Experimental Testing and Evaluation of Lithium-Ion Battery Cells for a Special-Purpose Electric Vacuum Sweeper Vehicle

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This work was supported by the European Regional Development Fund and company RASCO, Ltd., through the Next Generation Municipal Equipment: Electric Compact Urban Vacuum Sweeper with an ICT System Project under Grant KK.01.2.1.01.0020.

ABSTRACT

Battery-powered electric vehicles are gradually expanding their market outside of the typical public and private transportation sector. A good example is a growing demand for electrification of special-purpose vehicles such as compact urban vacuum sweeper trucks. These vehicles are characterized by low production numbers and specific limitations such as restricted volume for battery placement, specific working conditions, requirement to supply electro-hydraulic systems, etc. Therefore, the selection of optimal battery cell and identification of its required characteristics is not a straightforward task. This article addresses this by presenting a methodology for selecting optimal battery cell for compact urban vacuum sweepers. A laboratory testing procedure is established to measure electric and heating characteristics of candidate battery types and battery producers. After evaluation of the experimental test results using the Analytic Hierarchy Process (AHP), the most appropriate battery cell is selected. The experimental tests and the presented AHP methodology prove that battery cell selection for a specific purpose based solely on manufacturers’ datasheet can result in a sub-optimal decision.

INDEX TERMS

Lithium-ion batteries, experimental testing, compact urban vacuum sweeper, special-purpose electric vehicle, analytic hierarchy process.

I. ABBREVIATIONS

ACT Adjusted Consumption Test
AHP Analytic Hierarchy Process
DEC Declared Energy Capacity (Wh)
EC Energy Capacity (Wh)
ET Energy Test
FCT Fast Charge Test
LCO Lithium Cobalt Oxide
LMO Lithium Manganese Oxide
LFP Lithium Iron Phosphate
MCC Max Charge Current (A)
MDC Max Discharge Current (A)
MTI Maximum Temperature Increase (°C)
NCA Lithium Nickel Cobalt Aluminum Oxide
NMC Lithium Nickel Manganese Cobalt Oxide

II. INTRODUCTION

Electric vehicles are one of the main pillars of reducing our ecological footprint [1]. However, fully electric vehicles still have drawbacks that slow down their rollout. According to [2], the main reason for not buying an electric vehicle are high investment cost, lack of public infrastructure and lower driving range as compared to the gasoline-powered vehicles.

Research on different batteries for electric vehicles studied in [3] and [4] highlights energy density characteristics of lithium-ion batteries as a significant drawback for their application in the vehicle industry. Thus, an improvement in battery performance can greatly improve utilization characteristics and economy of electric vehicles. Battery advancements, e.g. increased energy density and decreased sensitivity to environmental temperature, make them an
attractive alternative to the existing internal combustion engine-powered vehicles.

This work focuses on electric compact urban vacuum sweeper trucks, traditionally powered by 62–75 kW Diesel engines. Electric compact municipal vacuum sweepers are characterized by a multipurpose design that enables their usage during all seasons. They can be used for cleaning and washing public municipal surfaces, spreading deicing materials and even snow ploughing. In order to meet the functionality requirements, two essential criteria must be met. First, it is necessary to provide sufficient volume for connecting the equipment and installing the necessary waste tanks, severely limiting the size of the battery. Second, the battery needs to provide enough power not only to the motor drive and the common systems in the vehicles (cooling, ventilation, air conditioning, auxiliary systems), but also to drive the electrohydraulic systems used for cleaning the streets. A commercial example of an electric municipal vacuum cleaner can be found in [5].

A. LITERATURE REVIEW

A detailed technical and theoretical description as well as a general overview of batteries is available in [6]. Currently dominant batteries are based on lithium and this research thus focuses on lithium-based batteries. An overview of lithium-ion batteries used specifically for electric vehicles is presented in [7]. LCO, LMO, LFP and NMC battery types are presented and compared as the most promising batteries for electric vehicles. An evaluation of performance of various lithium-ion batteries for use in electric vehicle applications is presented in [8]. The authors compare and evaluate capacity and efficiency performance, charging capabilities, Butler-Volmer phenomenon (electrical current dependence on the electrode potential), thermal characteristics, cycle life and cost of NCA, LFP and NMC batteries. The study shows that NMC batteries have the highest energy density, NCA and NMC batteries have the best charging and discharging capabilities in terms of ampere-hours and the highest energy efficiency, while LFP batteries demonstrate the highest thermal stability.

Technological development and battery research is important both in the industry and the research community due to increasing applications of lithium-ion batteries in home appliances, consumer electronics, transportation, and power system industry. Technology readiness level generally starts with computer modelling and simulations, moves to hardware-in-the-loop simulations and, finally, results in experimental testing.

1) MODELING AND SIMULATION

Categorization of battery models focused on vehicular applications presented in [9] divides and summarizes them into electrochemical, stochastic, analytical and electrical-circuit models. A model suitable for simulating the behaviour of dynamic battery characteristics in Cadence-compatible simulators with the ability of predicting runtime, steady-state and transient response is presented in [10]. In [11] an accurate model of a lithium-ion battery operation in the day-ahead electricity market is presented and an impact of using a widely accepted inaccurate battery charging model on balancing costs is demonstrated. The presented model is based on laboratory testing and utilizes the state-of-energy vs. maximum energy charging capacity in one time period curve.

As information on the main battery parameters are very important, the authors in [12] present a method for establishing the available capacity, the state-of-charge and the state-of-health of a battery with unknown charging history using a two-pulse current method. The presented method applies two current pulses to a battery to stabilize its voltage and accurately estimates the main parameters of a battery within 30 seconds. A state-of-charge estimator for lithium-ion batteries based on the square-root least-squares algorithm for online battery model parameter estimation extended with Kalman-Bucy filter is presented in [13]. The model alleviates problems of the ampere-hour integration (an unknown initial value of the state-of-charge) and the voltage-based (an accuracy problem of the open circuit voltage to state-of-charge relation) state-of-charge estimation methods. Accuracy of the model is demonstrated using Matlab Simulink and the presented model showed better performance compared to the traditional Coulomb counting methods. The authors in [14] present a method for state-of-health estimation with the standardized 10-second discharge resistance test. Battery’s internal resistance is estimated directly using the system identification techniques based on operating data collected under normal electric vehicle operation. The method provides precise and accurate estimates of the internal resistance.

