energies

Article

A Method for Assessing the Technical Condition of Traction Batteries Using the Metalog Family of Probability Distributions

Jacek Caban [1,*], Arkadiusz Małek [2] and Dariusz Kroczyński [3]

1 Department of Automation, Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 36, 20-618 Lublin, Poland
2 Department of Transportation and Informatics, WSEI University, Projektowa, 20-209 Lublin, Poland; arkadiusz.malek@wsei.lublin.pl
3 Dakro, Nałęczowska 73, 20-701 Lublin, Poland; dk@dakro.pl
* Correspondence: j.caban@pollub.pl

Abstract: The aim of the research presented in the article is to use the Metalog family of probability distributions to assess the technical condition of traction battery packs from electric and hybrid vehicles. The description of the research object, which is a battery pack from a hybrid vehicle, will be provided. Then, a system for controlled charging and discharging of individual cells in a battery pack will be reviewed. It is an essential diagnostic and research device used to determine the capacity of individual cells. The capacity values of all battery cells will then be analyzed using the Metalog probability distribution family. The use of this tool allows us to determine the Probability Density Function for the entire battery pack. Based on this, the diagnostician is able to assess the technical condition of the tested package and decide on its further fate. It can be intended for repair, employed as a stationary energy storage facility, or used for disposal. The algorithm for assessing the technical condition of traction batteries proposed by the authors can be used in all battery packs regardless of the type of cells used and their energy capacity.

Keywords: traction batteries; energy storage; diagnostics; Metalog; artificial intelligence

Citation: Caban, J.; Małek, A.; Kroczyński, D. A Method for Assessing the Technical Condition of Traction Batteries Using the Metalog Family of Probability Distributions. *Energies* **2024**, *17*, 3096. https://doi.org/10.3390/en17133096

Academic Editor: Ali Saberi Mehr

Received: 12 May 2024
Revised: 15 June 2024
Accepted: 20 June 2024
Published: 23 June 2024

1. Introduction

Currently, there is an increasingly noticeable tendency to adopt electric vehicles in the transport sector. This is manifested in the increasing number of models presented by manufacturers of trucks, city buses, and passenger cars. This situation is confirmed by numerous scientific and research publications in this area, of which it is worth mentioning, for example: [1–14]. Despite the growing interest in electric vehicles, alternative fuels for piston combustion engines are constantly being developed. Gas fuels such as LPG for gasoline [15,16] and diesel engines [17,18], NG [19], CNG and LNG [20–22], various biofuels [23,24], and biodiesel from various raw materials [25–30] or hydrogenated vegetable oil (HVO) [31,32] are the examples of this progress. Another expanding field of research is related to fuel cells [33,34]. Recently, there has been a lot of emphasis placed on hydrogen as a possible fuel. The following research studies are interesting in this area [35–38]. As can be concluded from the abovementioned examples, the transport sector has many challenges ahead, and the next most urgent one today is the development of electric vehicles and providing them with the appropriate amount of energy.

Traction batteries are found in both electric and traditional vehicles. In battery vehicles (BEV—Battery Electric Vehicles), traction batteries are charged from external sources of electricity. The energy stored in them is used to drive the traction electric motor, which is the only source of drive for the vehicle's wheels. Of course, such a battery is recharged with the energy recovered during regenerative braking. This significantly increases the range of the electric vehicle, especially in city traffic, where the act of braking certainly occurs often. Hybrid vehicles have two drive sources. The first is the internal combustion engine, which is the main source of propulsion for the vehicle, especially on longer routes. The second is the electric drive system, which supports the operation of the combustion engine, especially during acceleration. In hybrid vehicles (HEV—Hybrid Electric Vehicle), traction batteries collect energy generated during braking [39]. The second source of electrical energy for charging the traction battery in a hybrid vehicle is an internal combustion engine operating under more steady-state operating conditions, driving a generator. However, the latest version of hybrid vehicles with the ability to recharge the traction battery from external sources is increasingly appearing on the market and in workshops. It is called a Plug-in hybrid (PHEV—Plug-in Hybrid Electric Vehicle).

Vehicle traction batteries usually consist of individual lithium-ion cells that are connected in series and parallel to form battery modules, which in turn form battery packs. Series connection allows an increase in the voltage of the entire package, and parallel connection allows an increase in the charging and discharging current of the packages. Small electric city vehicles, hybrid vehicles, and small electric commercial vehicles have battery packs with a capacity of several kWh. Electric vehicles of the Compact class (and higher classes) have traction battery packs with a capacity from 40 to 100 kWh. As a result of this, these vehicles have a real range from 400 to 500 km on a single charge [40].

One of the directions of research on traction batteries is the possibility of charging them with high currents. Scientists and engineers working in research and development projects have developed and implemented on the market quick charging systems for traction batteries of vehicles with powers of up to 350 kW. Currently, the most popular battery technology used in the automotive industry is lithium-ion batteries of the NMC type (lithium Nickel Manganese Cobalt oxides). They have replaced the previously used LFP ($LiFePO_4$) lithium batteries, which are now used for stationary energy storage due to their lower fire risk [41,42]. It is worth mentioning here that the LTO (Lithium Titanium Oxide) lithium-ion batteries can be charged and discharged with high currents [43]. Their usage significantly shortens the battery charging time.

The entire operation of the traction battery is managed by the BMS (Battery Management System) module. It is responsible for monitoring the voltage and the temperature of individual cells or battery modules in the package. Knowing the voltage values of individual cells, it is able to display the current state of charge of the entire SoC package (State of Charge) to the driver. Moreover, it is able to manage the balancing process of the entire package [44]. Battery voltage balancing involves balancing the charge level of individual cells connected in series or parallel, depending on the design [45]. Each battery has its own individual characteristics and may have slight differences in charge level and internal resistance. As the battery is operated in the vehicle, these differences can increase, leading to uneven wear and the reduced overall performance of the battery pack. Balancing involves adjusting the charge level of each cell to ensure that they are as close to each other as possible. Scientists are currently working on new methods for balancing battery packs, which are intended to significantly increase the number of fully charged and discharged battery packs. This, of course, reduces the aging process of the batteries and extends their proper operation time in the vehicle [46,47]. Scientists have developed, and engineers have already implemented, in industrial practice, a large number of algorithms and techniques that allow the health of individual cells or entire battery packs to be determined [48]. Very interesting and useful methods for assessing the technical condition of batteries from electric vehicles have been described by Hassini et al. [49]. However, the presented methods and decision thresholds apply especially to NMC and LFP battery cells. Various failure modes and capacity degradation mechanisms of NiMH traction batteries were presented by Young et al. [50]. Solutions to increase cycle stability are summarized in useful tables covering cell design, negative and positive electrodes, separators, electrolytes, and other equipment. After examining the single-cell capacity decline problem, the next step recommended by the authors is to investigate the consistency of capacity decline across a multi-cell battery module.

Battery pack diagnostics is a challenging research area that requires extensive knowledge and experience [51]. This is due to the fact that vehicle traction battery packs are complex mechatronic devices. In addition to the cells and the BMS system mentioned above, the battery packs have a thermal management system (TMS) [52]. Its purpose is to heat or cool the battery pack depending on the operating conditions. Preheating typically occurs when starting a cold electric vehicle at low ambient temperatures [53]. Cooling is required, especially when charging the batteries quickly and with high power [54]. Appropriate temperature management of individual battery cells contributes to extending the time of their correct operation and increases the safe use of the entire electric vehicle. Due to the important role of TMS, scientists are still developing the components for its construction and algorithms for their effective control [55,56]. Due to the complex structure of automotive battery packs, their diagnostics must involve checking the correct operation of each component, mechanical and electrical connections, and the control of these components [57]. The diagnostician must also have advanced diagnostic devices to establish data transmission with the battery pack installed in the vehicle or removed from the vehicle. Battery pack diagnostics usually allow the pack to be qualified for repair or disposal [58,59]. Presently, the oldest battery packs in Toyota hybrid vehicles are over 25 years old. They are often still functional and used. Sometimes, they require small mechanical or electrical repairs or replacement of individual components. Sometimes, the damage to battery packs due to overheating, flooding, or fire is so great that it can only be disposed of [60]. Automotive companies are forced to take responsibility for battery packs introduced to the market after the period of proper vehicle operation has ended. Scientists are working on ways to design battery packs so that they are easy to disassemble and dispose of [61–64]. In the area of battery cell production, scientists are developing, and engineers are trying to apply innovative production methods in practice, such as 3D printing [65]. A big challenge is to reduce energy consumption in the entire production process of traction batteries [66]. An important aspect of research and development is increasing safety, especially related to the mobile use of traction batteries [67–69]. Electrical and thermal modeling [70] is used to develop even faster methods of charging traction batteries [71,72]. Materials engineering is of great importance in this area [73,74]. The traction battery packs for automotive applications are characterized by high energy capacities. Their production and later disposal should be environmentally friendly [75].

If the traction battery loses more than 20% of its nominal energy capacity, the vehicle owner should consider its diagnosis and repair [76]. If the repair processes are not able to restore higher performance and the traction battery is still functional and safe, it may have other uses. The second life of a traction battery can usually be in the form of a stationary energy storage device [77,78]. In this application, the maximum energy capacity is not as important as in a vehicle, where it directly affects the range of the electric vehicle. The attractive price and relatively high energy capacity of the used traction battery pack make people willing to buy them and use them to store the surplus energy produced by photovoltaic systems [79–81]. This is a way to become independent from the energy obtained from the power grid.

Electric vehicles are the most ecological if the energy from Renewable Energy Sources is used to charge their traction batteries. More and more often, owners of single-family houses design and build a photovoltaic system with a sufficiently high peak power so that it can supply both the house and an electric vehicle with electricity [82,83]. Electric vehicles are the important components in the home energy production and consumption systems [84]. Their large number and, consequently, high demand for energy must be taken into account in national energy strategies [85].

The aim of the research presented in this article is to use the Metalog family of probability distributions to assess the technical condition of traction battery packs from electric and hybrid vehicles [86]. The second chapter will describe the research object, which is a battery pack from a hybrid vehicle. Then, a system for controlled charging and discharging of individual cells in a battery pack will be presented. It is an essential diagnostic and research device used to determine the capacity of individual cells. The capacity values of all battery cells will then be analyzed using the Metalog family of probability distributions [87]. Using this tool will allow us to determine the Probability Density Function for the entire battery pack. Based on its progress, the diagnostician will be able to assess the technical condition of the tested package and decide on its further fate. It can be intended for either repair, it could be used as a stationary energy storage facility, or only for disposal. The algorithm for assessing the technical condition of traction batteries proposed by the authors can be applied in all battery packs regardless of the type of cells used and their energy capacity.

The Metalog family of probability distributions turned out to be very effective, and the authors used it to select the power of the photovoltaic system for their electric vehicle and vice versa [88]. Metalog is a flexible probability distribution that can be used to model a wide range of density functions using only a small number of parameters obtained from experts. Scientists prefer using the Metalog family of distributions to describe processes in various fields of science, such as theology, mathematics, and electronics. A mathematical description and many interesting examples can be found on the website of the authors of this methodology [89].

2. Research

2.1. Research Objects

The objects of the research will be the battery packs from Toyota hybrid vehicles. The appearance of the traction battery packs from Toyota hybrid vehicles is shown in Figure 1. The new battery made of nickel-metal hydride (NiMH) cells is smaller and lighter than older solutions due to the changed structure of the set and the use of a compact cooling system. The capacity is identical in both hybrid solutions (6.5 Ah), but the battery has a larger number of cells (180, previously 168) and operates at a higher voltage (216 V, previously 201.6 V). The upper drawing in Figure 1 shows the battery pack with wiring, and the lower drawing shows the battery pack without wiring. The presentation of the electrical diagram seems unnecessary to us because the package contains 28 series-connected battery cells. An electrical diagram is certainly needed for a more complicated battery pack architecture in which there are serial and parallel connections of both cells in modules and modules in the pack.

