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Selection of cells and analysis of the energy storage system for a solar car

Abstract: The presented study describes the research carried out on the selection of cells for the "Perła" solar car. The study aimed to select optimal cells in terms of car efficiency and related costs. In particular, we focused on an innovative approach, utilizing pouch-type cells. The research included cell discharge tests and an analysis of the results obtained from the numerical model. During the discharge tests, the cells were subjected to a constant current value to measure their efficiency and capacity. Based on the collected data, a numerical model was developed that included battery prices and car performance depending on the type of cell. Particular attention was paid to the cost-performance analysis. The research presented in the article provides valuable information for electric car battery system designers, helping them to make informed decisions regarding the selection of cells. The article is an important contribution to the development of solar car technology and can contribute to improving their efficiency and competitiveness in the market. The analysis results showed that different types of cells significantly impacted both the cost and performance of a solar car. It was found that battery price and performance varied depending on the cell type. Batteries utilizing pouch-type cells had an impressive 82% cost reduction, providing substantial savings for potential

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users. Additionally, these batteries had the potential to achieve a 2% greater range than batteries using commonly used 18650 cells, which are widely used in the automotive industry. The novelty lies in the presentation that introducing pouch-type cells as an innovative element of the battery system can improve efficiency and competitiveness in the market.

KEYWORDS: solar cells, solar car, energy efficiency, discharge tests, energy storage

Introduction

The renewable energy sector is developing rapidly and is of great interest to us. By 2030, the European Union plans to introduce a number of regulations regarding EVs to support reducing greenhouse gas emissions by 55% compared to 1990 (2030 Climate & Energy Framework 2023). According to a report by the European Environment Agency, the transport sector was responsible for around a quarter of the total carbon dioxide emissions in the European Union in 2019. As much as 71.7% of these emissions came from road transport (CO_2 emissions from cars: facts and figures (infographics) | News | European Parliament). Global warming is a very destructive phenomenon, and therefore, it is crucial to develop tools to allow for its limitation. One of the ways to do so is to use electric cars instead of ones with combustion engines. Predictions point to the development of the electric cars industry in Europe. By 2030, it is projected that 250 million electric cars will be driving on European roads (IEA International Energy Agency 2019), and as early as 2020, growth was seen in the number of electric cars by several percent (10% in 2020 and 18% in 2021) (New registrations of electric vehicles in Europe). The prognosis for 2030 indicates a more stringent target of 70 g CO_2/km for cars, which could reduce total CO_2 emissions from transportation by 5% and dependence on oil by over 2% compared to current regulations (Thiel et al. 2016). Such developments in electromobility could assist the EU in achieving its emission reduction goals and making progress towards its 2050 objective of climate neutrality (2050 long-term strategy 2023). European governments are implementing solutions to help popularize electric vehicles. For instance, French building regulations have been modified so that since 2018, every newly constructed single-family and multi-family home must be equipped with an electric vehicle charging point. This step aims to encourage residents to transition to more environmentally friendly forms of transportation while facilitating the use of electric vehicles by ensuring easy access to charging infrastructure. Norway, the Netherlands, and India are preparing regulations to completely phase out combustion engine vehicles from the market for new vehicles after 2025. These actions are taken to accelerate the transition to greener modes of transportation and reduce air pollution emissions (Janczewski 2017).

Unfortunately, most current solar car projects are still just curiosities developed by start-ups and student research groups like ours. From the first concepts of solar cars in the 1960s, only one design was commercialized, and its premiere was in 2022. We are talking about Lightyear 0, which, due to its price exceeding EUR 250 thousand. The small impact of powering from panels on the actual range was not very popular. Its production was stopped after only two months. Apart from that, there are also versions of EVs available with slight support in the form of energy from solar panels, such as the Toyota BZ4X Premiere Edition. However, they are not considered full-fledged solar cars because solar energy powers the batteries only when the ignition is turned off, and while driving, it is not used only to power on-board devices. Despite everything, the accelerating development of electric cars in the past few years has brought more new solar car prototypes, and more and more companies are striving to release cheap vehicles with such a solution.

In the sector of batteries for electric cars, a wealth of different types of cells that are distinguished by unique chemical properties can be found. Each cell brings new perspectives, offering a variety of combinations of performance, energy density, durability, and cost. Thanks to this, new possibilities lead us towards a more sustainable and ecological future while ensuring the efficiency and comfort of using electric vehicles. However, lithium-ion batteries excel in many advantages, which makes them undoubtedly the most effective solution in the field of batteries for electric cars (Diouf and Pode 2015; Ding et al. 2019). Lithium-ion batteries have a high electrochemical potential and high energy density. This means that they are able to store a larger amount of energy compared to other types of cells, which translates into a greater range of electric vehicles on a single charge (Xie and Lu 2020).

Moreover, lithium-ion batteries have a low memory effect, which means that as a result of frequent charging and discharging, they lose their capacity at a slower pace. Unlike other types of cells, such as nickel-cadmium, lithium-ion batteries are more resistant to this issue (Sasaki et al. 2013). Additionally, energy losses during the storage of lithium-ion cells are minimal, even if the battery is not used for an extended period. Furthermore, lithium-ion cells are relatively safe to operate (Liu et al. 2019). With proper design and the implementation of appropriate battery management systems, the risk of an uncontrolled chemical reaction occurring is minimalized. Other types of cells, such as lead-acid cells, may be more liable to these issues (Biensan et al. 1999; Albright et al. 2012). The technology of lithium-ion cells has made significant progress over the past decade and is currently highly developed and mature (Doughty et al. 2010; Van Noorden 2014; Homa et al. 2022). The battery in a solar car is crucial as it is the primary energy source that powers the vehicle. It stores electrical energy which is later utilized by the electric motor to convert it into motion. Therefore, the battery's performance, capacity, and durability significantly impact the vehicle's range and overall performance (Koniak and Czerepicki 2017). The capacity of the cells indicates the amount of energy they can store, expressed in ampere-hours (Ah) or milliampere-hours (mAh). The cell capacities vary depending on the type of cell and its size. For 18650-sized Li-ion cells, a standard capacity varies depending on the type of cell and its size. For 18650-sized Li-ion cells, the standard capacity value is 3,500 mAh, while for 21,700 cells, it is already 5,000 mAh (Quinn et al. 2018).

