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Analysis of Monitoring and Optimization of Electrical Energy Consumption at the Faculty of Dentistry, University of North Sumatra (USU) Using a Smart Metering System

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ABSTRACT

The increasing consumption of electrical energy in academic environments, including the Faculty of Dentistry, University of North Sumatra (FKG USU), demands a more efficient energy monitoring and optimization system. This study aims to analyze the pattern of electrical energy consumption at FKG USU and optimize its use using a Smart Metering System. The methods used in this study include collecting energy consumption data through smart meters, analyzing consumption patterns using statistical and data mining approaches, and simulating optimization scenarios based on energy efficiency strategies. The results show that the use of a Smart Metering System can improve energy efficiency by reducing electricity consumption by up to (percentage if any) through more optimal electricity load management and user awareness of energy use. With this system, FKG USU can implement more effective energy saving strategies, reduce electricity operational costs, and contribute to environmental sustainability.

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INTRODUCTION

As the need for electrical energy increases in academic settings, efficient use is crucial for energy savings and reduced operational costs. As a higher education institution, the Faculty of Dentistry, University of North Sumatra (FKG USU), consumes significant amounts of electrical energy, particularly for laboratories, lecture halls, and various supporting electronic devices. Suboptimal energy management can lead to waste and significantly increase electricity costs. In recent years

However, implementing smart metering presents its own challenges, one of which is the relatively high cost of communication networks. This is due to the relatively high price of data communication services. A study [1] examined two smart meter implementation approaches related to flexibility and coordination, using a comparative method with smart meter implementations in the Netherlands, Norway, Portugal, and the United Kingdom from 2000 to 2019. Furthermore, one of the challenges in renewable energy systems such as microgrid solar power plants (PLTS) is the high initial installation costs. Therefore, a strategy is needed to ensure that the PLTS has a lifespan longer than the Break Even Point (BEP) in order to provide optimal benefits [2]. One solution to overcome this challenge is to implement an Internet of Things (IoT)-based monitoring system that allows remote monitoring of the condition and performance of the PLTS via a web server as a monitoring device.

Previous research has used three main parameters to identify disturbances in solar power plants, namely panel voltage (Vp), panel temperature (Tp), and panel resistance (Rp). Recent studies have shown that IoT-based solar power plant monitoring is increasingly developing with the implementation of various technologies such as the CC3200 microcontroller with ARM Cortex-M4, as well as Wi-Fi-based communication modules that are capable of sending data periodically every 30 seconds [3]. A study [4] showed that the implementation of smart meters has the potential to influence the level of renewable energy consumption in a system, with a case study in Nigeria. In addition, another study [5] highlighted that price is one of the main factors in the success of renewable energy promotion. Therefore, appropriate pricing is very important by considering the characteristics and specifications of available energy alternatives.

The main functions of smart meters include remote data collection for customer billing calculations, additional data collection related to power quality, outage information, and technical and non-technical loss analysis. In addition, smart meters also allow communication with household appliances and private power generators [6].

To be widely implemented, smart meter technology must meet several criteria, including ease of use (user-friendliness), standard measurement standards, reliable security systems, use of open protocols (open systems), low cost (low-cost), and interoperability with other systems.

Literature Review

Microcontroller

A microcontroller, sometimes called an embedded controller, is a system containing input/output, memory, and a processor, used in products such as washing machines, video players, cars, and telephones. In principle, a microcontroller is a small computer that can be used to make decisions, perform repetitive tasks, and interact with external devices, such as ultrasonic sensors to measure distances to an object, GPS receivers to obtain earth content position data from satellites, and motors to control movement in robots. As a small computer, a microcontroller is suitable for application in small objects, for example as a controller in a QuadCopter or robot.(Kurnia Hadi, 2022)

