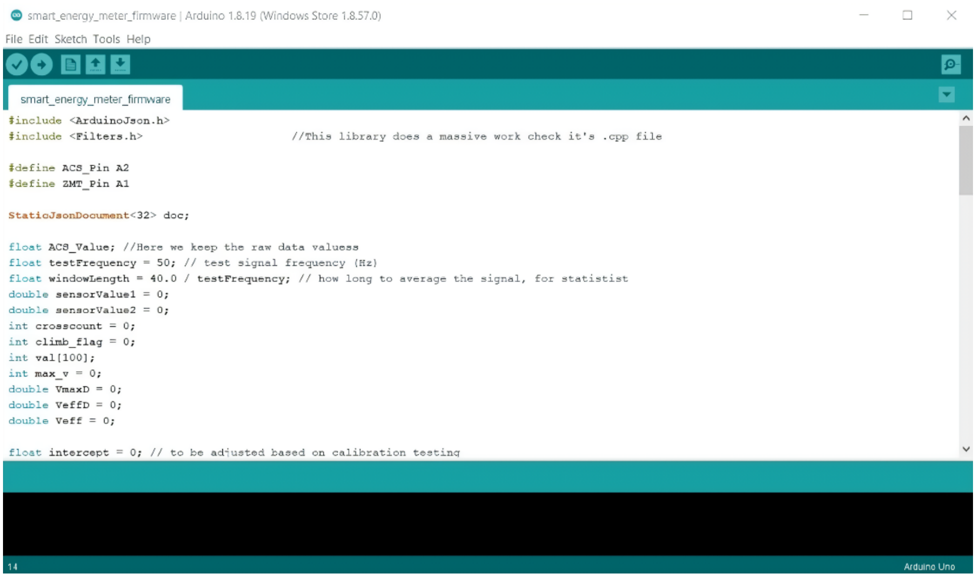

Figure 9. Arduino code testing for energy calculation

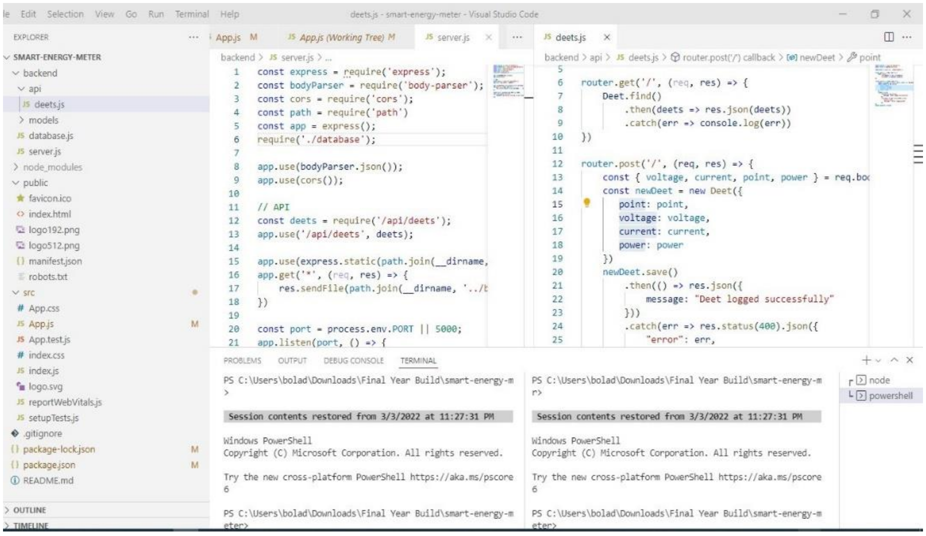

Figure 10. Visual Studio Code interface

3.2. Hardware implementation

System testing involves testing the integrated system with the loads to evaluate the system's compliance with the specified objectives/requirements. It involves measuring the energy consumption and monitoring test loads. In this project, two different loads were tested. The testing in Figures 11 and 12 used an electric iron with a power rating of 1750 W to 2200 W, four 60 W bulbs. After proper testing had been implemented, the sensor readings results were displayed on the web application system. The experiment results showed that the Raspberry Pi could help control consumer load, thus saving electricity bills and reducing the tariff rate. The Pi would also receive input wirelessly regardless of the interrupted power supply and control the states of the load attached to it in real-time. Table 2 shows the amount of power being consumed by each electrical device during testing.

Figure 11. System testing with iron

Figure 12. System testing to control load with four 60 W bulbs

Table 2. Load chart of the tested electrical devices

S/N	Load	Voltage (V)	Current (A)	Power (W)
1	No load	238.12	0.00	0.00
2	Electric iron	238.22	7.25	1727.10
3	Kettle	233.36	9.40	2202.21
4	4 (60 W bulbs)	234.55	1.12	254.14

Figure 13 shows the real-time measurement of any load connected to the smart energy meter. The mini channels indicate different units connected to the smart meter when the prototype has been installed in a residential building. Each channel can directly control certain loads to reduce and shift consumption. It also has a timer to display how long the connected appliances operate. Figure 14 shows another method of displaying the energy readings with varied coloured line charts in instantaneous mode. After a while, the consumer can manually turn on or off the load using the web application.