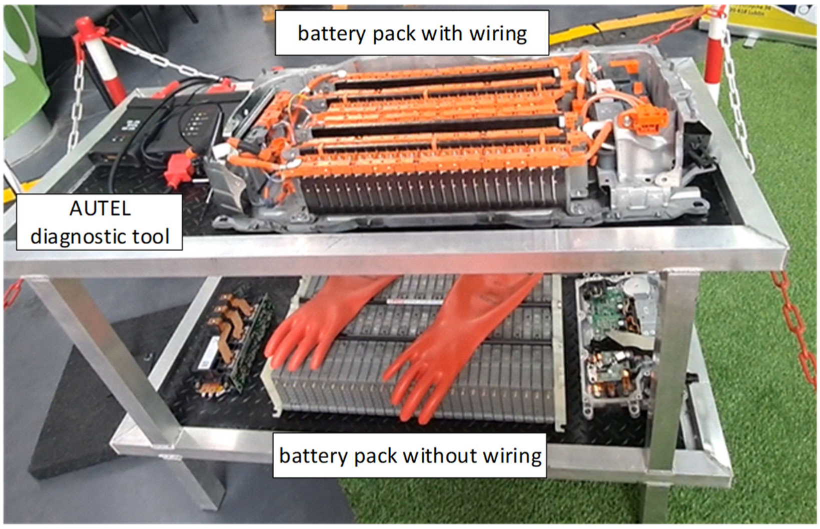

Figure 1. Traction battery packs from Toyota hybrid vehicles.

The NiMH battery (6.5 Ah/201.6 V), very often used in Toyota vehicles, has an energy capacity of approx. 1.3 kWh. In turn, the TS (and HB) models already have a lithium-ion battery with a capacity of approx. 0.75 KWh (3.6 Ah/207.2 V). All such important differences must be known or quickly found by a professional service technician dealing with the repair of hybrid and electric vehicles. A necessary skill of such a service employee is the ability to perform electrical measurements (voltage, current) of individual battery cells as well as the ability to charge and discharge them in a controlled manner. The authors have all the necessary equipment for this purpose.

2.2. Research Bench

A very important device is a system for controlled charging and discharging of 38 lithium-ion battery cells simultaneously. A view of such a device during operation is shown in Figure 2.

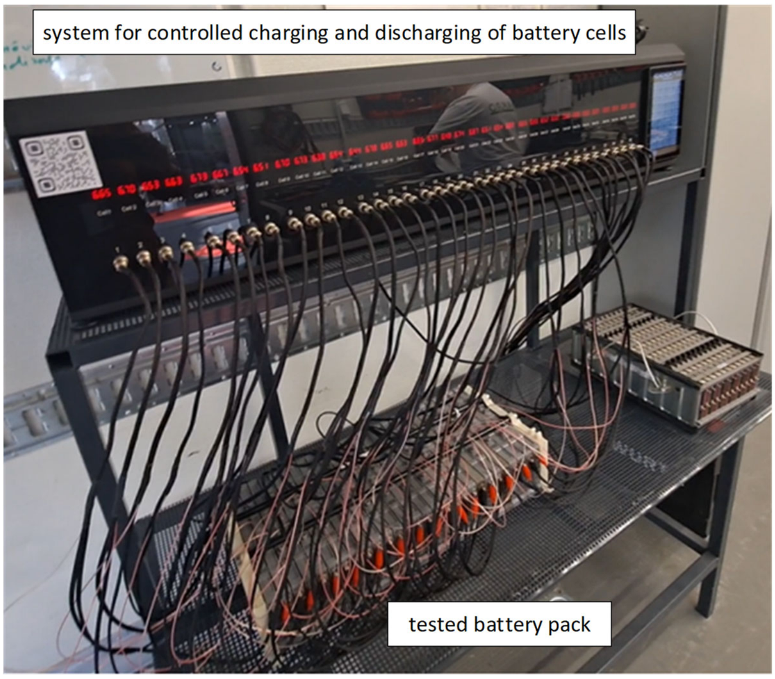

Figure 2. System for controlled charging and discharging of 38 lithium-ion battery cells simultaneously.

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 synchronously for all solutions used in Toyota hybrid vehicles. If we want to test a large battery pack with high energy capacities (from 40 to 100 kWh), then it is necessary to test each battery module or several modules at the same time.

The measurement and research system is used to assess the state of balancing of the battery pack by the BMS installed in the vehicle and to assess the capacity of all battery cells in the pack. One of the main reasons why balancing battery packs is important is to ensure the optimal use of the battery capacity. If some cells are more charged than others, the battery will not be able to use its full capacity. Battery cells with reduced capacity will discharge faster, which will negatively affect the capacity of the entire battery pack. Balancing allows for even consumption of each battery so that the full capacity of the set can be used.

Several factors influence the accuracy of assessing the technical condition of a hybrid vehicle's traction battery. The first one results from the use of a system for controlled charging and discharging of 36 battery cells at the same time. The system ensures that each cell is charged and discharged with the same current. At the same time, the temperature of each cell is monitored. The temperature of the heat dissipation system is also monitored during the pack unloading process. The use of the Metalog family of probability distributions allows us to determine the value of the capacity of battery cells in a package with accuracy in the probability distribution. The use of the presented measurement and analytical method allows for accurate determination of the technical condition of individual battery cells and the entire battery pack. The authors' experience shows that tests of the capacity of individual battery cells should be carried out at a constant ambient temperature in the temperature range of 15 ÷ 25 °C.

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. Due to such functions, it is possible to accurately analyze the available online and offline diagnostic data. Based on previous experience using the Metalog family of probability distributions, the authors decided to employ the known tool also to assess the technical condition of traction battery packs. Measurement data in the form of CSV (Comma Separated Values) records can then be processed using classic methods and artificial intelligence. This approach enables the employment of less qualified employees to examine the technical condition of the traction batteries. However, their work will be supported by the results from the advanced measurement data processing. This approach will also significantly shorten the duration of the diagnostic process itself. Based on the known and interpreted capacity values of individual cells in the battery pack, specific models can be created, and based on them, the pack can be classified into one of the groups: for repair, for use as a stationary energy storage facility, or for disposal. The research was conducted using GeNIe version 4.0, an academic software. This is a tool offered by BayesFusion, a company that deals with data analysis, modeling, and decision support [87].

Before the authors used the Metalog family of probability distributions, car repair shop employees had a very difficult task of classifying battery packs for further operation, repair, or disposal. In the report from the measuring device, they only had the capacity charts of individual battery cells presented in Figure 3, and the table with measurement results presented in Table 1. The diagnosticians themselves had to decide which cells should be replaced and which should be left. Less experienced workers had great difficulty with this. They usually come to their superiors or boss for advice. The research presented in the article allowed for the development of an effective method for assessing the technical condition of batteries and their classification for further use, repair, or disposal.

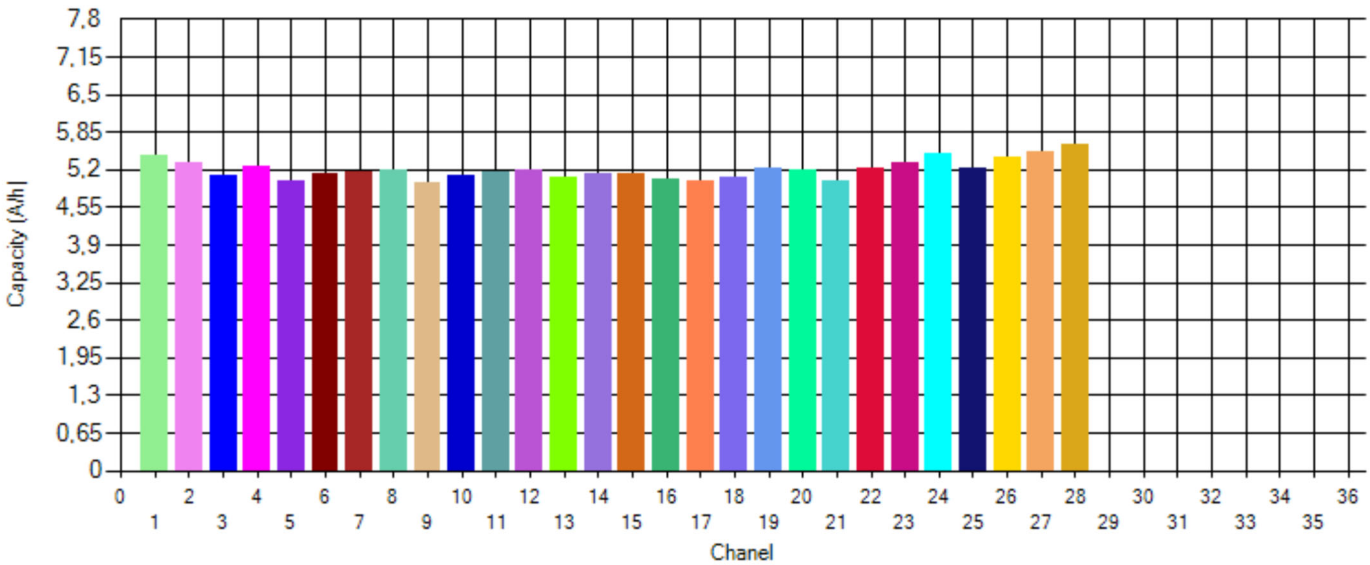

Figure 3. Results of capacity measurements of individual cells of the battery pack from the hybrid Vehicle 1.

Table 1. Results of discharge measurements of individual cells in the hybrid Vehicle 1 battery pack.

Cell	Capacity (A/h)	Percent from Maximum Capacity	Working Time	Reason for Stopping
1	5.445	83.77%	01:05:22	Discharge minimum voltage
2	5.316	81.79%	01:03:49	Discharge minimum voltage
3	5.087	78.25%	01:01:03	Discharge minimum voltage
4	5.245	80.7%	01:02:59	Discharge minimum voltage
5	5.015	77.16%	01:00:13	Discharge minimum voltage
6	5.13	78.93%	01:01:36	Discharge minimum voltage
7	5.158	79.35%	01:01:55	Discharge minimum voltage
8	5.18	79.69%	01:02:11	Discharge minimum voltage
9	4.962	76.34%	00:59:34	Discharge minimum voltage
10	5.084	78.22%	01:01:02	Discharge minimum voltage
11	5.164	79.45%	01:02:00	Discharge minimum voltage
12	5.204	80.06%	01:02:28	Discharge minimum voltage
13	5.071	78.01%	01:00:52	Discharge minimum voltage
14	5.146	79.16%	01:01:46	Discharge minimum voltage
15	5.146	79.18%	01:01:46	Discharge minimum voltage
16	5.039	77.52%	01:00:30	Discharge minimum voltage
17	5.01	77.08%	01:00:08	Discharge minimum voltage
18	5.063	77.9%	01:00:46	Discharge minimum voltage
19	5.234	80.52%	01:02:49	Discharge minimum voltage
20	5.206	80.09%	01:02:29	Discharge minimum voltage
21	4.995	76.85%	00:59:59	Discharge minimum voltage
22	5.236	80.55%	01:02:51	Discharge minimum voltage
23	5.309	81.67%	01:03:44	Discharge minimum voltage
24	5.489	84.44%	01:05:55	Discharge minimum voltage
25	5.24	80.61%	01:02:54	Discharge minimum voltage
26	5.42	83.39%	01:05:03	Discharge minimum voltage
27	5.508	84.74%	01:06:07	Discharge minimum voltage
28	5.633	86.67%	01:07:39	Discharge minimum voltage

3. Discussion

Research on the test stand presented in Section 2.2 was carried out for four curious cases. Each of them is different, which is confirmed by the classic statistical methods as well as the latest tools using advanced Metalog probability distributions [88]. For each case, measurement results will be presented, and the analysis of the obtained results will be performed. A case study will be conducted for each battery pack, which will be supported by an expert description of the research itself and the selected contexts related to the probable use of the battery being studied. This is possible because the authors have extensive experience in the diagnosis, servicing, and repair of electric vehicles. The authors also cooperate with a local company dealing with such repairs. The research and development projects are carried out together and can be quickly implemented in the workshop practices.