Pouch-type cells are characterized by larger size and have a rectangular shape. The pouch cells, such as the LG E78 cells used in the study, have a capacity of 78 Ah (*LG E78 datasheet*). Battery voltage is the potential difference between its terminals and is measured in volts (V). The voltage of a single Li-ion cell ranges from 2.8 V to 4.2 V. Going beyond this voltage range can lead to cell damage or even an ignition. On the other hand, current is the amount of energy passing through the battery per unit of time and is measured in amperes (A). The maximum charging current of a cell is an important parameter as it determines and affects the charging time of the battery – the higher the charging current, the shorter the charging time is (Wang et al. 2023). The discharge current directly affects the vehicle's range and operating time. The larger the power consumed by the vehicle's motors, the higher the discharge current is, and the faster the cells discharge (Lu et al. 2017). Therefore, it is important to design a battery with the highest possible capacity and optimize the propulsion system's efficiency to increase the vehicle's operating time and range. An example of such a battery is the one used in the Tesla Roadster electric car, where in 2009, a maximum range of 287 km on a single charge was achieved. The battery consisted of 6831 cells of 18650 type and had a capacity of 150 Ah (Kelty). Another example of an electric vehicle is Lightyear One, introduced in 2019, which can travel 625 kilometers on a single charge. The battery has an energy capacity of 60 kWh and an energy efficiency level of 96 kW/km (Lightyear One).

Table 1 presents a comparison of capacity, energy efficiency and range on a single charge for various modern electric vehicles (Useable battery capacity of fully electric vehicles cheatsheet – EV Database).

Table 1. Comparison of capacity, energy efficiency, and range on a single charge for different electric vehicles

Tabela 1. Porównanie pojemności, efektywności energetycznej i zasięgu na jednym ładowaniu dla różnych samochodów elektrycznych

Vehicle model	Capacity [kWh]	Energy efficiency [Wh/km]	Range [km]	Cells type
Mercedes EQS SUV 500	108,40	221	490	pouch
Volvo EX90 Twin Motor	107,00	235	455	pouch
Audi Q8 e-tron 55 quattro	106,00	214	495	pouch
BMW iX xDrive50	105,20	208	505	prismatic
Rolls-Royce Spectre	100,00	220	455	cylindric
Tesla Model X Plaid	95,00	209	455	cylindric
Tesla Roadster	53,00	120	387	cylindric
Lightyear One	60,00	96	625	cylindric

Comparing the efficiency, capacity and range of electric vehicles, the table provides valuable information about the key parameters of these vehicles. Analyzing this data can lead to conclusions regarding the capabilities of electric cars. By comparing the performance and capacity of electric vehicle batteries, we can determine the range of a vehicle on a single charge.

This study focuses on analyzing the performance of battery potentially used in a storage system of a car being developed as part of the "Perła" (Pearl) project by the AGH Eko-Energia

Student Research Group (Perła – AGH EKO-ENERGIA). In particular, the focus was on researching innovative pouch-type cells, which stand out in terms of their parameters compared to other types of cells. The ultimate goal of the car being built is to participate in international solar car competitions such as the iLumen European Solar Challenge in Belgium and the Bridgestone World Solar Challenge in Australia (iLumen European Solar Challenge, no date; World Solar Challenge 2023).

The "Perła" project will feature a composite body, primarily composed of carbon fiber, along with an optimized arrangement of 5 m^2 solar panels with a total power of around 1 kW that will eventually cover 20% of the car's energy demand (the power needed to maintain a speed of 70 kilometers per hour is approximately 5 kW). The power from them will supply the battery directly. The entire construction will be powered by 2 engines with a total power of 24 kW. Thanks to them, it will also be possible to recover energy during braking, which the driver can turn off manually to reduce resistance. An essential aspect of the "Perła" project is that the students will do the entire design and implementation. An innovative aspect of the analysis conducted is the comparison of the performance of pouch cells in terms of battery construction costs and efficiency with the 18650 and 21700 cell types. Pouch cells are highly appreciated and widely used in electric vehicles due to their efficiency and design flexibility.

The research focused on the discharge characteristics of pouch cells, such as their ability to deliver high currents and voltage stability during discharge. Additionally, the temperature of the cells during discharge tests was also analyzed. The conducted research will provide valuable information and insights regarding the utilization of pouch cells in electric vehicles. It may contribute to further advancements in electric propulsion battery technology.

Based on the experimental analysis, guidelines were developed to design a complete battery for a solar car project.

1. Materials and methods

The choice of cells used in a solar car is associated with a comparison of many parameters and requirements set by Student Research Group Eko-Energia. To choose the best-suited cells for solar cars in terms of range and cost, with sufficient other parameters required for a safe car operation, an advanced algorithm was made to compare technical properties and the cost of the entire battery, and discharge tests were made. The sheet prepared by our team allows us to compare parameters such as the maximum range of a car and, therefore, the number of laps that can be done during the competition on one full battery discharge at any given constant speed. The results acquired during the discharge tests of cells show how much energy we are able to acquire from one cell on full discharge. Table 2 presents the list of cells that have been tested.

Table 2. List of tested cells

Tabel 2. Lista testowanych ogniw

Cell	Rated capacity [mAh]
LG INR18650 MJ1	3,500
Samsung INR21700-50E	5,000
LG INR21700 M50	4,900
LG LGX E78	78,000

Pictures of the tested cells are shown below.

Fig. 1. LG INR18650 MJ1 cells

Rys. 1. Ogniwa LG INR18650 MJ1

Fig. 2. Samsung INR21700-50E cells

Rys. 2. Ogniwa Samsung INR21700-50E

Fig. 3. LG INR21700 M50 cells

Rys. 3. Ogniwa LG INR21700 M50

Fig. 4. LG INR18650 MJ1 cells

Rys. 4. Ogniwa LG INR18650 MJ1

Certain assumptions were made for the calculations in the numeric model regarding the assumed type of motor controller, operating voltage, and the intended energy capacity of the entire battery. The motor controller was assumed to operate at a 96 V voltage, while the targeted energy capacity of the final battery was set at 20 kWh. The chosen energy value for the battery was based on the desired parameters specified for the vehicle.

Li-ion cells are characterized by a voltage that decreases approximately from 4.2 to 3.0 V during safe operation. The discharge characteristics of cells indicate the capacity that can be utilized within a given voltage range. Taking into account the voltage range of interest for the cells and the discharge characteristics found in the datasheets. Table 3 presents the percentage value of total cell capacity utilized within the voltage range in which the cell operates. Discharge characteristics were validated through our own cell discharge tests.