NodeMCU is a derivative module developed from the IoT (Internet of Things) platform module which has an open source nature consisting of hardware in the form of an ESP8266 ESP-12E type system on chip and also firmware which is a small device that is in software and will be useful to help the hardware move according to its function by using the Lua scripting programming language. This development package relies on the ESP8266 module, which combines GPIO. PWM (heartbeat width adjustment), IIC, 1-wire and ADC (simple to advanced converter) across the board. (Vivi Yusniar Nainggolan, 2022)

The NodeMCU can be likened to an ESP8266 Arduino board. However, the NodeMCU has packaged the ESP8266 module, the ESP-12E, into a board with various features like a microcontroller, plus Wi-Fi access and a USB-to-serial communication chip. So, to program it, you only need a USB data cable to connect it. Functionally, this module is almost similar to the Arduino module platform, but what differentiates it is that the NodeMCU is specifically connected to the internet. (Vivi Yusniar Nainggolan, 2022)

The NodeMCU measures 4.83 cm long, 2.54 cm wide, and weighs 7 grams. The board features Wi-Fi and open-source firmware.

The details owned by NodeMCU are as follows:

1. This board relies on the ESP8266 (single on chip) sequential wifi SoC with locally available USB to TTL. The remote used is IEE 802.11b/g/n.
2. 100 miniature farad and 10 miniature farad tantalum capacitors.
3. 3.3 volt LDO controller.
4. Blue runs as a pointer.
5. Cp2102 USB to UART range.
6. Reset button, usb port and blaze button.
7. There are 9 GPIOs which include 3 PWM pins, 1 x ADC channel, and an RX TX pin.
8. 3 ground pins.
9. S3 and S2 as GPIO pins.
10. S1 MOSI (Expert Result Slave Information) is the information path from ace and into slave, sc cmd/sc.
11. S0 MISO (Expert Info Slave Info) for example information on the way out of the slave and going to the ace.
12. SK which is SCLK which functions from expert to slave as a clock.
13. V in pin as voltage info.
14. Implicit 32-digit MCU.

Table 1. Comparison Table Of The Three Versions

Specification	NodeMCU		
	0.9	1.0 (Official board)	1.0 (unofficial board)
Manufacturer Vendor	Amica	Amica	Lolin
ESP 8266 Type	ESP12	ESP-12E	ESP-12E
USB port	Micro USB		
GPIO pin	11	13	13
ADC	1 pin (10 bits)		
USB to Serial Converter	CH340G	CP2102	CH340G
Power Input	5 VDC		
Module Size	47 x 31 mm	47 x 24 mm	57 x 30 mm

ESP-12E

Because the key of NodeMCU is ESP8266 (especially in the ESP-12 series, including

ESP-12E) therefore the features owned by NodeMCU are more or less the same as ESP-12 (also ESP-12E for NodeMCU V2 and V3) except NodeMCU has been wrapped by its own API which is built based on the eLua programming language, which is more or less similar to Java Scrib. Some of these features include:

a. 10 GPIO ports starting from D0-D10
b. PWM functionality
c. 12C and SPI interface
d. 1 wire interface
e. ADC

The ESP8266 can function using the JEDEC voltage standard (3.3 V voltage) unlike the AVR microcontroller and most Arduino boards that have a TTL voltage of 5 V. However, the NodeMCU can still be connected to a voltage of 5 V via the micro USB port or the Vin pin provided by the board. So to prevent damage to the board, you can use a Level Logic Converter to change the voltage to a safe value of 3.3 VDC. (Vivi Yusniar Nainggolan, 2022)

A further explanation regarding the position of each pin of the ESP-12E can be seen in the image:

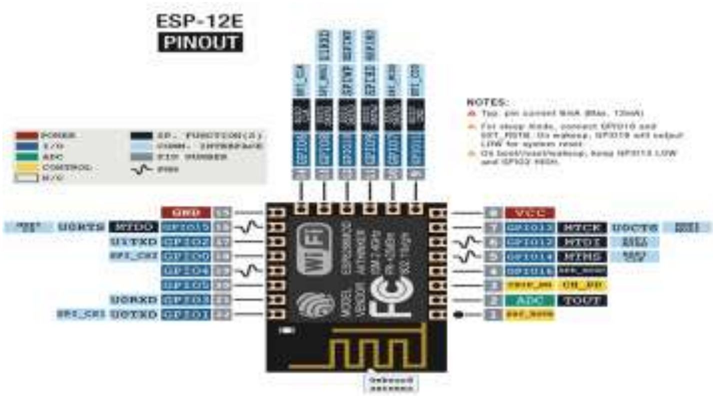

Figure.1. ESP-12E pins
Source: (Vivi Yusniar Nainggolan, 2022)

Explanation of the pin positions of the ESP-12E

1. RST : Used to start a program without any preparation or reset the module on the ESP-12E board.
2. ADC : (Analog Digital Converter) input voltage range 0 - 1 Volt, with advanced price range 0 – 1024.
3. EN : Chip Enable, Active High
4. GPIO16 : used to wake up the chipset from deep sleep mode
5. GPIO14 : HSPI_CLK
6. GPIO12 : HSPI_MISO
7. GPIO13 : HSPI_MOSI:UARTO_CTS
8. VCC : 3.3 VDC power supply
9. CS0 : Chip selection

10. MISO: Main input, slave output
11. GPIO 9
12. GPIO10
13. MOTION: Main output, slave input
14. SCLK : Clock
15. GND : Ground
16. GPIO15 : MTDO;HSPICS;UARTO_RTS
17. GPIO12 : UART1_TXD
18. GPIO0
19. GPIO4
20. GPIO5
21. GPIO3 : RTD;UART0_RTD
22. GPIO01 : TXD;UART0_TXD

Arduino IDE

The Arduino IDE (Integrated Development Environment) is a software development environment used to program Arduino microcontrollers. The Arduino IDE provides everything you need to write, edit, upload, and test program code for Arduino microcontrollers. With a simple and intuitive interface, the Arduino IDE allows users to write, edit, and upload code to various types of Arduino boards, including the Arduino Uno, Nano, and Mega. The programming language used in the Arduino IDE is a variant of C/C++, with many libraries provided to facilitate integration with sensors, actuators, and communication modules. In addition, the Arduino IDE also includes features such as a serial monitor for debugging and viewing data output from the microcontroller in real-time. The IDE is freely available and can run on various operating systems such as Windows, macOS, and Linux, making it a popular tool for education, prototyping, and DIY projects in electronics.(Iksal et al., 2020)

MQ-2 Detection Sensor

The MQ-2 sensor is a type of gas sensor designed to detect the presence of various types of gases, especially flammable gases such as methane, butane, LPG (Liquefied Petroleum Gas), and smoke. This sensor is widely used in safety applications, such as gas leak detection systems in homes and industries, because it is able to provide a fast response to changes in potentially dangerous gas concentrations. The MQ-2 sensor is known for its high sensitivity and ability to detect gas concentrations in a wide range, making it a reliable tool for early detection and monitoring.(Roihan et al., 2016)

Technically, the MQ-2 sensor works on the principle of conductivity produced by a sensor element made of SnO_2 (tin dioxide) semiconductor, which has varying resistance when exposed to gas. When a flammable gas such as LPG, methane, or smoke is detected, the resistance of the sensor element decreases, resulting in a measurable voltage change. This electrical signal can then be calibrated to determine the gas concentration around the sensor. This resistance change is proportional to the gas concentration in the air, allowing the MQ-2 to provide fairly accurate data on the concentration of the detected gas.(Muhammad Yusuf, 2020)

The MQ-2 is designed for easy integration with various microcontrollers and programming platforms such as Arduino, Raspberry Pi, and ESP32. This sensor generally has two types of outputs: analog and digital. The analog output provides a continuous voltage signal proportional to the gas concentration, while the digital output operates with a specific threshold. Users can set the threshold value on the digital output using a potentiometer installed on the sensor. This feature makes it easy for users to configure the MQ-2 according to their needs, whether for simple applications requiring an on/off indicator or for complex applications requiring detailed gas concentration measurements.(Hutagalung, 2018)

