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Research article

Modification of Polycrystalline PV String for Charging on Electric Scooter

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Abstract: Electric scooters rely on batteries to power BLDC motors, which are traditionally recharged through the household electricity grid. However, alternatives like solar energy are being explored to reduce dependency on conventional power sources. A challenge arises due to the discrepancy in voltage compatibility between standard solar panels and scooter batteries. Typically, a 36 V scooter battery requires a higher voltage input than the 18 V output of a single solar panel. This requires modifications to align solar cell design with battery voltage requirements. This study implements a PZEM-015 sensor for monitoring battery energy consumption. The contribution of this study is twofold: to develop and optimise solar cell modification for effective battery charging and to assess battery consumption concerning speed and travel duration. Testing reveals that a series circuit modification yields an average voltage of 39.2 V and an average current of 0.55 A, resulting in 21.8 Wp of power output. Analysis of scooter performance indicates that maintaining speeds between 4.16 m/s and 5.55 m/s significantly extends travel time and conserves battery energy. These findings highlight the potential of modified solar PV in enhancing electric scooter efficiency and sustainability.

Keywords: solar cell, charging, polycrystalline, electric scooter

1. Introduction

In Indonesia, the main electricity utility company, Perusahaan Listrik Negara (PLN), predominantly relies on fossil fuels as its primary energy source. However, the continued heavy reliance on fossil energy poses an imminent threat to energy security in the near future. Urgent action is needed, and energy conservation stands out as a critical measure. Embracing renewable energy presents a viable pathway towards energy conservation [1], [2].

Renewable energy, derived from naturally replenishing resources, offers promising solutions for sustainable energy practices. Among these, solar energy shines as a leading contender due to its consistent availability year-round and its environmentally friendly nature [3], [4]. Meanwhile, rapid technological advancements continuously strive to optimise energy usage and address the growing scarcity of fossil fuels [5].

In the transport sector, which heavily relies on energy resources, fossil fuels remain the predominant choice [6]. However, the development of electric vehicles, including scooters or electric scooters, has gained traction as a means to reduce dependence on fossil fuels [7]. Electric scooters, powered by batteries that drive BLDC motors, typically rely on PLN for recharging, prompting exploration into alternative energy sources to decrease reliance on household electricity [8]. Photovoltaic (PV) cells offer a promising solution, using semiconductor-based materials to convert solar energy into electrical energy. By harnessing this technology, solar energy can be utilised to recharge scooter batteries [9], [10].

Nevertheless, aligning the voltage output of standard solar panels with the specific requirements of scooter batteries presents a significant challenge. Typically, a 36V scooter battery demands a higher voltage input than the 18V output of a single solar panel, hindering optimal charging [8]. To address this issue, innovative modifications are required. This study proposes designing and adapting solar cells to match the voltage requirements of scooter batteries.

In addressing these challenges, this study aims to design and modify solar cells for electric scooters. The goal is to develop solar panel modifications optimised to meet the voltage needs of scooter batteries. Additionally, the study utilises a PZEM-015 sensor as a monitoring tool to assess battery energy consumption accurately. Through these efforts, this study paves the way for improved efficiency and sustainability in electric scooter technology.

Based on the provided context, this study aims to achieve the following objectives: first, to explore the design and modification processes required to transform solar cells into efficient solar panels; second, to determine the charging duration of batteries utilising the developed solar panels; and third, to assess the energy consumption patterns of electric scooter batteries concerning both speed and travel duration.

