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MAINTENANCE, DIAGNOSTICS AND REPAIR OF TRACTION BATTERIES FOR HYBRID VEHICLES

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Abstract

Hybrid vehicles have been widely used for more than 25 years, and their traction batteries are exposed to demanding operating conditions, particularly in urban traffic characterized by frequent regenerative braking and acceleration. Such patterns lead to progressive degradation of cell capacity and performance, highlighting the need for reliable diagnostic and repair methodologies. This article presents a comprehensive approach to traction battery diagnostics and repair for hybrid vehicles. A mobile diagnostic service, equipped with specialized instrumentation, enables simultaneous controlled charge–discharge testing of multiple battery cells. The collected measurement data are analyzed using the Metalog probability distribution family, which offers flexibility and precision in modeling the statistical characteristics of battery degradation. The methodology is demonstrated through three representative case studies of Toyota hybrid vehicle batteries. These cases illustrate different degradation pathways: gradual natural capacity fading, accelerated local overheating, and severe long-term deterioration. For each case, the approach allows for classification of cells and battery packs into categories suitable for further use, repair through selective replacement, or recycling. The integration of engineering diagnostics with statistical modeling significantly improves the accuracy of state-of-health assessments and supports efficient decision-making in practice. The mobile service context further demonstrates the method's applicability, allowing diagnostics and repair to be performed directly at the customer's site. The findings highlight both the economic benefits, by reducing the cost of battery replacement and extending vehicle lifetime, and the ecological advantages, by enabling second-life applications and supporting safe recycling. Thus, the

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proposed methodology contributes to sustainable battery management and strengthens the role of diagnostics in advancing electromobility.

Keywords: hybrid vehicle; traction battery; electric motor; traction battery diagnostics; Metalog probability distribution family

1. Introduction

Hybrid vehicles have been on the market for over 25 years. At first, they were supposed to be just an intermediate link between internal combustion engine-powered vehicles and battery-driven vehicles with electric motors [32]. Hybrid vehicles have been on the market for so long and in recent years have been the best-selling type of vehicle [52, 53, 54]. This is due to the undeniable advantages of hybrid vehicles [47]. Hybrid vehicles, as the name suggests, have at least two different power sources [38]. The first is usually an internal combustion engine powered by one of the fossil fuels such as petrol or diesel. The second is usually an electric motor powered by electricity stored on board the vehicle in the traction battery. Adding an additional electric motor to the basic drive of the vehicle in the form of an internal combustion engine resulted from the precise energy balance on board the vehicle. Operational specialists knew perfectly well that every vehicle irretrievably loses very large amounts of energy during braking. The kinetic energy of the vehicle is dissipated by the braking system components. It turns out that the braking process can be partially or even completely carried out by an appropriately selected electric energy generator in the form of a DC generator or alternator (AC generator). The first experiments in this area have already shown that very large amounts of energy can be recovered during regenerative braking [4]. This energy is stored on board hybrid vehicles in traction batteries [48]. Normal operation of a hybrid vehicle has shown that in urban driving conditions there is a very large number of braking processes during which very large amounts of energy can be recovered. At the same time, the specificity of urban driving is also characterized by a very high demand for driving power resulting from the need to repeatedly accelerate the vehicle after complete stops or after reducing the driving speed. Each acceleration of the vehicle requires a large amount of energy to overcome various resistances to motion and to achieve the desired driving speed. The energy stored in the vehicle's traction battery can be used to support the basic drive unit of the vehicle. It is enough to power an additional electric motor, which in certain driving conditions will support the internal combustion drive unit [30]. The same electric machine (generator/electric motor) can be used both to recover braking energy and to generate driving power. The combustion engines of hybrid vehicles can run on petrol, diesel [66], LPG, CNG or other types of alternative fuel [13, 17, 56]. The use of biofuel in the hybrid drive makes it even more environmentally friendly [23]. And it's not just about CO_2 emissions, but also lower emissions of regulated exhaust gas components such as HC, CO, PM and NO_x [19]. Such hybrid and multi-fuel drive systems are eagerly used by taxi drivers and large taxi corporations, as they are characterized by a very long driving range on a single refueling

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and low operating costs [5, 42, 58]. These advantages have resulted in almost all hybrid vehicles used in Poland as taxis being also converted to LPG power [14, 62]. Powering the combustion engines of hybrid vehicles with alternative fuels also contributes to increasing the operational refinement of these engines [25, 26, 57]. Hybrid drives can also use other power sources such as hydrogen fuel cells and hydrogen-powered combustion engines [27]. Hydrogen is a very good fuel for hybrid vehicles, especially if produced from energy from Renewable Energy Sources [55].

Such a hybrid vehicle described above was characterized by the following advantages:

1) It is able to recover braking energy and store it in the on-board traction battery, which translates into significantly less energy being lost during braking.
2) Energy from the traction battery is used to support the basic internal combustion drive unit during starting and acceleration processes, which translates into lower fuel consumption.
3) Theoretically, it is able to move on one of the two drives in the event of a lack of fuel in the other.
4) Generating drive by both sources of the hybrid drive ensures better acceleration of the vehicle.
5) Supporting the operation of the internal combustion engine in the dynamic acceleration process by the emission-free electric motor ensures lower total exhaust emissions of the hybrid vehicle.

Due to the above features, hybrid vehicles are highly valued by their users as economical and ecological vehicles. Hybrid drives are also suitable for trucks [37, 46] and buses [9, 10, 18]. Savings in fuel consumption are highly valued especially during the economic crisis characterized by high prices of fuels from fossil sources [11]. Ecology is an observable global trend that aims to slow down or reverse the processes of global warming [7, 40].

The first hybrid vehicles to enter the market include the Toyota Prius. The Toyota Prius is a compact passenger car with a hybrid drive Hybrid Synergy Drive manufactured by the Japanese automotive concern Toyota Motor Corporation since 1997 [67]. Depending on the generation, these vehicles had combustion engines with different displacement and maximum power. They also differed in the type of battery cells used in the package and its energy capacity. The control system for both the combustion engine and electric motors was also subject to continuous development. The latest Toyota Prius is a Plug-in Hybrid Electric Vehicle (PHEV). This means that its traction battery pack has a significantly larger capacity and must be recharged by connecting to an external power source, such as a charging station. In this case, the energy recovered from regenerative braking plays only a supplementary role.

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1.1. Battery diagnostics: state of the art

Diagnostics of hybrid vehicles covers a very wide range of tests. This is due to the fact that current hybrid vehicles are very complex mechatronic devices. They are built from many mechanical and electrical systems, which in almost every case already have advanced electronic control.

In this article, the authors will only deal with the diagnostics of traction batteries in hybrid vehicles. Hybrid vehicles, like their combustion predecessors, must be equipped with an on-board diagnostics system (OBD). Using the OBD connector, the diagnostician can connect to the battery pack in the vehicle and obtain a lot of diagnostic information. These include, among others, error codes that accompany damage to the battery pack. On their basis, breaks in electrical circuits, short circuits and exceeding the correct signal levels from individual components of the battery pack can be identified quite quickly. In addition, the OBD system allows reading the current operating parameters of the entire system and performing functional tests while stationary and while driving. The latest diagnostic devices enable connection to many models of hybrid vehicles from different manufacturers. Advanced software contains information that helps the diagnostician in diagnosing and repairing the battery pack [6]. These include electrical diagrams of the battery architecture itself (along with information on the nominal capacity, number of cells, their connection in series or parallel) as well as algorithms for performing selected diagnostic or repair activities. Diagnosing a battery pack is more difficult when it is removed from the vehicle and we do not even know its history of use. However, there are advanced diagnostic devices that can communicate with battery packs removed from vehicles. They have a number of adapters with various plugs through which the diagnostic device can communicate with the Battery Management System (BMS). The role of this system will be described later in the article.

