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A Smart Home Architecture for Energy Conservation and Multiple Energy Source Management

Indra Kurniawan[1,*], Irfan Dwiguna Sumitra[1]

[1] Postgraduate Faculty, Universitas Komputer Indonesia, Indonesia, Jl. Dipatiukur No. 112-116 Bandung, West Java, 40132, Indonesia

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ABSTRACT

Smart home architecture has been widely applied in energy conservation efforts by improving control and monitoring of energy use. Energy conservation efforts can be made by controlling energy consumption and accommodating other energy sources that are environmentally friendly or renewable. Renewable energy sources can now be built quickly and affordably, for example, solar panels. This study aims to build a smart home architecture that prioritizes energy conservation and managing multiple energy sources. The method used in this research is applying the Fuzzy Multi-criteria Decision Making model and Artificial Neural Network embedded in the Single Board Computer and ESP8266 system with the Internet of Things concept. This research results in an intelligent hardware architecture and software system that can be controlled via a smartphone or PC for energy-saving efforts increasing awareness of energy use and managing multiple energy sources that are affordable and easy to implement at home.

1. Introduction

Energy conservation efforts are a strategic action to use energy to a minimum and as effectively as possible, which is very popularly promoted worldwide. One of the energy conservation efforts is to build individual awareness about the importance of using as much energy as needed. In addition, energy conservation can be done using environmentally friendly or renewable energy such as solar energy using solar panels.

There are two categories of energy sources, namely renewable and non-renewable energy. Petroleum, coal, natural gas, and nuclear energy are categorized as non-renewable energy. While hydroelectricity, wind, geothermal, biomass energy, and solar are categorized as renewable energy [1].

On a small-scale, solar panels are very affordable and easy to install but have limited power. Solar panels can be configured in series and parallel to form a solar panel array for more significant power requirements.

* *Corresponding author.*
E-mail address: indra.75121014@mahasiswa.unikom.ac.id

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The downside of this configuration is that it requires a large-capacity battery and a much more expensive high-power solar charge controller. A single setup consisting of a 100Wp solar panel, solar charge controller, and a 50Ah 12V battery can provide 0.4-0.8kWh of energy daily, depending on the weather. In an off-grid solar power generation system, the energy produced is stored in batteries and then used to power specific electronic equipment. The problem with this system is that not all the energy produced every day is fully utilized due to limited battery capacity.

In this research, we built and analyzed several single solar panel setups managed so automatically that the energy produced can be used optimally. In addition, smart home architecture is also needed that prioritize energy conservation and build awareness of energy use at home. The main idea is to design a sensor control unit [2]. It relays wirelessly to control switching on and off and determine the power source from different energy sources (renewable and non-renewable energy) for electronic devices at home using centralized computational decision-making. The smart home architecture built in this study still uses electrical energy from the grid but will prioritize the use of electricity from solar panels or other renewable energy sources.

This research aims to build a smart home architecture that can accommodate renewable energy sources even on a small scale. This architecture is expected to be one of the methods for energy conservation efforts. In addition, energy conservation also means cost savings which can also be a solution and strategy in post-Covid-19 economic problems for the community [3-5].

2. Related Research

Energy conservation efforts and renewable energy innovation are research areas that are currently developing and are included in one of the Sustainable Development Goals (SGDs). In smart home architecture is discussed for intelligent energy use in a multiple-user home by using WIFI to track someone's presence in a room [6]. The paper also describes the proposed architecture comprehensively. However, the article only uses energy from one non-renewable energy source. In multiple renewable energy sources are discussed for power management on microgrids with connected utilities. However, there is no real-time monitoring and automation method for selecting energy sources [7].

3. Methods and Materials

This study uses a research and development methodology by analyzing and referring to literature studies, previous studies, and other references. The method used to solve this research problem is the application of fuzzy multi-criteria decision making (FMCDM), artificial neural network (ANN), ESP8266 microcontroller application, and IoT-based modules. The block diagram of the smart home architectural design that will be built and tested can be seen in Figure 1.

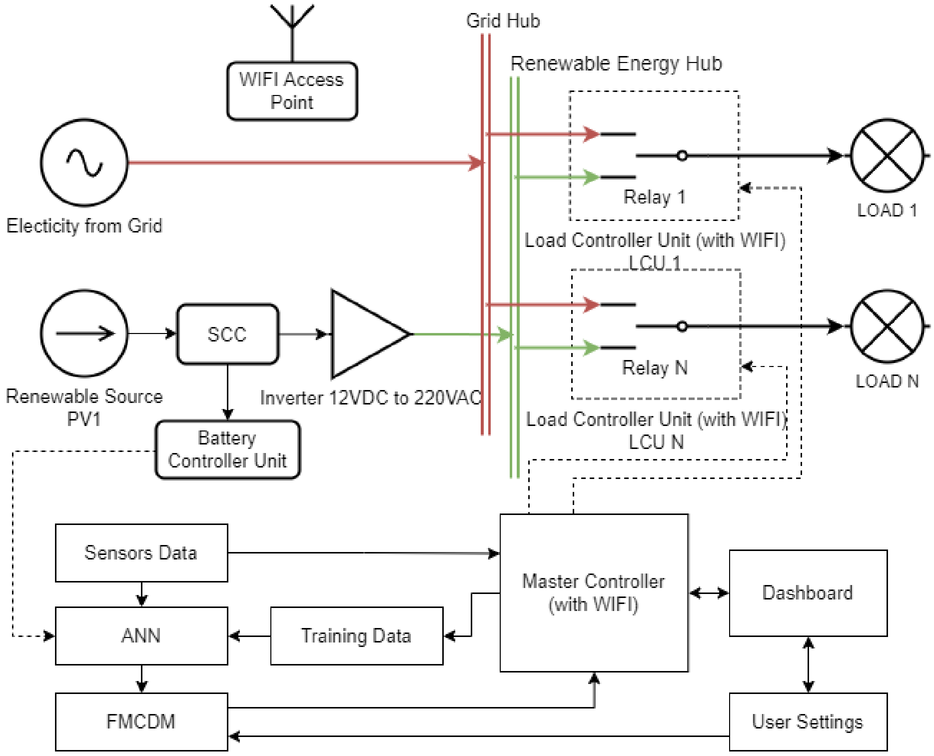


Fig. 1. Smart home architecture design

As shown in the block diagram above, each load (electrical device) is controlled via a Controller Unit which will provide electrical power from the grid or renewable energy sources. The determination of the use of electrical power is controlled based on the results of the decisions on the FMCDM block and the output of the ANN block. The function of the ANN is to provide an additional criterion for the FMCDM block based on training data and sensor data.

