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Research Paper

# Study on Solar Powered Electric Vehicle with Thermal Management Systems on the Electrical Device Performance

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## Abstract

This study aims to determine the reliability of applying a thermal management system in conjunction with Internet of Things in solar electric cars. In conventional electric cars or those whose driving energy source comes from gasoline fuel; the applied thermal management system is mainly used as a coolant for the internal combustion engine. However, for electric cars the thermal management system may be used for the main components such as controllers that convert solar module energy into electricity and batteries. Results from tests utilizing six DC fans for air cooling of the thermal management system yield two variations of battery charging conditions from the solar modules, namely variations of 25 and 400 turns of the trimmer constant current step-up charger. Test results from the proposed thermal management system show that the highest step-up charger temperature is 35.75 °C with voltage of 57.64 V for the variation of 25 laps. The test results on the battery voltage and temperature show that the highest battery temperature reaches 31.75 °C with voltage of 57.3 V at the variation of 25 rounds.

**Keywords:** Electric vehicle; Thermal management system; Voltage; Current; Efficiency

## 1. Introduction

In recent years, the transportation system has been growing rapidly. This is evidenced by the rise of transportation means in the form of electric vehicles, with electric cars having the most noticeable increasing presence. An electric car uses battery as a driving energy source and an energy storage [1]–[3]. Along with their increase in popularity, the development of electric cars continues to be actively ongoing. Various components and aspects of electric cars have attracted researchers around the world in an attempt to advance electric car technologies [4], [5]. For example, some researchers have been focusing on the effect of aerodynamics applied to electric cars while some others are looking for ways to make electric cars more autonomous.

According to the report published by the International Energy Agency (IEA) in 2023 on the

Global Electric Vehicle Outlook, the electric car market is experiencing exponential growth as sales exceed 10 million units in 2022. This represents 14% of the total new cars sold in 2022 compared to around 9% in 2021 and less than 5% in 2020 [6]–[9]. Three international markets dominate the sales globally with China leading the markets at around 60% of the global electric car sales. Consequently, more than half of electric cars on roads worldwide are in China and the country has already exceeded its electric vehicle sales target for 2025. In Europe as the second largest market, sales of electric cars increased by more than 15% in 2022. This translates to more than one out of every five cars sold in Europe is an electric car [10]. ales of electric cars in the United States, which is the third largest market, increased by 55% in 2022 and reached sales share of 8%. Data from the same IEA report further states that electric car research in 2023 is central to the development of the transportation sector [11], [12].

Research and development of electric cars does not only focus on aerodynamic aspects, but also concerns policy [13], competition with conventional vehicles [14]–[16], consumer acceptance [17], production [18], energy management [19]–[21], and the weaknesses of electric cars [22]. For example, an electric car requires a special place for charging its battery where the car must be stopped for a certain amount of time [23]–[25]. Such a condition forces the user to allocate time to wait until the car battery is sufficiently charged and ready to use again. However, this issue may be ameliorated by utilizing an on-board energy generator that operates simultaneously with the car. An example of this is a solar power plant embedded in the exposed body of the car [26]–[28]. With electric cars considered to be a solution to reduce gas emissions [29], the addition of the solar power plant on electric cars further supports the movement for a healthier environment and helps promote investments in the renewable energy sector [30], [31]. To utilize solar energy to charge a battery, solar modules or solar panels typically use some type of a charge controller circuitry [32]–[34]. In terms of solar cell technology, the monocrystalline type currently offers the highest efficiency between 15% and 20%. Careful consideration in choosing a particular type of monocrystalline cell is therefore crucial in electric car applications due to the limited space available to place the solar panels on the car body. To further optimize the use of solar energy to charge the battery, the charge controller may be used in conjunction with the Internet of Things to facilitate a Battery Management System (BMS) to enhance the operation and performance of the battery [35]–[37]. While the BMS is an effective tool in coordinating energy flow among its major components (solar module, battery, and loads), its performance is greatly affected by the operating temperature of the components. Therefore, one means for further improving the effectiveness of the BMS and its components is to employ a Thermal Management System (TMS).