Traction batteries of hybrid vehicles usually consist of individual cells, which are connected in series due to the required voltage level. Cylindrical or prismatic cells are placed in a sealed housing, which protects them from physical damage. The housing also protects vehicle users and mechanics from electric shock, the voltage of which in the case of hybrid vehicles reaches over 200 V. The housing also allows the entire battery pack to be screwed to the vehicle body or chassis. In addition, the housing contains electrical connectors and fluid system nozzles. The housing must be lightweight and durable. It is usually made of aluminium or pressed sheet metal. The appearance of the housing itself allows the diagnostician to make initial determinations regarding the technical condition of the battery pack. If the housing is damaged or crushed, it should be suspected that the vehicle may have been involved in a road accident, and the battery pack itself may then pose a significant threat to the diagnostician and the repair shop.

After dismantling the casing, the diagnostician can see all the components of the battery pack. In addition to the previously mentioned battery cells, you can immediately see a lot of

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electronics and electrical wires with connectors. Electronics include various types of printed circuit boards (PCB). These are usually two main electronic systems: the aforementioned Battery Management System (BMS) and the Thermal Management System (TMS) [20, 50, 63]. The first one is primarily responsible for the process of safe charging and discharging of individual battery cells in the pack. To make this possible, the BMS must know the exact voltages of all battery cells. Then, it is possible to implement algorithms for charging the battery to the maximum permissible voltages and cutting off the power supply when individual battery cells reach the minimum voltage. In order for both the driver and the diagnostician to know the actual state of charge of the battery, the BMS system determines the so-called State of Charge (SoC) [41]. This is the current level of battery charge specified in percentages from 0% to 100%. The BMS exchanges information about the current operating parameters of the battery system with other control units in the hybrid vehicle, usually using a CAN communication line. In the event of damage occurring and detected in the battery system, it is automatically electrically disconnected from the vehicle using relays [39]. The second, but also very important role of the BMS is to balance all cells in the pack. Its purpose is to obtain very similar voltages in all cells of the battery pack. This has a positive effect on the durability of such a pack and its performance in the form of the actual energy capacity available to the user. The task of the second management system TMS is to maintain the appropriate temperature of the entire battery pack in various driving conditions of the hybrid vehicle [22]. In order to heat and cool selected battery packs, electrical (resistive) and mechanical (liquid systems) heating/cooling systems are used [64]. In summary of this part of the article, it should be mentioned that all components of the battery pack in a hybrid vehicle can be a source of faults and damage [45]. During diagnostics, the mechanical connections of all components should be checked. Faulty mechanical connections can cause coolant leaks and friction between components caused by vibrations while driving. As a result, this can lead to many types of damage. The condition of electrical connections is equally important, including the condition of individual electrical wires and entire wiring harnesses. PCBs in battery packs are often mounted without any housings and can be easily damaged mechanically or electrically. Therefore, they are very often the subject of general and specific visual inspection using a microscope. At this point, it should be mentioned that only trained persons who have confirmed authorizations to perform electrical work at high voltages of up to 1 kV may perform diagnostics of hybrid vehicle battery packs. For voltages exceeding safe voltages, a special protective glove should be used. The most common damage to traction battery components in hybrid vehicles includes flooding by coolant, damage to electrical connector pins due to corrosion, damage to surface-mounted components (SMD) on PCBs, and cold solder joints [36]. Voltage and temperature sensors for individual battery cells are usually mounted on PCBs [1]. Of course, damage to the battery cells themselves has not been mentioned here so far. However, the entire rest of the article will be devoted to this issue. The best scenario for the operation of a battery pack in a hybrid vehicle is a slow loss of energy capacity as a result of many thousands of charge and discharge cycles. It is important that such natural performance degradation applies to all battery cells at the same time [15, 33]. However, this is not always the case. This is due to the different parameters of individual battery cells after the

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production process. For example, they may differ slightly in internal resistance, which affects their charging and discharging. It is therefore important that the entire pack is managed by a BMS system that includes an efficient balancing system for all battery cells in the pack [24]. It is worth mentioning here that there are different battery cell balancing systems. They are usually divided into active and passive balancing systems. An experienced diagnostician is able to distinguish them quite quickly. Damaged battery packs from hybrid vehicles can be reconditioned or safely recycled [31]. Batteries from hybrid vehicles that have lost energy capacity but are still functional and safe can count on a second life in applications other than automotive [3, 16, 43]. Currently, scientists and engineers from large technology companies are constantly developing new types of traction batteries designed specifically for hybrid vehicles [21].

Traction batteries constitute the most valuable component of modern electric and hybrid vehicles, often representing more than half of the total cost of a new battery electric vehicle and a slightly smaller proportion in hybrid vehicles. This economic aspect clearly demonstrates why the development of diagnostic and repair methodologies is of strategic importance not only for vehicle users but also for manufacturers, workshops, and recycling companies. Reliable diagnostics directly translate into lower operating costs, extended lifetime of vehicles, and greater consumer trust in electromobility. At the same time, they support the principles of a circular economy by enabling reuse and safe recycling of battery components. Therefore, traction battery diagnostics should be perceived as a key area of automotive engineering, combining technical, economic, and ecological dimensions.

1.2. Aim of the study

On the subject of damage to individual cells, it is necessary to mention other than natural causes of degradation of battery cell performance. Probably the most common cause of accelerated loss of energy capacity of individual battery cells is overheating. It may be the result of additional resistance in the series connection of battery cells. A weak weld or tightening of the mounting screws with too little force may result in the generation of high temperatures, which may then damage individual battery cells and in extreme cases lead to the battery pack catching fire. The best way to determine the technical condition of the battery pack from a hybrid vehicle is to dismantle it from the vehicle and carry out a controlled process of charging and discharging all battery cells simultaneously. Such tests are the main goal of the article and will be described later in it. A test stand designed for testing 38 battery cells simultaneously will also be presented and described. The measurement data obtained during testing of battery cells will then be processed using the Metalog probability distribution family. It will be shown that this is very useful software for determining the technical condition of battery packs from hybrid vehicles.

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The main objective of this study is to present and validate a methodology for diagnosing traction battery packs from hybrid vehicles using controlled charge–discharge tests of individual cells combined with statistical analysis based on the Metalog probability distribution family. This approach allows for quantification of the state of health of each cell and the entire pack, facilitates decision-making regarding repair or recycling, and supports the development of more effective diagnostic standards for workshops.

By integrating engineering practice with advanced statistical tools, the study demonstrates a systematic method that not only identifies degraded cells but also provides a scientific basis for reusing or discarding them. In this way, the proposed methodology contributes to improving the economic and ecological performance of electromobility and supports the principles of circular economy.

2. Materials and Methods

2.1. Research object

The research focuses on traction battery packs used in Toyota hybrid vehicles. Typical examples of these packs, removed from the vehicles, are presented in Figure 1 to illustrate their overall layout and packaging within the vehicle structure. In the newer generation of Toyota hybrids, the traction battery is built from nickel–metal hydride (NiMH) cells. Compared with the earlier design, this pack has been redesigned to be more compact and to reduce mass, which has been achieved by modifying the internal arrangement of the modules and integrating a more efficient, space-saving cooling system. Although both the previous and the updated packs have the same rated capacity of 6.5 Ah, the electrical architecture is different: the newer pack contains more cells connected in series (180 instead of 168), resulting in a higher nominal voltage of 216 V compared with 201.6 V in the earlier version. This change in configuration allows the battery to deliver higher system voltage without increasing the ampere-hour capacity, while at the same time improving packaging and weight characteristics.