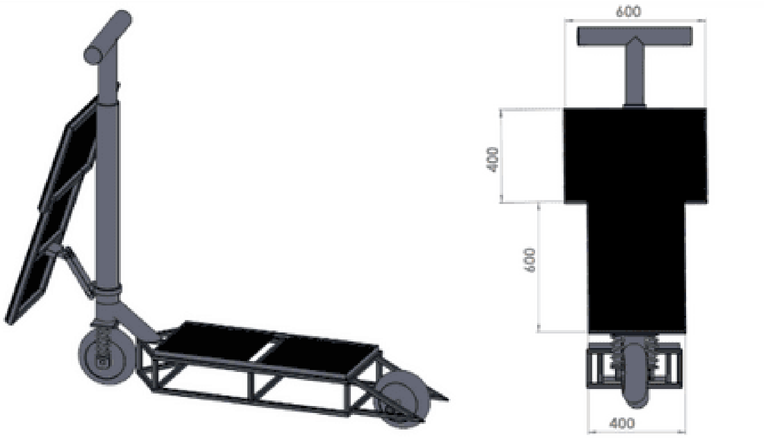
2. Methods

This study employs a combination of literature review and experimentation. The literature review involves gathering relevant references and theoretical foundations pertaining to the modification of solar cells for electric scooters and data collection methodologies for monitoring purposes. The experimental approach includes designing modifications to convert solar cells into solar panels and developing mechanical designs for electric scooters. Real-time monitoring tools are utilised throughout the study.

2.1. Electric Scooter Design

The electric scooter is designed using SolidWorks software, with the frame constructed from 2 mm thick 3 x 3 angle iron. As seen in Figure 1, the footrest is made of plywood, measuring 41 x 36 cm. Component placement utilises transparent acrylic material, with a 33 x 39.5 cm size for housing the battery components, BLDC controller, and shunt resistor, and 19 x 17.8 cm for accommodating the solar charge controller (SCC) and PZEM-015. Meanwhile, the solar panel electrical lines and monitoring tools were designed using CorelDRAW software. The electrical lines for the solar panel are drawn to represent the wiring layout, while labels for each component and a layout for the monitoring tools are designed to ensure precise placement on the acrylic material. The designs are exported in DXF format for manufacturing, maintaining attention to detail and adherence to specifications throughout the design process.

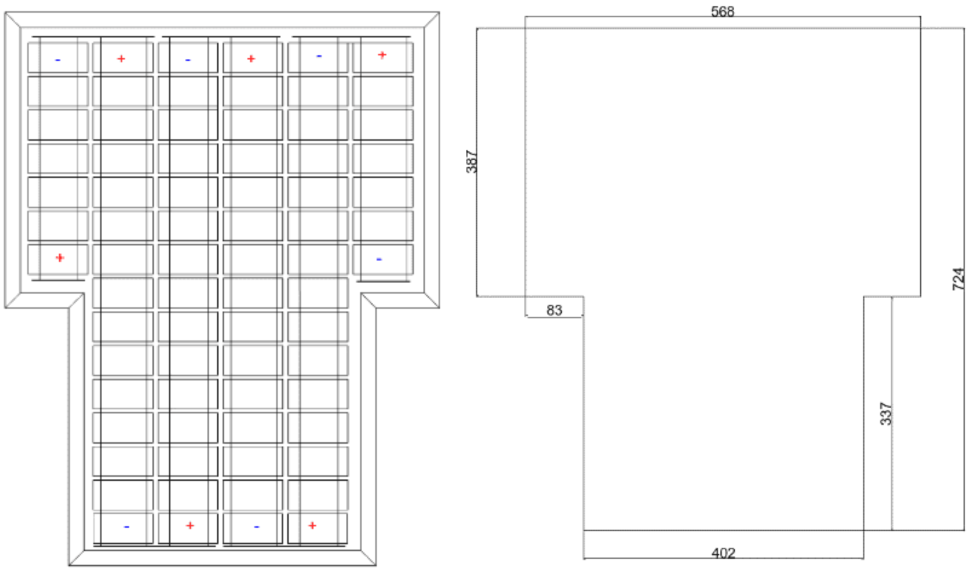
Figure 1. Electric scooter design.



