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EXPERIMENTAL EVALUATION AND ANALYSIS OF 18650 BATTERY ENERGY CAPACITY AND PERFORMANCE PARAMETERS

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Purpose: The primary objective of this paper was to present the research findings on 18650 batteries, with an emphasis on consumer selection practices, as well as the challenges and support mechanisms related to product quality. Additionally, the study aimed to identify critical issues that could inform future legislative changes related to 18650 batteries.
Design/methodology/approach: The study employed a survey-based methodology, wherein participants were queried regarding the battery features they prioritize during their procurement process. The second phase of the study involved technical measurements of selected 18650 batteries, including their actual capacity and mass. A measurement system was designed and implemented, utilizing a solution that optimally replicated the user's real-world battery charging conditions.
Findings: The web-survey allowed for the identification of the most important characteristics of batteries from the customers' perspective. As a result of the research, significant discrepancies were found between the declared and measured parameters of the batteries. It was identified that there is a lack of legal regulations governing the quality parameters that are important to consumers of this type of energy source.
Research limitations/implications: The necessity for establishing appropriate standards for 18650 batteries has been demonstrated.
Practical implications: Considering the number of charge and discharge cycles for these products, batteries with lower capacities impose a substantial environmental and economic burden, as they require more frequent replacement and recycling.
Social implications: The need to enhance production and quality control standards for 18650 batteries has been emphasized to ensure the production of high-quality products that minimize environmental impact while maximizing consumer benefits.
Originality/value: The parameters of 18650 batteries most relevant to consumers are presented, along with discrepancies between the specifications declared by manufacturers and their actual performance. The findings can assist producers in making informed decisions during the prototyping phase to enhance product quality, and guide legislators in developing appropriate legal standards.
Keywords: lithium-ion batteries, energy capacity, quality, customer.
Category of the paper: Research paper.

1. Introduction

The 18650 battery is a cylindrical lithium-ion cell commonly used in applications such as laptop computers, power tools, and electric vehicles. 18650 rechargeable batteries are named for their external dimensions. 18650 batteries offer high energy density, good cycle life and strong discharge capabilities. They are characterized by superior performance in terms of current efficiency and capacity. Energy capacity is one of the key performance indicators of lithium-ion batteries and remains an active area of research. The battery capacity reflects how much energy can be stored into a fully charged battery. The required capacity of this type of batteries depends on its intended application (Axsen, Burke, Kurani, 2010). In this regard, 18650 batteries are increasingly replacing AA and AAA batteries in portable devices and have recently emerged as a preferred choice among consumers for powering a range of devices, including flashlights, electric toys, electric vehicles, and energy storage systems (Gaines, Cuenca, 2000; Maisel et al., 2023). The same batteries are utilized in laptops, power tools, and power banks and even in drones (Czerniak, Gacek, Szopa, 2021, 2023a, 2023b). Their popularity is driven by their high energy density, long life cycle, and relatively low cost. Choosing the right 18650 depends on capacity, discharge rate and application requirements. The batteries discussed in this article, distributed on the Polish as well as the European market, exhibit markedly divergent quality parameters. Quality characteristics such as battery capacity, durability, presence of protective electronics, and even dimensions should be taken into account. Ensuring the quality of these batteries is critical for both safety and efficiency of use.

The motivation for this research originated from an analysis of 2019 data sourced from the Eurostat platform, which assessed the recycling efficiency of batteries and accumulators across all EU Member States. In 2019, Poland ranked second, just behind Croatia, in terms of recycling efficiency (Figure 1). During this period, Eurostat (*Portable batteries and accumulators...*, 2019) reported that Poland's battery collection and recycling rate was 72.6%, which is significant compared to other EU countries. It should be noted that the 2019 data were not available for two Member States. For Romania, the data presented in Figure 1 is from 2018, while for the Netherlands, the data is estimated.