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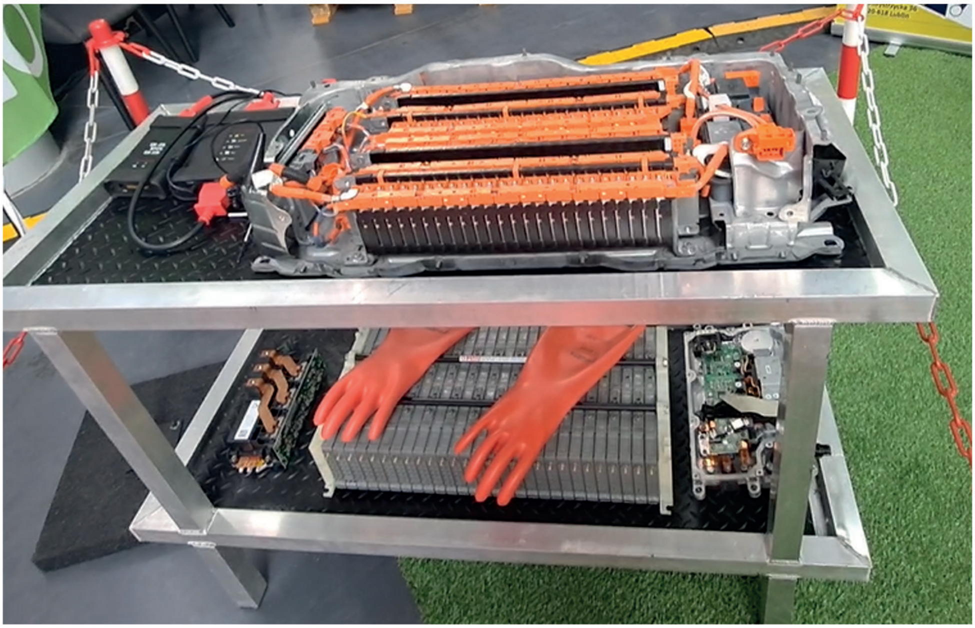

Fig. 1. Traction battery packs from Toyota hybrid vehicles

The nickel–metal hydride (NiMH) battery rated at 6.5 Ah and 201.6 V, widely implemented in Toyota vehicles, provides an overall energy capacity of around 1.3 kWh. This type of battery, commonly installed in the Toyota Prius (second and third generations) as well as in Toyota Auris Hybrid models, serves as a typical example of energy storage systems used in full hybrid electric cars. In contrast, the TS and HB versions of these vehicles are equipped with lithium-ion packs offering a lower capacity of roughly 0.75 kWh (3.6 Ah/207.2 V). Such technical distinctions should be well understood – or at least easily accessible – to qualified service technicians responsible for diagnosing and repairing hybrid or electric drivetrains. Essential competencies for such professionals include performing precise electrical diagnostics of individual cells (measuring voltage and current) and conducting controlled charge-discharge procedures. The authors possess all the specialized instruments required to carry out these operations.

2.2. Research bench

The test stand for battery packs from electric and hybrid vehicles is located in a mobile service built on board a truck. The appearance of such a mobile service is shown in Figure 2. The service built on the vehicle allows for the provision of diagnostics, service and repair services for electric and hybrid vehicles not only stationary but also at the customer's place

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anywhere in Europe. The vehicle is equipped with the necessary diagnostic and testing devices designed to work with vehicles of various brands. The vehicle is also used to conduct practical training in diagnostics and repair of electric and hybrid vehicles.

Fig. 2. Mobile electric vehicle service presented by Dakro at the Automotive Technology Fair 2024 in Poznań

A very important device used in battery cell diagnostics is a system for controlled charging and discharging of 36 lithium-ion battery cells simultaneously. A view of such a device during operation is shown in Figure 3.

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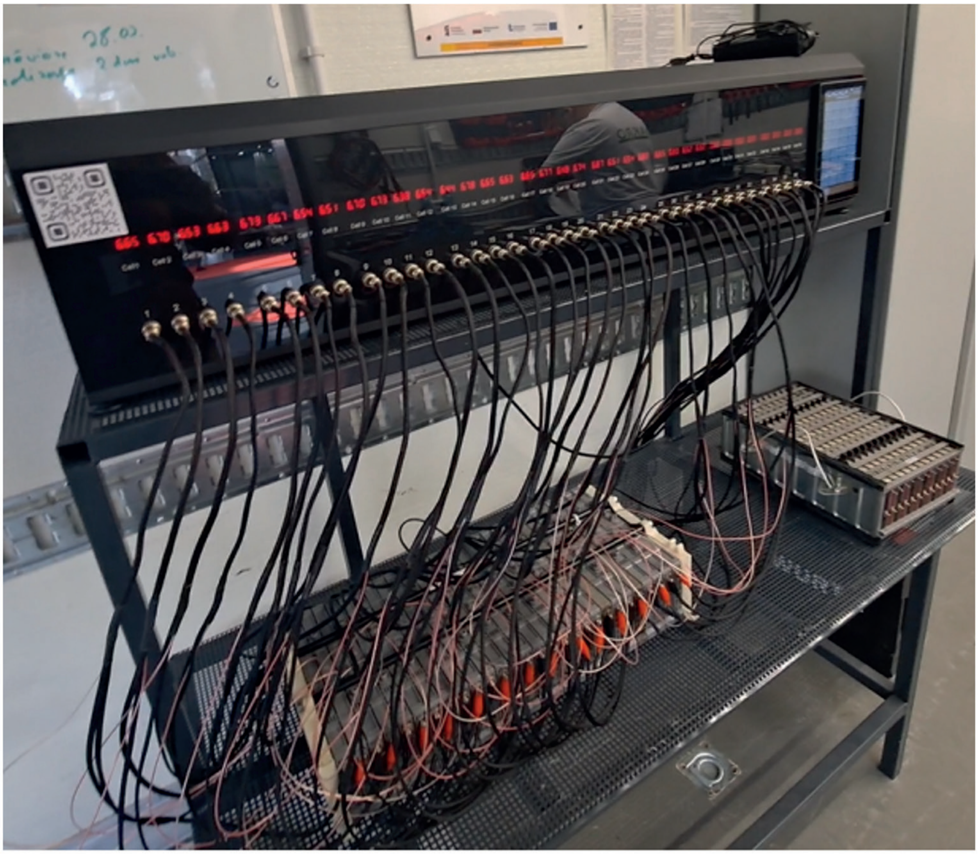

Fig. 3. An apparatus capable of performing controlled charging and discharging operations on 38 lithium-ion battery cells concurrently

The device has a color display, on which you can observe the charging and discharging parameters of individual battery cells. The system operating parameters during the discharge process of all 28 battery cells from a Toyota hybrid vehicle are shown in Figure 4. The device shows the discharge current, current voltage and the electrical energy consumed during discharge. Additionally, we can read the temperature of each cell.