3.1 A Smart Home Concept

Smart Home is a home concept that utilizes technology, such as computers, communication, control, security, and artificial intelligence, so homes can be better managed and enable more sophisticated automation.

Smart homes have several prominent features, including [8]. 1) Smart homes can increase the comfort, security, convenience, and interactivity of home life and optimize people's lifestyles. 2) Smart homes can support online payment. 3) Support perfect intelligent service. 4) Smart homes enable users to monitor and interact with the home via an online system and find abnormal processing. 5) Smart home realizes real-time meter reading and security service of the water meter, electric energy meter, and gas meter for high-quality service. 6) Smart homes can realize the interaction between users/consumers and power grid companies, obtain information on electricity consumption and electricity prices, set electricity consumption plans, and so on, guide scientific and rational use of electricity, and advocate family awareness to save energy and to protect the environment.

3.2 Internet of Things

Internet of Things (IoT) is a concept where the thing can exchange data over a network [9]. IoT defines an environment of interconnected computing devices with different data exchange and connectivity components. IoT often implements machine-to-machine communication technologies [10]. In the IoT concept, computing devices are usually embedded systems with sensors and actuators connected via the internet for specific functions based on the embedded program. IoT is the technology that must be implemented to face future problems along with disruptive technology, big data, agile processing, hybrid server, pervasive computing, and ubiquitous access/transaction [11].

IoT devices typically use a microcontroller that can be easily programmed through an integrated development environment (IDE) such as Arduino IDE. The microcontroller that is often used is the AT-mega microcontroller series (such as ATmega32, ATmega328, and ATmega2560) which is popularly used on Arduino modules. The disadvantage of these microcontrollers is that they require additional modules to connect to the network. Fortunately, some microcontrollers support the IoT concept and have built-in wireless communication functions, such as the ESP8266.

3.3 ESP8266 Microcontrollers

ESP8266 is a 32-bit microcontroller with TCP/IP (Transmission Control Protocol/Internet Protocol) network support produced by Espressif Incorporated. ESP8266 has 17 general-purpose inputs/outputs which can be programmed. The ESP8266 has sufficient capabilities and features to build IoT applications and dramatically simplifies the development process [12]. In addition, ESP8266 is an ultra-low power module with a power-saving mechanism in the WIFI protocol.

The ESP8266 is intended explicitly for UART to WIFI Smart Device, Sensor, Smart Light, and Smart Plug applications. The ESP8266 can be used to develop sensor products via the I2C interface. In the sensor application, data from the sensor can be sent to the ESP8266 using the I2C interface and then sent to the server wirelessly. ESP8266 can use Pulse Width Modulation (PWM) for Smart Light applications. The ESP8266 functional block diagram can be seen in Figure 2.

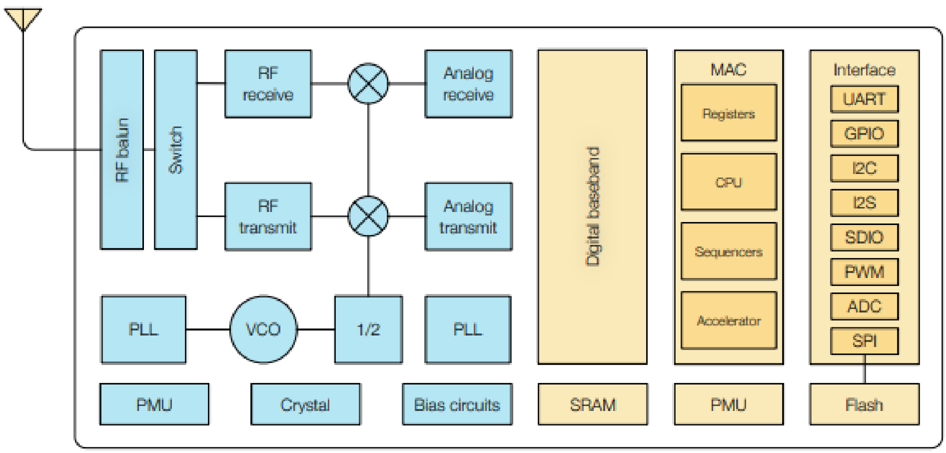


Fig. 2. ESP8266 block diagram

3.4 The Electrical Energy Sensing

Energy conservation efforts will be measured by monitoring energy use. In energy monitoring is carried out using the RaspberryPi3-based PZEM-004t module [13]. In this research, the measurement of energy consumption uses the Current Transformer CT YHDC SCT-013-000 component and its equivalent component. A component or module is needed to measure the voltage and electric current flowing at each load to calculate electrical energy. The formula used to calculate the power or energy used or Real Power is as follows

$$P = \frac{1}{T}\int u(t) \times i(t)dt \equiv U \times I \times \cos(\varphi) \tag{1}$$

P is Real Power, u is root-mean-square (RMS) voltage, i is root-mean-square (RMS) current, and cos ($\boldsymbol{\varphi}$) is the power factor. The real power in discrete time uses the following formula:

$$P \equiv \frac{1}{N}\sum_{n=0}^{N-1} u(n) \times i(n) \tag{2}$$

where u(n) is sampled instance of u(t), i(n) is sampled instance of i(t), and N is several samples. Real power is calculated simply as the average of N voltage-current products.

3.5 Artificial Neural Network

Artificial Neural Networks (ANN) is a computational system that follows the workings of neural networks in the brain. ANN is like the human brain processing input. ANN can be trained by determining known inputs and results. ANN is useful for classification, clustering, prediction, and pattern recognition [14].

ANN consists of 3 layers: the input layer, hidden layer, and output layer. Depending on the system's complexity, the hidden layer may consist of many separate layers. In general, the ANN model and Block Functional Diagram can be represented in Figure 3 and Figure 4. Output $Y = F(Y_{in})$ and $Y_{in} = \sum_i^m (x_i \times w_i)$ Where i is, the input index and m is the length of the input array. Activation function (F) can be linear activation $F(x) = x$ or sigmoid activation function $F(x) = sigm(x)$.