Table 3. Percentage value of total cell capacity utilization and cell operating range

Tabela 3. Wartość procentowa całkowitego wykorzystania pojemności ogniwa i zakresu działania ogniwa

Cell	Operating range [V]	Percentage value [%]
LG INR18650 MJ1	3.00–4.20	86
Samsung INR21700-50E	3.00–4.20	88
LG INR21700 M50	3.00–4.20	88
LG LGX E78	3.10–4.15	95

Source: Test Results for LG INR18650-MJ1 3,500 mAh 18650 Li-ion Battery | Power Cartel, no date; Introduction of 21700 50E, no date; LG INR21700 M50 5,000 mAh Li-Ion Rechargeable Battery (no shrink-wrap) | 3D CAD Model Library | GrabCAD).

Percentage value – the ratio of a cell's effective capacity to its rated capacity over a given working voltage range.

This value increases along with the extension of the working voltage range of the Li-ion cell. Overextending the working voltage range of the cells results in their faster degradation. In addition, attention should be paid to the voltage ranges allowed for the cells in use. The highest "percentage value" was selected for the final use (capacity factor) while maintaining optimal working conditions for the Li-ion cells.

With such selected values, an initial comparison was made between the obtained technical parameters of the cells and the cost of the entire battery. Then, after the discharge tests of the cells, the percentage value in the algorithm was changed to the actual value.

Even though E78 cells have the highest capacity, this does not influence the number of their cycle lifes – the number of charge and discharge cycles that a cell can complete before losing performance. Table 4 presents an approximate number of cycle lifes of each cell declared by the producers. It can be noticed that, similar to total capacity utilization, the cycle life of cells increases with increasing capacity.

This parameter is key to assessing the vehicle's costs of operating a vehicle with a particular battery in the long term.

Figure 5 presents a graph showing the relationship between the design objectives, the calculated parameters, and the obtained results. This graph shows the complexity of selecting suitable cells for an electric vehicle battery.

Table 4. Number of cell cycle life

Tabela 4. Przewidywana liczba cykli ładowania/rozładowania

Cell	Cycle life
LG INR18650 MJ1	400
Samsung INR21700-50E	500
LG INR21700 M50	500
LG LGX E78	700

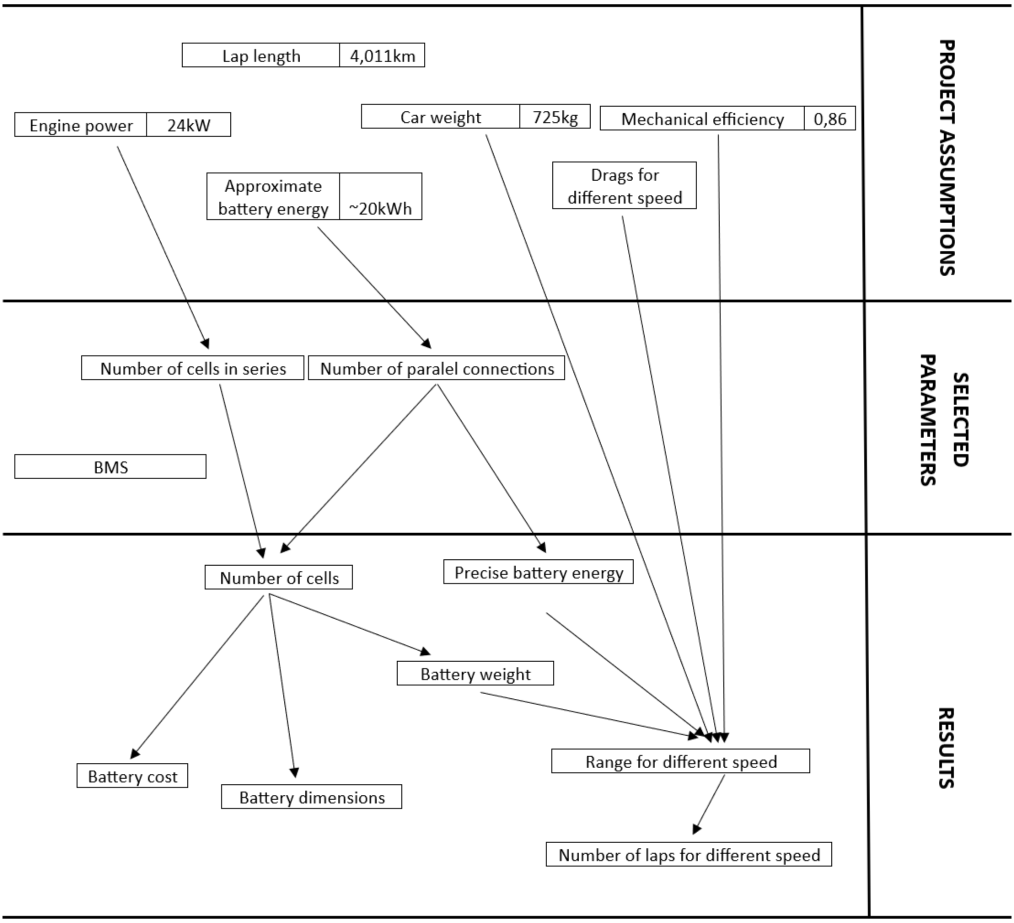

Fig. 5. Graph representing design dependence

Rys. 5. Wykres przedstawiający zależności projektowe

The choice of the right cells for a battery is a process that requires consideration of many factors, such as the assumed approximate energy of the battery, the power of the engines, the weight of the car, and other parameters.

The battery parameters, such as the number of cells in series and parallel connection, are selected based on the previous assumptions. Using the necessary formulas, the final number of all cells, the price of the entire battery, the range of the car, or the number of laps completed by the car on the track in the competition is calculated.

A battery in electric vehicles is defined by several important indicators that are critical for their performance and use. The key indicators are battery capacity, range, and the power needed to maintain a certain speed.