The TMS in combination with BMS can be inherently applicable to an electric car. This is due to the fact that the TMS is especially important in an electric car to help maintain car components' internal temperature to meet the recommended working temperature [38]–[41]. If in a conventional gasoline-powered car the TMS is needed to cool the internal combustion engine, then in an electric car the TMS can support the cooling of the battery as well as the charge controller [42]–[44]. n this paper, the implementation of the TMS is carried out on a solar-powered electric car that focuses on thermal management of a universal step-up charge controller and five units of 12V 20Ah Lead Acid batteries which are series connected to produce a 60V 20Ah battery pack. The universal step-up charger has a recommended working temperature of -40 °C to +85 °C, while the Lead Acid batteries have a recommended working temperature from +20 °C to +30 °C.

## 2. Methods

Solar-powered electric cars are typically equipped with fans that function as part of the TMS component. For the project described in this paper, there are six fans used. Four fans are placed in the battery compartment area with fan codes 1,2,3,4 and two others are placed in the electrical box (near the universal step-up charger) with fan codes 5 and 6. Testing of the applied TMS is conducted by operating the car's electric charging using solar power through a universal step-up charger with two variations of the constant current trimmer rotation, namely the 25 and 400 clockwise rotations. The fan rotational speed is regulated using a Pulse Width Modulation (PWM) signal obtained from the interpolation of temperature readings via the MAX6675 temperature sensor. The PWM signal is provided by the ESP32 microcontroller to drive the IRFZ44N MOSFET and then to the 12 VDC fan. At the same time, the temperature reading data and PWM values are displayed on the Android application via the Internet of Things network and stored on the Internet of Things server (Firebase) for further analysis.