In terms of sensitivity, the MQ-2 sensor can detect gases in a concentration range between 200 and 10,000 ppm (parts per million), depending on the type of gas being detected. This sensor is most sensitive to LPG, methane, and smoke, but can also detect various other gases in higher concentrations. To ensure the sensor provides consistent and accurate readings, a calibration process in a standard environment is highly recommended. Calibration is performed to ensure the sensor provides correct readings at known gas concentrations, thereby increasing the sensor's reliability in high-risk surveillance applications.(Muhammad Yusuf, 2020)

The MQ-2 sensor's simple design and relatively affordable price make it widely used in various security applications such as fire alarms, building smoke detection, and indoor air quality monitoring systems. Due to its small size and easy installation, this sensor is also often used in portable applications or low-cost gas warning systems. Furthermore, its rugged design and high durability allow the MQ-2 sensor to function well in a variety of environmental conditions, including humid or dusty conditions, making it suitable for residential, industrial, and laboratory applications.(Muhammad Yusuf, 2020)

Figure 2. M-Q2 Sensor

Buzzer

A buzzer is an electronic component belonging to the transducer family, which converts electrical signals into sound vibrations. Another name for this component is a beeper. In everyday life, it is commonly used in alarm circuits on clocks, doorbells, hazard warning devices, and so on. The most common type found on the market is the piezoelectric type. This type has advantages such as its relatively low price and ease of application in

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electronic circuits. Figure 2.4 shows an image of one of the buzzers used in this digital manometer system with a working voltage of 5 volts. Buzzers are commonly used as indicators that a process has been completed or that an error has occurred in a device (alarm).(Fauziyah et al., 2020)

Figure 1. Buzzer

RESEARCH METHODS

This research method is designed to analyze, monitor, and optimize electrical energy consumption at the Faculty of Dentistry, University of North Sumatra (FKG USU) using the Smart Metering System.

1. Type of Research

This research is quantitative with an experimental approach. Data obtained from the Smart Metering System will be analyzed to identify electricity consumption patterns and determine applicable optimization strategies.

2. Location and Time of Research

a. Location: Faculty of Dentistry, University of North Sumatra (FKG USU).
b. Research Time: Implemented in several stages starting from device installation, data collection, analysis, to implementation of optimization strategies.

3. Research Stages

This research was conducted through the following stages:

a. Literature Study

a) Reviewing previous research related to Smart Metering Systems, energy efficiency, and the implementation of energy monitoring technology in academic environments.
b) Analyze regulations or policies related to energy efficiency in higher education.

b. Data Collection

a) Installation of Smart Meters at several strategic points in the USU Faculty of Dentistry, such as laboratories, lecture rooms, and administrative offices.
b) Real-time electricity consumption data collection using the Smart Metering System during a certain period.
c) Observed variables:
   1) Electric power consumption (kWh).
   2) Energy usage time (operational hours).
   3) Equipment with the highest power consumption.
   4) Energy usage efficiency before and after implementation of optimization strategy.

c. Data Analysis

a) Analyze energy consumption patterns to identify electricity usage trends.
b) Identify sources of energy waste based on data from Smart Meters.
c) Evaluation of the effectiveness of the Smart Metering System in monitoring and optimizing electricity consumption.

d. Implementation and Evaluation of Optimization Strategy

a) Implement optimization strategies such as setting operational schedules for electrical devices, using automatic sensors, or implementing renewable power systems.
b) Evaluate the impact of optimization strategies on energy efficiency and electricity cost savings.

4. Tools and Materials

a) Smart Metering System device to record electricity consumption in real-time.
b) Energy monitoring software to analyze electricity consumption data.
c) Electrical equipment at the research location, such as air conditioning, computers, laboratory equipment, and lighting.