- A battery capacity is described as the product of the number of paralleled cell connections, the nominal capacity of a single cell, and the percentage usage of the capacity. This parameter determines the amount of electricity the battery can store and deliver to the vehicle's engines. The higher the capacity, the greater the range of the electric vehicle.
- The power required to maintain a certain speed depends on the aerodynamic drag and the speed of the vehicle. In the case of electric vehicles, this power refers to the electrical energy that must be supplied by the battery to maintain a certain speed. The higher the aerodynamic drag and the higher the speed, the more power is required to keep the vehicle moving at that certain speed.
- The range of an electric vehicle depends on several factors, such as battery capacity, vehicle speed, aerodynamic coefficient, and the power needed to maintain speed. A high battery capacity, lower speed, better aerodynamic coefficient, and less power are needed to maintain speed, which contribute to a longer vehicle range per charge.

The necessary formulas for calculating the given values are shown below.

1. Battery capacity

$$U_n\ [\mathrm{V}] = u_n \cdot S_c \text{ – nominal battery voltage} \tag{1}$$

$$Q\ [\mathrm{Ah}] = \eta_B \cdot P_c \cdot q_n \text{ – battery capacity} \tag{2}$$

$$E_n\ [\mathrm{kWh}] = Q \cdot U_n/1000 \text{ – energy capacity} \tag{3}$$

where:

u_n – nominal voltage of one cell,
q_n – nominal capacity of one cell,
S_c – series connection,
P_c – parallel connection,
η_B – percentage of consumption.

2. Power required for sustaining velocity

$$O_v \text{ [N]} = M \cdot g \cdot \eta_t \text{ – velocity resistance} \tag{4}$$

$$O_A \text{ [N]} = (S_p \cdot \rho_p \cdot \eta_A \cdot v^2)/2 \text{ – aerodynamic resistance} \tag{5}$$

$$P \text{ [kW]} = (O_A + O_v) \cdot v/1000 \tag{6}$$

where:

M – car mass (battery mass included),
η_t – rolling resistance,
η_A – aerodynamic factor,
g – gravitational acceleration,
v – velocity,
ρ_p – air density,
S_p – front surface.

3. Range

$$Z \text{ [km]} = (E_n \cdot v \cdot \eta)/P \tag{7}$$

where:

η – mechanical efficiency.

Discharge tests of cylindrical cells were carried out in the university laboratories. Cell discharge tests are used to check cell capacity and performance. They simulate the real conditions of battery use by controlled discharging and measure the time that elapses from the moment of full charge to the moment of complete discharge. Thanks to this, it is possible to determine how long a given battery will work in real conditions, which is crucial in the case of powering electric vehicles. Figures 6 and 7 show the electrical diagrams of the cell testing systems.

The system includes a high-power resistor, a 24 V contactor that allows the current to flow to the resistor, and a measurement board that collects voltage and current data depending on time and sends them to the computer. In addition, the system uses an additional clamp-on ammeter and a voltmeter to validate the results sent from the measurement card to the computer. During the measurements, the cell temperature and all connections in the circuit were measured with a thermal imaging camera.

The electrical system for testing cylindrical cells consisted of an electronic load from Array. It allows the cells to be loaded with a maximum current of 30 A. It automatically measures the time, voltage, and current values on the cell. These data were entered into the algorithm for further processing. Also, for safety, the temperature values on the cell were measured.

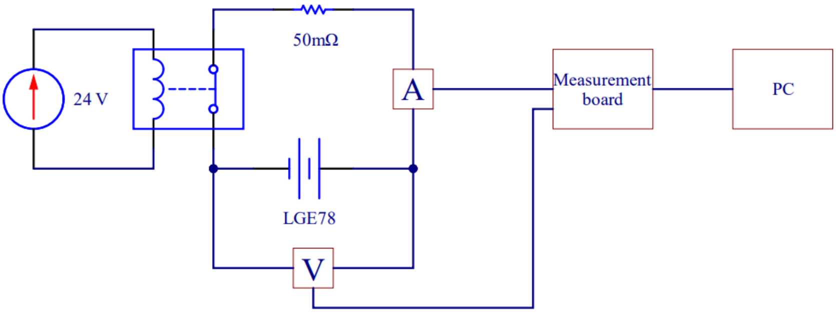

Fig. 6. Electrical diagram of cells LG E78 testing system

Rys. 6. Schemat elektryczny stanowiska testowego dla ogniw LG E78

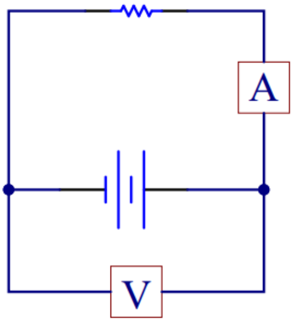

Fig. 7. Electrical diagram of cylindrical cells testing system

Rys. 7. Schemat elektryczny stanowiska testowego dla ogniw cylindrycznych

2. Results and discussion

Within the conducted research, the authors aimed to identify the most cost-effective and high-performing cells for solar car batteries. We paid special attention to innovative pouch-type cells, examining their voltage stability during discharge. The research involved conducting discharge tests and analyzing the results using an advanced numerical model.

During the analysis of cylindrical and pouch cells, nominal voltage values were taken into account. For cylindrical cells, the nominal voltage is 3.6 V, while for pouch cells, it is 3.67 V. Another important aspect is the maximum energy and power of the entire battery, which were adopted as assumptions.

The adopted values of series and parallel connections of cells in Table 5 form the basis for calculations and design of the battery system. These determinations will enable the achievement of an optimal configuration that ensures the desired energy parameters and battery performance.

Table 5. Selected configuration of serial-parallel connections for batteries with assumed parameters

Tabela 5. Wybrane konfiguracje połączeń szeregowo-równoległych dla baterii z założonymi parametrami

Cell1	Serial connection	Parallel connection
LG INR18650 MJ1	27	70
Samsung INR21700-50E	27	48
LG INR21700 M50	27	48
LG LGX E78	26	3

Multiplication of the adopted connections, which corresponds to the total number of cells used, was used to calculate the weight of the battery and its costs for specific cells. These calculations are crucial for determining the battery parameters and assessing its costs. The following graphs present the battery results concerning the total battery mass, battery cost, vehicle range, and the number of laps that can be driven on a single charge, depending on the type of cell used. The discharge results for various constant discharge currents for cylindrical cells and a constant load value for the LG E78 cell are also presented.

These graphs provide a visual summary of the obtained results and allow for easy analysis between different battery parameters. They enable the assessment of the impact of selecting a specific cell on the battery's mass, costs, range, and performance, and a simple analysis between different battery parameters. Thanks to them, it is possible to assess the impact of choosing a specific cell on the weight, price, range, and performance of the battery.