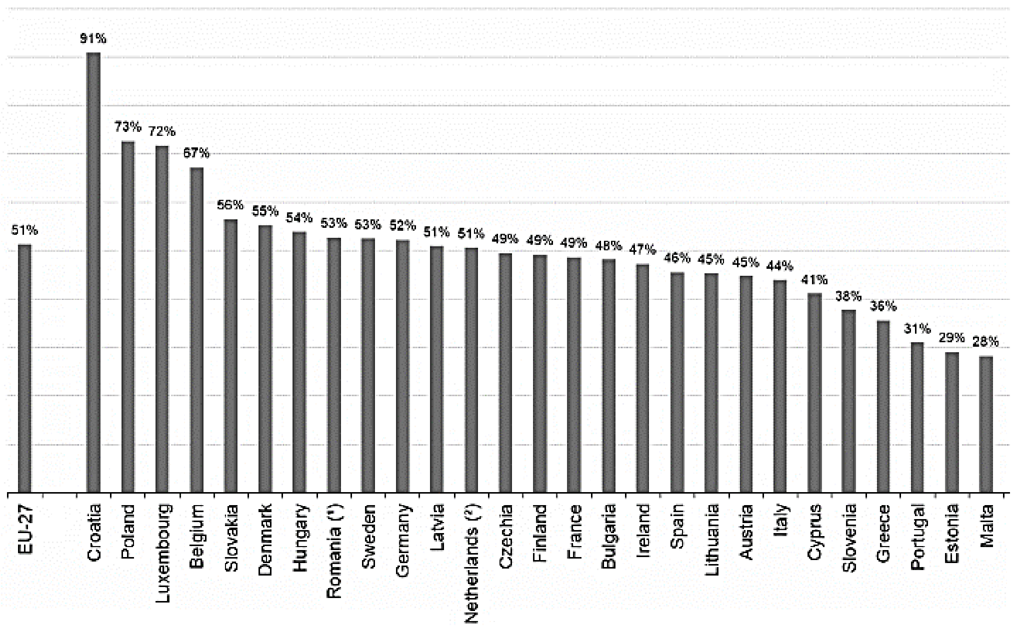

Figure 1. Portable batteries and accumulators collected for recycling (%), EU, 2019.

Source: based on Eurostat Statistic Explained data (Portable batteries and accumulators..., 2019).

The process of recycling batteries significantly impacts both the environment and a country's budget. Consequently, high-quality batteries positively influence their durability and lifespan, leading to economic and ecological benefits (Axsen, Burke, Kurani, 2010; Doolan, Boyden, 2016; Maisel et al., 2023). The primary objective of this paper was to present the research findings on 18650 batteries, with an emphasis on consumer selection practices, as well as the challenges and support mechanisms related to product quality. Additionally, the study aimed to identify critical issues that could inform future legislative changes related to 18650 batteries. The parameters of 18650 batteries most relevant to consumers are presented, along with discrepancies between the specifications declared by manufacturers and their actual performance. The findings can assist producers in making informed decisions during the prototyping phase to enhance product quality, and guide legislators in developing appropriate legal standards. An attempt was also made to assess battery quality using an indirect method based on mass measurements. The method was validated through electrical testing.

2. Literature review

Addressing the topic of establishing criteria for evaluating 18650 batteries to clearly determine the parameters that differentiate their quality, a literature study was conducted. This involved analyzing available sources that cover this subject matter. The initial approach adopted by the authors was to analyze the existing standards (ANSI, 2021; IEC, 2017a, 2017b, 2019; JSA, 2007, 2015; PKN, 2017) which outline the fundamental criteria that manufacturers must adhere to.

Standard dimensions for 18650 batteries follow IEC (International Electrotechnical Commission) and other industry standards. The name itself indicates the size. According to IEC 60086-4 (2025), the typical dimensions are 18.0 mm ± 0.2 mm diameter and 65.0 mm ± 0.2 mm length. However, the actual length may vary depending on the type of cell. The length of an unprotected cell is approximately 65.0 mm and a protected cell (with BMS/protection circuit) up to 70 mm.

IEC 62133 (2017a) – the most widely accepted safety standard for lithium-ion batteries – covers electrical, mechanical and thermal safety. The capacity of the 18650 battery is measured in mAh (milliampere-hours) and/or Wh (watt-hours). The typical capacity of this power source is in the range of 1200-3600 mAh and a high capacity cell up to approximately 5000 mAh. IEC 61960 (2024) describes capacity ratings (mAh), discharge rates and cycle life tests, defines energy density and efficiency criteria. Energy density is a common measure of battery energy, measured as the total Wh/kg of the battery (Zubi et al., 2018), and is a fundamental parameter that affects battery performance, dimensional constraints, mass, and operating costs. Nominal voltage for these batteries is in the range of 3.6-3.7 V, fully charged voltage is 4.2 V, and discharge voltage (cutoff) is 2.5-3.0 V. IEC 62660-1 (2019) and IEC 62660-2 (2018) (Automotive Li-ion Battery Standards) describe capacity, impedance, cycling and safety tests for electric vehicle (EV) applications. SAE J2464 (Automotive Safety Standard) (2021) is also used for electric vehicle (EV) and hybrid vehicle battery packs. JIS C 8715-2 (Japanese Industrial Standard) (2019) covers aging characteristics, cycle life and charging efficiency. Typical life for the 18650 battery is estimated at 300-1000 cycles and more, so the range is very wide and depends on how the battery is used. Factors affecting battery life are: depth of discharge (DoD) (very unfavorable 100% discharge), operating temperature (high temperatures degrade cells), charging rate (fast charging shortens life). The ideal operating range for lithium-ion cells is 0°C to 45°C when charging and -20°C to 60°C when discharging. High temperatures can increase capacity fade and cause thermal runaway, while low temperatures reduce discharge capacity. Based on this standard, protection circuitry is required to prevent overcharging, over-discharging, and short-circuiting. For safety, protected cells and proper charging methods should always be used. Common safety and protection issues with 18650 batteries include overcharging (protective circuitry should be used), short circuiting (causes fire/explosion), and deep discharge (shortens life). The following protections are used: PCB (Protection Circuit Board)/BMS (Battery Management System), thermal sensors, and safety ventilation.