2.2. Modified Solar Panel Design

The solar panel design is seen in Figure 2. The design was crafted using AutoCAD software. Milky white acrylic, measuring 60x75 cm and 5 mm thick, is selected for housing the solar cells. These cells will later be affixed to the acrylic using sealant. Each acrylic sheet is precisely cut to match the design specifications. The solar panel frame is constructed using letter U aluminium, featuring a width of 2 cm on each side. Essential tools and materials employed in the solar panel assembly include polycrystalline PV, solar tab wire, bus wire, a flux pen, a 60 W soldering iron, solder wire, clear acrylic as glass, and milky white acrylic as a holder for the solar cells.

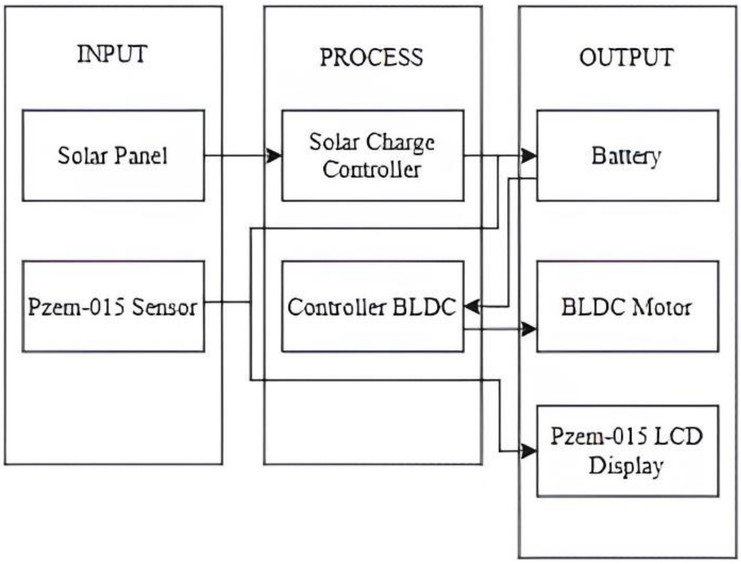
Figure 2. Modified solar panel design.



2.3. Block Diagram

The system block diagram, as shown in Figure 3, illustrates the functionality of the solar panel, which operates when exposed to sunlight, generating direct current (DC) electricity. Subsequently, the Solar Charge Controller (SCC) regulates the current and voltage output from the solar panel to the battery, ensuring optimal charging while safeguarding against overcharging and over-discharging. The battery, in turn, supplies electrical power to the Brushless Direct Current (BLDC) controller, which manages the distribution of current and voltage from the battery to the BLDC motor. Concurrently, the PZEM sensor is employed to measure various DC electrical parameters, including voltage, current, active power, and active energy, associated with the battery and BLDC motor load. The BLDC motor converts electrical energy into mechanical energy, serving as the load monitored by the PZEM-015 sensor. Data captured by the DC Wattmeter PZEM-015 is then displayed on the LCD for monitoring purposes.

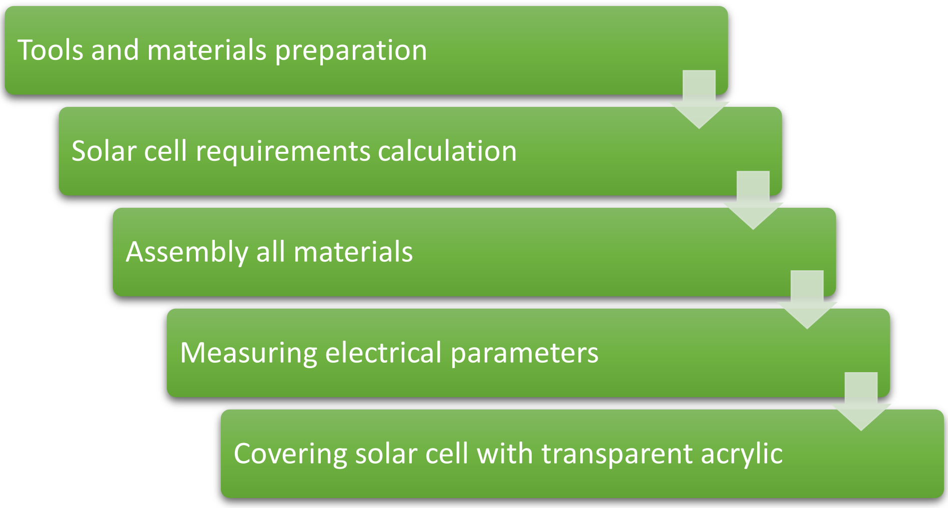
Figure 3. Block diagram.