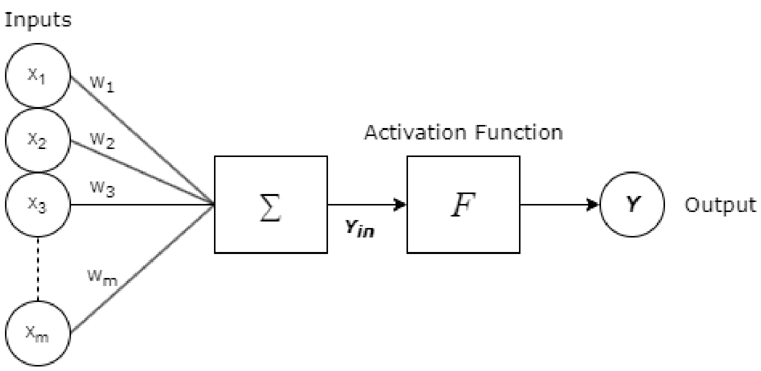


Fig. 3. ANN general model

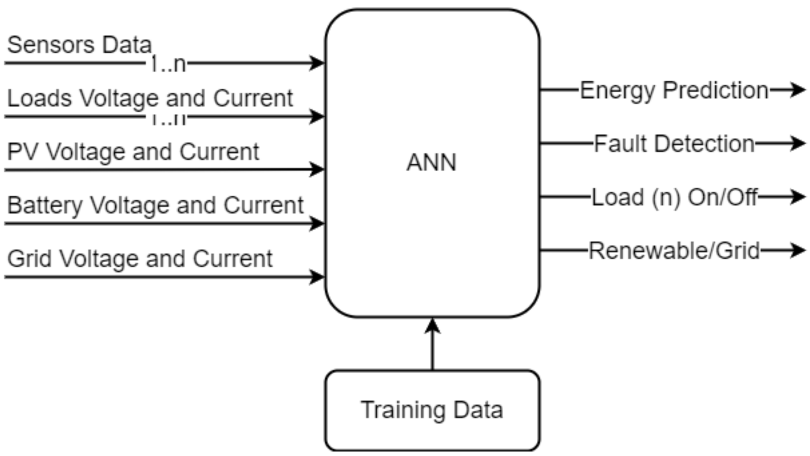


Fig. 4. ANN block functional diagram

In this study, as represented in Figure 4, ANN processes data from sensors, load current and voltage, solar panel current and voltage, battery current and voltage, and maximum grid power to produce predictions of total available energy, failure detection on solar panel and battery systems, data for adding weight to the criteria for the FMCDM block on the criteria for selecting renewable or non-renewable energy sources and the decision to turn on or off specific electronic devices [15]. The training data for the ANN block is stored in a database on the server.

3.6 Fuzzy Multi-Criteria Decision Making

Multi-Criteria Decision Making (MCDM) is a method for making decisions on several alternative decisions with several criteria being considered. MCDM is used when the weight of the importance of each criterion and the degree of suitability of each alternative to each criterion contains uncertainty. In this study, FMCDM decides whether a device uses renewable energy sources, non-renewable energy sources, or turns the device off, as seen in Figure 5.

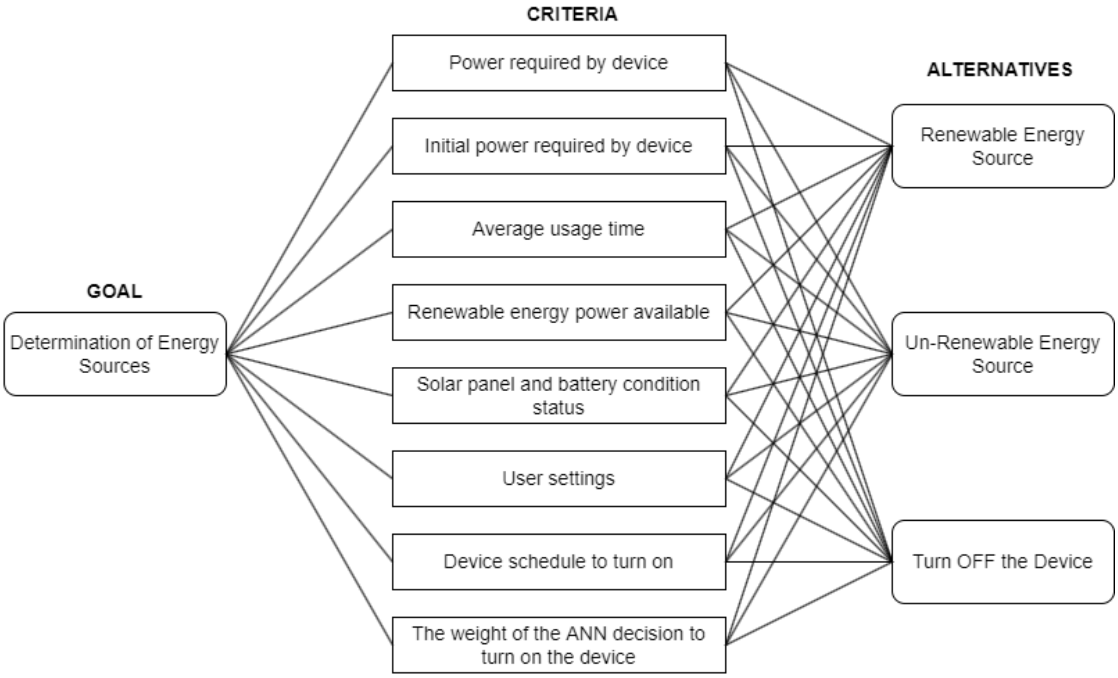


Fig. 5. FMCDM decision map

In this study, FMCDM decides whether a device uses renewable energy sources, non-renewable energy sources, or turns the device off, as seen in Figure 5. The criteria used in FMCDM for this purpose include 1) power required by the device, 2) initial power required by the device, 3) average usage time, 4) renewable energy power available, 5) solar panel and battery condition status, 6) user settings for the device, 7) device schedule to turn on or off and 8) the weight of the ANN decision to turn on the device.

The FMCDM method is often used for decision-making systems on energy-related problems [16]. FMCDM is used to model the decision-making of CCHP systems with different energy sources. In also discussed using Simple Additive Weighting (SAW) and Relative Preference Relation methods to quickly and easily solve FMCDM problems [17-19].

4. Results and Discussion
4.1 Proposed Smart Home Architecture

On the other hand, smart home capabilities like electricity automation and scheduling, remote control, and energy usage monitoring. As seen in Figure 6, the proposed smart home architecture can prioritize the optimal use of renewable energy through better sensing using ANN and automated decision-making using the FMCDM method [20].