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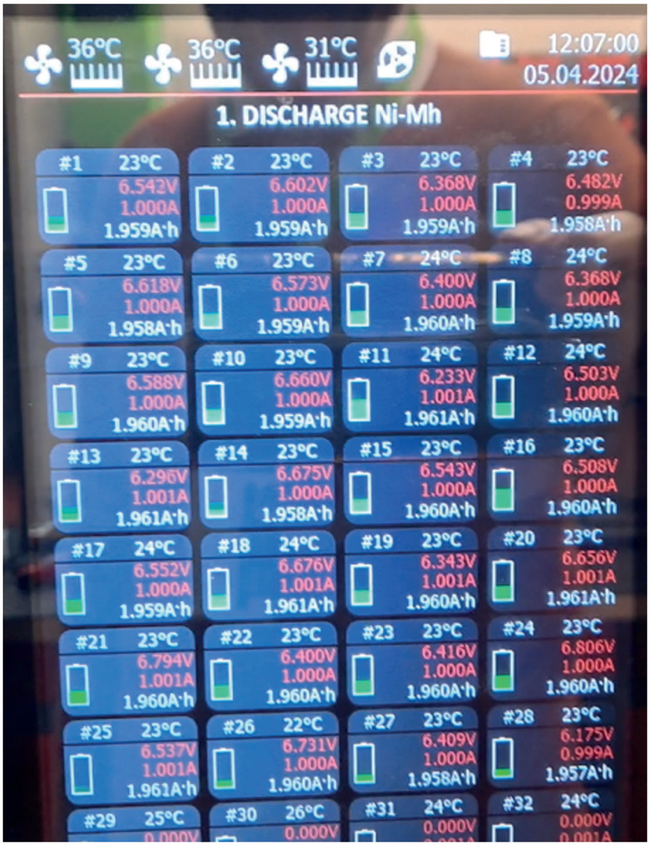

Fig. 4. Battery cell tester panel during operation

The system for controlled charging and discharging of 38 lithium-ion battery cells simultaneously is able to provide an assessment of the technical condition of all battery cells simultaneously for all solutions used in Toyota hybrid vehicles.

The measurement and research system is used to assess the state of balancing the battery pack by the BMS built into the vehicle and to assess the capacity of all battery cells in the pack. In the case where some cells are more charged than others, the battery will not be able to use its full capacity. Cells that are more charged will discharge faster than others, which leads to a reduction in the total capacity of the set. Balancing allows for even use of each battery, thanks to which the full capacity of the set can be used.

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2.3. Methodology

In the 21st century, many diagnostic devices are Internet of Things devices. This means that these devices are able to acquire, save and process measurement data and use Internet technologies and cloud data storage for this purpose. Thanks to such functions, it is possible to accurately analyze diagnostic data online and offline. Based on previous experience with the Metalog probability distribution family [29], the authors chose to apply this well-established analytical tool to evaluate the technical condition of traction battery systems. Up to now, both the developers of this methodological approach and other researchers have employed the Metalog family of probability distributions across multiple scientific domains [28, 69]. The methodology has already been effectively utilized by the authors to support the selection of electric vehicles compatible with specific photovoltaic systems and to evaluate the potential production of yellow hydrogen derived from renewable energy inputs [34, 35, 49].

The methodology developed for this study focuses on the systematic diagnostics of traction battery packs from Toyota hybrid vehicles. The procedure has been designed to ensure reproducibility, safety, and accurate evaluation of the technical condition of individual battery cells as well as the entire pack.

The diagnostic workflow consists of the following stages:

1. Removal and preparation of the battery pack: the traction battery is carefully disconnected from the vehicle, with all safety protocols observed. The outer casing is inspected visually for mechanical damage, leaks, or corrosion.
2. Segmentation of the pack: the battery is separated into individual modules and cells. Electrical connections are secured and properly insulated before testing.
3. Initial measurements: open-circuit voltage (OCV) of each cell is recorded prior to cycling. The state-of-charge (SoC) is adjusted to approximately 30–50% to ensure safe and standardized test conditions.
4. Controlled charge–discharge cycles: cells are subjected to repeated charge and discharge processes at defined current levels (typically 0.5–1 C), until cut-off voltages are reached. The test sequence enables assessment of cell capacity, internal resistance, voltage stability, and thermal behaviour.
5. Data recording and analysis: all measured parameters are logged digitally, processed using statistical tools, and evaluated in relation to nominal values of new cells.

The following parameters are measured and analyzed:

- Capacity (Ah): calculated from the total discharged energy during controlled cycling.
- Internal resistance (mΩ): determined from voltage drops under defined load conditions.
- Voltage (V): monitored throughout charging/discharging to evaluate deviations from expected profiles.

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- Temperature (°C): recorded using integrated sensors to detect potential overheating or hotspots.
- Balancing condition: assessed by comparing voltage differences across cells.

All diagnostic tests are conducted under controlled ambient conditions of 20–25°C. The battery state-of-charge prior to testing is standardized (30–50%) to minimize safety risks and ensure comparability. Discharge tests are performed until the lower cut-off voltage of each cell is reached, while charging is stopped at the maximum rated voltage.

Due to the high voltages involved (up to 200–250 V for Toyota hybrid packs), strict safety procedures are followed:
- Use of protective insulated gloves and tools certified for up to 1 kV.
- Verification of pack voltage before disassembly.
- Secure work area with insulated mats and fire extinguishers suitable for lithium-based cells.
- Prevention of accidental short-circuits by insulating connectors and using appropriate fixtures.
- Continuous monitoring of cell temperatures during cycling to prevent thermal runaway.

A key element of the methodology is the specialized system for controlled charging and discharging of up to 38 battery cells simultaneously. The device allows precise adjustment of current and voltage profiles and provides real-time monitoring of all test parameters. Key specifications include:
- Voltage measurement accuracy: ±0.01 V.
- Current measurement accuracy: ±0.02 A.
- Temperature measurement accuracy: ±1°C (via integrated thermocouples).
- Adjustable charge/discharge currents from 0.1 A to 10 A.
- Data logging and communication via USB/Ethernet for further statistical analysis.

The system's color display presents real-time data for each cell, including discharge current, instantaneous voltage, cumulative capacity, and temperature. Results are automatically stored for subsequent processing using the Metalog probability distribution family, which provides a flexible statistical framework for assessing degradation.

3. Results

From among the many battery packs tested from Toyota hybrid vehicles, the authors selected 3 characteristic cases. Using the device described in Chapter 2.2, all individual cells in the battery pack were completely discharged. Then, they were recharged and then subjected to controlled discharge. It is during controlled discharge that the reserve energy capacity of individual cells is determined. Its value is then related to the nominal energy capacity of the

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battery cells, which characterizes their properties at the beginning of their life. The nominal energy capacity for all battery packs is 6.5 Ah.

3.1. Case 1

Case 1 is an example of natural degradation of battery pack performance. After completing the tests of all cells, the measuring device automatically generates a report of the tests performed. Such a report contains the measured capacities of individual cells of the pack (Figure 5), the results of the battery pack discharge measurements (Table 1), the course of the voltage of individual cells during the battery pack discharge process (Figure 5), the course of the measurement of the energy capacity of individual cells during the battery pack discharge process (Figure 6) and several other values measured during the tests.