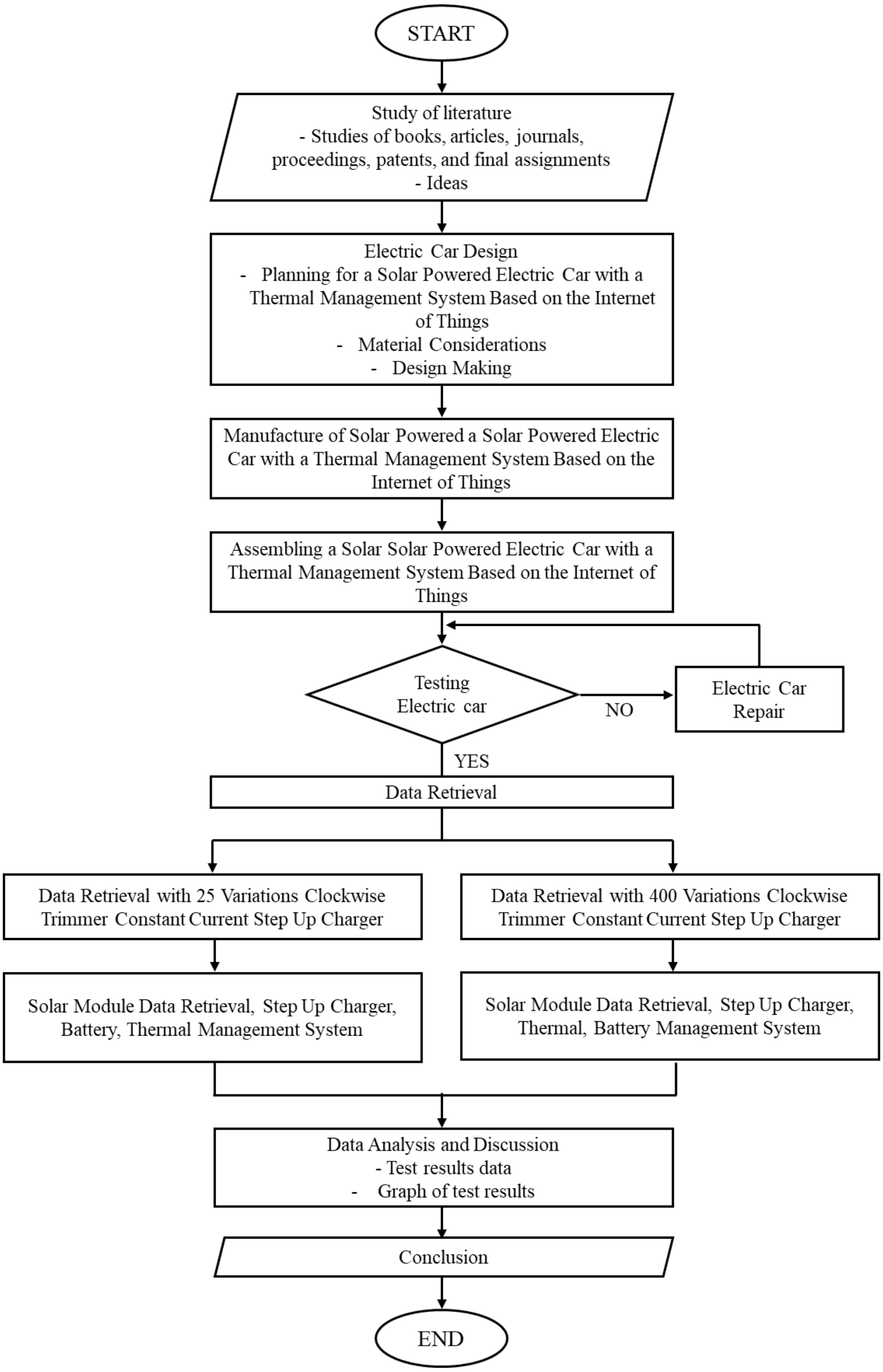


**Figure 1.** Algorithm of the development of thermal management system for solar powered electric cars

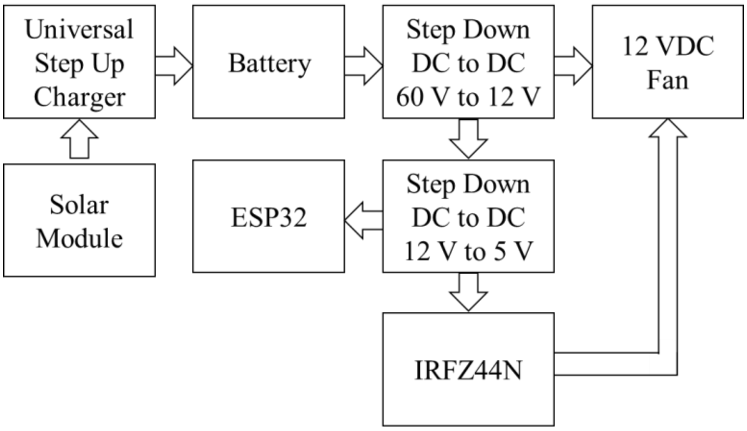


**Figure 2.** Wiring diagram of the solar-powered charging system

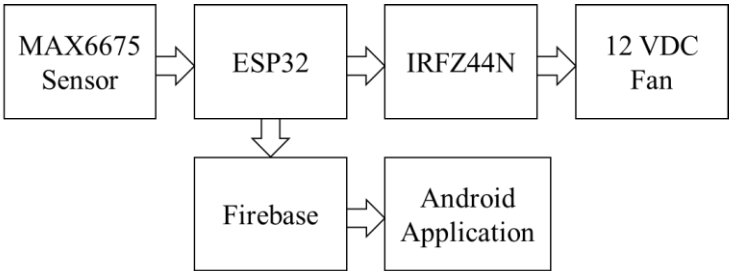


**Figure 3.** Block diagram of the Internet of Things system

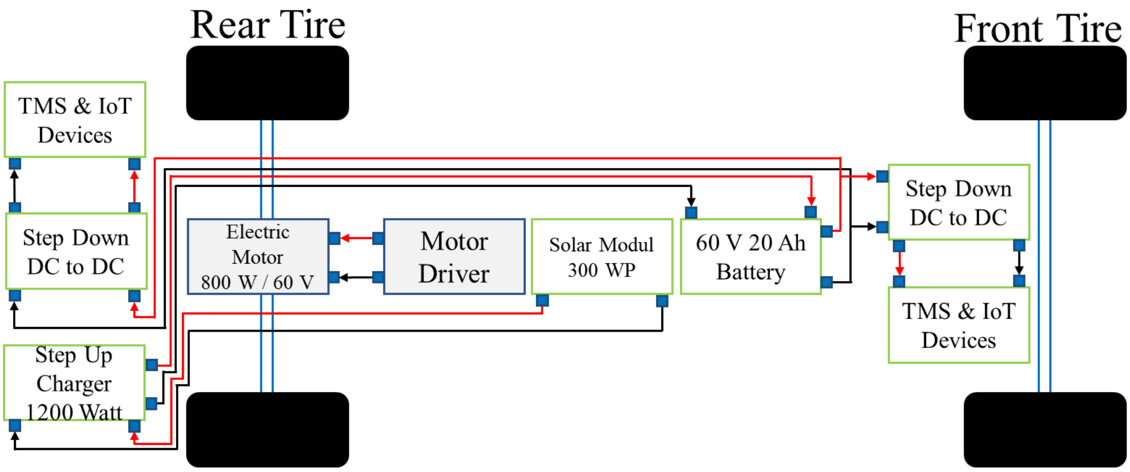


**Figure 4.** Functional diagram of the solar-powered electric car

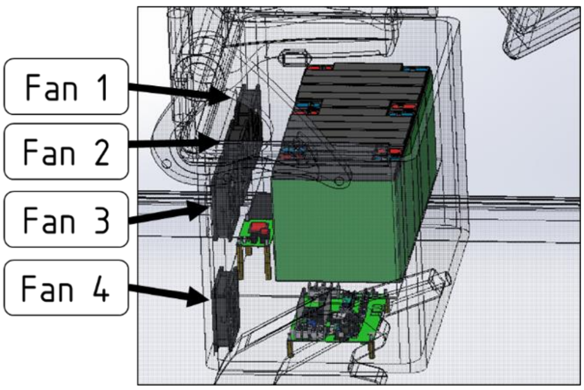


**Figure 5.** The battery compartment area of the solar-powered electric car

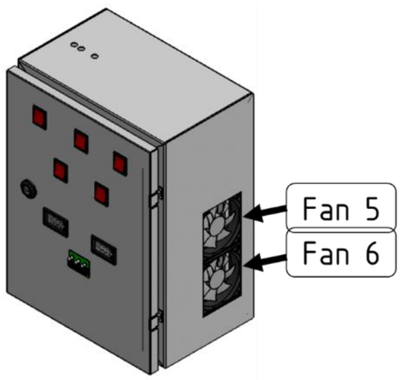


**Figure 6.** The electrical box of the solar-powered electric car

To calculate the required pulse width modulation (PWM) signal value, the following formula is being used:

$$PWM_{now} = \frac{(T_{now} - T_{min})}{(T_{max} - T_{min})} \times (PWM_{max} - PWM_{min}) \quad (1)$$

where PWM is the Pulse Width Modulation value resulted from interpolation of the temperature reading, T is the current temperature value read by the MAX6675 sensor (°C), $T_{min}$ is the minimum temperature value set for conversion to a Pulse Width Modulation signal (+20 °C), $T_{max}$ is the maximum temperature value set for conversion to a Pulse Width Modulation signal (+30 °C), $PWM_{max}$ is the maximum signal value of the ESP32 microcontroller for 12-bit resolution is 4095, and $PWM_{min}$ is the minimum signal value of ESP32 microcontroller for 12-bit resolution is 0.

The input voltage ($V_{fan}$) for the fan can be calculated using the following equation:

$$V_{fan} = \frac{(PWM_{now} - PWM_{min})}{(PWM_{max} - PWM_{min})} \times (V_{inputmax} - V_{inputmin}) \quad (2)$$

where $V_{fan}$ is the input voltage of fan (V), $V_{input\ max}$ is the maximum input voltage (12 VDC), and $V_{input\ min}$ is the minimum input voltage (0 VDC).

Calculation of the speed of the fan (vfan):

$$n_{fan} = \frac{(V_{input} - V_{oprmin})}{(V_{oprmax} - V_{oprmin})} \times (n_{max} - n_{min}) \quad (3)$$

where $n_{fan}$ is the speed of the fan (m/s), $V_{input}$ is the input voltage of the fan or $V_{fan}$ (V), $V_{oprmin}$ is the minimum operating voltage for the fan to rotate (6 VDC), $V_{oprmax}$ is the maximum operating voltage for the fan to rotate (12 VDC), $n_{max}$ is the maximum speed of the fan (2.0 m/s), and $n_{min}$ is the minimum speed of the fan (0.0 m/s).