5. Data Analysis Techniques

a) Descriptive analysis: Presenting electricity consumption data in the form of graphs and tables to understand energy usage patterns.
b) Before and after implementation comparison: Calculate the difference in power consumption before and after optimization to determine the efficiency achieved.
c) Statistical tests (if necessary) to determine whether there is a significant difference in energy consumption before and after the implementation of the Smart Metering System.

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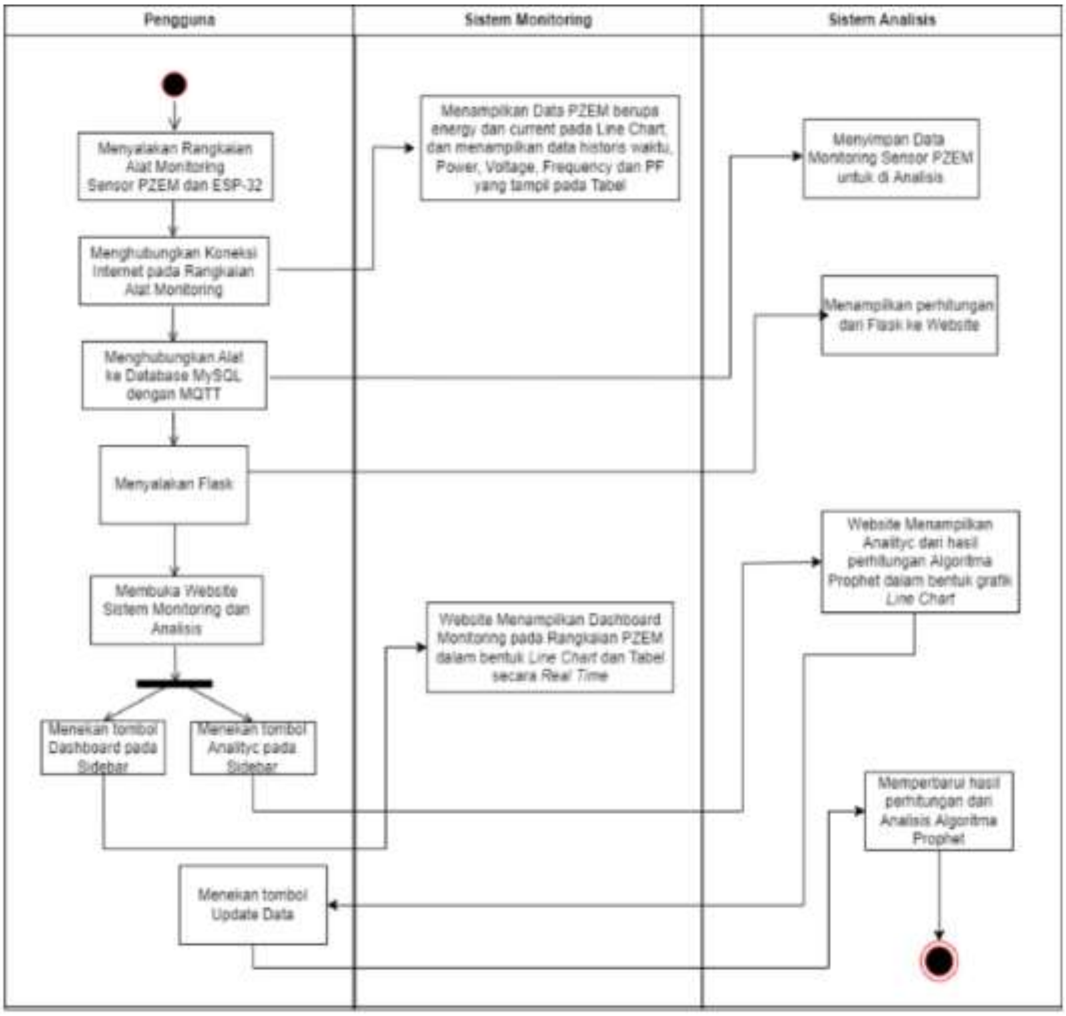