This architecture requires new power lines to channel power from renewable energy sources so that the house has two power lines, namely renewable energy lines and non-renewable energy lines. Any electronic equipment that requires electrical power will be connected to the Controller Unit (CU) device and will automatically be powered by renewable or non-renewable energy sources based on 1) user control, 2) sensors and 3) computational decision results.

The CU device is continuously connected to the Master Controller Unit (MCU) via a wireless network (WIFI Access Points) [21]. The CU device has a unique ID needed to distinguish one device from another. Each CU device has two relays, two additional sensor ports, and a built-in energy sensor to calculate energy consumption. Thus, each CU can be connected to a maximum of two additional sensors if needed [22].

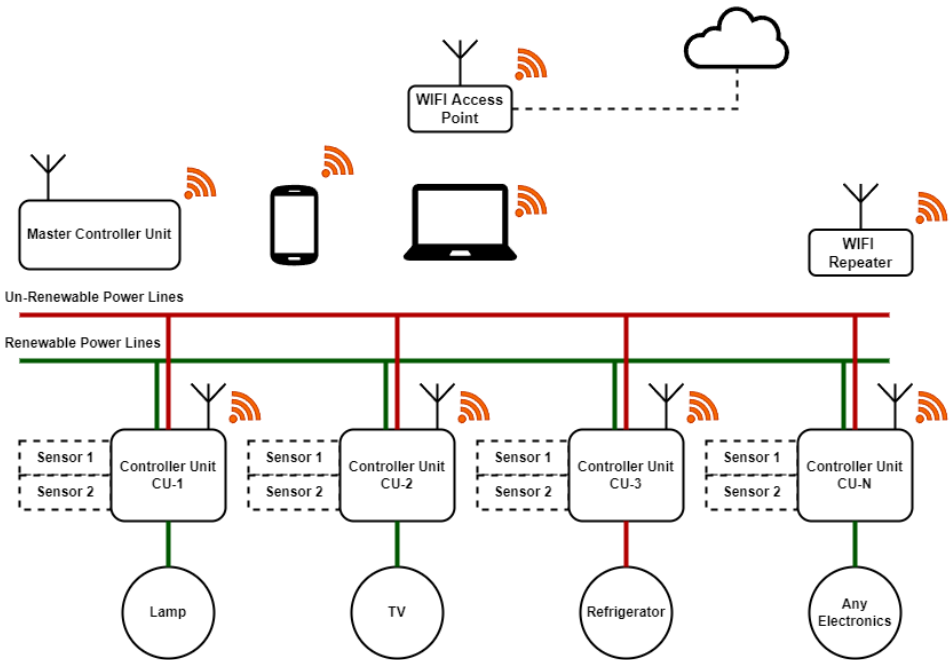


Fig. 6. Proposed smart home architecture

The MCU is a web server serving REST APIs, WebSockets for data exchange, and plain HTTP, which can provide web pages for user interactivity (dashboards). The MCU uses a Single Board Computer (SBC) in this smart home architecture like the RaspberryPi or LattePanda. However, any PC that can run Apache Web Server or Internet Information Server (IIS) should work without problems. SBC is recommended because it has a small form factor and is more energy efficient than PCs or laptops. The deployment diagram for MCU and CU can be seen in Figure 7.

This architecture fully utilizes wireless networking to simplify network topology and ease of installation. However, in the case of a large house with thick walls, a WIFI Repeater device is needed so that the WIFI signal remains strong and can be received by the CU device without signal problems.

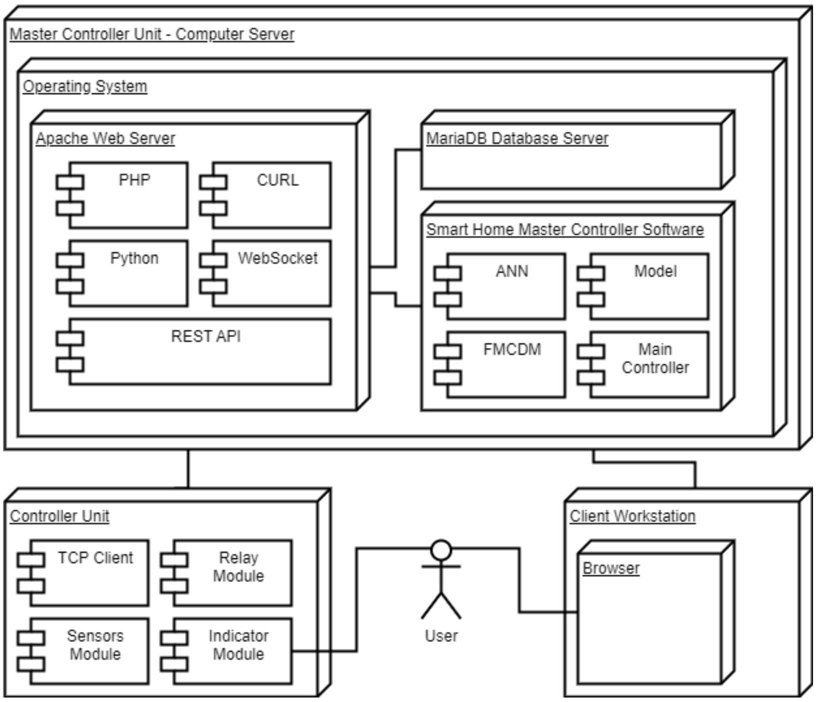


Fig. 7. Smart home deployment diagram

4.2 The Design of the Controller Unit

The Controller Unit (CU) consists of three main components: the ESP8266 microcontroller, an energy sensor using a Current Transformer, and two relays. The ESP8266 microcontroller is a core component of relay controllers and sends sensor data to the Master Controller Unit. The CU block diagram can be seen in Figure 8.