18650 batteries can be divided into two distinct groups based on their functionality. The first group features a protruding positive terminal and is designed for compatibility with the sockets found in portable devices. The second group, characterized by a flush positive terminal, is intended for assembly into battery packs. These packs are constructed from multiple batteries connected in series and parallel. The number of batteries is determined by the required voltage and current output, tailored to the specific device. A second feature differentiating the two groups of batteries is the implementation of a protection device within their structure, in the form of an electronic board, in the first group. This protection circuitry is designed to safeguard the battery against over-discharging and over-charging. The second group of batteries does not incorporate such protection, as this function is managed by the electronics that control the entire pack. There are numerous brands of this type of battery available on the Polish market.

The subsequent step involved reviewing the literature on 18650 batteries, which, however, includes specification of the chemical structure of the batteries and details the tests conducted to determine their technical parameters (Beard, 2019; Czerwiński, 2012). Common 18650 battery types are:

- IMR (Lithium Manganese Oxide – $LiMn_2O_4$), which are characterized by high discharge rate, safer, medium capacity. They are used in vapes and power tools.
- INR (Lithium Nickel Manganese Cobalt – $LiNiMnCoO_2$), which are characterized by high capacity and good discharge rate. They are used in EVs (Tesla Model S uses 18650 packs) and power banks.
- ICR (Lithium Cobalt Oxide – $LiCoO_2$), which are characterized by high capacity but lower discharge rate. They are used in laptop computers and flashlights.
- IFR (Lithium Iron Phosphate – $LiFePO_4$), which are characterized by long cycle life, high safety and lower energy density. They are used in solar battery banks and e-bikes.

Safety standards are described in UL 1642 (2022), Underwriters Laboratories, USA standard, where we can find instructions on safety tests for lithium-ion cells, including overcharge, short circuit, drop tests, and thermal abuse. UL 2054 (2021) (Battery Packs) applies to complete battery packs and ensures BMS (Battery Management System) safety. UN 38.3 (2023) (United Nations Transportation Standard) requires for shipping lithium-ion batteries includes altitude, thermal, vibration, shock, impact, and overcharge tests. IEEE 1725 and IEEE 1625 (Battery Certification for Mobile Devices and Laptops) define battery reliability, charging efficiency and failure prevention.

Environmental and recycling standards are also inextricably linked to the issue of safety. RoHS (Restriction of Hazardous Substances Directive) (EU & International) describes restrictions on toxic materials such as cadmium, lead and mercury in lithium batteries. EU Battery Directive 2006/66/EC regulates the manufacture, recycling and disposal of lithium-ion batteries. ISO 14001 (Environmental Management Standard) (2024) requires sustainable production & recycling of batteries.

The authors' analysis of the literature also showed that some manufacturers deliberately overstate the mass of their products to give the impression of superior electrical performance. Consumer feedback and examples of such unethical practices are documented on online forums dedicated to this topic. The authors found instances where 18650 batteries were filled with a bulk substance to increase their mass but contained a smaller prismatic battery with low capacity inside (Hartley-Barnes, 2016; Cheap 18650 cells…, 2024; Chinese 18650 Lithium-ion Batteries…, 2024; Test ogniw Li-ion 18650…, 2024). An analysis of the available literature revealed that there are no well-defined criteria for the characterization of 18650 batteries, but rather general issue about batteries and primary cells. It does not address these batteries as a commercial product or define criteria that could guide customers. The authors failed to identify the standards required to restrict the commercialization of low-quality batteries that may overheat, swell, or leak electrolyte. Consequently, the authors decided to undertake research focused on consumer awareness and expectations regarding this product category. The study is particularly pertinent to the current EU energy policy, which is based on the principles of decarbonization, competitiveness, and sustainability but may have wider application to consumer protection contexts.