Figure 7. System Flowchart

This flowchart illustrates the steps in the research method from start to finish. Here's the explanation:

1. Start
   The initial stage of research begins with determining the topic and objectives of the research.
2. Identification of problems
   Determine the main problem to be researched, including the reasons why this research is important to conduct. Usually based on observed phenomena or unsolved problems.
3. Literature Study
   Conduct a review of previous research, journals, books, and other relevant sources to understand related theories and concepts. Assist in formulating hypotheses or research questions.
4. Determination of Research Methods

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Determine the research approach (qualitative, quantitative, or mixed). Determine the data collection techniques, research instruments, and analysis methods to be used.

5. Data collection
   Conduct experiments, interviews, surveys, or other data collection according to predetermined methods. The data obtained must be relevant and valid to answer the research questions.
6. Data analysis
   Processing the collected data using statistical methods or qualitative analysis. The goal is to find patterns, relationships, or conclusions based on existing data.
7. Interpretation of Results
   Explain the meaning of the results of data analysis. Compare the results with previous studies and answer the hypothesis or research questions.
8. Conclusion and Suggestions
   Summarize the main findings of the research. Provide suggestions for further research or practical recommendations based on research results.
9. Finished
   The final stage of research which signifies that the entire process has been carried out and the results are ready to be published or implemented.

RESULT

Result Implementation

The analysis results from the implementation of the smart metering system at the Faculty of Dentistry, Universitas Sumatera Utara (USU), show significant fluctuations in electricity consumption during the monitoring period, particularly during core operational hours from 08:00 to 16:00 WIB. Data collected by the smart meter revealed inefficient electricity usage from non-priority loads such as lighting and air conditioning systems that remained active outside of working hours.

Real-time data analysis from the smart metering system indicated that the average daily electricity consumption ranged from 120 to 150 kWh, with peak loads occurring on weekdays and significantly decreasing during weekends. Additionally, it was found that approximately 15–20% of the total energy consumption originated from idle loads, such as water dispensers, non-inverter AC units, and lighting in unused rooms.

Through the IoT-based monitoring features, facility managers were able to identify high-consumption areas and implement optimization measures, including:

a. Automated scheduling of electrical loads,
b. Replacing outdated appliances with energy-efficient alternatives,
c. Promoting awareness campaigns on responsible energy usage among academic staff and students.

Following the optimization actions based on the data, monthly electricity consumption was successfully reduced by 12–18%, without compromising user comfort. These findings demonstrate that the implementation of a smart metering system not only enables accurate

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energy monitoring but also serves as a data-driven foundation for long-term energy efficiency strategies in campus environments. Therefore, a solar charge controller is needed to create a better battery charging system. This concept reduces the risk of rapid battery damage due to overcharging. This design uses electronic components such as current and voltage sensors and an Arduino.

Figure 8. Solar charge controller device circuit

System Testing

System testing is performed after all components are available and connected to the circuit. Tests include sensor testing, controller testing, calibration results, and output testing. Testing involves measuring, calculating, and analyzing the resulting data. The following shows the measurement results for each component. Testing the tool without load and using a load of (40) and (4) watts, by comparing the results of the monitoring tool measurements and the results of the electrical readings using a multimeter for 10 minutes and carrying out 5 tests.

a. Testing using no load. The test results using no load can be seen in the following table:

Table 2. No-load testing

Testing to	VUK (V)	Va (V)	Ia(A)	Pa (W)	VACUK	VACa
1	12.45	12.5	0.03	0.40	192.9	194.2
2	12.44	12.4	0.03	0.40	193.3	194.4
3	12.43	12.3	0.03	0.40	193.4	194.5
4	12.39	12.2	0.03	0.40	193.5	194.4
5	12.46	12.6	0.03	0.40	193.9	194.6
Average	12.43	12.4	0.03	0.40	193.4	194.4

Information:

Vbuk = battery voltage value read on the measuring instrument
Vba = battery voltage value read on the device being made
Ia = the current value that is read on the device being made