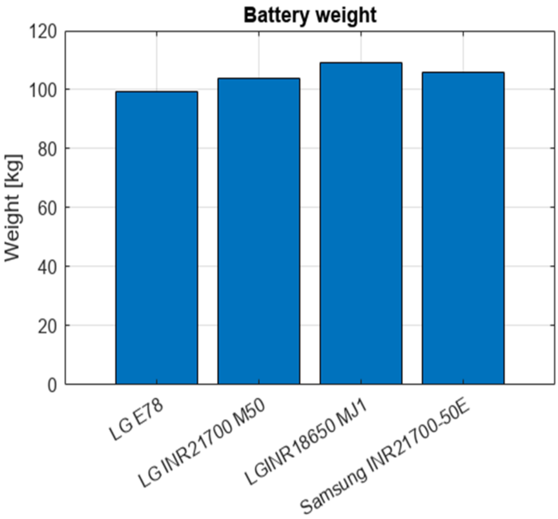

Fig. 8. Battery weight depending on the used cell

Rys. 8. Waga baterii w zależności od wybranego typu ogniw

The data in the graph show the dependence between the masses of batteries that meet the requirements and the cells from which they were built. By analyzing the results, it can be seen that the individual weight varies depending on the cells used. The best results in terms of weight are batteries made of LG E78 cells, which weigh less than 100 kg. The batteries are slightly heavier for other selected cells and vary from 100 to 110 kg. The obtained results indicate relatively small mass differences between different types of cells, which makes cell selection unaffected by overall weight.

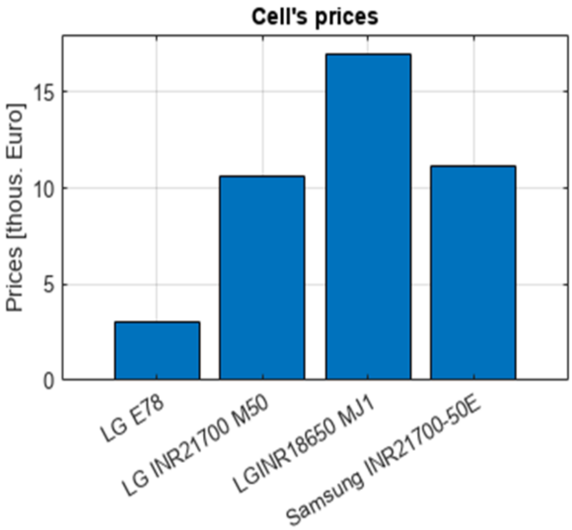

Fig. 9. Comparison of the prices of the whole battery depending on the used cell

Rys. 9. Porównanie kosztów baterii w zależności od wybranych ogniw

The presented chart illustrates the dependence of model battery prices that fulfill the requirements of the project. We observe large differences in prices, which mainly depend on the size of the cells used. The graph illustrates the greatest advantage of pouch-type cells over cylindrical ones. The graph shows that a battery consisting of the smallest 18650 cells turned out to be 6 times more expensive than a battery of a similar capacity made of pouch cells. 18650 cells are widely recognized and widely used, but the production of this type of cells is associated with high costs due to technological requirements related to their production and construction. As a result, their price is much higher than other cells. For the 21700 cell type, the battery price is about three times the cost of the pouch cell option. This type of cell represents a newer standard and offers a higher capacity compared to the 18650 cells. However, production costs and materials used in their construction still impact the battery price, resulting in higher costs compared to pouch-type cell solutions. A factor that has not been taken into account is the cost of the battery case. Due to much lower casing stiffness than cylindrical cells, pouch-type cells require a more complex and expensive cemented construction, making obtaining a safer battery possible. On the other hand, the pouch cell structure allows for easier heat dissipation from a battery made from such cells compared to cylindrical cells. Passive cooling is sufficient, and it is done by placing a thin copper plate on each battery segment. Thanks to the phenomenon of convection, the heat from the plates flies upwards, where an airflow is introduced, which successively cools them. Due to the great differences in the prices of the cells themselves and the fact that evaluating and comparing the exact construction costs of both batteries is extremely complicated, it was deemed that such a price comparison was sufficient.

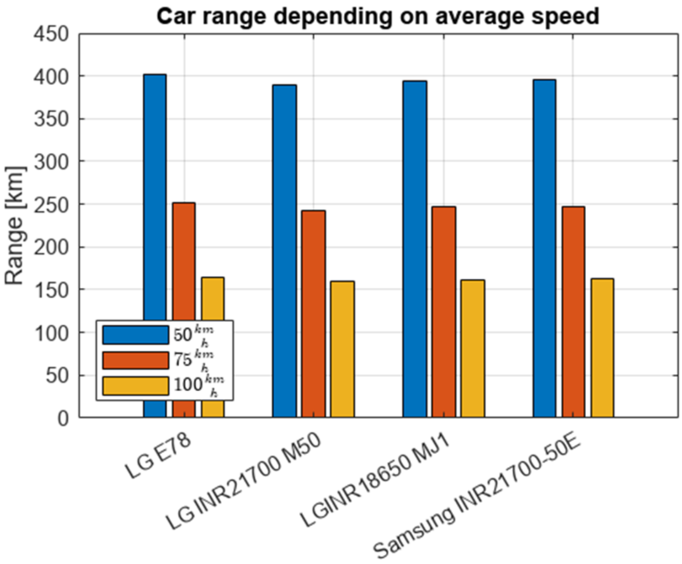

Fig. 10. Car ranges on a single charge depending on the cell used and its constant velocity

Rys. 10. Zasięg auta w zależności od ogniw wykorzystanych do konstrukcji baterii oraz prędkości przejazdu

The set of data presented in the graph shows the dependence of the maximum distance that a vehicle moving at a constant speed can cover, depending on the model batteries on different types of lithium-ion cells. The depicted bars show the range depending on the speed of the vehicle. In the graph, you can see that the smallest bars represent the range value for the speed of 100 km/h, while the next larger bars refer to the lower speeds: 75 and 50 km/h. These values represent the maximum distance the vehicle can travel while maintaining a constant speed before the battery is discharged. The analysis of the graph shows that the differences in ranges between different types of cells are insignificant. The vehicle performs marginally better with pouch cells than with other cells.