2.4. Solar Panel Modification Flowchart

The modification begins with gathering tools and materials necessary for crafting solar panels. The initial steps involve assessing individual solar cells' current and voltage output. Once these metrics are determined, the solar cell assembly requirements are calculated. Subsequently, soldering the solar cells together using Tab Wire facilitates their connection. Using a multimeter, testing ensues to evaluate the current and voltage flow within the assembled solar cell strings arranged in a series circuit. Placing the interconnected solar cells onto milky white acrylic follows, adhering to the designated design layout. String connection involves linking one string's positive terminal to the subsequent string's negative terminal using Bus Wire, followed by soldering. Output connection to the bus wire cable ensues, bypassed by the solar panel cable with the addition of a diode at the input of the terminal block. Finalising the assembly, the solar panel is encased within a frame. Post-modification, the solar panel undergoes testing with a multimeter, and subsequent recording of current and voltage measurements is conducted. Figure 4 shows the flowchart of the solar panel modification process.

Figure 4. Solar panel modification flowchart.



2.5. Electrical System Circuit

The electrical system circuit design entails a solar power generation system constructed to serve as a primary source of electrical energy for battery charging purposes. Safety measures in this 50 Wp solar PV include using a fuse for protection. Additionally, a PWM-type Solar Charge Controller interfaces with a lithium-ion battery, providing the SCC with a 36VDC input voltage. A PZEM-015 Sensor Module is integrated to monitor battery energy consumption. The BLDC motor electrical system comprises a BLDC controller, responsible for regulating current and voltage distribution from the battery to the BLDC motor, along with a gas throttle for speed control and a dashboard LCD display to furnish the driver with essential information on speed, battery level, and driving mode. Figure 5 describes the electrical system circuit of the solar cell-based electric scooter.

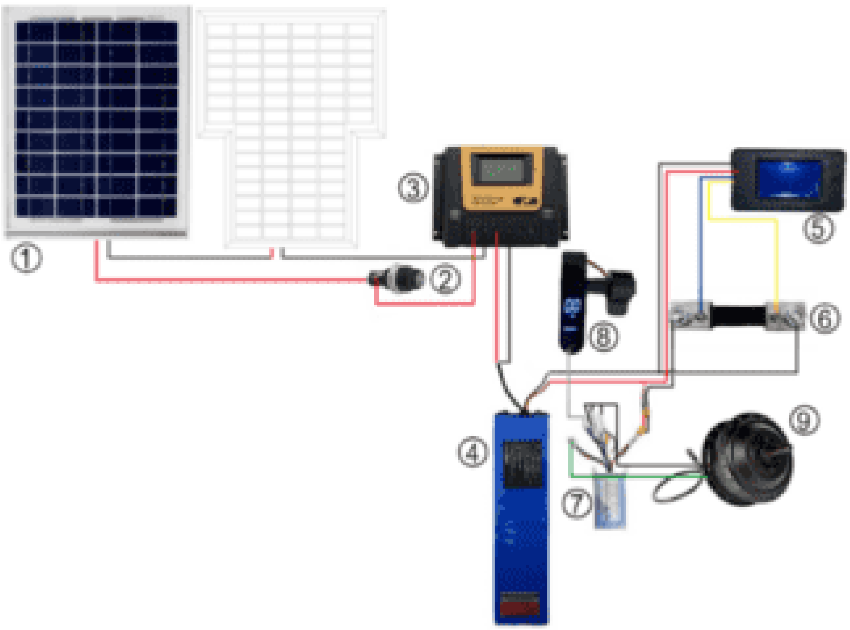


Figure 5. Electrical system circuit. Description: 1) solar panel; 2) fuse holder and fuse 3 A; 3) solar charge controller; 4) li-ion battery; 5) PZEM-015 sensor module; 6) shunt resistor; 7) BLDC controller; 8) gas throttle and LCD dashboard; 9) BLDC motor.