3.1. Case 1

To start with, it is always worth analyzing a positive case. The first battery pack came from a several-year-old hybrid vehicle. The owner did not observe any negative signs in the operation of the hybrid drive system. The reason for conducting the tests was the owner's curiosity about whether his vehicle was working properly. The battery pack was removed from the vehicle, and tests were carried out, consisting of the complete discharge of all battery cells and their controlled recharging and discharging. The measurement results presented in this article refer to the final controlled discharge process of the battery cells.

The software included in the device allows it to automatically generate a report on the tests performed. The results of measuring the capacity of individual cells in the battery pack from a hybrid vehicle are shown in Figure 3. The results of measuring the discharge of individual cells in the battery pack are shown in Table 1. The table includes the number of a specific battery cell and its calculated capacity, the percentage of maximum capacity, and the discharge time. The table was taken from a report automatically generated by the measurement system. The comma as the decimal separator has been retained.

At first glance, the measurement data presented in Figure 3 supports the initial assessment that the capacities of individual battery cells have quite large values and are similar to each other. A lot of information about the technical condition of the tested battery pack is provided by relating the measured capacity value of a given battery cell to the reference value. Such a reference value may, of course, be the nominal capacity value for a new vehicle. The nominal capacity value for the cells in this pack is 6.5 Ah. The measurements and calculations presented in Table 1 indicate that the capacities of individual cells range from 76.34 to 86.67% of the nominal capacity. A diagnostician performing the tests at a measurement and testing station knows this much about the technical condition.

By making further statistical calculations, we can learn more about the technical condition of the tested package. The basic statistical analysis of the capacity of individual cells of the battery pack from the hybrid Vehicle 1 is presented in Table 2. It shows that the minimum value of the capacity was 4962 Ah, and the maximum value was 5633 Ah. The average value for all 28 cells was 5.20482 Ah with a standard deviation of 0.169515 Ah.

Table 2. Basic statistical analysis of the capacity of individual cells in the battery pack from the hybrid Vehicle 1.

Count	**28**
Minimum	4.962
Maximum	5.633
Mean	5.20482
StdDev	0.169515

For the tested package, a histogram of the capacity of individual cells of the battery pack from the hybrid Vehicle 1 was prepared along with the course of the normal distribution, which is presented in Figure 4. Both the histogram, the Empirical Distribution Function (Figure 5), and the Probability Density Function (Figure 6) show that the obtained measurement results are very close to a normal distribution.

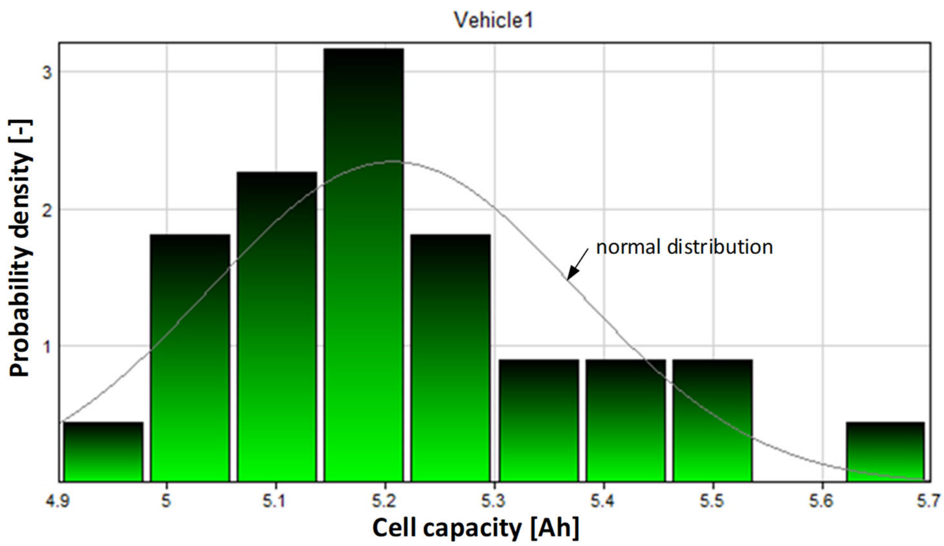

Figure 4. Histogram of the capacity of individual cells of the battery pack from the hybrid Vehicle 1 along with the course of the normal distribution.

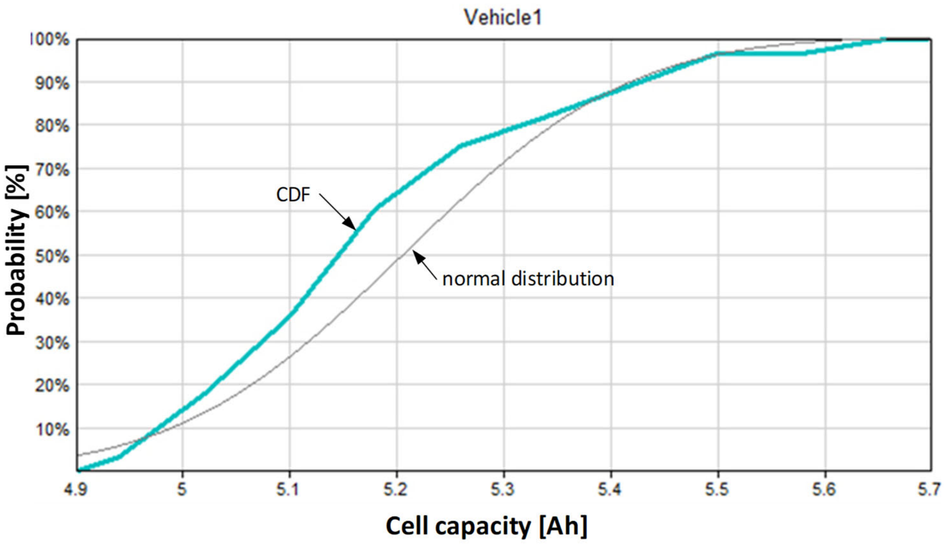

Figure 5. Cumulative Distribution Function (CDF) is used to measure the capacity of individual cells of the battery pack from the hybrid Vehicle 1 along with the mileage for a normal distribution.

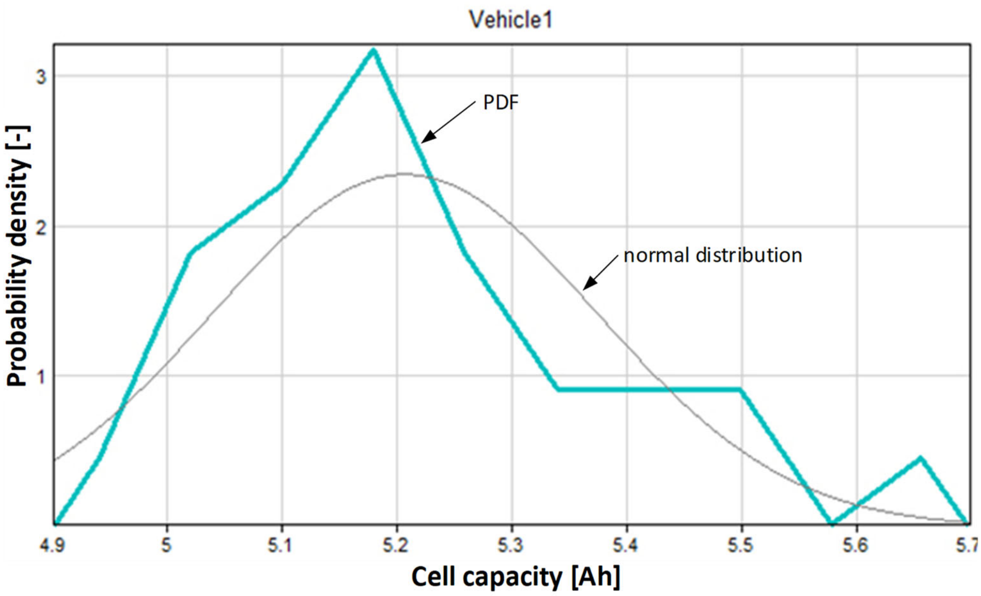

Figure 6. Probability Density Function (PDF) for the capacity of individual cells of the battery pack from the hybrid Vehicle 1, along with the mileage for a normal distribution.

Even more information about the tested battery pack is provided by an extended statistical analysis of the capacity of individual cells of the battery pack from the hybrid Vehicle 1. The results are presented in Table 3. The quantile analysis indicates that only approximately 5% of the tested cells are in the capacity range below 5 Ah.

Table 3. Extended statistical analysis of the capacity of individual cells of the battery pack from the hybrid Vehicle 1.

Probability	
0.05	4.994999885559
0.25	5.084000110626
0.5	5.179999828339
0.75	5.309000015259
0.95	5.507999897003

When using the GeNIe 4.0 Academic software, the Cumulative Distribution Function CDF (Figure 7) and the Probability Density Function PDF (Figure 8) were then generated for the capacity of individual cells of the battery pack from the hybrid Vehicle 1. The maximum of the Probability Density Function (PDF) occurs at a value of approximately 5.1 Ah, and all the measured capacities of battery cells are within a narrow range.

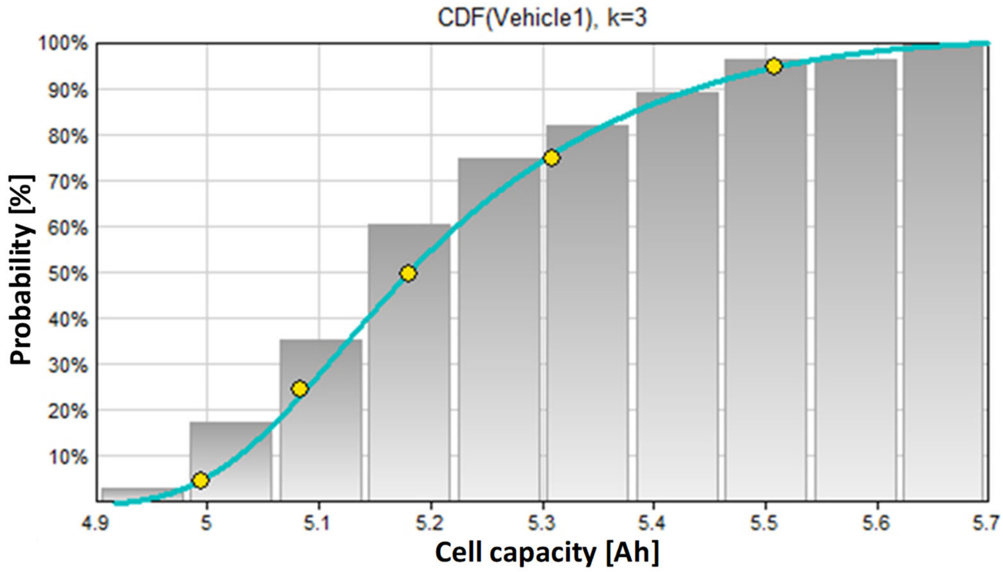

Figure 7. Cumulative distribution function CDF (sea color line) and quantile parameters (yellow symbols) for the capacity of individual cells of the battery pack from the hybrid Vehicle 1.