The graph shows the maximum number of laps of the former Formula 1 circuit Zolder, which is used for the iLumen solar car competition organized in Belgium. A lap on this track is 4.011 km. The data assumes a vehicle moving at a constant speed. The chart includes different model batteries based on different types of lithium-ion cells. The analysis of the results indicates a relationship between the type of cells and the vehicle's ability to cover a certain number of laps.

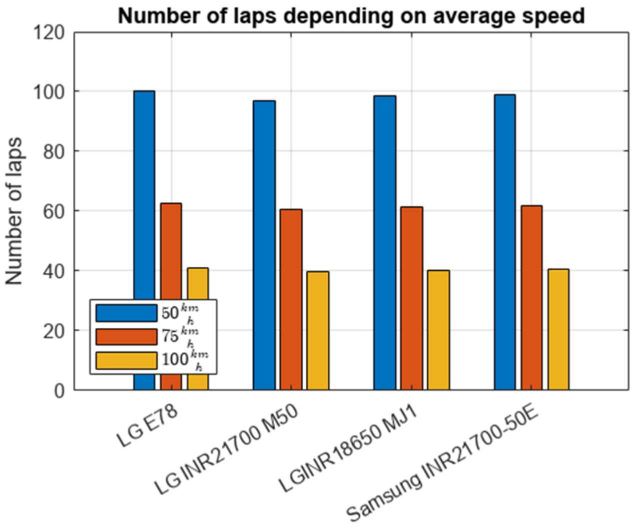

Fig. 11. Number of laps driven on a single charge depending on the cell used and its average velocity

Rys. 11. Liczba okrążeń wykonanych na w pełni naładowanym akumulatorze w zależności od wybranych ogniw i prędkości przejazdu

We observe that the differences between the different types of cells become more pronounced when the vehicle's constant speed is lower. This means that the lower the speed, the greater the differences in the vehicle's ability to complete a certain number of laps depending on the cells used. It is worth noting that these differences result from the technical parameters and characteristics of individual cells. The number of laps driven on a single charge is crucial in the context of taking part in the competition because this result is scored very strongly in the competition.

The discharge chart of the Samsung INR21700-50E cell illustrates the relationship between discharge time and cell voltage. This lithium-ion cell is known for its high energy density, translating to long-lasting performance. The presented data allows us to understand how the energy inside the cell gradually decreases over time.

The horizontal axis on the graph represents time in minutes, while the vertical axis represents the level of cell charge, expressed as cell voltage. Initially, at the beginning of the process, the charge level of the Samsung INR21700 cell was 4.16 V. Over time, a gradual decrease in the cell charge level can be observed. This decrease is gradual in nature.

The graph presents discharge data of the cell at a constant current of 2.5 and 5 A. A higher current value leads to a faster discharge of the cell. The selected current values are based on the maximum power of the motors used in the solar car, where 5 A represents the maximum current that will flow through a single cell, and 2.5 A is half of that current. The energy utilized by the cell at a current of 2.5 A within the voltage range from the maximum voltage to 3.0 V amounted to 88% of the manufacturer's declared 4,400 mAh. For a current of 5 A, these results were lower and amounted to 86% and 4,300 mAh.