## 3. Results and Discussion

Tests carried out on the TMS of the constructed solar-powered car produced the following data which were read and gathered through the internet of things network.

Variation 1: Variation of Trimmer Constant Current Step-up Charger 25 Clockwise Rotations. The results that show the performance of variation 1 are illustrated in **Figure 7**.

Changes in voltage and temperature of the step-up charger over time is shown in **Figure 7**. The results show that as the step-up charger output voltage increases, the temperature increases. Similarly, when the step-up charger output voltage begins to decrease, the temperature also decreases. The highest temperature observed is 35.75 °C corresponding to output voltage of 57.64 V at time 11:55:02, while the lowest temperature is 22.25 °C with output voltage of 51.3 V at time 07:44:02.

Fans 5 and 6 were tested as the thermal management of the step-up charger and related components as depicted in **Figure 8**. The results indicate that for every increase or decrease in the step-up charger temperature, the fans always rotate at a maximum speed of 2.0 m/s. This occurs because the two fans receive 12 VDC supply continuously. The results further demonstrate that the fans act as thermal management because they are able to maintain the temperature of the step-up charger up to the highest temperature of 35.75°C with fan speed of 5.6 of 2 m/s at time 11:55:02. The lowest temperature is measured at 22.25 °C with fan speed of 5.6 at 2 m/s at time 07:44:02. Therefore, the highest and lowest values are successfully maintained within the operating temperature range of the step-up charger, which is -40 °C to +85 °C.

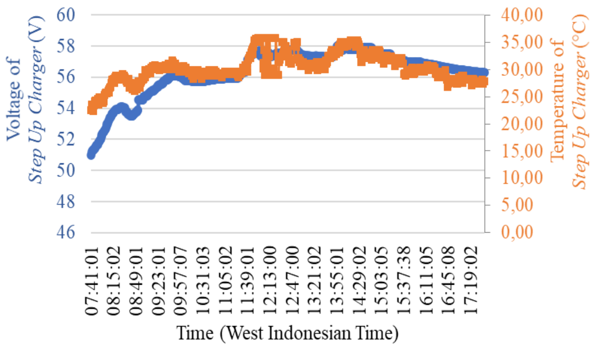


**Figure 7.** Characteristics of Step-up charger voltage and temperature toward time

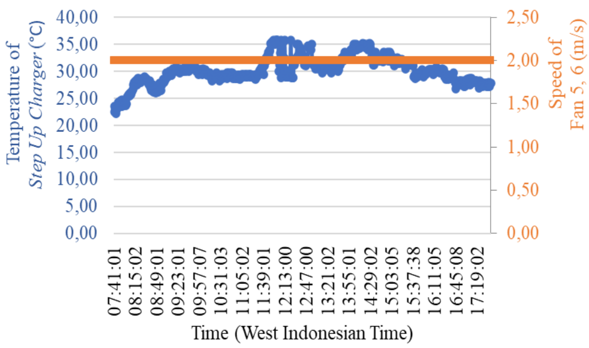


**Figure 8.** Step-up charger temperature and fan speed toward the time

The sensor for measuring temperature is placed only in one of the batteries. This is because when measurements are made with a digital thermometer, the temperature of each battery is measured the same; thus, there is no need to install one sensor for each battery. **Figure 9** shows the battery voltage and temperature with respect to time. The data show that the battery voltage and temperature tend to rise, then gradually decrease. The highest temperature value is 31.75 °C with output voltage of 57.43 V at time 12:41:03. The lowest temperature value is 19.50 °C with a voltage of 50.92 V at 07.42.03.