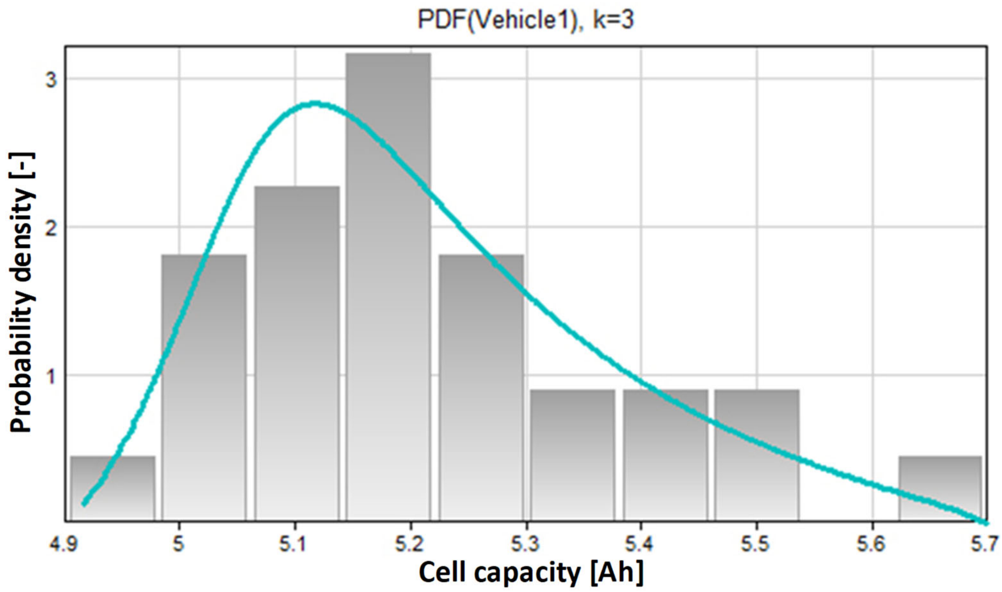

Figure 8. Probability Density Function PDF (sea color line) for the capacity of individual cells of the battery pack from the hybrid Vehicle 1.

The analyses presented above show that despite the loss of approximately 20% of its capacity, the battery pack of the hybrid Vehicle 1 is in good technical condition. Achieving such results for a BEV vehicle would, unfortunately, qualify it for the replacement of the battery pack. The hybrid vehicle, on the other hand, can be operated with this package for many years. Older Toyota vehicles had packages with a much larger capacity (1.3 kWh) than the new ones (0.75 kWh). This means that old battery packs in Toyota hybrid vehicles are able to function properly even if they lose half of their nominal capacity.

3.2. Case 2

The results of capacity measurements of individual cells of the battery pack from the hybrid Vehicle 2 are shown in Figure 9.

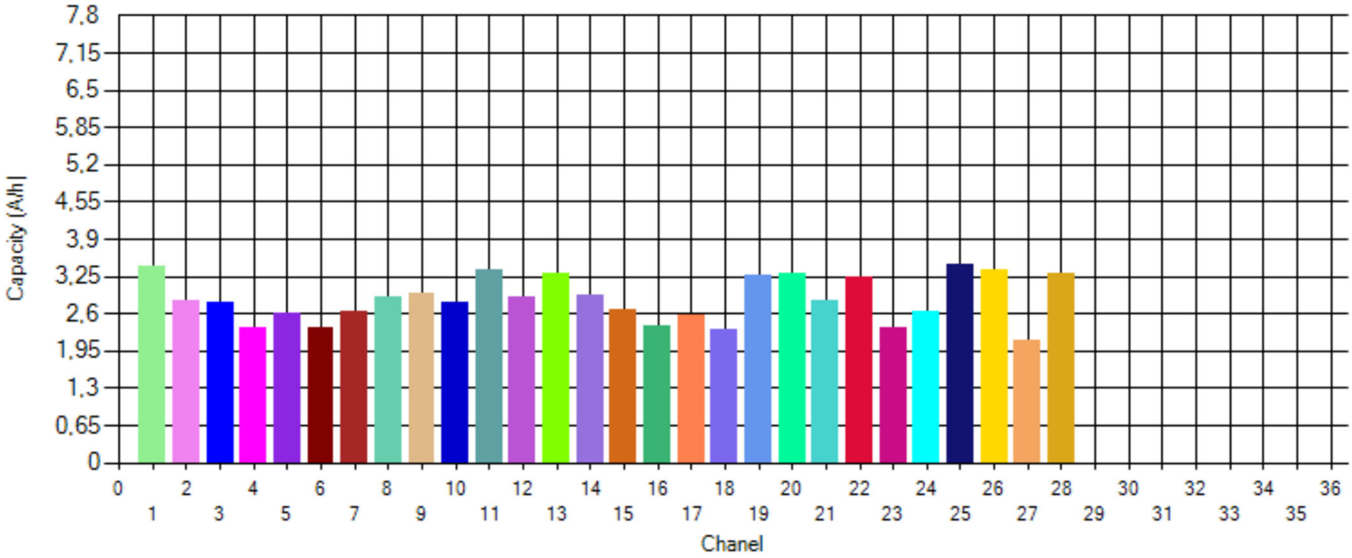

Figure 9. Results of capacity measurements of individual cells of the battery pack from the hybrid Vehicle 2.

Using the GeNIe 4.0 Academic software, the Cumulative Distribution Function CDF (Figure 10) and the Probability Density Function PDF (Figure 11) were then generated for the capacity of individual cells of the battery pack from the hybrid Vehicle 2. The maximum of the Probability Density Function (PDF) is for a capacity of approximately 3 Ah.

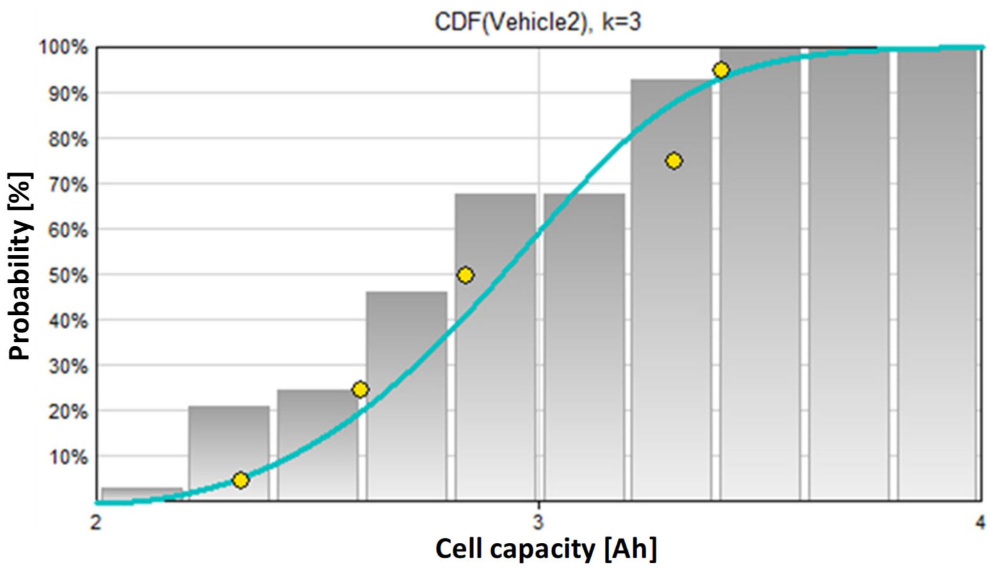

Figure 10. Cumulative distribution function CDF (sea color line) and quantile parameters (yellow symbols) for the capacity of individual cells of the battery pack from the hybrid Vehicle 2.

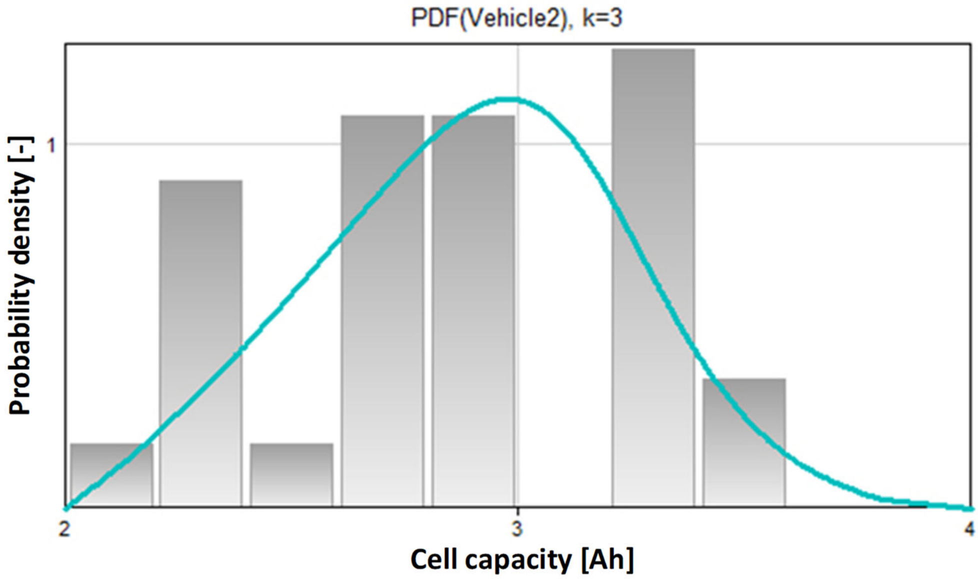

Figure 11. Probability Density Function PDF (sea color line) for the capacity of individual cells of the battery pack from the hybrid Vehicle 2.

In Case 2, we are dealing with a battery pack that has lost more than half of its original capacity. However, the standard deviation is 0.39 Ah, which is rather small. To reduce it even further, the authors suggest replacing the weakest cell (no. 27) with a cell with a capacity from 3.00 to 3.25 Ah. As mentioned earlier, older Toyota vehicles have battery packages with a capacity of 1.3 kWh. The capacity of the packages in new vehicles of the same class is 0.75 kW. Over the years, the manufacturer decided that it was sufficient for this type of vehicle. This means that old battery packs in Toyota hybrid vehicles are able to function properly even if they lose more than half of their nominal capacity, and Case 2 confirms this principle.

3.3. Case 3

The results of the capacity measurements of individual cells of the battery pack from a hybrid vehicle 3 are shown in Figure 12.