A state-of-health estimation method based on integration of the estimation effects of different health indicators and calculation of the weight coefficient of each indicator using the analytic hierarchy process is presented in [15]. The experimental life cycle tests on an NMC battery cells are performed to verify the presented method. An initial performance of the battery cells is determined using the static capacity test, resistance test, hybrid pulse test and three representative simulated driving schedule tests (federal urban driving schedule, inspection and maintenance driving schedule and dynamic stress test). The aging cycles consists of two patterns, the charging (constant current mode) and the discharging (several discharge steps with the same current excitation) pattern.

2) EXPERIMENTAL TESTING

A step toward real-life battery performance assessment is achieved by laboratory testing. The authors of [16] share a valuable experience on usage and ageing testing of lithium-based and sodium-nickel-chloride-based batteries used for providing ancillary services to the power system. The experimental results show a significant difference in degradation of batteries depending on the types of test cycles for different types of batteries. An interesting research from the vehicular technology standpoint tests lithium-ion batteries under
different temperature conditions, vibration frequencies and vibration directions [17]. NCA batteries were used in the tests and the results indicate that battery characteristics are significantly more affected by the ambient temperature than the road vibrations. Importance of an adequate and reliable management of parallel-connected lithium-ion battery cells is noted in [18], as the experimental tests showed that the management of parallel-connected lithium-ion battery cells with different levels of degradation causes further degradation of the whole battery pack. It is shown that the degraded cells in the parallel connection force the healthier cells to discharge at a higher current. The increased current and power lead to a higher polarization voltage drop and generation of more heat, which causes accelerated cell degradation.

Evaluation of LFP batteries for electric vehicle applications is presented in [19]. Five different commercial LFP batteries with different power and energy ratings were tested according to the recommendations from [20]. The following experimental procedures were conducted: commissioning (identification and weighting of the batteries), energy efficiency, specific energy (Wh/kg) and specific power (W/kg) capabilities tests at various C-rates, thermodynamic tests, fast-charging tests and aging tests. The results indicate that all of the tested batteries met the short-term U.S. Advanced Consortium goals [20], while the long-term results were achieved only for energy efficiency and cycle life under standard conditions. Specific power and fast charging capability test results did not meet the goals for most of the tested cells.

Additional experimental analyses of LFP battery for electric vehicle applications are presented in [22], [23] and [24]. In [22], the results of 50 moderate charging and discharging cycle tests of an LFP battery cell at the ambient temperature of 20°C are presented and analysed. The results demonstrate less than 0.5% loss of capacity, which can be used to extrapolate to the supplier’s claimed 1000 cycles before the capacity falls to 80%. The realistic road tests were conducted at ambient temperatures of −20°C, 0°C, +20°C and +40°C. The results reveal increased capacity and power degradation at low temperatures.

Two different test benches are used in the experiments described in [23], one for the tests in the steady state, and the other one under the dynamic operation conditions. Battery electrical characteristics, capacity-temperature dependence, ageing effects and energy storage efficiency under different currents and the dynamic performance are evaluated. It is shown that the charging / discharging efficiency at 1C rate is higher than charging / discharging efficiency at currents much lower than 1C rate. Even though the value of the lost power in the internal resistance of the battery is low for lower C-rates, chemical reactions inside the battery are slower because of the material deterioration inside the cell.

Results of the capacity test, power capability test, open-circuit voltage test and voltage hysteresis test of an LFP battery are presented and evaluated for the hybrid electric vehicle application in [24]. Evaluation of the capacity tests and power capability tests at various states of charge and temperatures indicate degradation of cell performance at low ambient temperatures. Open-circuit voltage tests reveal only small variation at different ambient temperatures.

Electric vehicle application of LCO cells is evaluated in [25], where the results of cycling and loading tests are presented. The results demonstrate that cells perform well according to the manufacturer’s specifications at ambient temperatures above 0°C in both Ah and Wh capacity, but a depression of capacity is revealed at temperatures lower than 0°C.

In [26], the authors conduct an experimental performance analysis of the lithium-polymer battery cell. Battery cell capacity, battery energy efficiency, temperature effects on performance of batteries, self-discharge, fast charging ability and realistic load tests were all conducted and analysed. It is determined that the resulting battery efficiency is over 96% at temperatures between +20°C and +40°C. The temperature test shows that the battery performs well at temperatures between 0°C and +40°C, but its efficiency and capacity decrease at temperatures below 0°C. The battery self-discharge is less than 5% per month. Results from the fast charging ability and realistic load tests are close to the values of the long-term United States Advanced Battery Consortium goals [20].

A concise overview of the performed literature review is provided in Table 1 for a quick reference. It indicates that a comprehensive comparison of the testing results of different lithium-ion batteries has not yet been performed in the literature.

**TABLE 1. Literature overview.**

| Review | Modelling and simulation | Modelling based on experimental testing | Experimental testing and evaluation of one batteries |
|--------|--------------------------|----------------------------------------|--------------------------------------------------|
| [6], [7], [8] | [9], [10], [13] | [11], [12], [14], [15] | [16], [17], [18], [19], [22], [23], [24], [25], [26] |

**B. SCOPE OF WORK AND CONTRIBUTION**

In this work, we conduct performance tests on different battery cells with the aim of determining the optimal battery cell for usage in a special-purpose vehicle, i.e. electric compact urban vacuum sweeper. The tests are conducted according to the European standard EN 15429-2 [27] and additional rigorous tests are designed according to the specific performance requirements on the sweeper. Hence, the contribution of this article is twofold:

- First, the design of a methodology for evaluation of battery cells for an electric compact urban vacuum sweeper.
Second, the experimental testing and categorization of different lithium-ion battery cells using the Analytic Hierarchy Process.

It is important to note that, as will be shown in this work, evaluation of the battery cell characteristics based merely on technical characteristics given by the manufacturers can result in sub-optimal battery cell selection. However, the analysis of experimental results resolves that problem and identifies the optimal battery cell for a given purpose.

The rest of this article is structured as follows. Section III describes the experimental equipment used in this research and the battery cells that were tested and evaluated. This section also elaborates the AHP algorithm used for evaluation of battery cells’ characteristics and experimental testing results. Four experimental tests conducted on each battery cell are described in Section IV. Presentation and analysis of the results of experimental tests is presented in Section V. In Section VI the tested battery cells were evaluated and the optimal battery cell was identified using the AHP. Finally, a brief overview of this article and most relevant conclusions are provided in Section VII.

### III. DESCRIPTION OF THE EXPERIMENTAL TESTBED

#### A. TESTED BATTERY CELLS

Table 2 lists the tested lithium-ion battery cells and presents their basic characteristics (nominal voltage, maximum charge and discharge current, capacity and energy). All tested cells are 18650-type, i.e. cylindrical with 18 mm diameter and 65 mm height, and they are shown in Figure 1. Energy capacity is measured on five battery cells of each type to ensure a valid representation of each type of the battery cell. They are all available for purchase in bulk quantities, which is essential for their installation in commercial vehicles. However, producers’ names and cell models are intentionally not disclosed.