3. Materials and methods

The research strategy involved a two-step process: an web-survey and testing of the electrical and physical parameters of 18650 batteries. The authors administered a web-survey to the customers of small batteries, in order to have clearer information on the most important characteristics of batteries and the battery features they consider when making a purchasing decision. Respondents were randomly selected, but limited to people who are members of the world-famous social network. The web-survey was submitted by webpage and was structured in two stages: the first concerned the respondents' awareness of small batteries, while the second part was based on the structure of gender, age, education and place of residence. The research included an online survey with 152 respondents (75 women and 74 men; 3 individuals did not provide gender information). All respondents were under 50 years of age, with 55% under 20 years old, 42% between 20 and 30 years old, and the remaining 3% over 30 years old. Among the respondents, 57 lived in large cities, 50 in rural areas, 39 in small towns, and the rest did not provide information on their place of residence. Most respondents had secondary education (128), while a few had primary, vocational, or higher education.

The next step involved testing the performance and quality parameters of 18650 lithium-ion batteries through laboratory measurements. The 18650 batteries were purchased from a popular auction platform. A measurement system was designed and constructed, which was equipped with three independent measurement tracks, each dedicated to a single battery under test (Figure 2).

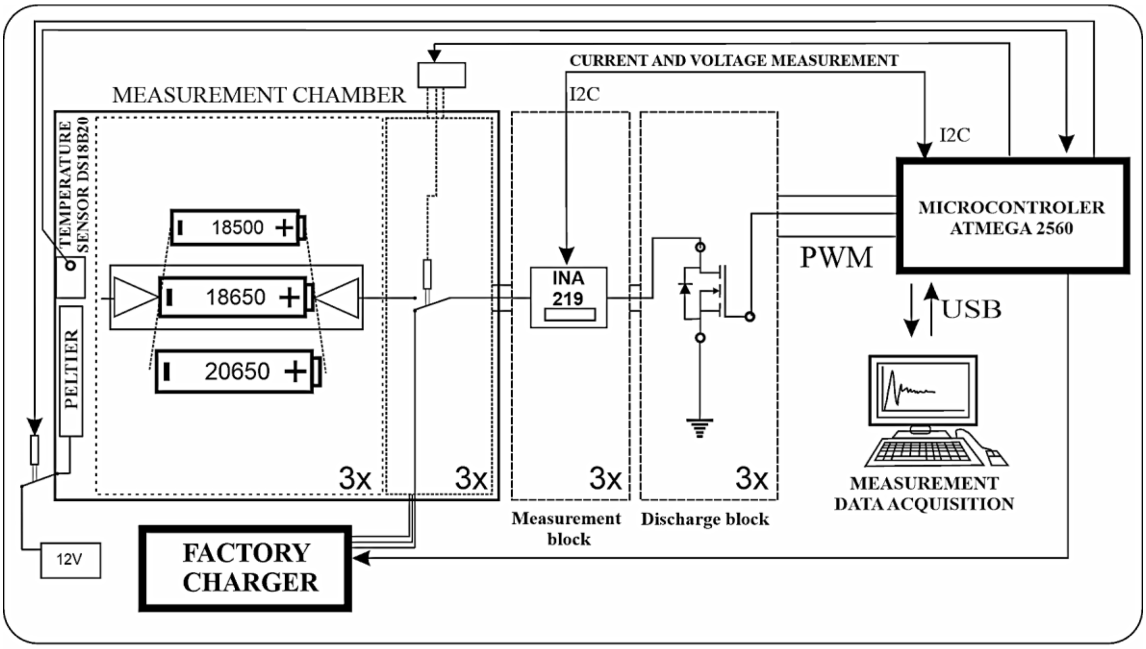

Figure 2. Measurement chamber schema.

Source: own study based on (Czerniak, Gacek, Hnatyszak, 2024).

The test chamber was equipped with temperature stabilization during battery charging and discharging (Bobobee et al., 2023; IEC, 2017a, 2017b). Charging of the test batteries was conducted using a specially adapted factory charger, which charged the batteries to a voltage of 4.2 V, in accordance with widely accepted standards for this type of battery (Fang et al., 2024). The solution adopted ensured the best representation of the user's actual battery charging conditions. The modification of the charger involved integrating components to monitor the charging and discharging processes and replacing its original charging sockets with those located within the temperature-stabilized measurement chamber. Additionally, the charger was modified to enable automatic selection of the charging mode via a computer controlling the measurement process. The second modification involved the automatic selection of the charging mode via a computer that controlled the measurement process. The battery was discharged using a digital load based on a PWM pulse-controlled MOSFET transistor, ensuring a constant discharge current during measurement. Both charging and discharging were monitored by a PC equipped with proprietary software, which not only supervised the measurement process but also archived the data. Current and voltage measurements were conducted using a 12-bit analog-to-digital converter integrated within the INA219 I2C. The results were read via the I2C bus, which was managed by an Atmega 2560 processor (Hoffman, 2018; Margolis, 2020). The entire system was calibrated with professional measuring equipment prior to commissioning and testing. The designed and constructed device enabled simultaneous automatic charging and discharging measurements on three independent tracks. Repeated measurements determined the actual capacities of the batteries, which were then compared with the capacities declared by the manufacturers.