As previously stated, the sensor for measuring temperature is placed only in one of the batteries. Fans 1, 2, 3, and 4 were tested next as the thermal management of the battery and components to maintain the battery temperature within the recommended operating temperature range of +20 °C to +30 °C. **Figure 10** shows that every increase or decrease in the battery temperature, the fan always rotates at a speed in accordance with the battery temperature. This further demonstrates the presence of fans acting successfully as thermal management device because they are able to maintain the battery temperature to a maximum of 31.75 °C with a fan speed of 1,2,3,4 of 2 m/s at time 12:41:03. The lowest temperature is measured to be 19.50 °C with a fan speed of 1,2,3,4 of 0 m/s at time 7:42:03. From **Figure 10**, it can be concluded that the use of a fan as a thermal management device is quite effective in maintaining the battery temperature to be within the recommended working temperature range, namely between +20 °C and +30 °C. However, there is an increase in the battery voltage with the rotational speed adjustment based on the battery temperature read by the sensor and processed by the ESP32 microcontroller to convert the temperature value into a signal value for the rotational speed setting of the fan.

The following explains the measurement results from Variation 2 which has the trimmer constant current step-up charger 400 clockwise rotation.

**Figure 11** shows the changes on the voltage and temperature of the step-up charger over time. Results from the figure indicate that as the step-up charger output voltage increases, the temperature increases. Likewise, when the step-up charger output voltage begins to decrease, the temperature also decreases. The highest temperature is measured to be 35.50 °C with voltage of 58.48 V at time 10:52:02. The lowest temperature is 22.25 °C with voltage of 55.83 V at time 07:42:04. The measured lowest and highest temperature values are maintained between the recommended operating temperatures of the step-up charger of -40 °C to +85 °C. This in turn means that that the step-up charger operates in a safe operating temperature.

**Figure 12** shows the change in the step-up charger temperature and fan speed over time. The fans referred to here are fans 5 and 6 because they are being used as the thermal management devices of the step-up charger and its related