3. Results and Discussion

3.1. Solar Cell Calculation

The total power of solar cell is calculated using equation (1).

$$P = V \times I \tag{1}$$

where P is calculated power, V is voltage of solar cell and I is the current of the system. The number of cells used in modifying solar cells into solar panels is 74 cells. As a result, the total power of solar cells in this modified system is obtained at 25.9 Wp.

Figure 6 illustrates the arrangement of solar cells connected in series, with each cell contributing to a separate string. This configuration yields a voltage output of 37 V and a current of 0.7 A. The objective of this series circuit is to achieve the 42 V battery charging voltage requirement. However, a limitation of this setup is the relatively low current output, which consequently leads to extended battery charging times [11].

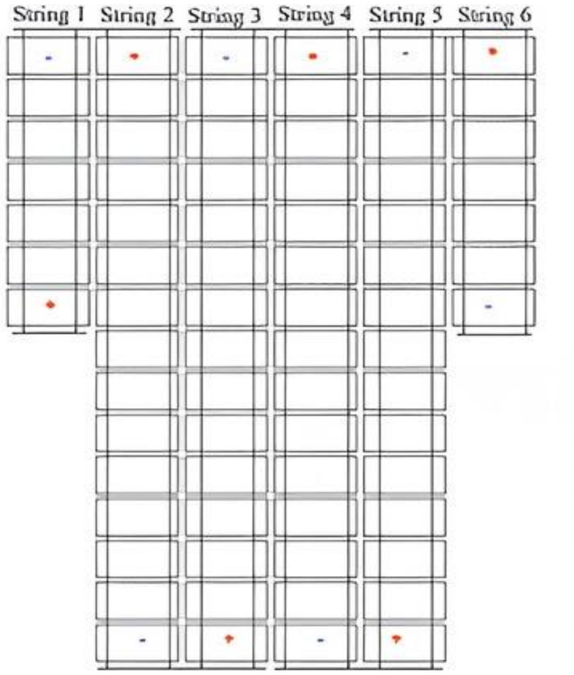


Figure 6. Solar cell arrangement in series.

3.2. Electric Scooter Modification

The electric scooter comprises three main components: the frame, the electric scooter drive system, and the charging system [11]. The frame of the electric scooter measures 845 mm in length, 350 mm in width, and stands 1000 mm tall, with a ground clearance of 70 mm. The electric scooter drive system integrates both electrical and mechanical elements, including a 36 V, 6 Ah lithium-ion battery; a 36 V 350 W BLDC motor wheel; a 36V 350W BLDC Controller; a gas throttle handle; and the requisite electrical system wiring. On the other hand, the charging system incorporates a 25.9 Wp solar panel installed on the stem of the electric scooter, along with an additional 20 Wp solar panel mounted on the rear deck. Figure 7 shows the result of the electric scooter modification.

Figure 7. Modified electric scooter.

3.3. Modified Solar Panel on Electric Scooter

The essential tools and materials required for the modification of solar panels include polycrystalline solar PV, solar tab wire, bus wire, flux pen, a 60 W soldering iron, solder wire, clear acrylic serving as glass, and white acrylic utilised as a holder for the solar cells. It is crucial to exercise caution during soldering, positioning the solar cells onto acrylic, and completing the solar panel assembly, as excessive pressure may lead to cell breakage. Furthermore, thorough attention should be paid to the positive and negative alignment of the solar cell tab wire when connecting each string to the bus wire. Once modified, the solar panel is affixed to the stem of the electric scooter. Angle iron and butterfly hinges are employed at the top to secure the panel during operation, while hollow iron supports are utilised for the window elbow hinge, facilitating the opening and closing of the solar panel. Figure 8 shows the modified solar panel on the electric scooter.