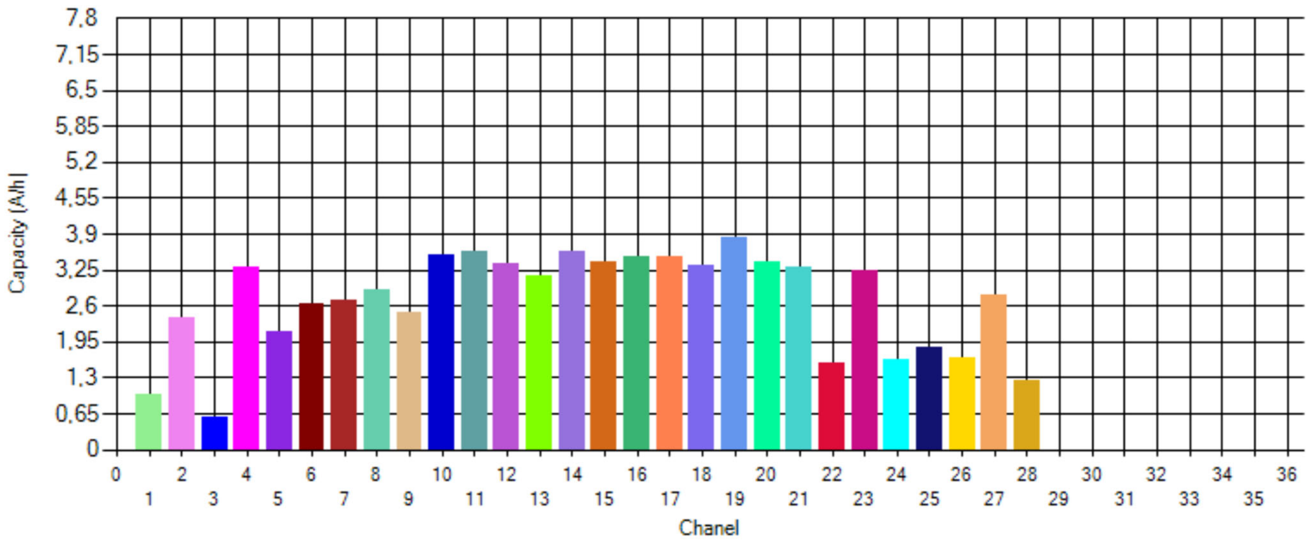

Figure 12. Results of capacity measurements of individual cells of the battery pack from the hybrid Vehicle 3.

Using the GeNIe 4.0 Academic software, the Cumulative Distribution Function CDF (Figure 13) and the Probability Density Function PDF (Figure 14) were then generated for the capacity of individual cells of the battery pack from the hybrid Vehicle 3.

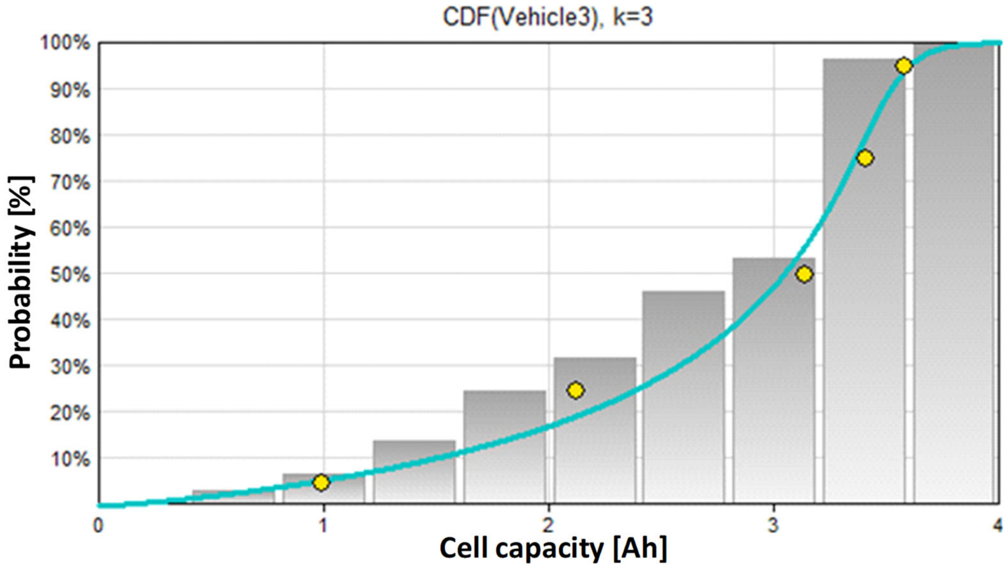

Figure 13. Cumulative Distribution Function CDF (sea color line) and quantile parameters (yellow symbols) for the capacity of individual cells of the battery pack from the hybrid Vehicle 3.

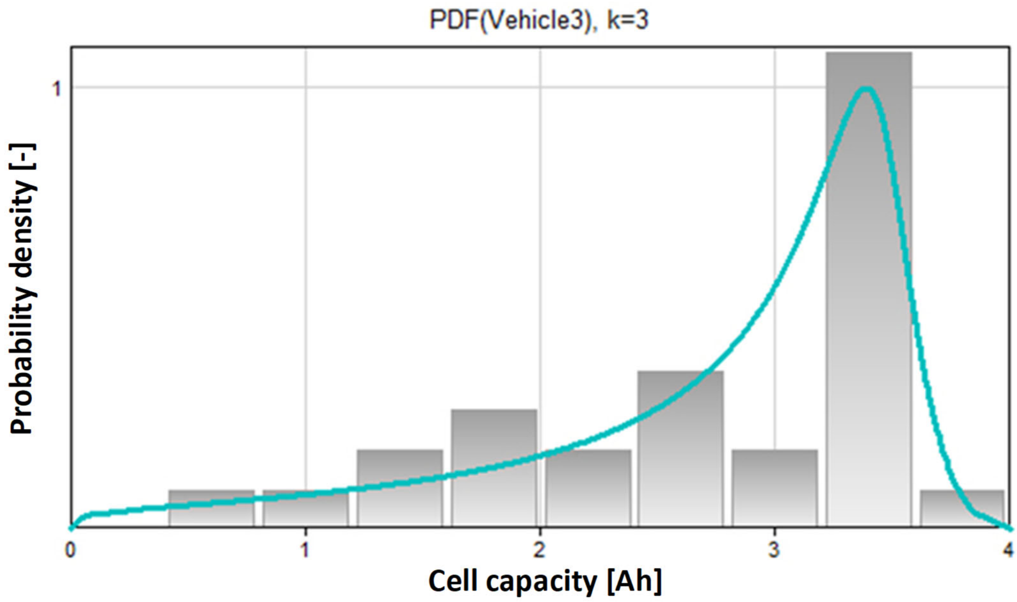

Figure 14. Probability Density Function PDF (sea color line) for the capacity of individual cells of the battery pack from the hybrid Vehicle 3.

In Case 3, we are dealing with a battery pack that is in poor technical condition and is no longer suitable for further use. This is due to the fact that all cells have lost more than half of their nominal capacity. The weakest are cell no. 3 and cell no. 1, which retained only 8.8% and 15.27% of their initial capacity, respectively. In this case, the authors propose replacing all cells with a capacity of less than 2.6 Ah. After such a regeneration process, this package will have a comparable performance to the one described in Case 2. It will serve the vehicle for several more years.

3.4. Case 4

The results of measuring the capacity of individual cells in the battery pack from a hybrid vehicle 4 are shown in Figure 15. The data presented in the graph show that individual cells have very different capacities, which are much lower than the rated capacity of 6.5 Ah. Additionally, there are vast differences between the lowest and the highest cell capacities.

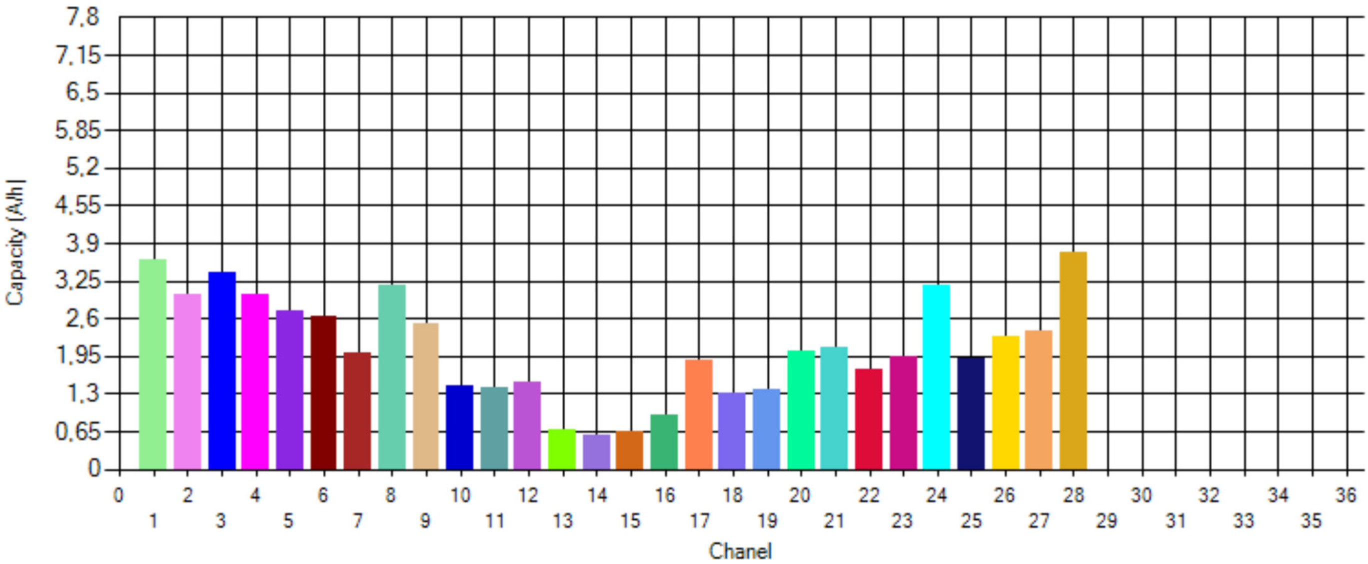

Figure 15. Results of capacity measurements of individual cells of the battery pack from the hybrid Vehicle 4.

Using the GeNIe 4.0 Academic software, the Cumulative Distribution Function CDF (Figure 16) and the Probability Density Function PDF (Figure 17) were then generated for the capacity of individual cells of the battery pack from the hybrid Vehicle 4. The Probability Density Function (PDF) trace clearly shows that high probability densities occur in a very wide range of measured cell capacities.

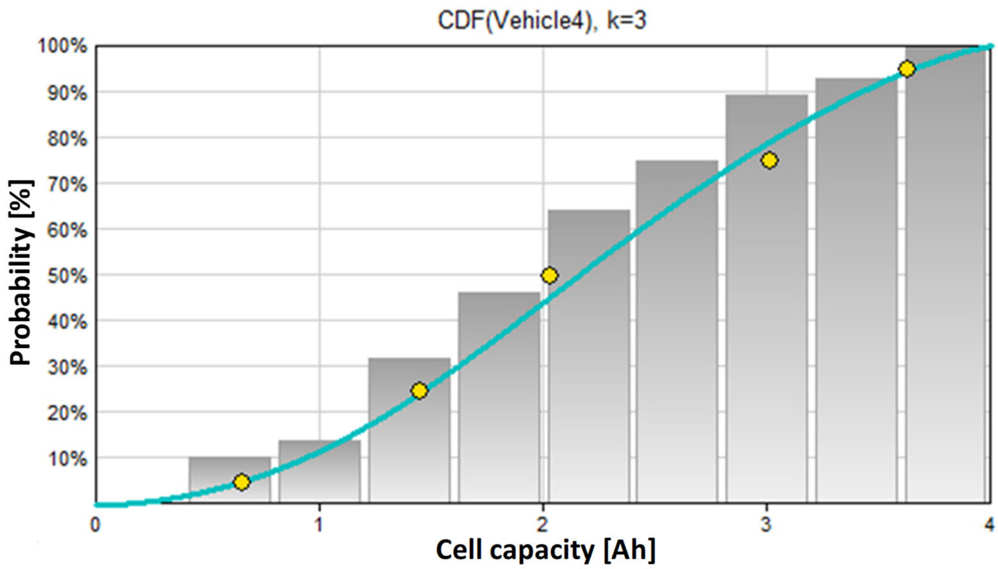

Figure 16. Cumulative Distribution Function CDF (sea color line) and quantile parameters (yellow symbols) for the capacity of individual cells of the battery pack from the hybrid Vehicle 4.