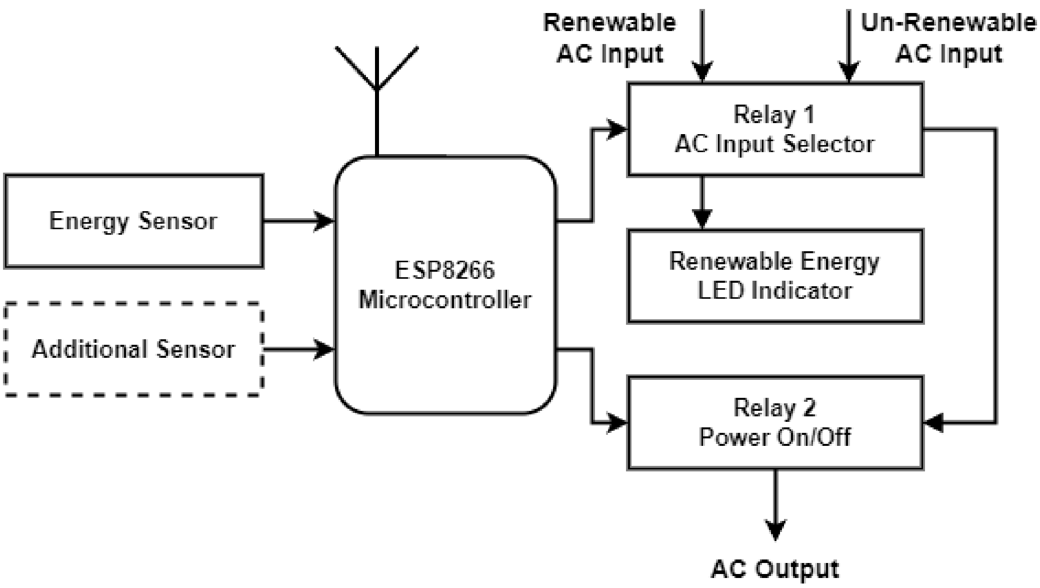


Fig. 8. CU functional block diagram

The CU circuit is simple and only uses an ESP8266 microcontroller, a current transformer as an energy sensor, a few resistors, capacitors, and a pair of transistors as relay drivers. Figure 9 shows the CU main schematic, and Figure 10 shows the CU relay block schematic. In the relay block, a pulldown resistor is connected to the base of the transistor to ensure a LOW condition when the circuit is turned on. The LED indicator will light up if the Relay1 input is HIGH, which indicates the selected energy source is a renewable energy source.

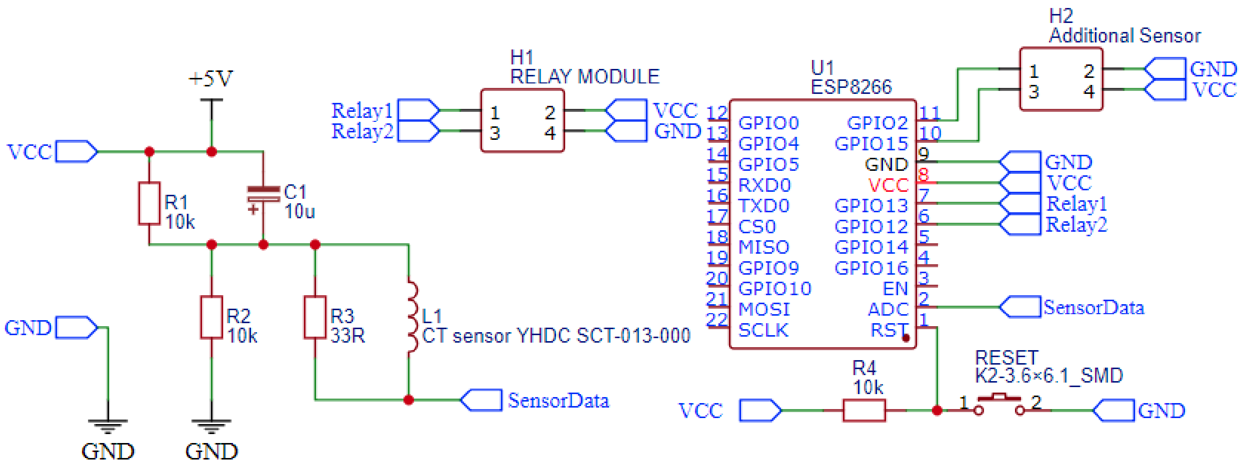


Fig. 9. CU main schematic

Relay1 functions as an energy source selector, while Relay2 functions to turn the output on and off. As shown in the circuit below, the relay input is connected via the H1 header to the microcontroller block. This is done to accommodate if the relay block needs to be replaced with a relay that can handle a larger current.

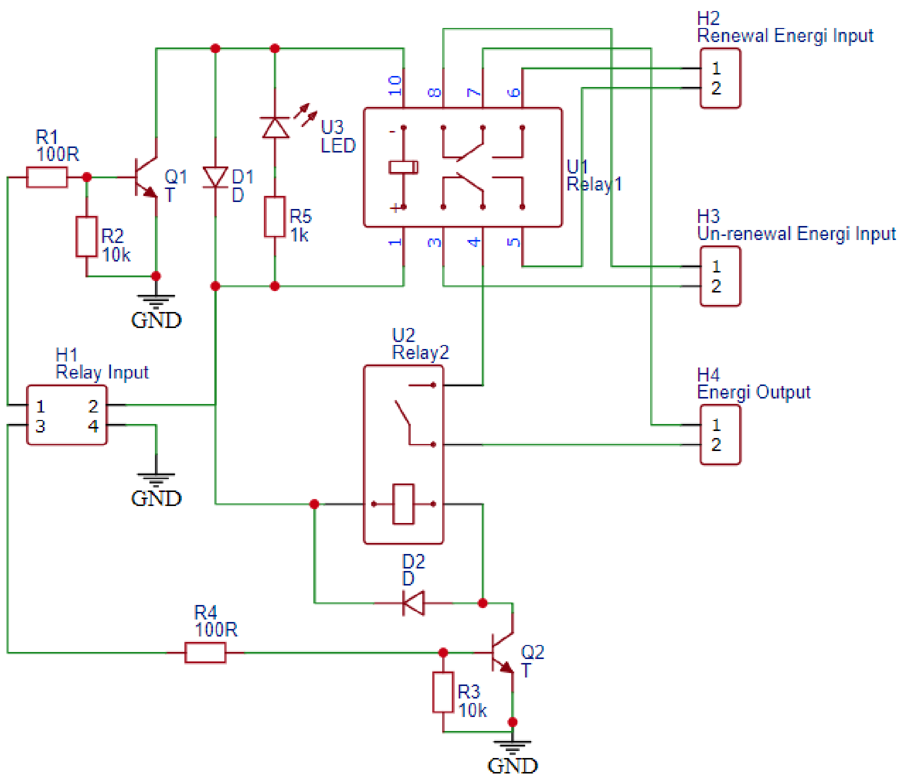


Fig. 10. CU relay block schematic

One thing that also needs to be designed is the cover box or an enclosure for the CU. Figure 11 is a cover box design for CU. The CU cover box needs to consider the safety factor because high-voltage terminals can electrocute people, or a short circuit occurs.