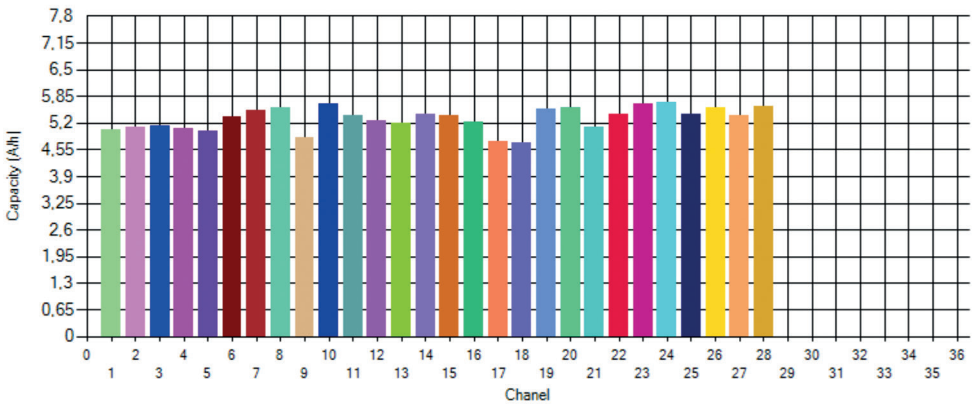

Fig. 5. Measured capacities of individual cells of battery pack 1

The measured reserve capacities of individual battery cells are shown in Figure 5. We can immediately see that all measured capacities are significantly lower than the nominal capacity. The report also includes some processing of the obtained measurement data. The measured values of the energy capacity of individual cells were referred to the maximum capacity and presented in percentages [%]. These data show that the capacity of individual cells in the pack has from 72.7% to 87.48% of the nominal capacity. The table also includes the discharge time of individual cells. As we can see from the data presented in the table, it was over 1 hour.

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Tab. 1. Battery pack 1 discharge measurement results

Cell	Capacity (Ah)	Percent from maximum capacity (%)	Working time	Reason for stopping
1	5.049	77.68	01:07:21	Discharge minimum voltage
2	5.084	78.22	01:07:48	Discharge minimum voltage
3	5.144	79.14	01:08:35	Discharge minimum voltage
4	5.077	78.11	01:07:42	Discharge minimum voltage
5	5.013	77.12	01:06:52	Discharge minimum voltage
6	5.359	82.30	01:11:28	Discharge minimum voltage
7	5.506	84.71	01:13:26	Discharge minimum voltage
8	5.567	85.64	01:14:15	Discharge minimum voltage
9	4.844	74.53	01:04:37	Discharge minimum voltage
10	5.680	87.39	01:15:46	Discharge minimum voltage
11	5.370	82.62	01:11:37	Discharge minimum voltage
12	5.272	81.10	01:10:18	Discharge minimum voltage
13	5.201	80.01	01:09:21	Discharge minimum voltage
14	5.409	83.22	01:12:09	Discharge minimum voltage
15	5.384	82.83	01:11:48	Discharge minimum voltage
16	5.212	80.19	01:09:31	Discharge minimum voltage
17	4.739	72.90	01:03:00	Discharge minimum voltage
18	4.726	72.70	01:03:01	Discharge minimum voltage
19	5.533	85.13	01:13:47	Discharge minimum voltage
20	5.565	85.61	01:14:12	Discharge minimum voltage
21	5.101	78.47	01:08:03	Discharge minimum voltage
22	5.424	83.45	01:12:20	Discharge minimum voltage
23	5.672	87.26	01:15:38	Discharge minimum voltage
24	5.686	87.48	01:15:51	Discharge minimum voltage
25	5.424	83.45	01:12:20	Discharge minimum voltage
26	5.583	85.90	01:14:24	Discharge minimum voltage
27	5.393	82.97	01:11:54	Discharge minimum voltage
28	5.620	86.46	01:14:58	Discharge minimum voltage

Cells with lower energy capacity reached the minimum discharge voltage faster, as can be seen in Figure 6 and Figure 7. The course of the discharge curve of a battery cell can provide the diagnostician with information about the internal resistance of a given cell. At this stage of diagnostics, special attention should be paid to deviations from the norm. If any battery cell behaves differently than the others, it is immediately treated as suspicious [51]. It is also worth looking at the temperature course of individual cells during charging and discharging. Their higher temperature during tests may also occur during normal operation [65]. The source of the higher temperature should be located and removed in order to protect this specific cell and others in the battery pack. To tell the truth, this is the only information that

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the diagnostician has had to assess the technical condition of individual cells in the battery pack. On this basis, he had to make a decision to classify the battery pack into one of 3 groups:

1. Suitable, for further use [44, 61];
2. Unsuitable, for repair [2, 12];
3. Unsuitable, for recycling [59].

Special precautions must be taken when storing battery cells for repair and recycling and when transporting them [8]. Special containers must be used to transport damaged battery cells [60].

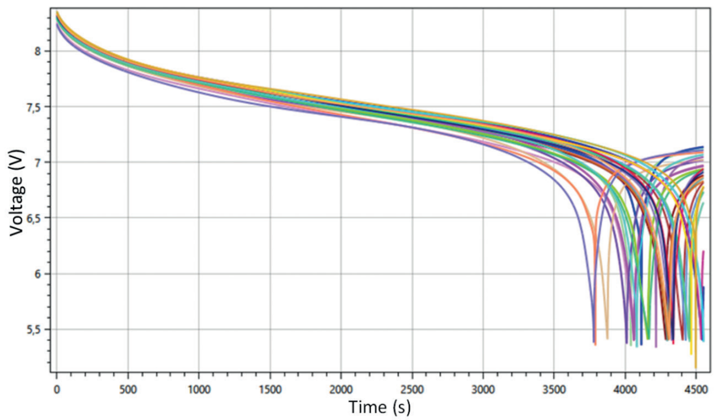

Fig. 6. The voltage curve of individual cells during the discharge process of battery pack 1

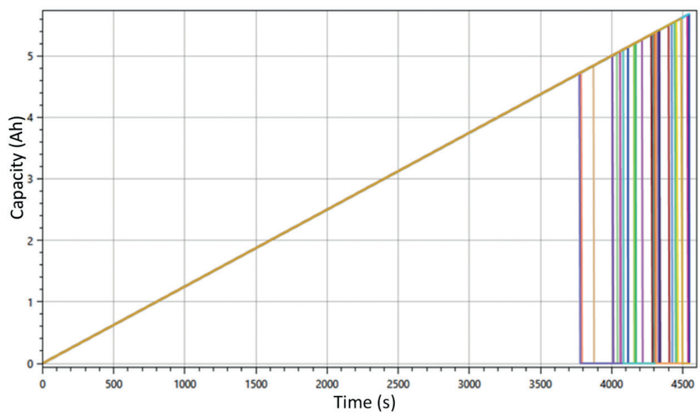

Fig. 7. The course of measuring the energy capacity of individual cells during the discharge process of battery pack 1

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To evaluate the technical condition of the cells in battery pack 1 in a systematic way, the measurement results were subjected to statistical analysis. All calculations were performed using the GeNIe 4.0 Academic software package [68]. In the first step, basic descriptive statistics of the measured capacities were obtained, as presented in Figure 8a. For this pack, the weakest cell exhibited a capacity of 4.726 Ah, while the strongest cell reached 5.686 Ah. The mean capacity of all cells was 5.308 Ah, with a standard deviation of only 0.278 Ah. Such a combination of a relatively high average value and a small spread of results is typical of a battery pack that remains in generally good technical condition. Additional insight is provided by the extended statistical analysis shown in Figure 8b. The percentile-based assessment indicates, for example, that the probability of a cell capacity being lower than 4.739 Ah is only 5%. This confirms that cells with clearly reduced capacity constitute only a small fraction of the entire pack.