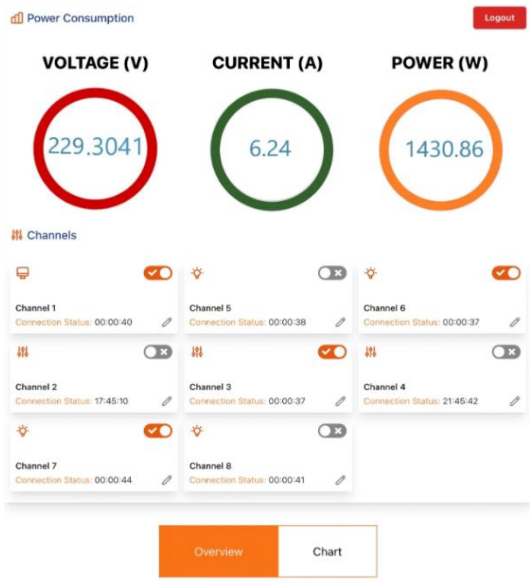

Figure 13. Notification displaying power consumption readings of the iron

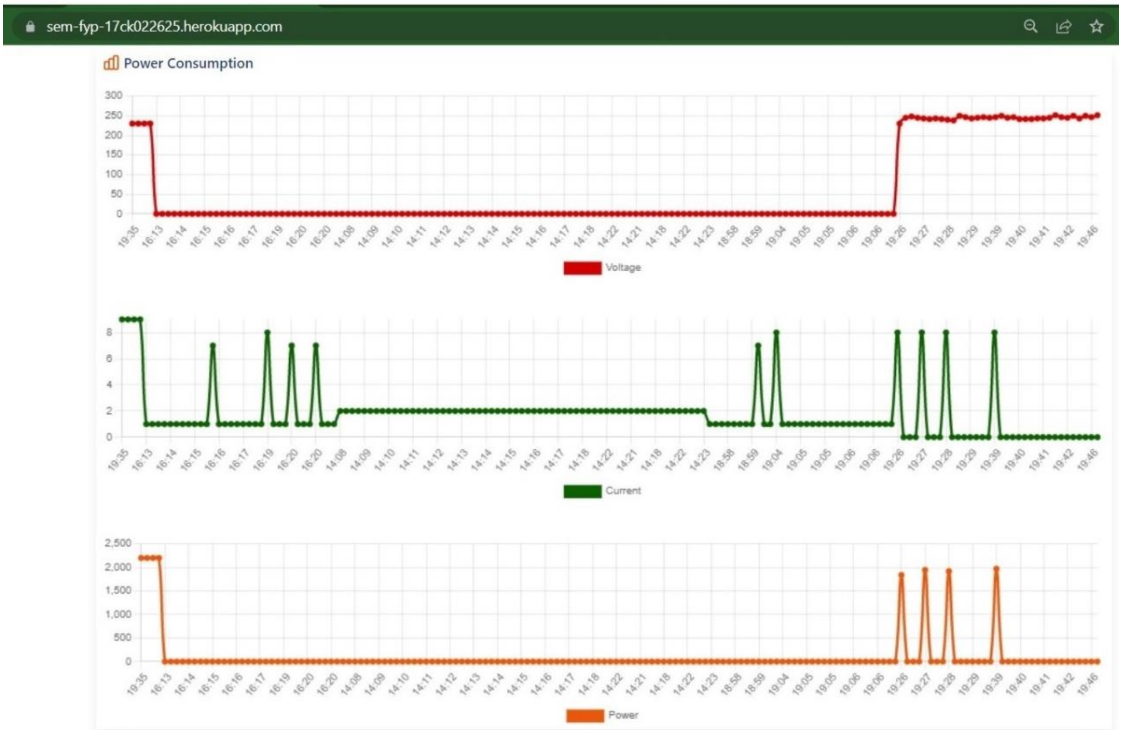

Figure 14. Line chart showing cumulative voltage, current, and power consumption

4. CONCLUSION

The successful development of an energy management technique prototype model to measure a load's power consumption with Raspberry Pi using a user-friendly web application has been discussed, as a prototype smart meter with measured values. It shows an easy transmission of collated data of monitored energy to a remote server for load optimization. Future work can consider creating similar energy conservation systems for the industrial sector, being the largest electricity consumer. The use of machine learning can be used to predict the amount of time it would take to consume a purchased amount of power units based on previous consumptions recorded by the energy meter. A regression algorithm can help estimate the time it would take to use up power in days.

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