Figure 8. Modified solar panel on electric scooter.

Additionally, the monitoring tools include a Solar Charge Controller, which provides vital information regarding solar panel performance, battery charging current, voltage, and charging status [12]. The PZEM-015 sensor module complements these functionalities by reading battery energy consumption and displaying comprehensive data on the LCD, encompassing voltage, current, power, energy, capacity, and battery condition. Figure 9 shows the monitoring system.

Figure 9. Monitoring system.

3.4. Modified Solar Panel Testing

Testing was conducted to assess the power output of the modified solar panel. The results of this testing, detailing the performance of the solar cells after modification into solar panels, are presented in Table 1.

Table 1. Modified solar panel testing results.

Time	Weather condition	Voltage		Current	
		V_{OC}	V_{max}	I_{SC}	I_{max}
09.00	Sunny	38.8	35.66	0.58	0.55
09.30	Sunny	38.7	35.78	0.59	0.57
10.00	Sunny	38.8	36.34	0.59	0.56
10.30	Sunny	39.5	36.57	0.60	0.57
11.00	Sunny	39.0	36.63	0.62	0.53
11.30	Sunny	38.8	37.19	0.68	0.56
12.00	Sunny	40.3	37.65	0.69	0.54
12.30	Sunny	40.1	37.45	0.68	0.55
13.00	Cloudy	39.3	37.32	0.65	0.57
13.30	Sunny	38.8	36.91	0.63	0.56
14.00	Sunny	39.5	37.21	0.64	0.54
Average		**39.2**	**36.79**	**0.63**	**0.55**

Table 1 displays the test results of the solar cell modification into solar panels, showcasing data on the open circuit voltage (V_{OC}) averaging 39.2 V, voltage at the maximum power point (V_{max}) averaging 36.79 V, short circuit current (I_{SC}) averaging 0.63A, and current at the maximum power point (I_{max}) averaging 0.55 A under both sunny and cloudy weather conditions. Based on the measurements provided in the table, the average power generated by the solar panel modification is calculated by multiplying V_{max} and I_{max}, resulting in 20.23 Wp.

Following the acquisition of the measurement results for the solar cell modification into solar panels, the next step involves determining the efficiency of the solar panels. This requires knowing the total photon power (P_{in}) [13]. Table 2 shows the specifications of modified solar panels.

Table 2. Modified solar panel specifications.

V_{max} (V)	I_{max} (A)	I_{SC} (A)	V_{OC} (V)
36.79	0.55	0.63	39.2

Based on the measurement, the total area of solar panel is around 0.411 m^2. The average radiation of the solar panel is 1000 W/m^2 (global light intensity at maximum radiation), and the panel produces a maximum power of 21.8 Wp. The calculation of the fill factor (FF) is conducted using equation (2), while the efficiency of the solar panel is determined using equation (3).

$$FF = \frac{V_{max} \cdot I_{max}}{V_{OC} \cdot I_{SC}} \tag{2}$$

$$\eta = \frac{V \times I \times FF}{Ir \times A} \times 100\% \tag{3}$$

From both equations, we can calculate that FF is 0.81, and η is 3.9%.

3.5. Battery Testing

The battery charging data collection process begins with a voltage reading of 34.4V, representing a discharged battery, and continues until the battery reaches full capacity at 40.6 V. Measurements are taken at 30-minute intervals over a duration of 5 hours. The objective of this test is to determine the charging duration required to fully charge the battery using the modified solar panels in comparison to the factory solar panels [14].