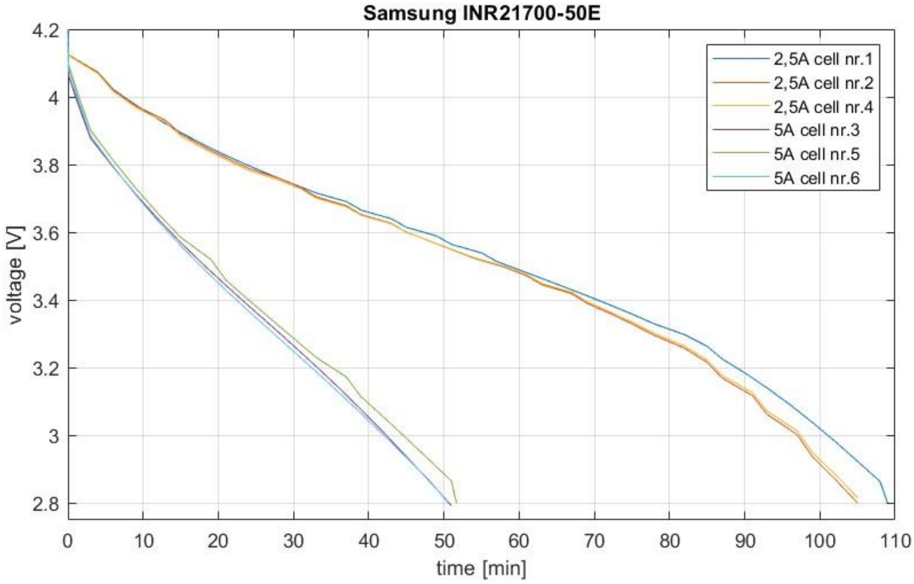

Fig. 12. Samsung INR21700-50E cell discharge chart for 5 A and 2,5 A current

Rys. 12. Rozładowanie ogniwa Samsung INR21700-50E dla prądu 5 A oraz 2,5 A

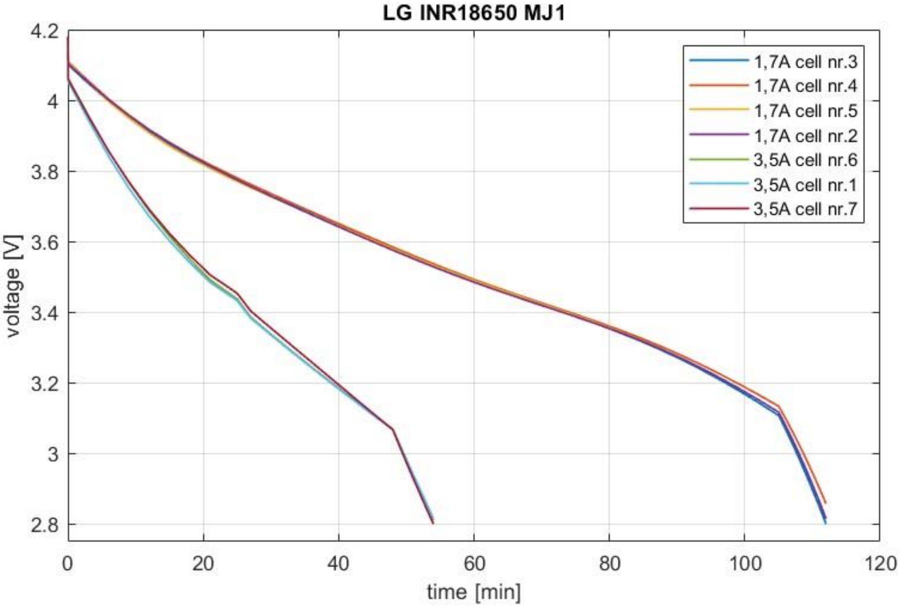

Fig. 13. LG INR18650 MJ cell discharge chart for 3,5 A and 1,7 A current

Rys. 13. Rozładowanie ogniwa LG INR18650 MJ dla prądu 3,5 A oraz 1,7 A

For the LG INR18650 MJ1 cell, discharge tests were conducted at current values of 1.7 A and 3.5 A. The methodology for determining current values remained the same. The cell discharged at a slower rate for the lower current value. In the case of a current of 1.7 A, the energy consumed by the cell within the voltage range from maximum voltage to 3.0 V amounted to 86% of the manufacturer's declared capacity, which is 3,010 mAh. For a current of 3.5 A, the energy amounted to 83%, equivalent to 2,905 mAh. Consistent results were obtained when different cells were discharged at the same current value.

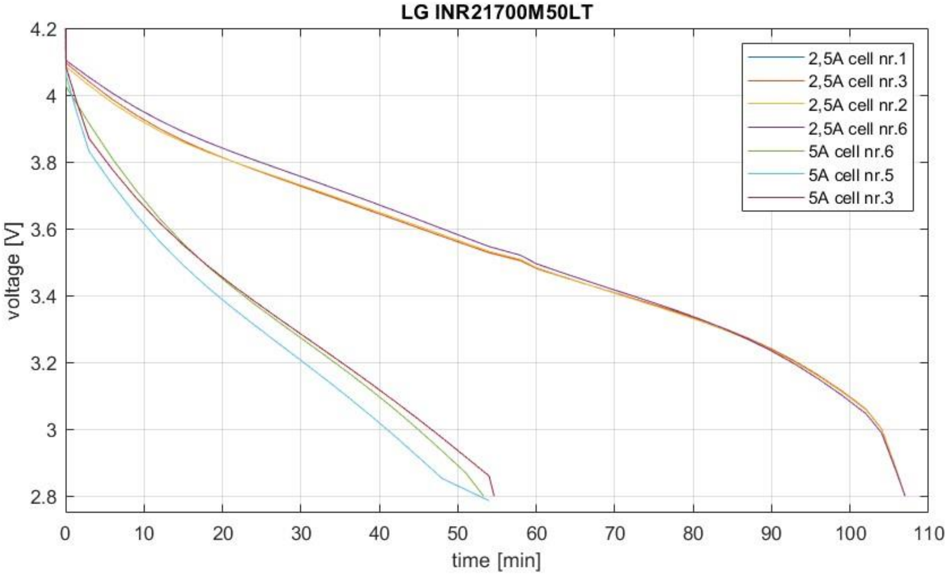

Fig. 14. LG INR21700 M50 cell discharge chart for 5 A and 2.5 A current

Rys. 14. Rozładowanie ogniwa LG INR21700 M50 dla prądu 5 A oraz 2,5 A

For the LG INR21700 M50 cell, discharge tests were also conducted at a current of 2.5 and 5 A. Similarly, the cell discharged at a slower rate for the lower current value. In the case of a current of 2.5 A, the energy consumed by the cell within the voltage range from the maximum voltage to 3.0 V amounted to 88 % of the manufacturer's declared capacity, which is 4,400 mAh. The results for a current of 5 A is the same.

During the discharge tests of the LG E78 cells, they were subjected to a constant resistance of 50 mΩ. The value of the resistance was selected using Ohm's law by dividing the cell voltage by the desired current. Remarkably, despite the high current values, the cell did not experience any significant temperature increase. Initially, during the voltage drop, the discharge processed slowly and the cell maintained a stable performance. However, a more rapid voltage drop was observed after reaching a voltage value of 3.1 V.

An extremely important conclusion drawn from this experiment is the demonstrated utilization of the cell's capacity, which amounted to approximately 95 % of its rated capacity. This is an

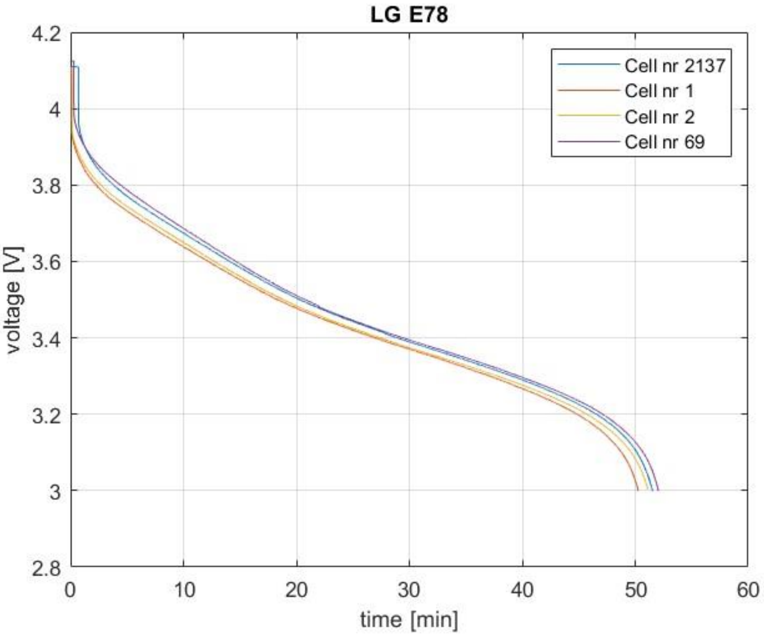

Fig. 15. Discharge chart of LG E78 cells

Rys. 15. Rozładowanie dla ogniw LG E78

excellent achievement as it signifies high efficiency and performance of the LG E78 cells. Such results confirm that these cells are durable and efficient during the discharge processes.

Since the cells experienced variable currents during the discharge process, Figure 16 presents a graph of the discharge current of the cells as a function of time.

The current varied throughout the discharge process of cells. This variation is due to the voltage drop across the cell at a constant resistance of the load. Initially, the current value was close to 100 A, but towards the end of the discharge process, it decreased to 75 A. The average current was determined to be 82 A by calculating the average of these current values.