4. Results

4.1. Web-survey

Initially, respondents were asked two main questions regarding their opinions on the most important battery features and the attributes they consider when making purchasing decisions. They were also given the opportunity to provide additional comments beyond the multiple-choice options. The data were processed using one-way analysis of variance (ANOVA) in Statistica 13.3. The responses to the first question are presented in a bar chart (Figure 3).

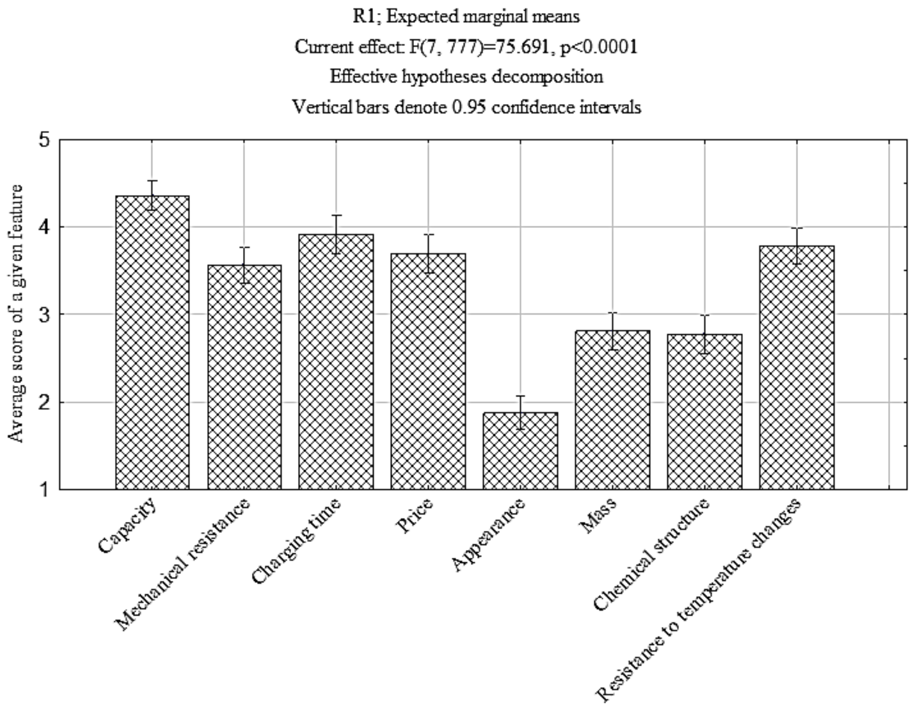

Figure 3. Respondents' average rating of key features of high-quality batteries.

Source: own study.

For the majority of respondents, the most important criteria characterizing a good battery were capacity, charging time, and resistance to low temperatures, while the least important factor was its appearance. The main effects of the analysis of variance, presented in the bar chart, are statistically significant, $F(7.777) = 75.691$, $p < 0.0001$. To verify the significance of differences between individual means within the series, a post-hoc Fisher's LSD test was conducted, confirming statistically significant differentiation between nearly all criteria. The only criteria not significantly differentiated from each other were ratings concerning price and mechanical resistance; price and charging time; and mass and chemical structure (Table1).

Table 1.
LSD test of respondents' average rating of key features of high-quality batteries

Cell No.	LSD test; variable: Average score. Probabilities for post hoc tests. Error: between MS = 0,94847, df = 777,00								
	R1	{1} 4,3571	{2} 3,5625	{3} 3,9196	{4} 3,9664	{5} 1,8750	{6} 2,8125	{7} 2,7768	{8} 3,7857
1	Capacity		**0,000000**	**0,000813**	**0,000000**	**0,000000**	**0,000000**	**0,000000**	**0,000013**
2	Mechanical resistance	**0,000000**		**0,006205**	0,303756	**0,000000**	**0,000000**	**0,000000**	0,086716
3	Charging time	**0,000813**	**0,006205**		0,086716	**0,000000**	**0,000000**	**0,000000**	0,303756
4	Price	**0,000000**	0,303756	0,086716		**0,000000**	**0,000000**	**0,000000**	0,492879
5	Appearance	**0,000000**	**0,000000**	**0,000000**	**0,000000**		**0,000000**	**0,000000**	**0,000000**
6	Mass	**0,000000**	**0,000000**	**0,000000**	**0,000000**	**0,000000**		0,783831	**0,000000**
7	Chemical structure	**0,000000**	**0,000000**	**0,000000**	**0,000000**	**0,000000**	0,783831		**0,000000**
8	Resistance to temperature changes	**0,000013**	0,086716	0,303756	0,492879	**0,000000**	**0,000000**	**0,000000**	

Note: R1 -repeater factor, Bold - significant values.