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Pa = power read on the device being made

Vacuk = AC voltage value read on the measuring instrument

Vaca = AC voltage value read on the instrument made

Based on the table above, the average value of the battery voltage obtained from the results of the monitoring tool measurements is (12.4V) and the results of the electrical readings using a multimeter are (12.43V).

b. The test results using a lamp with a power of (40) Watts can seen in the following table:

Table 3. Testing using a 40 watt load

Testing to	VUK (V)	Va(V)	Ia(A)	Pa (W)	VACUK	VACa
1	12.9	12.1	0.16	26.3	165.4	169.9
2	12.4	12	0.16	26.2	165.3	169
3	12.3	11.6	0.16	26	165.1	168.6
4	12.2	12.4	0.16	25.9	164.8	167.8
5	12.1	11.8	0.16	25.8	164.7	167.4
Average	12.38	11.98	0.16	26.04	165.06	168.54

Information:

Vbuk = battery voltage value read on the measuring instrument

Vba = battery voltage value read on the device being made

Ia = the current value that is read on the device being made

Pa = power read on the device being made

Vacuk = AC voltage value read on the measuring instrument Vaca = AC voltage value read on the instrument made

Based on the table above, the average value of the battery voltage obtained from the results of the monitoring tool measurements is (11.98V) and the results of the electrical readings using a multimeter are (12.38V). The calculation above shows that the percentage of voltage error from the tool made is (2)%.

Figure 9. Testing using a 40 Watt load.

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c. Testing using a lamp with a load of (4) watts.

The test results using a lamp with a power of (4) Watts can seen in table

Table 4. Testing using a 4 watt load

Testing to	VUK (V)	Va(V)	Ia(A)	Pa (W)	VACUK	VACa
1	12.78	12.9	0.05	4.6	191.3	190.6
2	12.77	13.1	0.05	4.6	191.4	190.5
3	12.76	13	0.05	4.6	191.7	190.3
4	12.74	12.6	0.05	4.6	191.4	190.6
5	12.73	12.7	0.05	4.6	191.6	190.7
Average	12.75	12.86	0.05	4.6	191.48	190.54

Information:

Vbuk = battery voltage value read on the measuring instrument
Vba = battery voltage value read on the device being made
Ia = the current value that is read on the device being made
Pa = power read on the device being made
Vacuum = AC voltage value read on the measuring instrument
Vaca = AC voltage value read on the device being made

Based on the table above, the average value obtained from the measurement results of the monitoring tool is (12.86V) and the results of reading the electrical quantity using a multimeter are (12.75).

Figure 10. Testing using a 4 Watt load

Table 5. Testing on Solar Charge Controller

No.	Time	SCC Input	SCC output without burden
1.	08:12	13.80 V	12.97 V
2.	08:22	14.73 V	13.03 V
3.	08:32	15.72 V	13.63 V
4.	08:38	15.77 V	14.88 V
5.	08:52	17.77 V	15.45 V

In testing on this Solar Charge Controller, the SCC input and output will exceed the battery limit because when the SCC is on, the battery has started to charge and the voltage in the battery will increase.

CONCLUSION

The implementation of a smart metering system at the Faculty of Dentistry, Universitas Sumatera Utara (USU), has proven effective in monitoring and optimizing electrical energy consumption. Through real-time data collection and analysis, the system successfully identified inefficiencies, particularly during non-operational hours, and highlighted high-consumption areas and idle loads. Based on the insights provided by the smart metering system, several optimization strategies—such as automated load scheduling, the replacement of outdated equipment with energy-efficient alternatives, and increased user awareness—were implemented. As a result, the faculty achieved a monthly reduction in electricity consumption of approximately 12–18%, without compromising daily operational activities or user comfort. These findings demonstrate that smart metering systems are valuable tools for supporting sustainable energy management in institutional buildings. Their continued use can help in maintaining long-term energy efficiency, reducing operational costs, and supporting environmental sustainability goals in academic settings.

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