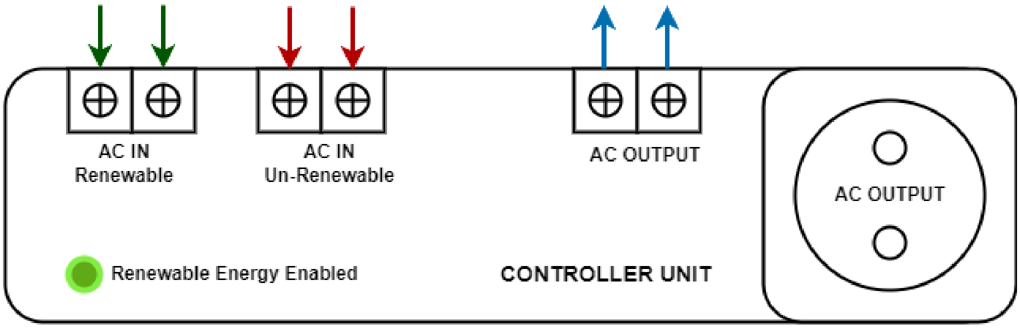


Fig. 11. CU enclosure panel design

4.3 The Design of Software Systems

The Master Controller Unit (MCU) is a central system that acts as smart home architecture's main processor and controller. The process of deciding on whether a device should use non-renewable or renewable energy sources is carried out at the MCU. MCU provides a web-based dashboard for smart home management that can be accessed using a browser. The MCU dashboard has five prominent use cases, including 1) Device Management, 2) Source Management, 3) Energy Monitoring, 4) Device Controlling, and 5) ANN Training. The MCU use case is represented in Figure 12.

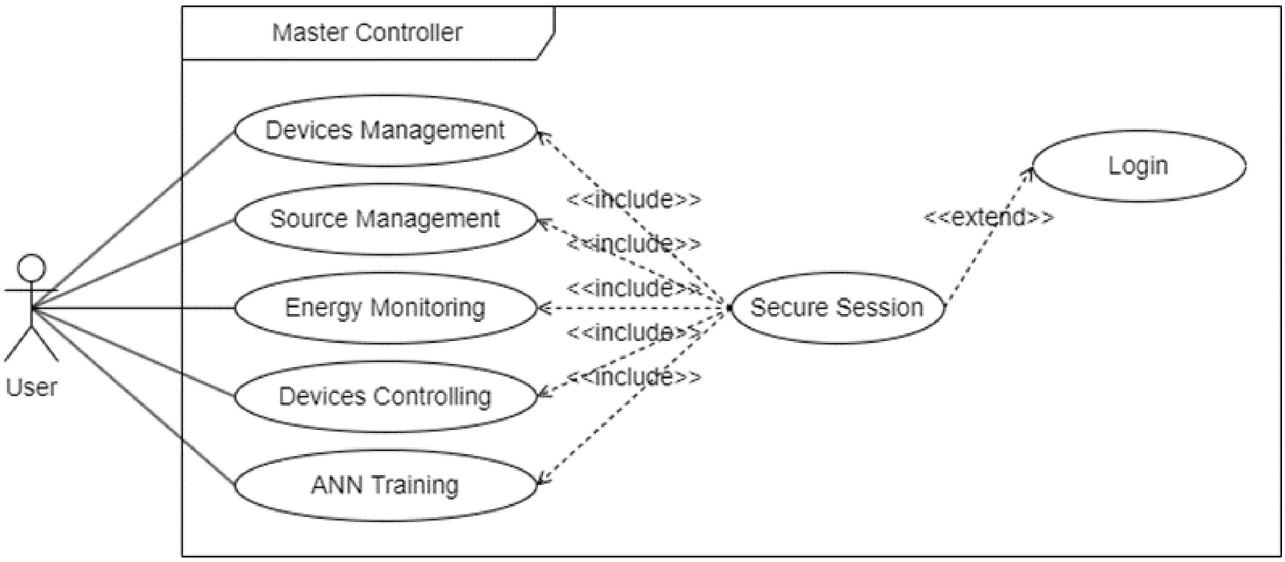


Fig. 12. Use case diagram

Device Management provides functions for device management in the smart home. Users can add device data, including device properties, such as device name, location, device power required, device initial power required, and so on. Each added device will automatically appear and can be controlled (on/off) via the dashboard by the user or automatically. Each added device must be associated with the CU used in that device to be controlled.

Source Management functions to add data on the energy sources available in the smart home along with their properties, such as maximum power and whether the energy source is renewable or not. Data on Source Management is one input criterion for the FMCDM and ANN blocks to make decisions. Therefore, the data entered in Source Management is essential to initial data that must be entered correctly to run properly.

Energy Monitoring is a display of the amount of energy used. This section also stores data records on previous use from time to time.

Device Controlling is a user interface for controlling electronic devices through the dashboard. Users can turn on and off electronic devices at home through a browser.

In the ANN Training section, users can add training data based on sensor data, time, and variables provided by the system, including; the prediction of the amount of renewable energy power remaining today, the total amount of power being used, and so on. ANN Training is also helpful if the user has additional sensors connected to the CU. For example, if a user wants to control a lamp based on a motion sensor or PIR sensor, then the user only needs to add data or certain sensor conditions and the desired light state (on/off).

Figure 13 is a web page template for the Master Controller dashboard. This template consists of a monitoring section in the form of graphics, the main menu, and a dynamic content section based on menu options.