Count	28
Minimum	4.726
Maximum	5.686
Mean	5.30846
StdDev	0.278446

(a)

Probability	Battery1
0.05	4.738999843597
0.25	5.100999832153
0.5	5.383999824524
0.75	5.56500005722
0.95	5.679999828339

(b)

Fig. 8. Basic a) and extended b) statistical data for the capacity of individual cells of battery pack 1

The next step of the calculations was to determine the Continous Distribution Function (CDF) and Probability Density Function (PDF) for the capacity of individual cells of battery pack 1. These functions are presented in Figure 9. The Probability Density Function (PDF) provides us with the most information on the technical condition of individual battery cells in the pack. Based on the x-axis range, we can see that all measured capacity values are in the range from 4.7 Ah to 5.7 Ah. The highest probability density occurs for the range from 5.2 Ah to 5.7 Ah with a maximum at about 5.5 Ah. Analysis of the Probability Density Function (PDF) course confirms the good general condition of the entire pack. However, in order to qualify it for selection group 1 – Suitable for further use, the authors recommend replacing all cells with a capacity of less than 5 Ah with cells with a capacity of more than 5.5 Ah. Therefore, only three cells no. 9, 17 and 18 should be replaced. Such a procedure will significantly improve the energy capacity of the entire battery pack.

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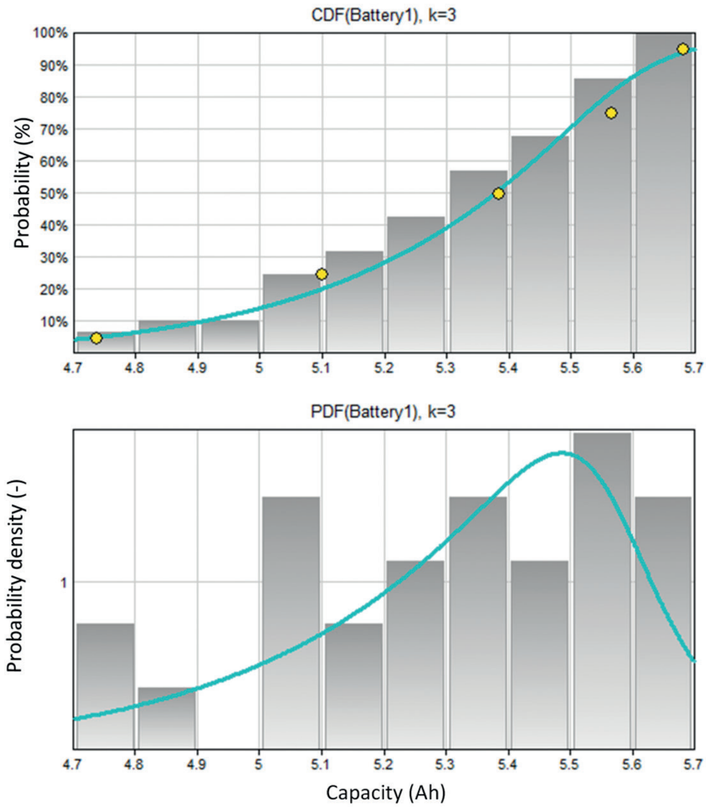

Fig. 9. CDF and PDF for the capacity of individual cells of battery pack 1

3.2. Case 2

Battery pack 2 already has significantly lower performance than battery pack 1. The measured capacities of individual cells of battery pack 2 shown in Figure 10 clearly show that the average capacity of individual cells in the pack is approaching the value of 3.25 Ah, which is 50% of the rated capacity.

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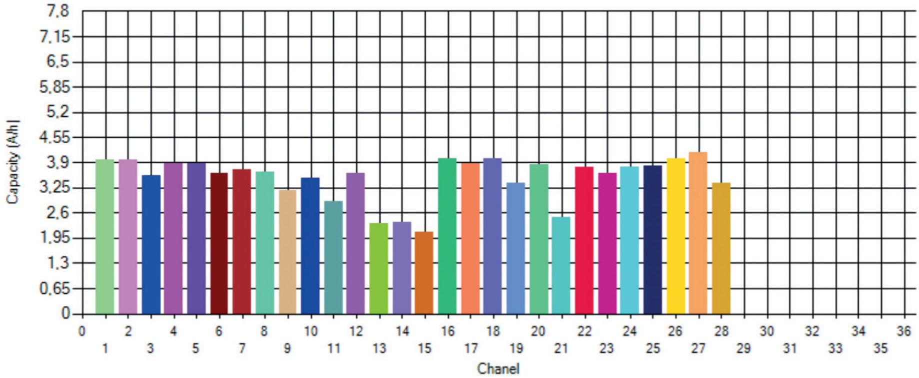

Fig. 10. Measured capacities of individual cells of battery pack 2

The automatic report generated at the end of the tests shows (Figure 10 and Table 2) that the capacity of 6 cells (No. 9, 11, 13, 14, 15, 21) is less than 50% of the nominal capacity. The graph in Figure 10 clearly shows that the cells with the smallest capacity are located next to each other in the entire package. This is especially true for cells No. 9, 11, 13, 14, 15. They are separated by cells No. 10 and 12, the capacity of which is not much more than 50% of the nominal capacity.

Tab. 2. Battery pack 2 discharge measurement results

Cell	Capacity (Ah)	Percent from maximum capacity (%)	Working time	Reason for stopping
1	3.979	61.21	00:59:41	Discharge minimum voltage
2	3.972	61.11	00:59:36	Discharge minimum voltage
3	3.565	54.85	00:53:29	Discharge minimum voltage
4	3.874	59.60	00:58:07	Discharge minimum voltage
5	3.878	59.65	00:58:11	Discharge minimum voltage
6	3.616	55.63	00:54:15	Discharge minimum voltage
7	3.724	57.30	00:55:53	Discharge minimum voltage
8	3.644	56.07	00:54:41	Discharge minimum voltage
9	3.187	49.04	00:47:49	Discharge minimum voltage
10	3.494	53.76	00:52:26	Discharge minimum voltage
11	2.882	44.34	00:43:14	Discharge minimum voltage
12	3.608	55.51	00:54:08	Discharge minimum voltage
13	2.322	35.72	00:34:50	Discharge minimum voltage
14	2.366	36.40	00:35:30	Discharge minimum voltage
15	2.103	32.35	00:31:33	Discharge minimum voltage
16	4.005	61.61	01:00:05	Discharge minimum voltage
17	3.857	59.34	00:57:51	Discharge minimum voltage

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Tab. 2. Battery pack 2 discharge measurement results; cont.

Cell	Capacity [Ah]	Percent from maximum capacity [%]	Working time	Reason for stopping
18	3.994	61.44	00:59:55	Discharge minimum voltage
19	3.373	51.89	00:50:35	Discharge minimum voltage
20	3.853	59.27	00:57:48	Discharge minimum voltage
21	2.480	38.16	00:37:13	Discharge minimum voltage
22	3.761	57.86	00:56:25	Discharge minimum voltage
23	3.620	55.69	00:54:18	Discharge minimum voltage
24	3.766	57.94	00:56:30	Discharge minimum voltage
25	3.816	58.70	00:57:14	Discharge minimum voltage
26	4.006	61.64	01:00:05	Discharge minimum voltage
27	4.147	63.80	01:02:12	Discharge minimum voltage
28	3.359	51.67	00:50:24	Discharge minimum voltage

The basic statistical data for the capacity of individual cells of battery pack 2 (Figure 11a) confirm what was already visible to the naked eye in Figure 10. This concerns the average capacity value and the standard deviation. It is noteworthy that the maximum measured capacity value is only 4,147 Ah, which is only 63.8% of the nominal capacity. The extended statistical data for the capacity of individual cells of battery pack 2 (Figure 11b) confirm that 95% of the cells have a capacity of less than 4,006 Ah.