Source: own study.

The answers to the second question regarding the most important criteria consumers use when purchasing a battery are presented in a column chart (Figure 4).

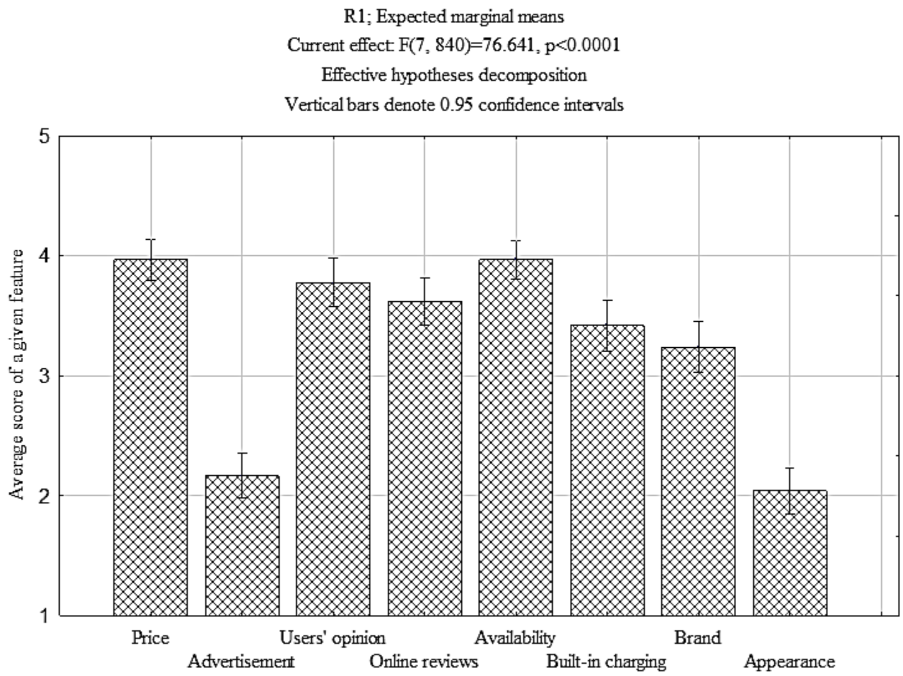

Figure 4. Respondents' average rating of key battery features in purchases decisions.

Source: own study.

For the majority of respondents, price and availability were the most important criteria determining the decision to purchase a particular brand of battery. The least important criteria were external appearance and the presence of the battery brand in advertisements.

The main effects of the analysis of variance, shown in the column chart, are statistically significant, F(7.840) = 76.641, p < 0.0001. A post-hoc Fisher's LSD test was performed to examine the significance of differences between the individual means within a given series, which confirmed statistically significant variation between almost all criteria. The ratings for price and user feedback and availability; mass and chemical structure; battery brand and having a built-in charger, were not significantly differentiated from each other (Table 2).

Table 2.
LSD test of respondents' average rating of key battery features in purchases decisions

Cell No.	LSD test; variable: Average score. Probabilities for post hoc tests.. Error: between = 0,92573, df = 840,00								
	R1	**{1} 3,9669**	**{2} 2,1653**	**{3} 3,7769**	**{4} 3,6198**	**{5} 3,9669**	**{6} 3,4215**	**{7} 3,2397**	**{8} 2,0413**
1	Price		**0,000000**	0,124752	**0,005131**	1,000000	**0,000012**	**0,000000**	**0,000000**
2	Advertisement	**0,000000**		**0,000000**	**0,000000**	**0,000000**	**0,000000**	**0,000000**	**0,316549**
3	Users' opinion	0,124752	**0,000000**		0,204643	**0,124752**	**0,004170**	**0,000016**	**0,000000**
4	Online reviews	**0,005131**	**0,000000**	0,204643		**0,005131**	0,109206	**0,002185**	**0,000000**
5	Availability	1,000000	**0,000000**	0,124752	**0,005131**		**0,000012**	**0,000000**	**0,000000**
6	Built-in charging	**0,000012**	**0,000000**	**0,004170**	0,109206	**0,000012**		0,141976	**0,000000**
7	Brand	**0,000000**	**0,000000**	**0,000016**	**0,002185**	**0,000000**	0,141976		**0,000000**
8	Appearance	**0,000000**	0,316549	**0,000000**	**0,000000**	**0,000000**	**0,000000**	**0,000000**	

Note: R1 -repeater factor, Bold - significant values.