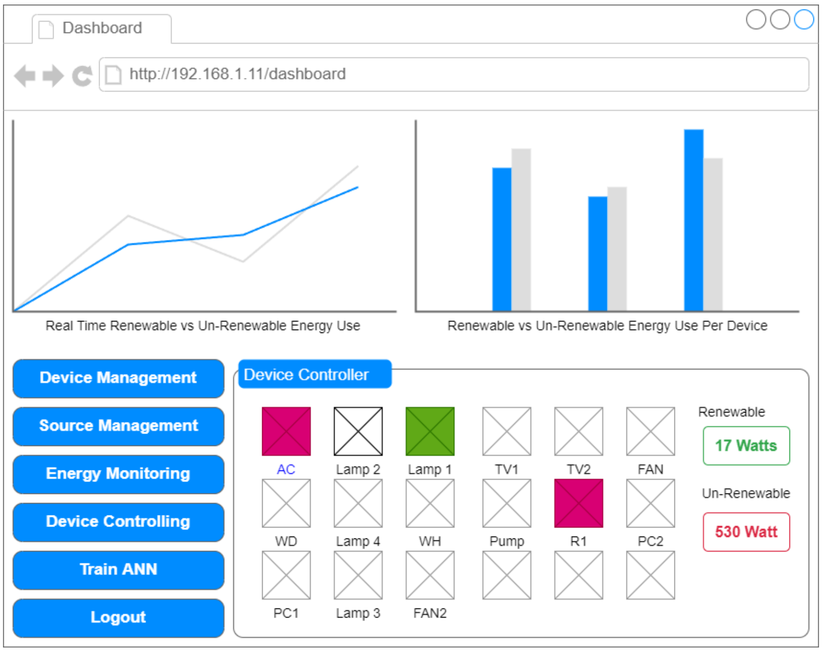


Fig. 13. Dashboard user interface template

4.4 Implementation and Testing

Implementing this smart home architecture for testing and experimental purposes requires several components. These components can be seen in Figure 14. The components used are general components and modules often used for IoT and microcontroller experiments.

As seen in Figure 14, components Used for Testing and Implementing Smart Home Architecture: (a) Raspberry Pi Zero W, (b) WeMos D1, (c) Relay Module, (d) 220VAC to 5VDC Switching Power Supply, (e) Large Current Sensor, (f) Small Current Sensor, (g) Voltage Sensor, (h) Passive Components, (i) Solar Panels, (j) Solar Charge Controller, (k) Lead Acid Battery, (l) DC to AC Inverter.

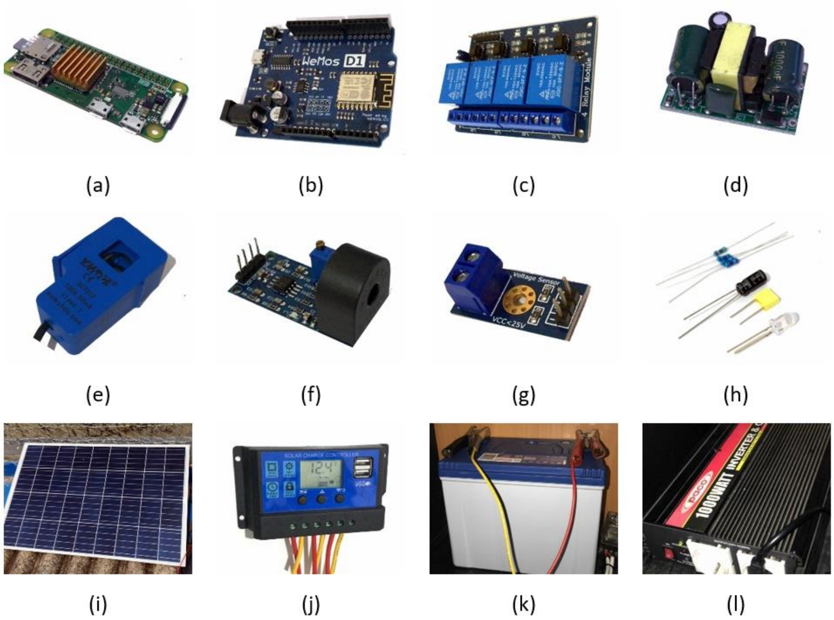


Fig. 14. Components of smart home architecture

Implementation and testing are the final stages of this research. Testing is done by implementing the proposed architecture. The test is carried out by measuring the voltage of the battery and solar panels every hour from 0 to 23 and recording renewable/non-renewable sources at four different loads. Figure 15 is the testing architecture, and Table 1 is the test results.

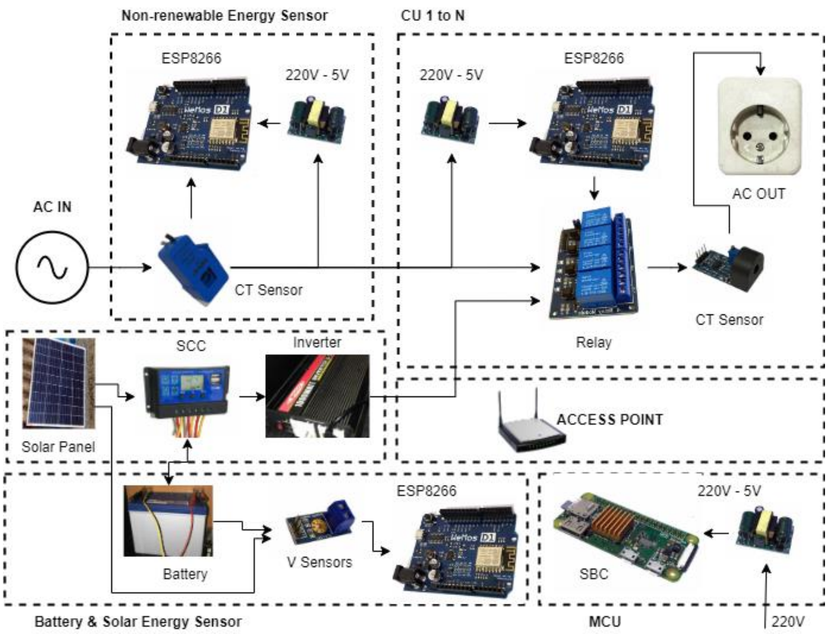


Fig. 15. Testing architecture

Table 1
Architecture test result

	Input			Output			
Hour	Grid	Solar	Battery	Load 1	Load 2	Load 3	Load 4
	2200 W	100 Wp	600 Wh	15 W	30 W	60 W	100 W
0	100%	0%	13.8 V	R	R	N	N
1	100%	0%	13.5 V	R	R	N	N
2	100%	0%	13.0 V	R	R	N	N
3	100%	0%	12.9 V	R	R	N	N
4	100%	0%	12.7 V	R	R	N	N
5	100%	0%	12.4 V	R	R	N	N
6	100%	15%	12.1 V	R	R	N	N
7	100%	22%	12.2 V	R	R	N	N
8	100%	47%	12.5 V	R	R	N	N
9	100%	47%	12.7 V	R	R	N	N
10	100%	54%	12.9 V	R	R	N	N
11	100%	82%	13.0 V	R	R	N	N
12	100%	95%	13.4 V	R	R	R	N
13	100%	98%	13.5 V	R	R	R	N
14	100%	90%	12.7 V	R	R	N	N
15	100%	81%	12.5 V	R	N	N	N
16	100%	61%	12.5 V	R	N	N	N
17	100%	36%	12.4 V	R	N	N	N
18	100%	3%	12.1 V	R	N	N	N
19	100%	0%	12.0 V	R	N	N	N
20	100%	0%	12.0 V	R	N	N	N
21	100%	0%	11.7 V	R	N	N	N
22	100%	0%	11.5 V	R	N	N	N
23	100%	0%	11.2 V	N	N	N	N