Table 3 presents the outcomes of battery charging on the first day. The charging voltage was rising from 34.40 V to 39.42 V. Throughout the first day of testing, the average solar panel voltage stood at 37.60 V, accompanied by an average current of 0.51 A. In Table 4, the results of the second day of battery charging are also depicted, indicating an initial voltage of 39.51 V, escalating to a final charging voltage of 40.67 V. During the second day of testing, the average voltage of the solar panel registered at 40.43 V, with an average current of 0.37 A. It's noteworthy that the decline in current occurs as the battery voltage approaches its maximum threshold, serving as a safeguard against potential battery damage. Furthermore, variations in sunlight conditions or shadows may also contribute to the observed decrease in current.

Table 3. Modified solar panel results on first-day testing.

Time	First day weather condition	Solar panels		Battery voltage (V)
		Voltage (V)	Current (A)	
09.00	Sunny	34.4	0.48	34.34
09.30	Sunny	35.3	0.48	35.00
10.00	Sunny	35.72	0.50	35.52
10.30	Sunny	36.62	0.52	36.55
11.00	Sunny	37.75	0.53	37.49
11.30	Sunny	38.26	0.55	38.12
12.00	Sunny	38.59	0.60	38.46
12.30	Sunny	38.86	0.56	38.73
13.00	Cloudy	39.22	0.50	39.17
13.30	Cloudy	39.42	0.46	39.33
14.00	Sunny	39.53	0.44	39.42
Average		**37.60**	**0.51**	

Table 4. Modified solar panel results on second-day testing.

Time	Second day weather condition	Solar panels		Battery voltage (V)
		Voltage (V)	Current (A)	
09.00	Sunny	39.60	0.38	39.51
09.30	Sunny	39.78	0.43	39.67
10.00	Cloudy	40.12	0.37	39.93
10.30	Sunny	40.19	0.37	40.03
11.00	Sunny	40.26	0.41	40.14
11.30	Sunny	40.35	0.42	40.23
12.00	Sunny	40.51	0.40	40.34
12.30	Cloudy	40.64	0.41	40.43
13.00	Cloudy	40.69	0.34	40.51
13.30	Sunny	40.72	0.32	40.62
14.00	Cloudy	40.79	0.28	40.67
Average		**40.33**	**0.37**	

3.6. Energy Consumption of Electric Scooter

This study collected data from road tests of the solar panel-based electric scooter on flat terrain, which encompasses speed, time, and battery energy consumption, as seen in Figure 10.

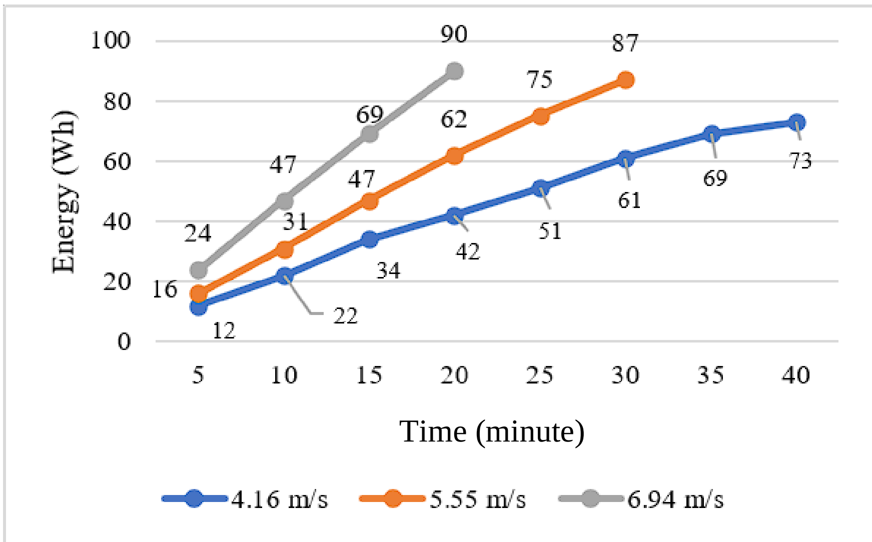


Figure 10. Energy consumption of modified electric scooter with different testing velocities.