Conclusions

The results of the analysis clearly showed that the type of cell has a significant impact, both on the cost and performance of the solar car. The obtained results could be important for the automotive industry, as they present an innovative approach in the use of pouch cells. The conclusions are a valuable source of information in the context of designing a solar car battery. In the future, authors plan to continue research on the cells concerning the integration of the solar panel

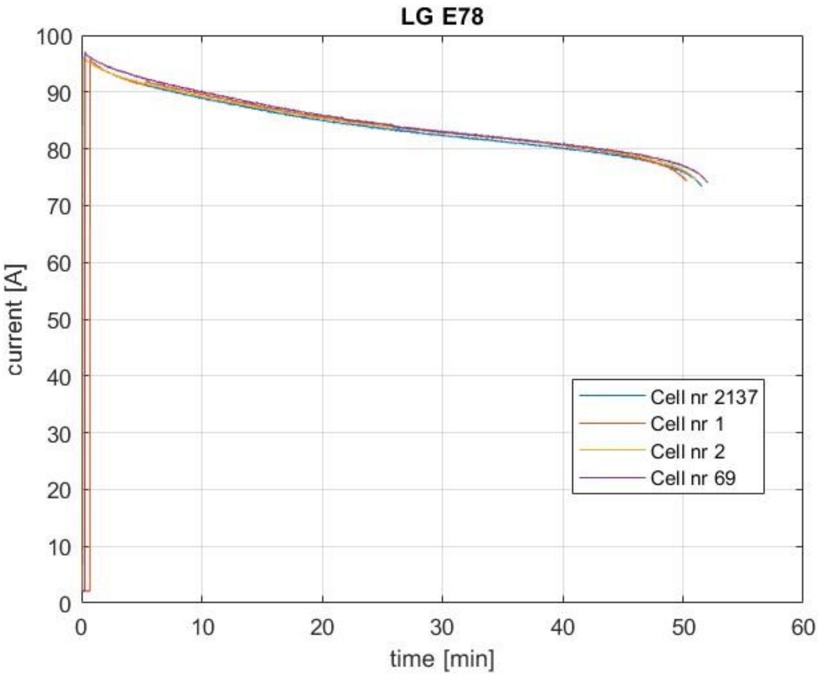

Fig. 16. The graph represents the current flowing through the LG E78 cells during discharge tests

Rys. 16. Prąd rozładowania dla ogniwa LG E78

system into the car's battery. Table 6 shows a comparison of the economic and performance parameter results obtained from the tested cells.

After examining the table, it is clear that pouch cells stand out due to the extremely attractive aspect of battery construction price. This feature is important for the potential use of these cells in the industry. In addition, these cells have a higher energy density and lower production cost than other cell types, reflecting their favorable market price. However, it is worth being very careful when using pouch cells, as they do not have the same casing stiffness as cylindrical cells. Thus, treating these cells properly and protecting them to avoid damage is necessary. A closer look at the battery built with LG E78 cells reveals that it has a minimal performance advantage compared to batteries using cylindrical cells. This is an important observation that can influence the selection of the right type of battery depending on the specific needs and priorities of the user. The research results contribute to the development of solar cars by showing the use of lithium -ion pouch cells, which significantly contribute to increasing the efficiency of car parameters and significantly reduce the cost of batteries. As the energy density of pouch cells is higher, it is possible to drive the car longer on one charge. The lower weight of the entire battery made of pouch cells and their greater operating range within its safe parameters also contribute to a longer ride. These conclusions are important for the further development and optimization of battery technology and for a better understanding of the potential benefits and limitations of different

Table 6. Comparison of obtained results

Tabela 6. Porównanie zebranych wyników

Cell1	Serial connection	Parallel connection	Range (for 50 km/h) [km]	Mass [kg]	Cost [Euro]
LG INR18650 MJ1	27	70	394.55	97.75	17,010.6
Samsung INR21700-50E	27	48	396.28	95.21	11,193.4
LG INR21700 M50	27	48	388.82	93.27	10,621.2
LG LGX E78	26	3	402.43	89.61	3,076.8

cell types. Future research directions may be based on the development of other cell chemistry used in car batteries or on effective energy recovery while driving.

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Dobór ogniw oraz analiza systemu magazynowania energii dla samochodu zasilanego energią słoneczną

Streszczenie

W prezentowanej pracy opisano badania przeprowadzone nad doborem ogniw do samochodu solarnego „Perła”. Celem badań był wybór optymalnych ogniw pod kątem wydajności samochodu i kosztów z tym związanych. W szczególności przeanalizowano ogniwa typu pouch. Badania obejmowały charakterystyki rozładowania ogniw oraz analizę wyników uzyskanych z modelu numerycznego. Podczas testów rozładowania ogniwa poddano działaniu prądu o stałej wartości, w celu pomiaru wydajności i pojemności. Na podstawie zebranych danych opracowano model numeryczny uwzględniający ceny akumulatorów oraz osiągi samochodu w zależności od rodzaju ogniwa. Szczególną uwagę zwrócono na analizę kosztów i wydajności. Badania przedstawione w artykule dostarczają cennych informacji projektantom systemów akumulatorów do samochodów elektrycznych, pomagając im w podejmowaniu świadomych decyzji dotyczących doboru ogniw. Artykuł stanowi wkład w rozwój technologii samochodów zasilanych energią słoneczną i może przyczynić się do poprawy ich efektywności i konkurencyjności na rynku. Wyniki analizy wykazały, że dobór ogniw miał znaczący wpływ zarówno na koszt, jak i wydajność samochodu zasilanego energią słoneczną. Stwierdzono, że cena i wydajność baterii różniły się w zależności od typu ogniwa. Baterie wykorzystujące ogniwa typu pouch charakteryzowały się imponującą redukcją kosztów o 82%, zapewniając potencjalnemu użytkownikowi znaczne oszczędności. Dodatkowo akumulatory te miały potencjał osiągnięcia o 2% większego zasięgu niż akumulatory wykorzystujące powszechnie stosowane w motoryzacji ogniwa 18650. Nowość polega na pokazaniu, że wprowadzenie ogniw typu pouch jako innowacyjnego elementu systemu akumulatorowego może przyczynić się do poprawy efektywności i konkurencyjności na rynku.

Słowa kluczowe: ogniwa fotowoltaiczne, samochód zasilany energią słoneczną,
efektywność energetyczna, testy rozładowania, magazynowanie energii