Cell 01 is based on LCO and has low energy capacity compared to the other tested cells, so the expectations of the energy tests for this cell are low. On the positive side, it has an above-average maximum discharging current, 25 A. As opposed to Cell 01, Cells 02 and 03 have rather high energy capacity, 11.84 Wh, but the maximum discharging current is quite low, which could result in poor performance at high loads. NCA Cells 04 and 05 have similar technical characteristics as the LCO battery. LMO Cells 06, 07 and 08 have the ability to withstand high discharge currents, while the cells themselves have high energy capacity. According to the technical characteristics, above-average results are expected in both energy and heating test results. LFP Cell 09, according to technical documentation of the manufacturer, have high maximum allowed current and long cycle life, but low energy capacity. Thus, good heating characteristics and specific charging and discharging results, but poor energy test results, are expected. NMC cells (Cells 10, 14, 15 and 16) with high energy capacity and high maximum allowed charging/discharging current should yield good results in both the heating and the energy tests. Cells 11, 12 and 13 with lower energy capacity are not expected to perform well in energy tests, but their heating characteristics should be good.

#### B. PRELIMINARY EVALUATION OF THE TESTED BATTERIES

The preliminary evaluation of the tested batteries is based on analysis of technical data provided by the manufacturers. Analytic Hierarchy Process (AHP) [28]–[30] is used to...
determine the optimal battery cell based on the criteria available in all manufacturers’ data: declared energy capacity, maximum discharge current, maximum charge current and price.

The algorithm used to calculate AHP is shown in Algorithm 1, where:

- PWC is Pair-Wise Comparison,
- C is Criteria,
- A is Alternative,
- PCM is Pair-Wise comparison Matrix,
- CM is Comparison Matrix,
- SR is Sum of Rows of comparison matrix,
- CSR is Column vector containing the Sum of each Row of comparison matrix,
- SAE is Sum of All Elements of SR,
- PV is Priority Vector,
- CI is Consistency Index,
- RCI is Random Consistency Index,
- CR is Consistency Ratio,
- CV is Comparison Vector and
- CWAC is Composite Weight of each Alternative Choice.

Relative pair-wise comparisons on scale 1 to 9 are:

- Maximum Discharge Current (MDC) is 2 time as important as Maximum Charge Current (MCC),
- Declared Energy Capacity (DEC) is 6 time as important as maximum charge current (MCC),
- Declared Energy Capacity (DEC) is 4 time as important as maximum discharge current (MDC),
- Price (P) is 2 time as important as maximum discharge current (MDC),
- Price (P) is 3 time as important as maximum charge current (MCC),
- Declared Energy Capacity (DEC) is 2 time as important as price (P).

The criteria pair-wise comparison matrix and the priority vector (normalized eigen vector of the criteria matrix) are shown in Table 3. According to the procedure described in Algorithm 1, the consistency index is 0.0344 and the random consistency is 0.9. Thus, the consistency ratio is 0.0382, which is lower than 10%, indicating acceptable inconsistency [28]. Comparison vectors, i.e. normalized values from the technical data from Table 2, and overall results (CWAC column) are shown in Table 4. The overall results of the AHP presented in Table 4 are shown in Figure 2, where Cell 10 is chosen as the optimal battery cell according to the declared technical data.

### Table 3. Criteria pair-wise comparison matrix and priority vector based on technical data.

|       | DEC | MCC | MDC | P   | The priority vector |
|-------|-----|-----|-----|-----|---------------------|
| DEC   | 1.00| 6.00| 4.00| 2.00| 0.51                |
| MCC   | 0.17| 1.00| 0.50| 0.33| 0.09                |
| MDC   | 0.25| 2.00| 1.00| 0.50| 0.15                |
| P     | 0.50| 3.00| 2.00| 1.00| 0.27                |

### Table 4. Comparison vectors and overall results (CWAC column) based on technical data.

| Internal mark of the cell | DEC | MCC | MDC | P   | CWAC |
|---------------------------|-----|-----|-----|-----|------|
| Cell 01                   | 0.044| 0.082| 0.083| 0.0655| 0.058 |
| Cell 02                   | 0.070| 0.044| 0.019| 0.0955| 0.068 |
| Cell 03                   | 0.071| 0.065| 0.027| 0.0734| 0.066 |
| Cell 04                   | 0.070| 0.033| 0.085| 0.0622| 0.064 |
| Cell 05                   | 0.063| 0.030| 0.121| 0.0638| 0.068 |
| Cell 06                   | 0.067| 0.082| 0.104| 0.0477| 0.068 |
| Cell 07                   | 0.056| 0.082| 0.083| 0.0678| 0.065 |
| Cell 08                   | 0.068| 0.082| 0.042| 0.0478| 0.061 |
| Cell 09                   | 0.029| 0.031| 0.042| 0.0694| 0.042 |
| Cell 10                   | 0.078| 0.070| 0.042| 0.0678| 0.070 |
| Cell 11                   | 0.054| 0.082| 0.083| 0.0716| 0.065 |
| Cell 12                   | 0.043| 0.082| 0.091| 0.0573| 0.057 |
| Cell 13                   | 0.065| 0.082| 0.083| 0.0478| 0.064 |
| Cell 14                   | 0.076| 0.050| 0.021| 0.0477| 0.059 |
| Cell 15                   | 0.073| 0.041| 0.033| 0.0573| 0.061 |
| Cell 16                   | 0.071| 0.063| 0.042| 0.0573| 0.063 |

### Figure 2. Overall results of the AHP based on technical data.

An advanced custom-made grid-tied bidirectional AC-DC converter (description available in [11]) is used for testing the batteries and measuring of input / output currents and voltages. Nominal output power of the converter is 1 kW, output DC voltage range is from 0 to 20 V, and the output DC current is limited to 50 A in both directions. The converter is controlled over a supervisory control and data acquisition system developed in National Instruments LabVIEW and controlled over a National Instruments cRIO. The testbed also contains a temperature sensor PT100-1020 with temperature range from $-70^\circ$C to $+500^\circ$C and temperature coefficient 3850 ppm/$^\circ$C, which is used for measurement of temperature on the surface of the battery cells. Temperature chamber KMH-408, with temperature range $-40^\circ$C to $+150^\circ$C,
Algorithm 1 Analytic Hierarchy Process

Input: C1, C2, ..., Cn ⇒ enter Criteria
Input: A1, A2, ..., Am ⇒ enter Alternatives (battery cells)

for i ← 1 to length(C) do
    for j ← 1 to length(C) do Input: PWC_{i,j} ⇒ create Relative Importance Pair-wise Comparisons Matrix
end for
end for