As shown in Table 1, cells shown in green (R) are renewable energy use, and cells shown in yellow (N) are non-renewable energy use. The system can only turn on three loads with renewable energy for a total power of 915Wh (plus additional saved power in a battery). However, in terms of selecting renewable/non-renewable energy automatically, the system shows an optimal decision. As seen in the last hours in Figure 16, renewable energy saved in the battery is fully used up, and all loads return to the grid's energy source position.

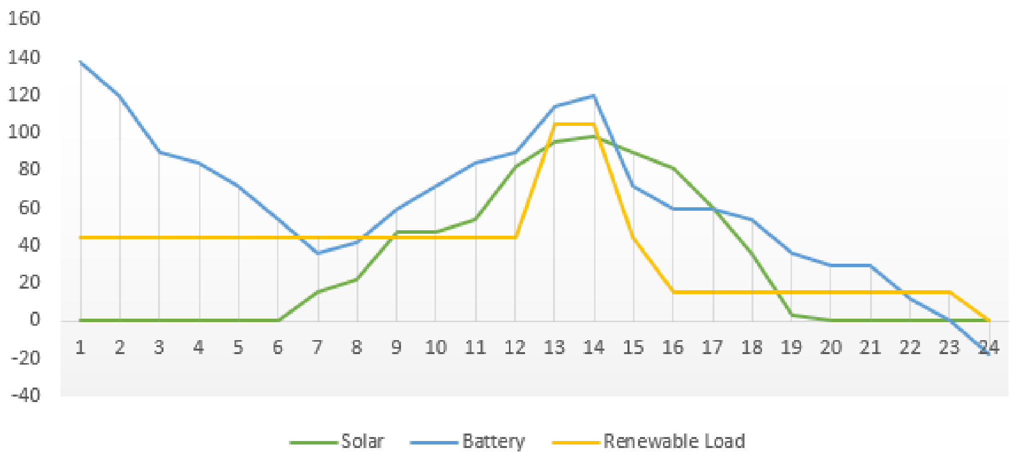
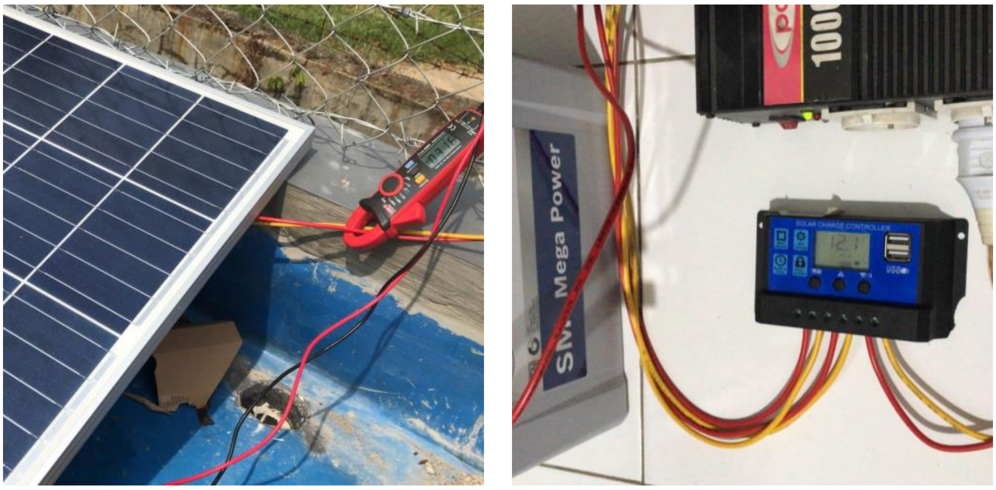


Fig. 16. Energy chart

Figure 16 shows a negative number on battery energy because the system is set to a minimum battery voltage of 11.5V. If the battery voltage is less than 11.5V, the battery must be recharged and cannot provide power. It can also be seen at 7 o'clock when the required power exceeds the battery's remaining power. However, the power from solar panels is available, and the system continues to turn on the load with renewable energy sources. When the power provided by the solar panels' increases, the battery begins to charge again, and the system considers between using power to run the load and charge the battery. This can be seen at 11 o'clock when the battery voltage has started to return to normal limits above 12V. The system turns on the additional load according to the total power generated. Vice versa, when the power from the solar panel decreases and the remaining power in the battery decreases, the system returns the load energy source to the grid following the prediction of available renewable power. The testing process is shown in the Figure 17.



(a) (b)

Fig. 17. Testing process: (a) On solar panel (b) On battery

During the testing process, it was found that the inverter used was consuming 15-25W of energy even without any load connected. Therefore, the selection of a suitable inverter needs to be considered in the application of this architecture. In addition, using a solar charge controller with the Maximum Power Point Tracking (MPPT) type is better than the Pulse Width Modulation (PWM) type because all the energy produced from the solar panel is converted with higher efficiency. Although the PWM technology in SCC is more straightforward and cheaper, this technology is inefficient because the difference in voltage generated from the solar panel and the battery charging voltage is not fully converted, so energy is wasted in the charging process. In contrast to PWM, the MPPT technology in SCC will convert the voltage difference into a larger current so that the energy produced by the solar panel is fully used to charge the battery or turn on the load. Unfortunately, the price of SCC with MPPT technology is much higher than SCC with PWM technology.

5. Conclusions

This research results in a smart home architecture consisting of smart hardware and software architecture for energy conservation efforts, increasing awareness of energy use and managing various energy sources. The proposed architecture is a smart home architecture that prioritizes the optimal and efficient use of renewable energy. Some advantages of implementing this smart home architecture include 1) being easy to implement, 2) fault tolerance, 3) being easy to manage multiple energy sources, and 4) being affordable and can be applied to start from a small scale to be developed gradually.

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