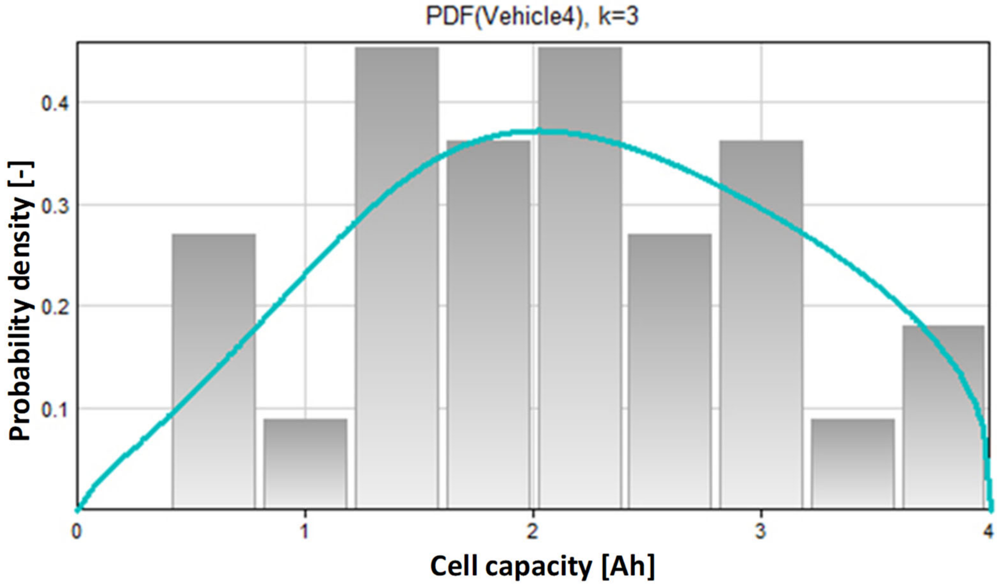

Figure 17. Probability Density Function PDF (sea color line) for the capacity of individual cells of the battery pack from the hybrid Vehicle 4.

Using the GeNIe 4.0 Academic software, the Cumulative Distribution Function CDF (Figure 18) and the Probability Density Function PDF (Figure 19) were generated for the polynomial coefficient k = 4, which describes the course of the CFD function even more precisely. In this case, the Probability Density Function PDF course is bimodal. Function extremes occur for capacity values of approximately 1.5 Ah and approximately 3 Ah. All 4 cases were modeled with a polynomial coefficient value of k = 3. The use of a larger polynomial coefficient of k = 4 only in Case 4 resulted in a significant difference in the PDF waveform and the occurrence of bimodal characteristics. It proves the existence of two large groups of battery cells with significantly different capacities within one package. The bimodal PDF waveform helps to quickly determine the technical condition of the battery.

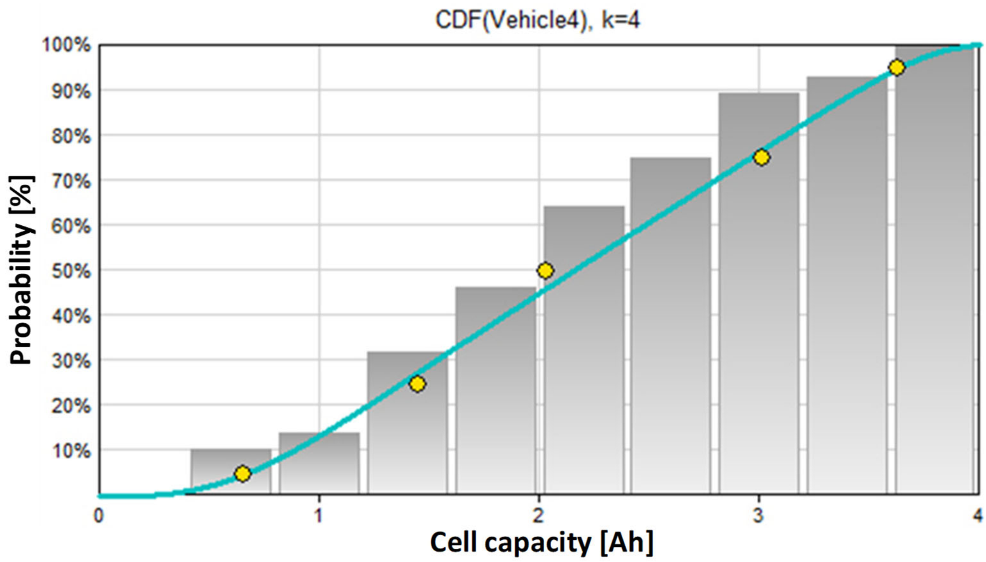

Figure 18. Cumulative Distribution Function CDF (sea color line) and quantile parameters (yellow symbols) for the coefficient k = 4 for the capacity of individual cells of the battery pack from the hybrid Vehicle 4.

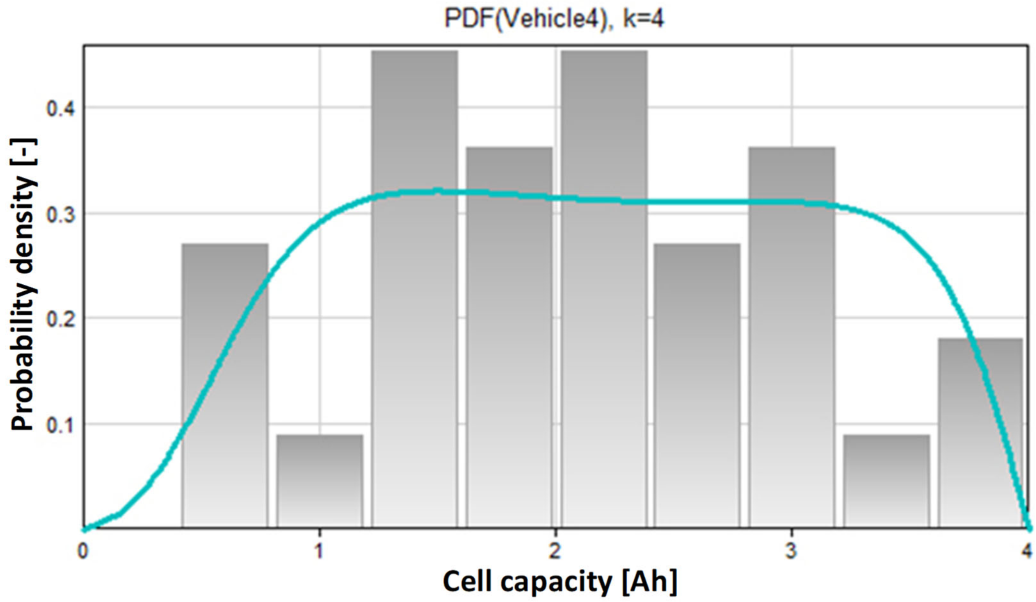

Figure 19. Probability Density Function PDF (sea color line) for the k = 4 factor for the capacity of individual cells of the battery pack from the hybrid Vehicle 4.

All these data indicate the poor condition of the tested battery pack. According to the authors, it is the only one that is not suitable for regeneration but to be disposed of. Only a few cells with a capacity greater than 2.6 Ah can be retained as spare parts for subsequent packages to be repaired. They would have been perfect for replacing the weakest battery cells presented in Case 3. The rest of the battery cells should be sent to a facility that handles this type of waste safely.

4. Conclusions

Hybrid vehicles have been on the market for over 25 years, while BEV electric vehicles have been on the market for approximately 15 years. An effective method of assessing the technical condition of their battery packs is required. Therefore, the method of measuring and analyzing the performance of battery packs from hybrid vehicles presented in the article is a response to this emerging need.

The presented method of assessing the technical condition of traction batteries requires advanced measurement and research equipment in the form of a system for simultaneously controlled charging and discharging of many battery cells. It is an essential diagnostic and research device used to determine the capacity of individual cells. The capacity values of all battery cells are then analyzed using the Metalog family of probability distributions. The application of this tool allowed us to determine the Probability Density Function for the entire battery pack of 4 different Cases. Based on its course, the diagnostician was able to assess the technical condition of the tested package and decide on its further fate. It could be intended for repair, use as a stationary energy storage facility, or disposal.

Based on the research carried out on 4 cases of NiMH battery packs from Toyota hybrid vehicles, they can be classified into specific groups:

(1) A functional package in which the aging processes proceed properly. It is characterized by the capacity of individual battery cells ranging from 100 to 50% of the nominal capacity. The PDF waveform is close to a normal distribution with a very small standard deviation between the capacities of individual cells.

(2) The package is faulty and needs to be repaired. It is characterized by the capacity of individual battery cells ranging from 0 to 100% of the nominal capacity. PDF waveform with one extreme with a very large standard deviation between the capacities of individual cells. The location of the extreme PDF indicates the purpose of repair. All cells with a capacity less than the extreme value should be replaced with cells

with a capacity equal to or greater than the extreme value. All cells with a capacity greater than 50% of the nominal capacity can be reused to compose a package of a given capacity.

(3) The package is beyond repair and should be disposed of. It is characterized by the capacity of individual battery cells ranging from 0 to 50% of the nominal capacity. PDF waveform with one or two extreme values with a very large standard deviation between the capacities of individual cells.

According to the authors, the algorithm for assessing the technical condition of traction batteries presented in the article may also be used in other types of traction batteries than the NiMH cells examined in the article. However, the threshold values determining the purpose of a specific cell and the entire battery pack must be set separately for each type of battery cell. The authors have access to a large number of NMC battery packs and intend to conduct detailed research in this area in the near future.

The authors plan to implement the described algorithm for assessing the technical condition of traction battery packs into workshop practice in the company they cooperate with. In this way, the proprietary algorithm will shorten the battery pack diagnostics time and increase its effectiveness. Tested packages will be much more efficiently assessed and classified for specific repair or other uses. As a result, the presented method can be classified as a Business Intelligence tool.

The authors intend to continue their research to confirm the effectiveness of assessing the technical condition of traction batteries derived from BEVs with high energy capacity of the package (above 40 kWh).

Author Contributions: Conceptualization, J.C., A.M. and D.K.; methodology, A.M.; software, A.M.; validation, J.C. and D.K.; formal analysis, J.C; investigation, D.K.; resources, J.C. and A.M.; data curation, D.K.; writing—original draft preparation, J.C., A.M. and D.K.; writing—review and editing, J.C., A.M. and D.K.; visualization, A.M.; supervision, J.C.; project administration, J.C. and D.K.; funding acquisition, J.C. and A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Dariusz Kroczyński is employed by Dakro, The other author declares no conflicts of interest.