CM ← PCM	⇒ initialize counter for while loop
i ← 1
while tolerance > acceptable_value do
    i ← i + 1
    CM ← CM × PCM
    CSR ← sum_of_each_row_of_CM
    SAE ← the_sum_of_all_elements_of_SR
    tolerance ← SR(i) ÷ CSR(i) − SR(i − 1) ÷ CSR(i − 1)
end while

PV ← SR(i) ÷ CSR(i) ⇒ calculate Priority Vector
for i ← 1 to length(C) do
    \( \lambda_{\text{max}} \) ← SAE + CM(i) + \( \lambda_{\text{max}} \) ⇒ calculate Consistency Index
end for

CI ← (\( \lambda_{\text{max}} \) − length(C)) ÷ (length(C) − 1) ⇒ define Random Consistency Index

switch length(A) do
    cases 2  RCi ← 0
    cases 3  RCi ← 0.58
    cases 4  RCi ← 0.90
    cases 5  RCi ← 1.12
    cases 6  RCi ← 1.24
    cases 7  RCi ← 1.32
    cases 8  RCi ← 1.41
    cases 9  RCi ← 1.45
    cases 10 RCi ← 1.49
    cases 11RCi ← 1.51
end switch

CR ← (CI/RCi) ⇒ calculate Random Consistency Ratio
if CR ≤ 10% then
    The inconsistency is acceptable ⇒ evaluate Inconsistency
else
    The inconsistency is not acceptable
end if

for i ← 1 to length(CV) do
    for j ← 1 to length(A) do Input: CV(i,j) ⇒ enter Comparison Vectors
end for
end for

CWAC ← PV × CV ⇒ calculate Composite Weight of Alternative Choices
The_best_result_location ← location(max(CWAC)) ⇒ location of Best Alternative (Optimal Battery Cell)

IV. DESCRIPTION OF EXPERIMENTAL TESTS
The designed battery pack to power a compact urban vacuum sweeper consist of a series of four identical segments, each made of a series of six modules (60 parallels of 4 cells in series). Overall, 5760 cells are connected in the battery pack. Nominal voltage of the pack is around 350 V, while the energy capacity ranges between 42 and 73 kWh, depending on the chosen battery cell.

All tests are conducted with the uniform initial nominal characteristics of the battery cells (charged to 100% state-of-charge with the same charging power and the same ambient conditions), and on the identical testbed (efficiency of the system and the measurement accuracy are consistent) in order to ensure the reliability of the test results. The testing environment is designed to simulate the real-world conditions of urban vacuum cleaning. The laboratory testing equipment is shown in Figures 3 and 4.
to make the results comparable. Prior to the tests, each cell had been inactive for at least five hours.

Charging/discharging current of one cell depends on the relation of the required power for one cell and its nominal power:

\[ I_{cell} = \frac{P_{bp}}{S760} \cdot \frac{C_{cell}}{E_{cell}} \]  

(1)

where \( P_{bp} \) (W) is the charging / discharging power of the battery pack, \( E_{cell} \) (Wh) the nominal energy capacity of a cell, and \( C_{cell} \) (Ah) the capacity of a cell.

Since the energy capacity is one of the most important criteria for evaluation, an energy test is conducted to identify the capacity of each cell at high power conditions. Energy capacity in standard operating conditions of the compact urban vacuum sweeper is tested by performing the adjusted consumption test cycle. In order to evaluate the charging characteristics, two different charging tests (constant current/constant voltage mode) are conducted. One with low power, to represent slow charging during the night, and the other with higher power to resemble the charging between the shifts during the day. Therefore, each battery cell was subject to the four tests presented in the following subsections.

A. ENERGY TEST
This test discharges battery cells with constant high power at almost 1C rate, which is the highest expected current during the highest consumption of the compact urban vacuum sweeper. The test is conducted on fully charged battery cells according to the manufacturers’ data sheets. The energy of a battery cell is measured simulating the sweeping mode at operating speed 5 km/h and 30% road slope. Calculated discharging power of one battery cell is \( P_{cell} = 8.829 \) W (discharging power of the battery pack \( P_{bp} = 50.86 \) kW).

B. ADJUSTED CONSUMPTION TEST
This experiment is conducted according to the sub-tests defined in standard EN 15249 with few adjustments, as shown in Figure 5. The test is repeated until the battery cell voltage reaches the discharge limit normalized for the tested battery cells. Battery cells remain inactive for 10 minutes between test cycles to reduce possible unrested battery effects [31]. The following sub-tests are conducted:

- Sub-test 1 (ST1): Propulsion prime mover at idle speed. Calculated power of one battery cell \( P_{cell} = 0 \) W (power of the battery pack \( P_{bp} = 0 \) kW).
- Sub-test 2 (ST2): 50% of the maximum operating speed, not exceeding 6 km/h. Calculated discharge power \( P_{cell} = 4.78 \) W (discharge power \( P_{bp} = 27.52 \) kW).
- Sub-test 3 (ST3): Maximum travel speed, not exceeding 40 km/h. Calculated discharging power \( P_{cell} = 7.31 \) W (discharge power \( P_{bp} = 42.09 \) kW).
- Sub-test 4 (ST4): 50% of the maximum operating speed, not exceeding 6 km/h. Calculated discharge power \( P_{cell} = 4.78 \) W (discharge power \( P_{bp} = 27.52 \) kW).

C. CHARGING AT 0.4C
Charging test at 0.4C is conducted after a full discharge in the Energy Test or Adjusted Consumption Test. The calculated charging power is \( P_{cell} = 3.82 \) W, which is close to 0.4C (battery pack charging at constant power \( P_{bp} = 22 \) kW).
D. Charging at 0.2C
This charging test is also conducted after a full discharge in the Energy Test or Adjusted Consumption Test. The calculated charging power is $P_{\text{cell}}=1.91$ W or approximately 0.2C (battery pack charging at constant power $P_{bp}=11$ kW).

V. Analysis of the Experimental Results
Measurements of current, voltage, temperature on the cell surface and time were conducted in all experimental tests, and the results were logged with a 1-second resolution. Based on the measured results, energy in Wh and energy capacity in Ah (Coulomb counting method) were calculated. As a result, state-of-charge and state-of-energy [11] can be expressed in percentages for every second of the conducted tests. In the electric vehicle industry, energy expressed in Wh is more convenient as the power of vehicles is expressed in W. Therefore, in this work the results related to energy are expressed in Wh and calculations of state-of-energy are used. Based on the measured temperature at the battery cell surface and the controlled temperature in the temperature chamber, a specific maximum temperature increase on the surface of a battery cell is calculated and expressed in °C/Wh in all tests.