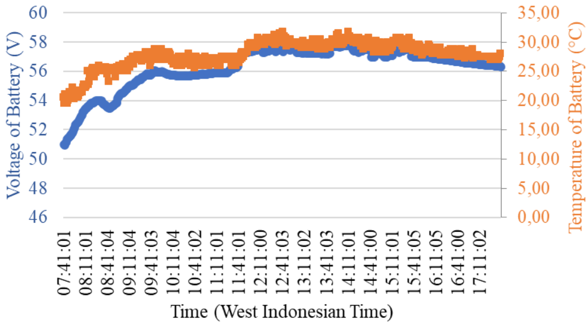


**Figure 9.** Battery voltage and temperature toward the time

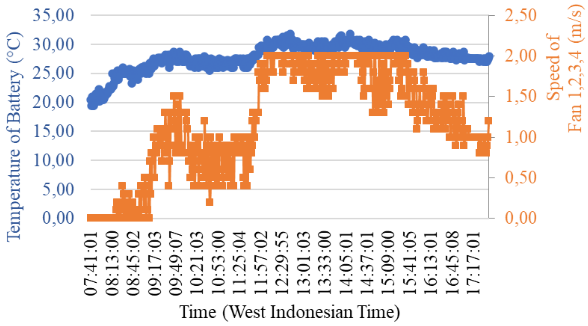


**Figure 10.** Battery temperature and fan speed toward the time

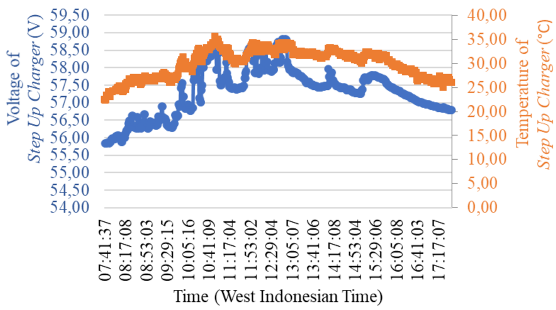


**Figure 11.** Step-up charger output voltage and temperature against time

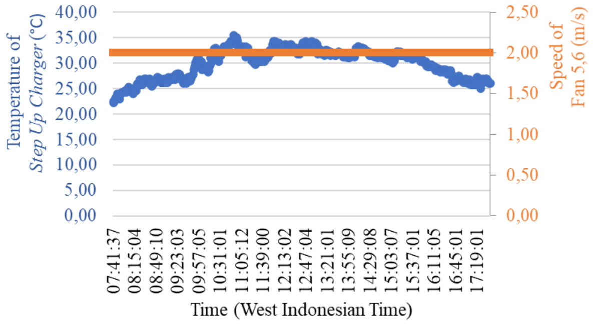


**Figure 12.** Step-up charger temperature and fan speed against time

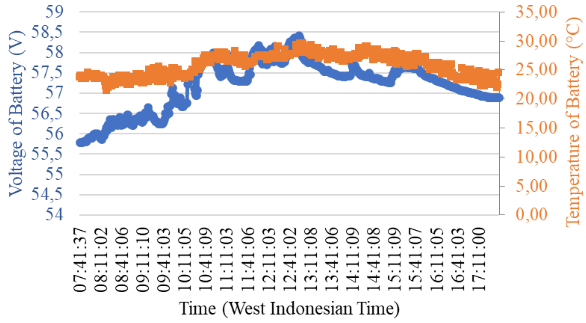


**Figure 13.** Battery voltage and temperature against time

components. According to the graph, for every increase or decrease in the step-up charger temperature, the fan always rotates at a maximum speed of 2.0 m/s. This is because the two fans continuously receive 12 VDC supply. The results further validate that the presence of a fan acts as a thermal management device because it is able to maintain the temperature of the step-up charger up to the highest temperature of 35.50 °C with a fan speed of 5.6 of 2 m/s at time 10:52:02. Meanwhile, the lowest temperature value was 22.25 °C with a fan speed of 5.6 of 2 m/s at time 07:42:04. The highest and lowest values are successfully kept within the recommended operating temperature of the step-up charger, which is between -40 °C and +85 °C.

**Figure 13** shows the change in battery voltage and temperature over time. The battery voltage and temperature tend to rise, then gradually decrease. The highest temperature value is 29.50 °C with voltage of 58.33 V at time 12:56:06 and the lowest is 21.50 °C with voltage of 56.15 V at time 08:19:08.

**Figure 14** shows the change in battery temperature and fan speed over time. Charts are created with reference to data per minute, not per hour. For the same reason as before, the sensor for measuring temperature is placed only in one of the batteries. Here, fans 1, 2, 3, and 4 serve as the thermal management devices for the battery and its components which enable rotational speed adjustment to maintain the battery operating temperature within the recommended operating temperature range of +20 °C to +30 °C. According to the graph, every increase or decrease in the battery temperature yields the fan always rotating at a speed according to the temperature value. The existence of a fan enables the battery temperature

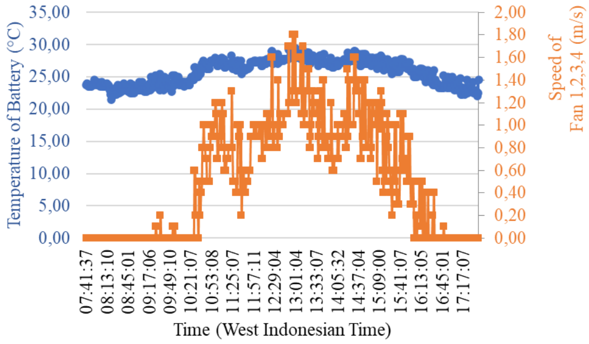


**Figure 14.** Battery temperature and fan speed against time

to be maintained with the highest temperature value of 29.50 °C with a fan speed of 1,2,3,4 of 1.80 m/s at time 12:56:06 and the lowest of 21.50 °C with a speed of fan 1,2,3,4 at 0 m/s at time 08:19:08. Once again, the highest and lowest values are successfully maintained within the recommended operating temperature of the battery, which is between +20 °C and +30 °C.

## 4. Conclusion

Based on the tests and analysis that have been carried out, a solar-powered electric car equipped with a Thermal Management System is capable of maintaining the temperature of main components such as the universal step-up chargers and batteries at the recommended working temperature, although at certain times the battery voltage may be slightly higher or less than standard operating range. Overall, the proposed Thermal Management System with air conditioning mechanism utilizing six fans is quite effective in carrying out its functions properly. Additionally, the added Internet of Things system also functions properly as evidenced from the obtained test data.

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## Author's Declaration

### Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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### Availability of data and materials

All data are available from the authors.

### Competing interests

The authorsdeclare no competing interest.

### Additional information

No additional information from the authors.

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