Abbreviations

BEV	Battery Electric Vehicles
BMS	Battery Management System
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
PHEV	Plug-in Hybrid Electric Vehicle
RES	Renewable Energy Source
SoC	State of Charge
TMS	Thermal Management System

References

1. Bayani, R.; Soofi, A.F.; Waseem, M.; Manshadi, S.D. Impact of Transportation Electrification on the Electricity Grid—A Review. *Vehicles* **2022**, *4*, 1042–1079. [CrossRef]
2. Barta, D.; Mruzek, M.; Kendra, M.; Kordos, P.; Krzywonos, L. Using of non-conventional fuels in hybrid vehicle drives. *Adv. Sci. Technol. Res. J.* **2016**, *10*, 240–247. [CrossRef] [PubMed]
3. Čulík, K.; Hrudkay, K.; Morgoš, J. Operating Characteristics of Electric Buses and Their Analysis. In Proceedings of the Transport Means—Proceedings of the International Conference, Kaunas, Lithuania, 6–8 October 2021; pp. 251–256.
4. Čulík, K.; Hrudkay, K.; Štefancová, V. Possibilities of Legislative and Economic Support for Electromobility in Slovakia. In *Lecture Notes in Intelligent Transportation and Infrastructure*; Springer: Berlin/Heidelberg, Germany, 2023; Part F1379, pp. 125–134.
5. Gnap, J.; Dockalik, M.; Dydkowski, G. Examination of the development of new bus registrations with alternative powertrains in Europe. *LOGI—Sci. J. Transp. Logist.* **2021**, *12*, 147–158. [CrossRef]
6. Hurtova, I.; Sejkorova, M.; Verner, J.; Sarkan, B. Comparison of electricity and fossil fuel consumption in trolleybuses and buses. *Eng. Rural Dev.* **2018**, *17*, 2079–2084. [CrossRef]
7. Kharchenko, V.; Kostenko, I.; Liubarskyi, B.; Shaida, V.; Kuravskyi, M.; Petrenko, O. Simulating the traction electric drive operation of a trolleybus equipped with mixed excitation motors and DC-DC converter. *East.-Eur. J. Enterp. Technol.* **2020**, *3*, 46–54. [CrossRef]
8. Nicoletti, L.; Köhler, P.; König, A.; Heinrich, M.; Lienkamp, M. Parametric modelling of weight and volume effects in battery electric vehicles, with focus on the gearbox. *Proc. Des. Soc.* **2021**, *1*, 2389–2398. [CrossRef]
9. Ribeiro, P.J.G.; Mendes, J.F.G. Public transport decarbonisation via urban bus fleet replacement in Portugal. *Energies* **2022**, *15*, 4286. [CrossRef]
10. Settey, T.; Gnap, J.; Synák, F.; Skrúcaný, T.; Dočkalik, M. Research into the impacts of driving cycles and load weight on the operation of a light commercial electric vehicle. *Sustainability* **2021**, *13*, 13872. [CrossRef]
11. Stakens, J.; Mutule, A.; Lazdins, R. Agriculture Electrification, Emerging Technologies, Trends and Barriers: A Comprehensive Literature Review. *Latv. J. Phys. Tech. Sci.* **2023**, *60*, 18–32. [CrossRef]
12. Stoma, M.; Dudziak, A. Future Challenges of the Electric Vehicle Market Perceived by Individual Drivers from Eastern Poland. *Energies* **2023**, *16*, 7212. [CrossRef]
13. Stopka, O.; Stopková, M.; Pečman, J. Application of Multi-Criteria Decision Making Methods for Evaluation of Selected Passenger Electric Cars: A Case Study. *Commun. Sci. Lett. Univ. Zilina* **2022**, *24*, A133–A141. [CrossRef]
14. Würtz, S.; Bogenberger, K.; Göhner, U.; Rupp, A. Towards efficient battery electric bus operations: A novel energy forecasting framework. *World Electr. Veh. J.* **2024**, *15*, 27. [CrossRef]
15. Beik, Y.; Dziewiątkowski, M.; Szpica, D. Exhaust emissions of an engine fuelled by petrol and liquefied petroleum gas with control algorithm adjustment. *SAE Int. J. Engines* **2020**, *13*, 739–759. [CrossRef]
16. Szpica, D. Fuel dosage irregularity of LPG pulse vapor injectors at different stages of wear. *Mechanika* **2016**, *22*, 44–50. [CrossRef]
17. Dittrich, A.; Beroun, S.; Zvolsky, T. Diesel gas dual engine with liquid LPG injection into intake manifold. In Proceedings of the Engineering for Rural Development, Jelgava, Latvia, 23–25 May 2018; pp. 1978–1983.
18. Pulawski, G.; Szpica, D. The modelling of operation of the compression ignition engine powered with diesel fuel with LPG admixture. *Mechanika* **2015**, *21*, 500–505.
19. Ding, S.-L.; Song, E.-Z.; Yang, L.-P.; Litak, G.; Wang, Y.-Y.; Yao, C.; Ma, X.-Z. Analysis of Chaos in the Combustion Process of Premixed Natural Gas Engine. *Appl. Therm. Eng.* **2017**, *121*, 768–778. [CrossRef]
20. Gnap, J.; Dockalik, M. Impact of the operation of LNG trucks on the environment. *Open Eng.* **2021**, *11*, 937–947. [CrossRef]
21. Jurkovic, M.; Kalina, T.; Skrúcaný, T.; Gorzelanczyk, P.; L'upták, V. Environmental Impacts of Introducing LNG as Alternative Fuel for Urban Buses—Case Study in Slovakia. *Promet-Traffic Transp.* **2020**, *32*, 837–847. [CrossRef]
22. Szpica, D.; Dziewiatkowski, M. Catalyst Conversion Rates Measurement on Engine Fueled with Compressed Natural Gas (CNG) Using Different Operating Temperatures. *Mechanika* **2021**, *27*, 492–497. [CrossRef]
23. Domański, M.; Paszkowski, J.; Sergey, O.; Zarajczyk, J.; Siłuch, D. Analysis of Energy Properties of Granulated Plastic Fuels and Selected Biofuels. *Agric. Eng.* **2020**, *24*, 1–9. [CrossRef]
24. Vignesh, R.; Ashok, B.; Senthil Kumar, M.; Szpica, D.; Harikrishnan, A.; Josh, H. Adaptive neuro fuzzy inference system-based energy management controller for optimal battery charge sustaining in biofuel powered non-plugin hybrid electric vehicle. *Sustain. Energy Technol. Assess.* **2023**, *59*, 103379. [CrossRef]
25. Dhande, D.Y.; Navale, S.J. Experimental investigations on the performance and emissions of compression ignition engine fueled with lower blends of neem-based biodiesel. *Arch. Autom. Engineer. Archiw. Mot.* **2024**, *103*, 57–76.
26. Duda, K.; Wierzbicki, S.; Mikulski, M.; Konieczny, Ł.; Łazarz, B.; Letuń-Łatka, M. Emissions from a medium-duty crdi engine fuelled with diesel-biodiesel blends. *Transp. Probl.* **2021**, *16*, 39–49. [CrossRef]
27. Imran, M.S.; Saleh, F.A. The Influence of Using Biodiesel Prepared from Cresson Oil on Emissions and Performance of CI Engines. *J. Ecol. Eng.* **2024**, *25*, 84–98. [CrossRef] [PubMed]
28. Matijošius, J.; Orynycz, O.; Kovbasenko, S.; Simonenko, V.; Shuba, Y.; Moroz, V.; Gutarevych, S.; Wasiak, A.; Tucki, K. Testing the indicators of diesel vehicles operating on diesel oil and diesel biofuel. *Energies* **2022**, *15*, 9263. [CrossRef]
29. Pawlak, G.; Skrzek, T. Combustion of raw Camelina Sativa oil in CI engine equipped with common rail system. *Sci. Rep.* **2023**, *13*, 19731. [CrossRef] [PubMed]

30. Szpica, D.; Czaban, J. Investigating of the combustion process in a diesel engine fueled with conventional and alternative fuels. In Proceedings of the 23rd International Scientific Conference, Transport Means—Proceedings of the International Conference 2019, Palanga, Lithuania, 2–4 October 2019; pp. 176–181.
31. Dittrich, A.; Prochazka, R.; Popelka, J.; Phu, D.N. Effect of HVO CNG dual-fuel operation mode on emissions and performance of CI engine. In Proceedings of the Engineering for Rural Development, Jelgava, Latvia, 24–26 May 2023; Volume 22, pp. 58–63.
32. Žvirblis, T.; Hunicz, J.; Matijošius, J.; Rimkus, A.; Kilikevičius, A.; Gęca, M. Improving diesel engine reliability using an optimal prognostic model to predict diesel engine emissions and performance using pure diesel and Hydrogenated Vegetable Oil. *Eksploat. I Niezawodn.—Maint. Reliab.* **2023**, *25*, 174358. [CrossRef]
33. Gechev, T. Progress in fuel cell usage as an auxiliary power unit in heavy-duty vehicles. In Proceedings of the 29th Technical and Scientific Conference on Transport, Ecology—Sustainable Development, EKO Varna 2023, Hybrid, AIP Conference Proceedings, Varna, Bulgaria, 18–20 May 2023; Volume 3104, p. 020006.
34. Sederyn, T.; Skawińska, M. Computational analysis of PEM fuel cell under different operating conditions. *Appl. Comput. Sci.* **2023**, *19*, 26–38. [CrossRef]
35. Balitskii, A.I.; Abramek, K.F.; Osipowicz, T.K.; Eliasz, J.J.; Balitska, V.O.; Kochmański, P.; Prajwowski, K.; Mozga, Ł.S. Hydrogen-Containing "Green" Fuels Influence on the Thermal Protection and Formation of Wear Processes Components in Compression-Ignition Engines Modern Injection System. *Energies* **2023**, *16*, 3374. [CrossRef]
36. Di Micco, S.; Romano, F.; Jannelli, E.; Perna, A.; Minutillo, M. Techno-economic analysis of a multi-energy system for the co-production of green hydrogen, renewable electricity and heat. *Int. J. Hydrogen Energy* **2023**, *48*, 31457–31467. [CrossRef]
37. Gilewski, M.; Czarnigowski, J.; Hunicz, J.; Dubeński, K.; Szafran, M.; Fronc, M. Model of a prototype vehicle powered by a hybrid hydrogen system. *J. Phys. Conf. Ser.* **2021**, *2130*, 012002. [CrossRef]
38. Synák, F.; Synák, J.; Skrúcaný, T. Assessing the addition of hydrogen and oxygen into the engine's intake air on selected vehicle features. *Int. J. Hydrogen Energy* **2021**, *46*, 31854–31878. [CrossRef]
39. Nadolski, R.; Ludwinek, K.; Staszak, J.; Jaśkiewicz, M. Utilization of BLDC motor in electrical vehicles. *Przegląd Elektrotechniczny* **2012**, *88*, 180–186.
40. Available online: https://ev-database.org/ (accessed on 15 June 2024).
41. Aghmadi, A.; Mohammed, O.A. Energy Storage Systems: Technologies and High-Power Applications. *Batteries* **2024**, *10*, 141. [CrossRef]
42. Cui, Y.; Shen, X.; Zhang, H.; Yin, Y.; Yu, Z.; Shi, D.; Fang, Y.; Xu, R. Intrinsic Safety Risk Control and Early Warning Methods for Lithium-Ion Power Batteries. *Batteries* **2024**, *10*, 62. [CrossRef]
43. Wang, C.; Liu, Z.; Sun, Y.; Gao, Y.; Yan, P. Aging Behavior of Lithium Titanate Battery under High-Rate Discharging Cycle. *Energies* **2021**, *14*, 5482. [CrossRef]
44. Karnehm, D.; Bliemetsrieder, W.; Pohlmann, S.; Neve, A. Controlling Algorithm of Reconfigurable Battery for State of Charge Balancing Using Amortized Q-Learning. *Batteries* **2024**, *10*, 131. [CrossRef]
45. Dinh, M.-C.; Le, T.-T.; Park, M. A Low-Cost and High-Efficiency Active Cell-Balancing Circuit for the Reuse of EV Batteries. *Batteries* **2024**, *10*, 61. [CrossRef]
46. Etxandi-Santolaya, M.; Mora-Pous, A.; Canals Casals, L.; Corchero, C.; Eichman, J. Quantifying the Impact of Battery Degradation in Electric Vehicle Driving through Key Performance Indicators. *Batteries* **2024**, *10*, 103. [CrossRef]
47. Maisuradze, M.; Li, M.; Carlomagno, I.; Gaboardi, M.; Aquilanti, G.; Plaisier, J.R.; Giorgetti, M. Aging Mechanism of Mn-Based Prussian Blue Cathode Material by Synchrotron 2D X-ray Fluorescence. *Batteries* **2024**, *10*, 123. [CrossRef]
48. Sun, C.; Qin, W.; Yun, Z. A State-of-Health Estimation Method for Lithium Batteries Based on Fennec Fox Optimization Algorithm–Mixed Extreme Learning Machine. *Batteries* **2024**, *10*, 87. [CrossRef]
49. Hassini, M.; Redondo-Iglesias, E.; Venet, P. Battery Passports for Second-Life Batteries: An Experimental Assessment of Suitability for Mobile Applications. *Batteries* **2024**, *10*, 153. [CrossRef]
50. Young, K.-h.; Yasuoka, S. Capacity Degradation Mechanisms in Nickel/Metal Hydride Batteries. *Batteries* **2016**, *2*, 3. [CrossRef]
51. Martínez-Sánchez, R.; Molina-García, A.; Ramallo-González, A.P. Regeneration of Hybrid and Electric Vehicle Batteries: State-of-the-Art Review, Current Challenges, and Future Perspectives. *Batteries* **2024**, *10*, 101. [CrossRef]
52. Yang, T.; Li, J.; Xin, Q.; Zhang, H.; Zeng, J.; Agbossou, K.; Du, C.; Xiao, J. Thermal Performance Analysis of a Prismatic Lithium-Ion Battery Module under Overheating Conditions. *Batteries* **2024**, *10*, 86. [CrossRef]
53. Zhang, Z.; Ji, C.; Liu, Y.; Wang, Y.; Wang, B.; Liu, D. Effect of Aging Path on Degradation Characteristics of Lithium-Ion Batteries in Low-Temperature Environments. *Batteries* **2024**, *10*, 107. [CrossRef]
54. Saxon, A.; Yang, C.; Santhanagopalan, S.; Keyser, M.; Colclasure, A. Li-Ion Battery Thermal Characterization for Thermal Management Design. *Batteries* **2024**, *10*, 136. [CrossRef]
55. Xu, C.; Ma, C.; Souri, M.; Moztarzadeh, H.; Nasr Esfahani, M.; Jabbari, M.; Hosseinzadeh, E. Numerical Investigation of Thermal Management of a Large Format Pouch Battery Using Combination of CPCM and Liquid Cooling. *Batteries* **2024**, *10*, 113. [CrossRef]
56. Sorensen, A.; Utgikar, V.; Belt, J. A Study of Thermal Runaway Mechanisms in Lithium-Ion Batteries and Predictive Numerical Modeling Techniques. *Batteries* **2024**, *10*, 116. [CrossRef]
57. Teixeira, R.S.D.; Calili, R.F.; Almeida, M.F.; Louzada, D.R. Recurrent Neural Networks for Estimating the State of Health of Lithium-Ion Batteries. *Batteries* **2024**, *10*, 111. [CrossRef]