**TABLE 5. Results of the Energy Test.**

| Internal mark of the cell | Discharging time (h) | Energy (Wh) | Specific discharged energy (Wh/h) | Maximum temperature increase (°C) | Specific maximum temperature increase (°C/Wh) |
|---------------------------|----------------------|-------------|----------------------------------|----------------------------------|---------------------------------------------|
| Cell 01                   | 0.70                 | 5.53        | 7.97                             | 7.80                             | 1.40                                        |
| Cell 02                   | 1.37                 | 10.61       | 7.75                             | 16.37                            | 1.54                                        |
| Cell 03                   | 1.16                 | 9.19        | 7.92                             | 17.52                            | 1.91                                        |
| Cell 04                   | 1.35                 | 11.14       | 8.25                             | 12.44                            | 1.12                                        |
| Cell 05                   | 1.13                 | 8.79        | 7.78                             | 11.27                            | 1.28                                        |
| Cell 06                   | 0.82                 | 4.48        | 5.46                             | 8.19                             | 1.83                                        |
| Cell 07                   | 1.05                 | 6.64        | 8.23                             | 7.69                             | 0.89                                        |
| Cell 08                   | 1.26                 | 10.43       | 8.28                             | 9.43                             | 0.90                                        |
| Cell 09                   | 0.54                 | 4.21        | 7.80                             | 9.43                             | 2.24                                        |
| Cell 10                   | 1.24                 | 9.96        | 8.03                             | 10.86                            | 1.09                                        |
| Cell 11                   | 0.98                 | 8.21        | **8.40**                         | **7.41**                         | 0.90                                        |
| Cell 12                   | 0.80                 | 6.38        | 7.98                             | 10.70                            | 1.68                                        |
| Cell 13                   | 1.11                 | 8.92        | 8.04                             | 10.16                            | 1.14                                        |
| Cell 14                   | 1.92                 | **11.40**   | 8.03                             | **7.61**                         | 0.67                                        |
| Cell 15                   | 1.47                 | 10.65       | 7.24                             | 11.26                            | 1.06                                        |
| Cell 16                   | 1.41                 | 10.35       | 7.34                             | 11.58                            | 1.12                                        |

**TABLE 6. Results of the adjusted consumption test.**

| Internal mark of the cell | Discharging time (h) | Energy (Wh) | Specific discharged energy (Wh/h) | Number of test cycles | Maximum temperature increase (°C) | Specific maximum temperature increase (°C/Wh) |
|---------------------------|----------------------|-------------|----------------------------------|-----------------------|----------------------------------|---------------------------------------------|
| Cell 01                   | 1.58                 | 6.31        | 4.01                             | 2.15                  | 3.50                             | 0.55                                        |
| Cell 02                   | 2.85                 | 10.32       | 3.80                             | 2.44                  | 5.50                             | 0.82                                        |
| Cell 03                   | 2.62                 | 10.16       | 3.88                             | 2.25                  | 10.43                            | 1.03                                        |
| Cell 04                   | 2.80                 | 11.72       | **4.19**                         | 2.40                  | 5.53                             | 0.47                                        |
| Cell 05                   | 2.47                 | 9.72        | 3.94                             | 2.12                  | 5.20                             | 0.53                                        |
| Cell 06                   | 1.92                 | 7.15        | 3.73                             | 1.64                  | **2.85**                         | 0.40                                        |
| Cell 07                   | 2.34                 | 8.86        | 3.79                             | 2.01                  | 3.34                             | 0.38                                        |
| Cell 08                   | 2.64                 | 10.80       | 4.09                             | 2.26                  | 4.47                             | 0.41                                        |
| Cell 09                   | 1.06                 | 4.29        | 4.05                             | 0.91                  | 3.47                             | 0.81                                        |
| Cell 10                   | 2.74                 | 10.69       | 3.90                             | 2.35                  | 7.12                             | 0.67                                        |
| Cell 11                   | 1.96                 | 8.13        | 4.15                             | 1.68                  | 4.39                             | 0.54                                        |
| Cell 12                   | 1.66                 | 6.58        | 3.96                             | 1.42                  | 6.62                             | 1.01                                        |
| Cell 13                   | 2.54                 | 9.09        | 3.93                             | 2.18                  | 5.68                             | 0.97                                        |
| Cell 14                   | 2.97                 | **11.80**   | 3.97                             | 2.55                  | **4.80**                         | **0.41**                                     |
| Cell 15                   | **2.99**             | 11.56       | 3.87                             | **2.56**              | 6.43                             | 0.56                                        |
| Cell 16                   | 2.90                 | 10.63       | 3.67                             | 2.49                  | 5.55                             | 0.52                                        |

Examples of logged measurements for Cell 04 tests are presented in Figures 6 and 7 to visualize the conducted tests. Thermal characteristic in the Adjusted Consumption Test shown in Figure 6 illustrates a temperature increase at low values of state-of-energy, i.e. high depth-of-discharge, of the tested cell (right-hand side of the cell discharge curve). This is due to higher stress levels induced in the electrodes because of a high mechanical expansion and contraction at high depth-of-discharge. The effects of battery resting can be noticed in Figure 7, which shows the discharging current-voltage characteristic of the Adjusted Consumption Test. Every interval with zero output current results in increased battery cell voltage. The magnitude of this phenomenon depends on the cell voltage at the end of the discharging period and the battery state-of-charge.

Tables 5–8 show the results of each of the four experimental tests. To make them easier to read, the results above average are highlighted with grey background, while the best result is also in bold font. The results in the tables cover time, energy, specific energy, maximum increase in the temperature during the test and specific increase in the temperature during the test. Due to the nature of the tests, Tables 5 and 6 show cell discharging time and discharged...
TABLE 7. Charging at 0.2C test results.