Source: own study.

Summarizing the survey results, the most important characteristics for consumers are battery capacity, price, and availability. To a lesser extent, consumers consider mass and chemical structure. The survey findings prompted the authors to conduct a technical study on 18650 batteries available on the Polish market. These batteries were divided into two price ranges: those priced up to 20 PLN and those above this amount.

4.2. Testing 18650 Batteries

All batteries were repeatedly charged and discharged at a current of 500 mA. The results are presented in a column graph (Figure 5).

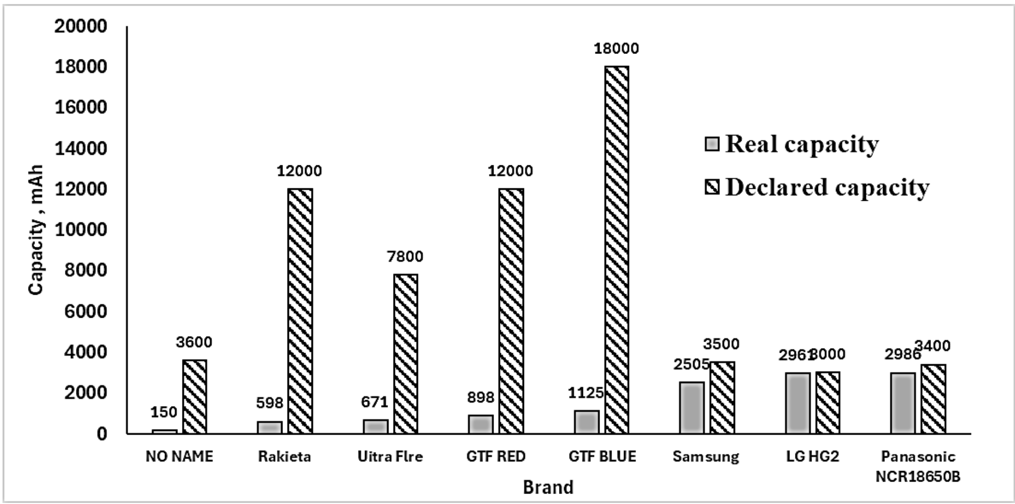

Figure 5. Declared capacity/measured capacity – temperature 21°C.

Source: own study.

As observed in the characteristic curve (Figure 5), the declared capacities significantly deviate from the measured capacities. To more clearly illustrate the differences between the declared capacities and the capacities measured with the testing equipment, the column chart displays the percentage values of the measured capacities relative to the declared capacities (Figure 6).

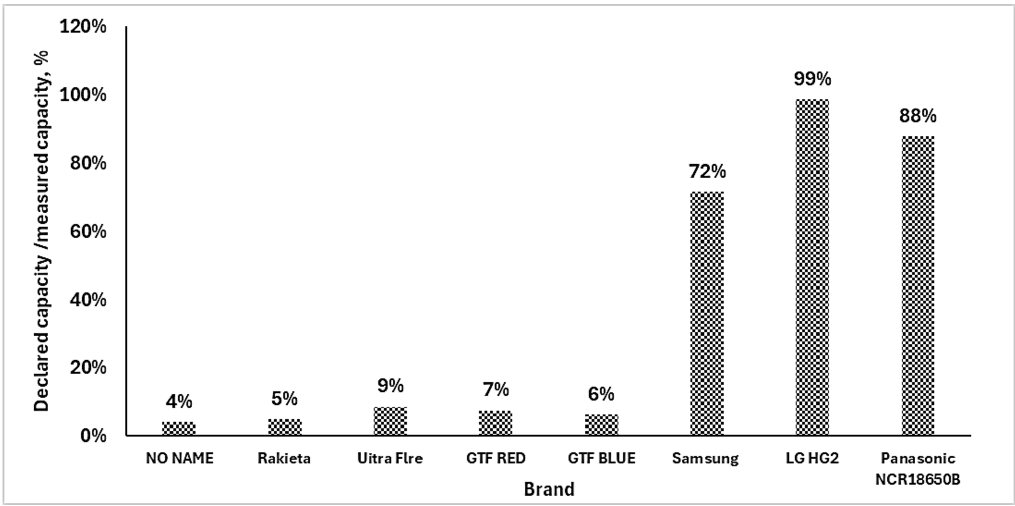

Figure 6. Percentage values of declared capacity vs. measured capacity.