Count	28
Minimum	2.103
Maximum	4.147
Mean	3.50896
StdDev	0.567433

(a)

Probability	Battery2
0.05	2.322000026703
0.25	3.37299990654
0.5	3.723999977112
0.75	3.878000020981
0.95	4.006000041962

(b)

Fig. 11. Basic a) and extended b) statistical data for the capacity of individual cells of battery pack 2

And again, the most information about the technical condition of the entire pack is provided by the Probability Density Function (PDF), shown in Figure 12. Its clear maximum occurs for a capacity of about 4 Ah. This means that there are few cells with significantly lower capacities that can be replaced. We are talking about cells no. 9, 11, 13, 14, 15. Replacing them with cells with a capacity higher than 3.8 Ah can significantly increase the capacity of the entire battery pack. However, the authors also recommend replacing cells no. 10 and 12. They are located in the vicinity of cells with the lowest capacity. The presence of many cells with significant performance degradation in close proximity may indicate other than natural causes of capacity loss. These may be local overheating, which affected an increasing number of cells.

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When installing replacement cells to battery pack 2, special attention should be paid to the quality of the electrical connections between the replaced cells. In the context of Case 2, a discussion should be held on the qualification of the pack in question for a given selection group. For the authors, this is clearly selection group 2. Unfit for repair. After replacing cells no. 9, 10, 11, 12, 13, 14, 15, the pack will obtain over 50% of its nominal capacity. According to the authors, this is a sufficient amount of energy for the hybrid vehicle to continue to contribute to the recovery of braking energy and support for dynamic states, especially during city driving. The energy capacity, significantly reduced in relation to the nominal value, will not, however, allow for the accumulation of larger amounts of energy and its use, for example, during extra-urban driving. The above line of reasoning is confirmed by the fact that the latest lithium-ion battery has a capacity of 0.75 kWh, which is 57.6% compared to the capacity of older batteries with a capacity of 1.3 kWh.

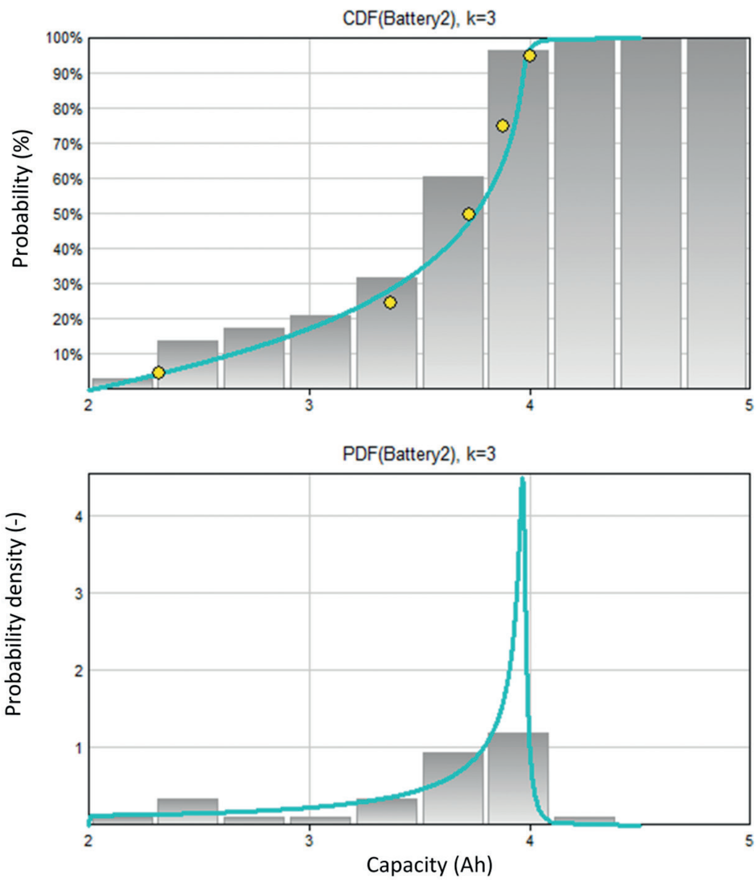

Fig. 12. CDF and PDF for the capacity of individual cells of battery pack 2

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3.3. Case 3

Case 3 presents the process of diagnosing the correctness of the operation and assessing the technical condition of the battery pack with the poorest performance. It was also the longest used pack of all three presented in the article. From the interview conducted with the vehicle user, it was possible to obtain information that the vehicle was becoming less economical over time and was characterized by poorer performance during acceleration. The tests of the energy capacity of individual cells are presented in Figure 13. They clearly show that most of the cells are characterized by a very small capacity of less than 2 Ah. Remember that it is the cells with the lowest energy capacity that affect the total energy capacity of the entire battery pack.

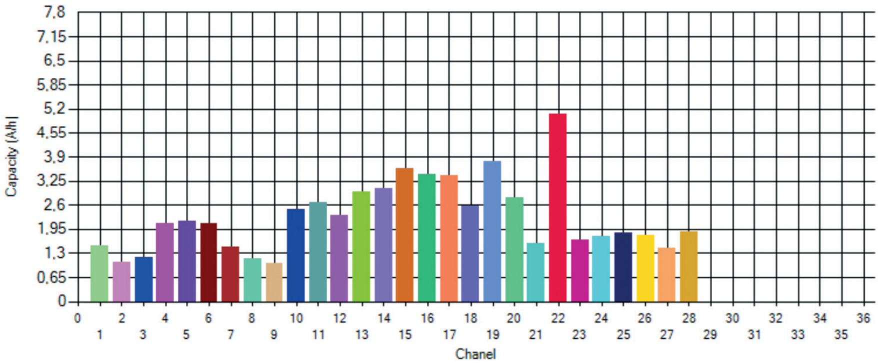

Fig. 13. Measured capacities of individual cells of battery pack 3

The measurement results presented in the tabular version (Table 3) immediately determine the numerically fatal condition of the entire battery pack. The weakest cells no. 2 and 9 retained only 16.08 and 15.62% of the nominal capacity, respectively. With the total capacity of the battery pack less than 20% of the nominal capacity, one cannot count on storing a large amount of energy from regenerative braking in this pack and releasing it during vehicle acceleration.

Tab. 3. Battery pack 3 discharge measurement results

Cell	Capacity (Ah)	Percent from maximum capacity (%)	Working time	Reason for stopping
1	1.491	22.94	00:22:22	Discharge minimum voltage
2	1.045	16.08	00:15:41	Discharge minimum voltage
3	1.174	18.07	00:17:37	Discharge minimum voltage
4	2.106	32.40	00:31:36	Discharge minimum voltage
5	2.178	33.51	00:32:41	Discharge minimum voltage
6	2.104	32.37	00:31:34	Discharge minimum voltage
7	1.463	22.50	00:21:57	Discharge minimum voltage

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Tab. 3. Battery pack 3 discharge measurement results; cont.

Cell	Capacity [Ah]	Percent from maximum capacity [%]	Working time	Reason for stopping
8	1.141	17.55	00:17:07	Discharge minimum voltage
9	1.015	15.62	00:15:14	Discharge minimum voltage
10	2.466	37.93	00:37:00	Discharge minimum voltage
11	2.677	41.19	00:40:10	Discharge minimum voltage
12	2.332	35.87	00:34:59	Discharge minimum voltage
13	2.960	45.55	00:44:25	Discharge minimum voltage
14	3.059	47.07	00:45:54	Discharge minimum voltage
15	3.589	55.22	00:53:51	Discharge minimum voltage
16	3.413	52.50	00:51:12	Discharge minimum voltage
17	3.381	52.02	00:50:43	Discharge minimum voltage
18	2.565	39.46	00:38:29	Discharge minimum voltage
19	3.772	58.03	00:56:34	Discharge minimum voltage
20	2.790	42.93	00:41:52	Discharge minimum voltage
21	1.550	23.85	00:23:16	Discharge minimum voltage
22	5.061	77.86	01:15:55	Discharge minimum voltage
23	1.671	25.70	00:25:04	Discharge minimum voltage
24	1.748	26.90	00:26:14	Discharge minimum voltage
25	1.840	28.30	00:27:36	Discharge minimum voltage
26	1.800	27.69	00:27:00	Discharge minimum voltage
27	1.443	22.20	00:21:39	Discharge minimum voltage
28	1.889	29.06	00:28:21	Discharge minimum voltage

The basic statistical data (Figure 14a) for the capacity of individual cells of battery pack 3 clearly indicate a very large spread between the maximum and minimum capacity values. It amounts to almost 4 Ah. The average capacity value is very small and amounts to only 2.276 Ah. The standard deviation is the largest of all the cases studied and amounts to 0.967 Ah. The percentile analysis indicates a very large share of cells with low capacity in the pack. The probability of a cell capacity of less than/equal to 2.106 Ah is as much as 50%. The probability of a cell capacity of less than/equal to 3.772 Ah is as much as 95%.