| Internal mark of the cell | Charging time (h) | Energy (Wh) | Specific charged energy (Wh) | Maximum temperature increase (°C) | Specific maximum temperature increase (°C/Wh) |
|--------------------------|-------------------|-------------|-----------------------------|-----------------------------------|-----------------------------------------------|
| Cell 01                   | 3.49              | 5.22        | 1.50                        | 1.84                              | 0.35                                          |
| Cell 02                   | 3.26              | 9.37        | 1.74                        | 1.54                              | 0.17                                          |
| Cell 03                   | 4.06              | 6.32        | 1.56                        | 2.21                              | 0.35                                          |
| Cell 04                   | 5.16              | 9.68        | 1.88                        | 1.24                              | 0.13                                          |
| Cell 05                   | 5.09              | 7.93        | 1.56                        | 1.42                              | 0.18                                          |
| Cell 06                   | 4.27              | 6.34        | 1.48                        | 1.05                              | 0.17                                          |
| Cell 07                   | 4.38              | 7.5         | 1.71                        | 0.52                              | 0.07                                          |
| Cell 08                   | 3.88              | 8.91        | 1.52                        | 0.86                              | 0.10                                          |
| Cell 09                   | 2.36              | 4.04        | 1.71                        | 1.58                              | 0.39                                          |
| Cell 10                   | 5.72              | 8.96        | 1.57                        | 2.13                              | 0.24                                          |
| Cell 11                   | 4.42              | 7.43        | 1.68                        | 1.91                              | 0.26                                          |
| Cell 12                   | 4.06              | 6.02        | 1.48                        | 0.93                              | 0.15                                          |
| Cell 13                   | 6.48              | 9.39        | 1.45                        | 2.49                              | 0.27                                          |
| Cell 14                   | 6.11              | 9.82        | 1.61                        | 1.08                              | 0.11                                          |
| Cell 15                   | 6.62              | 9.89        | 1.49                        | 1.66                              | 0.17                                          |
| Cell 16                   | 5.06              | 8.1         | 1.60                        | 2.24                              | 0.28                                          |

TABLE 8. Charging at 0.4C test results.

| Internal mark of the cell | Charging time (h) | Energy (Wh) | Specific charged energy (Wh) | Maximum temperature increase (°C) | Specific maximum temperature increase (°C/Wh) |
|--------------------------|-------------------|-------------|-----------------------------|-----------------------------------|-----------------------------------------------|
| Cell 01                   | 2.33              | 5.24        | 2.25                        | 3.77                              | 0.72                                          |
| Cell 02                   | 3.75              | 9.74        | 2.60                        | 3.13                              | 0.32                                          |
| Cell 03                   | 3.76              | 9.52        | 2.53                        | 4.92                              | 0.52                                          |
| Cell 04                   | 3.77              | 10.5        | 2.79                        | 3.09                              | 0.29                                          |
| Cell 05                   | 3.12              | 8.07        | 2.29                        | 3.51                              | 0.43                                          |
| Cell 06                   | 2.84              | 6.49        | 2.29                        | 1.96                              | 0.30                                          |
| Cell 07                   | 2.39              | 7.53        | 3.15                        | 2.99                              | 0.40                                          |
| Cell 08                   | 3.70              | 9.37        | 2.53                        | 2.98                              | 0.32                                          |
| Cell 09                   | 1.35              | 4.08        | 3.02                        | 3.29                              | 0.81                                          |
| Cell 10                   | 5.47              | 11.52       | 2.11                        | 4.11                              | 0.36                                          |
| Cell 11                   | 2.49              | 7.81        | 3.14                        | 0.96                              | 0.12                                          |
| Cell 12                   | 3.66              | 8.37        | 2.39                        | 4.44                              | 0.70                                          |
| Cell 13                   | 3.55              | 9.09        | 2.36                        | 3.86                              | 0.42                                          |
| Cell 14                   | 3.97              | 10.26       | 2.58                        | 2.96                              | 0.29                                          |
| Cell 15                   | 3.36              | 8.50        | 2.53                        | 4.5                               | 0.53                                          |
| Cell 16                   | 4.47              | 9.42        | 2.11                        | 4.49                              | 0.48                                          

Energy, while Tables 7 and 8 contain data on the charging time and charged energy. Temperature measurement results are presented and evaluated because safety aspects [32] and preservation of state-of-health of a battery [33] highly depend on its heating characteristics.

Energy Test results in Table 5 indicate that the highest discharging times and discharged energy are achieved for the battery cells with highest capacity (see Table 2). Cell 15 takes the longest to discharge (1.47 h), followed by Cells 14, 16 and 04. These cells have the highest amount of discharged energy as well. Best score in the amount of discharged energy is achieved by Cell 14 (11.40 Wh). However, when this is scaled to the battery cell capacity from Table 2, the highest specific discharged energy is achieved by Cell 11 due to its lower cell capacity (2500 mAh). Cell 11 has the lowest temperature increase during the test as well.

However, when scaled to the cell capacity, the lowest specific temperature increase is achieved by Cell 14. Based on the results of this test, the best performance is obtained by NMC Cells 11 and 14. Cell 11 is characterized by low capacity, but high specific discharged energy and low temperature increase, while Cell 14 is characterized by high capacity, high discharge time and energy and low specific temperature increase. However, it is important to note that the only cell, besides Cell 14, that has above-average results in all the categories is an LMO-based Cell 08.

To further examine the results of the Energy Test, output current and temperatures of Cells 01, 02, 10 and 14 are visualized in Figure 8. One can observe that the discharging time of Cell 01 is 50% shorter than the one of Cell 14. Cell 14 also has very low temperature increase compared to the other three cells in the graph. The highest temperature increase is observed for Cell 02.

Results of the Adjusted Consumption Test in Table 6 are quite similar to the Energy Test results in Table 5. Again, the only two cells with above-average results in all categories are Cell 08 and Cell 14. Furthermore, the longest discharging time is again achieved by Cell 15 and the highest amount of discharged energy by Cell 14. However, the highest specific discharged energy is achieved for Cell 04, which performed extremely well in this category in the Energy Test as well. The highest number of cycles is achieved by Cell 15, which has the second highest nominal energy capacity (3350 mAh).

However, the lowest temperature increase during the Adjusted Consumption Test is achieved by Cell 06, while the lowest specific temperature increase is gained by Cell 02. Overall, Cell 15 completed this test with the highest score in two categories, while performance of Cell 11 not as great as in the Energy Test.

To further evaluate the differences between specific cells, output current and temperature increase data during the Adjusted Consumption Test are presented in Figure 9. Discharging power in this test is lower than in the Energy Test so the resulting temperature increases in Figure 9 are much lower than those in Figure 8. Although at the beginning of the test the temperature of Cell 02 harshly increases, the worst result overall is achieved by Cell 10. Observing closely the temperature curve of Cell 02, and combining it with extremely poor results in the high-power...
Energy Test, the conclusion is that Cell 02 suffers from extremely high temperature increase under high output currents (above 1.5 A), while at lower currents this increase is not as dramatic.