Source: own study.

The first five brands were part of the product group priced below 20 PLN. These products had declared capacities that could not be achieved given the battery's chemical structure. In the second group of products, the difference between declared and measured capacities was minimal. The most favorable capacity was found in the LG brand, achieving 99% of its declared capacity in the study.

In the web-survey, respondents were asked about the importance of various battery characteristics, including mass and capacity. Statistical analysis indicated that mass was less important to consumers than capacity. Consequently, the authors investigated the correlation between measured capacity and battery mass. Identifying such a correlation could facilitate the selection of the best battery without requiring electrical measurements. The column chart (Figure 7) presents a comparison of these two parameters.

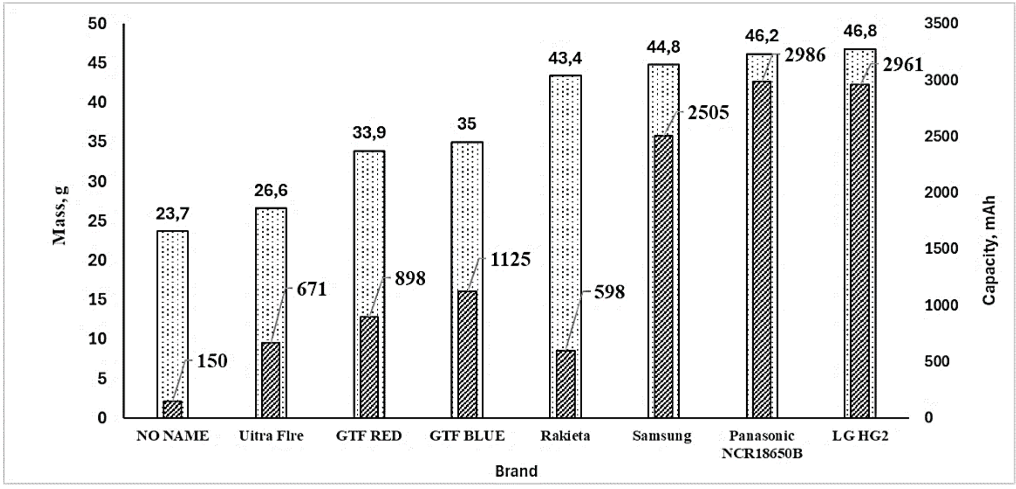

Figure 7. Battery mass – correlation of mass with capacity.
Source: own study.

As shown in the column chart (Figure 7), almost all batteries with a higher mass also exhibit a higher capacity. Only in one instance was a higher mass recorded for a battery with a low actual capacity. According to the design and mass analysis of batteries, mass measurements should be indicative of capacity (Czerwiński, 2012; Beard, 2019).

5. Discussion of Results and Conclusions

As part of this study, the literature on 18650 batteries and relevant standards for lithium-ion batteries were analyzed. It was found that there are no guidelines in the literature or existing standards that explicitly describe the parameters for 18650 batteries. In order to identify the most important features of these batteries from the consumer's point of view, a web survey was conducted asking respondents about the most important features and parameters that influence their purchasing decisions. Statistical analysis of the survey results indicated that the most important features were battery capacity and price. As a result, research focused on low- and mid-range products. The tests were conducted using a device designed to record the charging and discharging parameters of the batteries. The results demonstrated that the capacities of products in the lower price range (below PLN 20) did not correspond to the capacities declared by the manufacturers. The analysis clearly showed that cheaper products exhibited actual capacities less than 10% of their declared values. In contrast, products from the mid-priced range and well-known brands achieved up to 99% of the declared capacity. The research results indicate that purchasing batteries from reputable manufacturers is more reliable, as the declared capacities correspond to the measured values.

The study also investigated whether using product mass as a criterion could help select higher-quality products without electrical testing. Unfortunately, the research showed that some low-quality products have a mass similar to that of branded products. Manufacturers may achieve this mass through unethical practices, such as adding substances to increase the mass of the battery.

In conclusion, it is crucial to legislate the production of this type of energy source and protect consumers from unfair practices by manufacturers. Currently, there are no such regulations and consumers purchasing these goods in the Polish market rely mainly on opinions posted on auction portals. However, many of these opinions are unreliable due to a lack of knowledge about the electrical parameters of this type of energy source. As a result, consumers often purchase cheaper products that offer only a fraction of the capacity claimed by the manufacturer. Given the number of charge and discharge cycles for these products, lower capacity batteries have a significant environmental and economic impact because they need to be replaced and recycled more frequently. The recycling process is as costly for lower quality products as it is for higher quality products that last longer. The difference lies in their lifetime, which is closely linked to their capacity.

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