Based on the data provided in Figure 10, it is evident that the velocity at which the electric scooter operates significantly influences the required travel time and energy consumption. For instance, when travelling at a velocity of 4.16 m/s with a rider weighing 60 kg, the scooter takes 40 minutes to complete the journey, consuming 73 W of energy. In comparison, travelling at a speed of 5.55 m/s reduces the travel time to 30 minutes but increases energy consumption to 87 Wh. Similarly, at a velocity of 6.94 m/s, the travel time further decreases to 20 minutes, accompanied by a higher energy consumption of 90 Wh. These observations indicate a direct proportional relationship between speed and energy consumption for the solar cell-based electric scooter battery: higher speeds result in increased energy consumption and shorter travel times. Conversely, lower speeds lead to longer travel times but reduced energy consumption [15], [16].

3.7. Motor Torque Results

The total mass of the scooter consists of 3 kg of motor, 10 kg of iron frame, 3 kg of each panel, and 1 kg of battery. Assuming that the rider is 60 kg, the total mass of the bike and rider is around 80 kg. The total weight using g = 9.8 m/s^2 is 784 N. The relationship between velocity, rotation speed, and torque of the modified electric scooter is described in Table 5.

Table 5. Velocity, rotation speed, and torque results of modified electric scooter.

Velocity (m/s)	Rotation Speed (rpm)	Torque (Nm)
4.16	1,268.9	1.499
5.55	2,165.7	1.139
6.94	2,801.2	0.880

At a speed of 4.16m/s, the tachometer measurement indicates a BLDC motor rotation speed of 1,268.9 rpm, resulting in a torque of 1.499 Nm. As the speed increases to 5.55 m/s, the motor rotation speed measured by the tachometer rises to 2,165.7 rpm, yielding a torque value of 1.139 Nm. Further increasing the speed to 6.94 m/s leads to a motor rotation speed of 2,801.2 rpm, with a corresponding torque value of 0.88 Nm. From the provided data, it's evident that the torque generated has an inverse relationship with the motor rotation speed. As the motor rotation speed (Rpm) increases, the torque decreases [17].

4. Conclusions

After analysing the design modifications implemented on solar cells for electric scooters, several key conclusions emerge. The conversion of solar cells into solar panels, employing a series circuit approach from each cell to each string, yielded promising results. The test data revealed an average open circuit voltage (Voc) of 39.2 V, a voltage at the maximum power point (Vmp) averaging 36.79 V, a short circuit current (Isc) averaging 0.63A, and a current at the maximum power point (Imp) averaging 0.55 A, resulting in a power output of 20.23 Wp. Calculations also indicated a fill factor of 0.81 and a solar panel efficiency of 3.9%. Furthermore, the battery charging process with solar panels of varying specifications demonstrated a charging time of 10 hours, influenced by voltage and current disparities across each solar panel. It is important to note that the charging voltage must surpass the battery's charge voltage, with the maximum battery voltage reaching 42 V for a 36 V capacity battery, imposing a PV voltage exceeding 42 V.

In the electric scooter performance tests conducted with a rider weight of 60kg, lower to moderate speeds ranging from 4.16 m/s to 5.55 m/s exhibited extended travel times and reduced battery energy consumption. Specifically, at 4.16 m/s, the scooter required 40 minutes to travel, consuming 73 W of energy. Increasing the speed to 5.55 m/s reduced travel time to 30 minutes, with energy consumption reaching 87 Wh. Finally, at a speed of 6.94 m/s, the travel time decreased to 20 minutes, accompanied by an energy consumption of 90 Wh. These findings emphasise the effectiveness of maintaining lower to moderate speeds for prolonged travel durations and enhanced battery usage in electric scooters.

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Conflicts of Interest: The authors declare no conflicts of interest.

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