Tables 7 and 8 show the results for 0.2C and 0.4C charging tests. The shortest charging time is achieved for Cell 09 due to its very low nominal capacity (1500 mAh). The shortest charging time of high-capacity cells is achieved for Cell 03, whose nominal capacity is 3200 mAh and it charges at 0.2C within 4.06 hours. The highest amount of energy during the 0.2C charging test is injected in Cells 13, 14 and 15. However, this process takes over 6 hours. On the other hand, Cell 04 requires only 5.16 hours to charge 9.68 Wh. Cell 04 thus performs the best when observing specific charged energy. By far the lowest temperature increase is obtained for Cell 07.

Very similar results are achieved for the final test where cells are charged at 0.4C (Table 8). Cell 09 is again quickest to charge. However, the most energy is charged in Cell 10, but Cells 13, 14 and 15 perform above-average as well. The highest specific charged energy is achieved for Cell 07. As opposed to the 0.2C charging test, where it performs below-average, Cell 11 in the 0.4C charging test gains the lowest temperature increase.

VI. CHOOSING THE OPTIMAL CELL

Not all the conducted tests are equally important for application in compact urban vacuum sweepers, where the Energy Test and Adjusted Consumption Test play a key input in deciding on the optimal battery cell. On the other hand, the charging tests at 0.2C and 0.4C are used as control tests where a cell can fail only if the achieved results are well below an average. Therefore, the AHP is used to compare the results of the conducted tests and to choose the optimal battery cell for an urban compact vacuum sweeper. The criteria used for comparison are measured energy capacity and temperature increase in the four conducted tests, i.e. the Energy Test, Adjusted Consumption Test, and two charging tests. Relative importance’s of pairwise comparisons are:

- adjusted consumption test (ACT) is 2 times as important as energy test (ET),
- energy test is 3 times as important as slow charge test (SCT),
- energy test is 4 times as important as fast charge test (FCT),
- measured energy capacity (MEC) is 2 times as important as measured temperature increase (MTI),
- energy test, measured energy capacity is 2 times as important as price (P),
- energy test, measured temperature increase is 1 times as important as price,
- adjusted consumption test, measured energy capacity is 3 times as important as price,
- adjusted consumption test, measured temperature increase is 1.5 times as important as price,
- slow charge, energy test is 1 times as important as price,
- price is 2 times as important as slow charge, measured temperature increase,
- fast charge, measured energy capacity is 1 times as important as price,
- price is 2 times as important as fast charge, measured temperature increase.

The criteria pair-wise comparison matrix and the priority vector of AHP analysis of the experimental results are shown in Table 9. According to the procedure in Algorithm 1, the consistency index is 0.0209 and the random consistency is 1.45, resulting in the consistency ratio 0.0144, which is lower than 10% (inconsistency is acceptable). Comparison vectors, i.e. normalized values from the experimental results presented in Tables 5, 6, 7 and 8, are shown in Table 10.

A. OUTCOMES OF THE AHP

The overall results of the AHP analysis of the tested battery cells are presented in Table 10 and shown in Figure 10.
The optimal cell for the compact urban sweeper considering the results of the experimental testing is Cell 14. The main reason for this is the highest amount of discharged energy in both the Energy Test and the Adjusted Consumption Test. Also this cell exhibits very good thermal characteristics. The only below-average categories for this cell are charging times in the charging tests. However, these results have lower weight in the AHP method. Long charging times are caused by this cell’s high capacity (3500 mAh). Cell 10, which was considered optimal based on the manufacturers’ technical data, is only fifth best cell after the experimental testing. The main reason is that its high declared energy capacity was proven much lower in both the Energy Test and the Adjusted Consumption Test. In the Energy Test, the measured energy capacity is only 9.96 Wh, which is 13% lower than 11.40 Wh drained from Cell 14. In the Adjusted Consumption Test, Cell 10 performed slightly better, but again its 10.69 Wh capacity is significantly lower than 11.80 Wh of Cell 14. Cells 04, 08 and 11 also surpassed Cell 10 when experimental tests and AHP method is used. The main reasons for Cells 04 and 08 placing ahead of Cell 10 is their high measured energy capacity. However, Cell 11 has lower energy capacity, but shows very good thermal characteristics (it excels in the maximum temperature increase), which is sufficient for the third place in the AHP scores.

While some results are expected, e.g. charging time of Cell 09, which has the lowest capacity among the tested cells, is the shortest, some results are not as expected. For instance, the longest charging time is not achieved for cells with the highest energy capacity (Cells 10 and 14 have 3500 mAh capacity), but for Cell 15 (3350 mAh) in the 0.2C charging test and Cell 16 (3200 mAh) in the 0.4C charging test. The conducted tests also indicate that LCO battery cells have the worst characteristics when it comes to thermal ratings.

VII. CONCLUSION

The methodology for selecting an optimal lithium-ion battery cell for a compact urban vacuum sweeper presented in this article is based on analysis of the laboratory test results using the Analytic Hierarchy Process. Four experimental tests are conducted on sixteen different lithium-ion battery cells in the same ambient conditions. The proposed experimental tests were conducted under simulated real-world conditions, which is essential to verify and assess the suitability of a battery cell for a specific purpose. The conducted laboratory tests follow the European standard EN 15429-2, while the additional tests are designed according to the specific performance requirements on the sweeper. Results of the tests are evaluated and compared using the Analytic Hierarchy Process with the following criteria: measured energy capacity.
in all the tests, temperature increase in all the tests and price of the battery cell. The optimal lithium-ion battery cell selected with the proposed methodology is different than the battery cell selected solely on analysis of the manufacturers’ datasheets. So, although the manufacturers’ datasheets contain many useful information, it is shown that an analysis based exclusively on such data may result in sub-optimal battery cell selection.

In future work, the focus of the research will be in expanding the experimental tests with different ambient testing conditions, and in developing a more complex algorithm for evaluation of a larger scope of the battery cell characteristics.