Count	28
Minimum	1.015
Maximum	5.061
Mean	2.27582
StdDev	0.966979

(a)

Probability	Battery3
0.05	1.044999957085
0.25	1.549999952316
0.5	2.105999946594
0.75	2.960000038147
0.95	3.772000074387

(b)

Fig. 14. Basic a) and extended b) statistical data for the capacity of individual cells of battery pack 3

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From the course of the Probability Density Function (PDF) for the capacities of individual cells of battery pack 3, one can immediately notice very high probability densities occurring for small capacities with a value of d1 to 2 Ah (Figure 15). This completely disqualifies this battery pack from further use. It should be classified into selection group 3. Unsuitable, for recycling. However, the course of the Probability Density Function (PDF) tells us that there are cells in this pack with capacities of approx. 4 Ah and approx. 5 Ah. Battery cell no. 22 with a capacity of 5.061 Ah can be successfully used in Case 1. Battery cells no. 15, 16, 17 and 19 with capacities above 3.3 Ah can be used in an extreme situation (no cells with a capacity higher than 3.8 Ah) in Case 2, significantly improving the capacity of the entire battery pack. The authors' approach to diagnosing and repairing hybrid vehicle battery packs involves reusing the battery cells to restore the performance of the entire battery pack. However, they should undergo detailed testing before being reused in another pack. After replacing the battery cells, the entire pack should be fully charged and discharged again. Battery cells with a capacity of less than 3.3 Ah should be recycled by a company that provides this type of service.

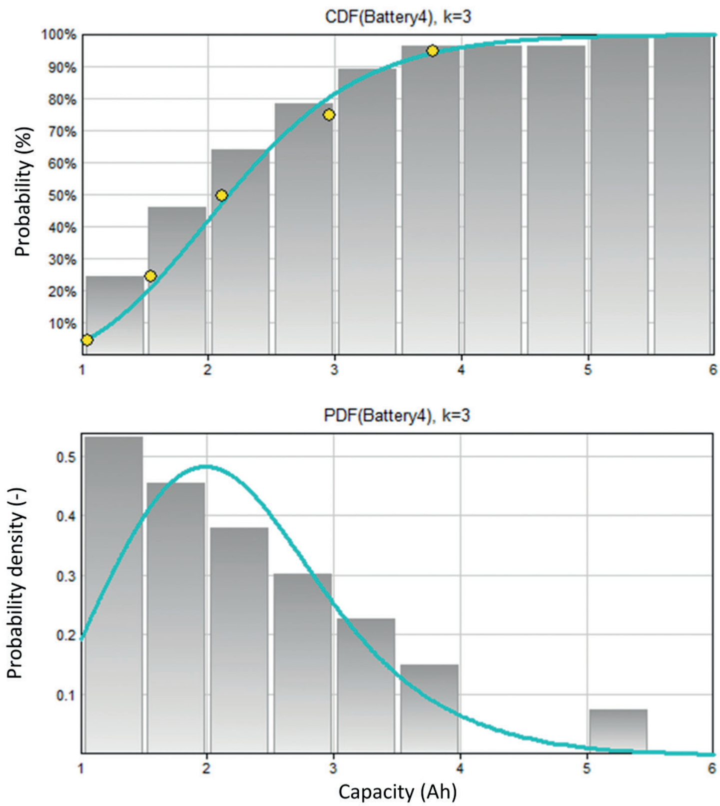

Fig. 15. CDF and PDF for the capacity of individual cells of battery pack 2

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4. Conclusions

The maintenance, diagnostic and repair of battery packs from hybrid vehicles results from market demand. A very large number of hybrid vehicles present on the Polish and European markets require diagnostics and repairs of battery packs after many years of operation. The article presents, tests and analyses 3 cases of battery packs from hybrid vehicles. They show that performance degradation processes can occur due to natural causes and in a slow manner (Case 1). Case 2 confirms the accelerated loss of capacity by neighboring battery cells, which were damaged probably as a result of overheating. Case 3 is an example of long-term operation of a battery pack in a hybrid vehicle without any control of the technical condition of the battery. This led to the loss of energy capacity by most of the cells constituting the pack.

The approach to diagnostics and repair of battery packs from hybrid vehicles presented by the authors assumes the reuse of battery cells in order to regenerate the performance of the entire battery pack. This approach is consistent with current trends related to the regeneration of automotive components and extending the life of individual components and thus entire vehicles.

A mobile service designed for the diagnosis and repair of electric vehicles, together with laboratory and test equipment, is a very useful facility for providing services of this type in various places. In particular, the device for the simultaneous controlled charging and discharging of 36 battery cells is helpful in effective diagnostics of individual battery cells and determining the technical condition of the entire battery pack. The authors demonstrated the usefulness of statistical methods and the Metalog probability distribution family for determining the technical condition of battery packs from hybrid vehicles. Processing the data obtained in the research using scientific tools effectively supports the selection of battery packs due to their suitability for further operation, the need for repair and withdrawal from use by sending for recycling. The applied approach to assessing the technical condition of traction batteries is already used by one of the Lublin workshops dealing with the repair of electric and hybrid vehicles. In the future, the authors intend to extend the research to other types of traction batteries used in electric and hybrid vehicles.

The results presented in this article confirm that traction battery diagnostics is not only a technical necessity but also a decisive factor in the economic viability of electric and hybrid vehicles. Since the battery pack represents more than half of the value of a new electric vehicle, even partial recovery or extension of its useful life leads to significant cost savings for the user and reduces the demand for new raw materials. The applied methodology, combining controlled charging/discharging tests with statistical tools from the Metalog distribution family, provides a scientific basis for practical decision-making in repair or recycling. Thus, the proposed approach contributes to more sustainable development of electromobility and reinforces the role of diagnostics as a crucial element in maintaining the competitiveness and environmental performance of modern vehicles.

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5. Nomenclature

BEV	Battery Electric Vehicles
BMS	Battery Management System
CDF	Continous Distribution Function
CNG	Compressed Natural Gas
FCV	Fuel Cell Vehicle
HEV	Hybrid Electric Vehicle
HVO	Hydrogenated Vegetable Oil
LNG	Liquide Natural Gas
LPG	Liquide Petroleum Gas
LTO	Lithium Titanium Oxide
NG	Natural Gas
NiMH	Nickel-Metal Hydride
NMC	Nickel Manganese Cobalt
OBD	On-board diagnostics system
OCV	Open-circuit voltage
PCB	Printed Crcuit Boards
PDF	Probability Density Function
PHEV	Plug-in Hybrid Electric Vehicle
RES	Renewable Energy Source
SMD	Surface-mounted components
SoC	State of Charge
TMS	Thermal Management System

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