58. Zhang, X.; Gong, A.; He, W.; Cao, Y.; He, H. A Lithium Battery Health Evaluation Method Based on Considering Disturbance Belief Rule Base. *Batteries* **2024**, *10*, 129. [CrossRef]
59. Wang, J.; Zhang, C.; Meng, X.; Zhang, L.; Li, X.; Zhang, W. A Novel Feature Engineering-Based SOH Estimation Method for Lithium-Ion Battery with Downgraded Laboratory Data. *Batteries* **2024**, *10*, 139. [CrossRef]
60. Olona, A.; Castejón, L. Influence of the Arrangement of the Cells/Modules of a Traction Battery on the Spread of Fire in Case of Thermal Runaway. *Batteries* **2024**, *10*, 55. [CrossRef]
61. Gerold, E.; Lerchbammer, R.; Antrekowitsch, H. Recovery of Cobalt, Nickel, and Lithium from Spent Lithium-Ion Batteries with Gluconic Acid Leaching Process: Kinetics Study. *Batteries* **2024**, *10*, 120. [CrossRef]
62. Guo, Y.; Liu, F.; Chen, F.; Chen, Z.; Zeng, H.; Zhang, T.; Shen, C. Recycling of Valuable Metals from the Priority Lithium Extraction Residue Obtained through Hydrogen Reduction of Spent Lithium Batteries. *Batteries* **2024**, *10*, 28. [CrossRef]
63. Mondal, A.; Fu, Y.; Gao, W.; Mi, C.C. Pretreatment of Lithium Ion Batteries for Safe Recycling with High-Temperature Discharging Approach. *Batteries* **2024**, *10*, 37. [CrossRef]
64. Zanoletti, A.; Carena, E.; Ferrara, C.; Bontempi, E. A Review of Lithium-Ion Battery Recycling: Technologies, Sustainability, and Open Issues. *Batteries* **2024**, *10*, 38. [CrossRef]
65. Mottaghi, M.; Pearce, J.M. A Review of 3D Printing Batteries. *Batteries* **2024**, *10*, 110. [CrossRef]
66. Schütte, M.; Degen, F.; Walter, H. Reducing Energy Consumption and Greenhouse Gas Emissions of Industrial Drying Processes in Lithium-Ion Battery Cell Production: A Qualitative Technology Benchmark. *Batteries* **2024**, *10*, 64. [CrossRef]
67. Mohanty, D.; Hung, I.-M.; Hsieh, C.-T.; Pan, J.-P.; Liu, W.-R. Critical Review on High-Safety Lithium-Ion Batteries Modified by Self-Terminated Oligomers with Hyperbranched Architectures. *Batteries* **2024**, *10*, 65. [CrossRef]
68. Jaffal, H.; Guanetti, L.; Rancilio, G.; Spiller, M.; Bovera, F.; Merlo, M. Battery Energy Storage System Performance in Providing Various Electricity Market Services. *Batteries* **2024**, *10*, 69. [CrossRef]
69. Maddipatla, S.; Kong, L.; Pecht, M. Safety Analysis of Lithium-Ion Cylindrical Batteries Using Design and Process Failure Mode and Effect Analysis. *Batteries* **2024**, *10*, 76. [CrossRef]
70. Rahman, M.; Baki, A. Electrical and thermal modeling of battery cell grouping for analyzing battery pack efficiency and temperature. *Energy Harvest. Syst.* **2024**, *11*, 20230039. [CrossRef]
71. Zhang, H.; Lin, W.; Kang, L.; Zhang, Y.; Zhou, Y.; Jiang, S. Highly safe lithium vanadium oxide anode for fast-charging dendrite-free lithium-ion batteries. *Nanotechnol. Rev.* **2024**, *13*, 20230179. [CrossRef]
72. Tendera, L.; Pegel, H.; Gonzalez, C.; Wycisk, D.; Fill, A.; Birke, K.P. Influence of temperature, state of charge and state of health on the thermal parameters of lithium-ion cells: Exploring thermal behavior and enabling fast-charging. *Future Batter.* **2024**, *1*, 100001. [CrossRef]
73. González-Morales, J.; Mosa, J.; Ishiyama, S.; Rosero-Navarro, N.C.; Miura, A.; Tadanaga, K.; Aparicio, M. Carbon-Free Cathode Materials Based on Titanium Compounds for Zn-Oxygen Aqueous Batteries. *Batteries* **2024**, *10*, 94. [CrossRef]
74. Bukya, M.; Meenakshi Reddy, R.; Doddipatla, A.; Kumar, R.; Mathur, A.; Gupta, M.; Garimella, A. Electro-thermal performance evaluation of a prismatic battery pack for an electric vehicle. *High Temp. Mater. Process.* **2024**, *43*, 20220311. [CrossRef]
75. Nastasi, L.; Fiore, S. Environmental Assessment of Lithium-Ion Battery Lifecycle and of Their Use in Commercial Vehicles. *Batteries* **2024**, *10*, 90. [CrossRef]
76. Nkembi, A.A.; Simonazzi, M.; Santoro, D.; Cova, P.; Delmonte, N. Comprehensive Review of Energy Storage Systems Characteristics and Models for Automotive Applications. *Batteries* **2024**, *10*, 88. [CrossRef]
77. Al Muala, Z.A.; Bany Issa, M.A.; Bello Bugallo, P.M. Integrating Life Cycle Principles in Home Energy Management Systems: Optimal Load PV–Battery–Electric Vehicle Scheduling. *Batteries* **2024**, *10*, 138. [CrossRef]
78. Salek, F.; Resalati, S.; Babaie, M.; Henshall, P.; Morrey, D.; Yao, L. A Review of the Technical Challenges and Solutions in Maximising the Potential Use of Second Life Batteries from Electric Vehicles. *Batteries* **2024**, *10*, 79. [CrossRef]
79. Rufino Júnior, C.A.; Riva Sanseverino, E.; Gallo, P.; Koch, D.; Diel, S.; Walter, G.; Trilla, L.; Ferreira, V.J.; Pérez, G.B.; Kotak, Y.; et al. Towards to Battery Digital Passport: Reviewing Regulations and Standards for Second-Life Batteries. *Batteries* **2024**, *10*, 115. [CrossRef]
80. Sarniak, M.T. Influence of Selected Weather Conditions on the Photovoltaic System Efficiency in Central Poland—Case Study. *Adv. Sci. Technol. Res. J.* **2024**, *18*, 177–186. [CrossRef] [PubMed]
81. Wheeler, W.; Venet, P.; Bultel, Y.; Sari, A.; Riviere, E. Aging in First and Second Life of G/LFP 18650 Cells: Diagnosis and Evolution of the State of Health of the Cell and the Negative Electrode under Cycling. *Batteries* **2024**, *10*, 137. [CrossRef]
82. Małek, A.; Marciniak, A.; Bartnik, G. The selection of an electric vehicle for the existing photovoltaic system—Case study in Polish climatic conditions. *Arch. Autom. Engineer. Archiw. Mot.* **2024**, *103*, 38–56. [CrossRef]
83. Novoa, L.; Brouwer, J. Dynamics of an integrated solar photovoltaic and battery storage nanogrid for electric vehicle charging. *J. Power Sources* **2018**, *399*, 166–178. [CrossRef]
84. Hassan, Q.; Abbas, M.; Tabar, V.; Tohidi, S.; Sameen, A.; Salman, H. Techno-economic assessment of battery storage with photovoltaics for maximum self-consumption. *Energy Harvest. Syst.* **2024**, *11*, 20220050. [CrossRef]
85. Lewicki, W.; Niekurzak, M.; Sendek-Matysiak, E. Electromobility Stage in the Energy Transition Policy—Economic Dimension Analysis of Charging Costs of Electric Vehicles. *Energies* **2024**, *17*, 1934. [CrossRef]
86. Keelin, T.W. The Metalog Distributions. *Decis. Anal.* **2016**, *13*, 243–277. [CrossRef]

87. Keelin, T.W.; Howard, R.A. *The Metalog Distributions: Virtually Unlimited Shape Flexibility, Combining Expert Opinion in Closed Form, and Bayesian Updating in Closed Form*; Stanford University: Stanford, CA, USA, 2021.
88. Available online: https://www.bayesfusion.com/2022/06/27/genie-4-0/ (accessed on 21 April 2024).
89. Available online: https://blogs.sas.com/content/iml/2023/02/22/metalog-distribution.html (accessed on 19 December 2023).