REFERENCES

[1] C. C. Chan and Y. S. Wong, “Electric vehicles charge forward,” IEEE Power Energy Mag., vol. 2, no. 6, pp. 24–33, Nov. 2004.
[2] V. Bobanac, H. Pandzic, and T. Capuder, “Survey on electric vehicles and battery swapping stations: Expectations of existing and future EV owners,” in Proc. IEEE Int. Energy Conf. (ENERGYCON), Piscataway, NJ, USA: Institute of Electrical Electronics Engineers, Jun. 2018, pp. 1–6.
[3] S. M. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi, “Energy storage systems for automotive applications,” IEEE Trans. Ind. Electron., vol. 55, no. 6, pp. 2258–2267, Jun. 2008.
[4] A. F. Burke, “Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles,” Proc. IEEE, vol. 95, no. 4, pp. 806–820, Apr. 2007.
[5] Dulevo International. Accessed: Nov. 20, 2020. [Online]. Available: https://www.dulevo.com/en/p/Dulevo_D.ZERO%C2%B2.xhtml
[6] D. Linden and T. B. Reddy, Handbook of Batteries. New York, NY, USA: McGraw-Hill, 2002.
[7] X. Chen, W. Shen, T. T. Vo, Z. Cao, and A. Kapoor, “An overview of lithium-ion batteries for electric vehicles,” in Proc. 10th Int. Power Energy Conf. (IPEC), Nov. 2012, pp. 230–235.
[8] N. Omar, B. Verbrugge, G. Mulder, P. Van den Bossche, J. Van Mierlo, M. Daoud, M. Dhaens, and S. Pauwels, “Evaluation of performance characteristics of various lithium-ion batteries for use in BEV application,” in Proc. IEEE Vehicle Power Propuls. Conf. Lille, France: IEEE, Sep. 2010, pp. 1–6.
[9] A. Shafiee, A. Momeni, and S. S. Williamson, “Battery modeling approaches and management techniques for plug-in hybrid electric vehicles,” in Proc. IEEE Vehicle Power Propuls. Conf., Sep. 2011, pp. 1–5.
[10] M. Chen and G. A. Rincon-Mora, “Accurate electrical battery model capable of predicting runtime and L-V performance,” IEEE Trans. Energy Convers., vol. 21, no. 2, pp. 504–511, Jun. 2006.
[11] H. Pandzic and V. Bobanac, “An accurate charging model of battery energy storage,” IEEE Trans. Power Syst., vol. 34, no. 2, pp. 1416–1426, Mar. 2019.
[12] M. Coleman, W. G. Hurley, and C. Kwan Lee, “An improved battery characterization method using a two-pulse load test,” IEEE Trans. Energy Convers., vol. 23, no. 2, pp. 708–713, Jun. 2008.
[13] I. Arasaratnam, J. Tjong, and R. Ahmed, “Battery management system in the Bayesian paradigm: Part I: SOC estimation,” in Proc. IEEE Int. Symp. Electr. Conf. Expo (IETEC), Piscataway, NJ, USA: Institute of Electrical Electronics Engineers, Jun. 2014, pp. 1–5.
[14] G. Giordano, V. Klass, M. Behm, G. Lindbergh, and J. Sjöberg, “Model-based lithium-ion battery resistance estimation from electric vehicle operating data,” IEEE Trans. Veh. Technol., vol. 67, no. 5, pp. 3720–3728, May 2018.
[15] J. Tang, Q. Liu, S. Liu, X. Xie, J. Zhou, and Z. Li, “A health monitoring method based on multiple indicators to eliminate influences of estimation dispersion for lithium-ion batteries,” IEEE Access, vol. 7, pp. 122302–122314, 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8805385/
[16] R. Benato, S. Dambone Sessa, M. Musio, F. Palone, and R. Polito, “Italian experience on electrical storage ageing for primary frequency regulation,” Energies, vol. 11, no. 8, p. 2087, Aug. 2018.
[17] L. Zhang, Z. Mu, and X. Gao, “Coupling analysis and performance study of commercial 18650 lithium-ion batteries under conditions of temperature and vibration,” Energies, vol. 11, no. 10, p. 2856, Oct. 2018.
[18] X. Gong, R. Xiong, and C. C. Mi, “Study of the characteristics of battery packs in electric vehicles with parallel-connected lithium-ion battery cells,” IEEE Trans. Ind. Appl., vol. 51, no. 2, pp. 1872–1879, Mar. 2015.
[19] D. Anseán, M. González, V. M. García, J. C. Viera, J. C. Antón, and C. Blanco, “Evaluation of LiFePO4 batteries for electric vehicle applications,” IEEE Trans. Ind. Appl., vol. 51, no. 2, pp. 1855–1863, Mar. 2015.
[20] Electric Vehicle Battery Test Procedures Manual, Revision 2, United States Adv. Battery Consortium, Southfield, MI, USA, 1996.
[21] Battery University. Accessed: Nov. 20, 2020. [Online]. Available: https://batteryuniversity.com
[22] F. P. Tredeau and Z. M. Salameh, “Evaluation of lithium iron phosphate batteries for electric vehicles application,” in Proc. IEEE Vehicle Power Propuls. Conf. Dearborn, MI, USA: IEEE, Sep. 2009.
[23] A. Marongiu, A. Damiano, and M. Héuer, “Experimental analysis of lithium iron phosphate battery performances,” in Proc. IEEE Int. Symp. Ind. Electron., Jul. 2010, pp. 3420–3424.
[24] J. Wang, Z. Sun, and X. Wei, “Performance and characteristic research in LiFePO4 battery for electric vehicle applications,” in Proc. 5th IEEE Vehicle Power Propuls. Conf. (VPPC), Sep. 2009, pp. 1657–1661.
[25] F. P. Tredeau, B. G. Kim, and Z. M. Salameh, “Performance evaluation of lithium cobalt cells and the suitability for use in electric vehicles,” in Proc. IEEE Vehicle Power Propuls. Conf. Harbin, China: IEEE, Sep. 2008, pp. 1–5.
[26] B. G. Kim, F. P. Tredeau, and Z. M. Salameh, “Performance evaluation of lithium polymer batteries for use in electric vehicles,” in Proc. IEEE Vehicle Power Propuls. Conf., Sep. 2008, pp. 1–5.
[27] Sweepers Part 2: Performance Requirements and Test Methods, European Standard EN 15429-2, 2012.
[28] T. L. Saaty, The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. New York, NY, USA: McGraw-Hill, 1980.
[29] H. H. M. H. Alhababi. A New AHP Model for Selecting the Best Battery for a Firefighting and Rescue Boat. Accessed: Nov. 20, 2020. [Online]. Available: http://irja.in
[30] F. Ben Ammar, I. H. Hafa, and F. Hammami, “Analytic hierarchy process selection for batteries storage technologies,” in Proc. Int. Conf. Electr. Eng. Softw. Appl., Mar. 2013, pp. 1–6.
[31] S. Mischie. Behavior of the Lead Acid Battery After the Rest Period. Accessed: Nov. 20, 2020. [Online]. Available: http://www.etc.upt.ro
[32] C. J. Govar and J. A. Banner, “Safety testing of lithium ion batteries for navy devices,” IEEE Aerosp. Electron. Syst. Mag., vol. 18, no. 1, pp. 17–20, Jan. 2003.
[33] M. Jafari, A. Gauchia, S. Zhao, K. Zhang, and L. Gauchia, “Electric vehicle battery cycle aging evaluation in real-world daily driving and vehicle-to-grid services,” IEEE Trans. Transport. Electrific., vol. 4, no. 1, pp. 122–134, Mar. 2018.

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