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Review

Development of an Informative Lithium-Ion Battery Datasheet

Weiping Diao [1,*], Chetan Kulkarni [2] and Michael Pecht [1]

[1] Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD 20742, USA; pecht@umd.edu
[2] KBR. Inc., NASA Ames Research Center, Moffett Field, CA 94035, USA; chetan.s.kulkarni@nasa.gov
* Correspondence: wdiao@umd.edu; Tel.: +1-240-383-6551

Abstract: Lithium-ion battery datasheets, also known as specification sheets, are documents that battery manufacturers provide to define the battery's function, operational limit, performance, reliability, safety, cautions, prohibitions, and warranty. Product manufacturers and customers rely on the datasheets for battery selection and battery management. However, battery datasheets often have ambiguous and, in many cases, misleading terminology and data. This paper reviews and evaluates the datasheets of 25 different lithium-ion battery types from eleven major battery manufacturers. Issues that customers may face are discussed, and recommendations for developing an informative and valuable datasheet that will help customers procure suitable batteries are presented.

Keywords: lithium-ion batteries; datasheets; specifications; battery manufacturers; end-users

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1. Introduction

Commercial lithium-ion batteries have been the dominant power supply for today's consumer electronics and high-power and energy mobile systems [1,2]. A technical specification sheet (datasheet) is a document that prescribes technical requirements to be fulfilled by a product, process, or service [3], is needed to choose and use a lithium-ion battery. A datasheet lists information about the product for both informational and advertising purposes [4]. Datasheets typically define the basic capabilities and performance characteristics, including product composition, methods of use, operating requirements, common applications, and product warnings.

Battery manufacturers usually provide two datasheets for a battery type: battery specifications and a safety datasheet. Sometimes these two datasheets are combined into one. A safety datasheet consists of standardized 16 sections, including information such as the material properties and hazards, the safe handling, and appropriate measures the customer can take when an unsafe event occurs. A complete battery specification sheet describes physical parameters, electrical performance and operating limits, reliability, safety, storage and transportation recommendations, and prohibitions, which is the focus of this paper.

Customers use lithium-ion battery datasheets to select the most appropriate battery for an application; these datasheets also guide product manufacturers to develop battery management systems for enhanced performance, reliability, and safety. A confusing or misleading term describing these performance parameters will affect a proper evaluation of the batteries and datasheet validation and may cause legal issues between customers and battery manufacturers. For example, a capacity term whose measurement condition is not explicitly listed can make the capacity warranty equivocal. Academia also test commercial lithium-ion batteries per the specifications to analyze and model degradation, failure, and protection mechanisms. Any inconsistencies can lead to studies using these batteries being incomplete, invalid, and not ready to be implemented for real-world applications. To date, however, there has been no dedicated review research conducted to investigate various problems in lithium-ion battery datasheets, based on the results of thorough literature research in the major academic publishers (IEEE, Elsevier, Wiley, MDPI, Springer, etc.) and Google scholar search with keywords such as "battery" and "datasheet" or "specification") [5–11]. This work is a first step toward filling this void by recommending improvements to the battery manufacturers.

Battery manufacturers often do not provide a datasheet to low-volume customers. Instead, these customers must search for the specific datasheet online and end up finding multiple datasheets for the same battery type. There are several ways to obtain lithium-ion battery datasheets, such as battery manufacturer websites, distributors, third-party sales websites, and online sources. For example, a popular battery type Panasonic NCR18650B has been used in customer electronics and space applications. The datasheet for this battery type is not available directly to the customer on the Panasonic website [12], but it is found on third-party sales websites [13] and online sources [14,15]. However, these datasheets contain conflicting information about some key battery parameters. Moreover, many authentic datasheets from world-known battery manufacturers have a myriad of issues, such as discrepancies in terminology, ambiguity, lack of critical electrical performance parameters, and misleading statements.

This paper is motivated by the difficulty of using battery datasheets to compare suppliers, conduct battery tests, and design products that require batteries. The information provided in the datasheet is insufficient for the end-users due to issues including discrepancies for the same term such as using one voltage reading to specify the capacity but another to specify the cycle life, lack of critical parameters such as the operating current limits, and ambiguity such as specifying a term's value without mentioning the measurement conditions.

This paper reviews and evaluates the datasheets of 25 different lithium-ion battery types from eleven major battery manufacturers: Panasonic, Samsung, LG Chem, A123, ATL, Routejade, EEMB, GMB, VPW, Toshiba, and Johnson Controls-SAFT. The formats include cylindrical, pouch, prismatic, and coin-type cells. The specified physical parameters, electrical performance, reliability, and safety are compiled and evaluated for each datasheet per standard definitions from the International Electrotechnical Commission (IEC), International Organization for Standardization (ISO), and ANSI (American National Standards Institute).

Recommendations are provided for battery manufacturers to develop an informative datasheet with clearly and completely defined items. An informative datasheet will make it easier for users to correctly compare suppliers' performance, evaluate the lifetime, and develop battery management systems with the appropriate voltage, current, and temperature limits.

2. Physical Parameters

Battery datasheets typically specify physical parameters such as cell dimensions and weight with the mean or the range. The datasheets specify the length, width, and thickness for the pouch and prismatic cells and the height and diameter for the cylindrical and coin cells.

Table 1 summarizes the physical parameters of each battery model. For the same battery manufacturer and format, there is inconsistency observed in specifying physical parameters. For example, Panasonic uses maximum, typical, or range to define the values for their different battery models. ATL 902738 specifies the thickness of new and swollen cells. However, the state-of-health (SOH) information (capacity retention) of swollen cells is missing.

Table 1. Physical parameters used in specifications.

Manufacturer	Model	Shape	Weight (g)	Diameter (mm)	Height (mm)	Length, Width, Thickness (mm)
Panasonic	NCR18650PF [16]	Cylindrical	Max. 48.0	Max. 18.5	Max. 65.3	—
Panasonic	NCR18650B [15]	Cylindrical	Max 48.5	Max. 18.5	Max. 65.3	—
Panasonic	NCR18650BD [17]	Cylindrical	Max. 49.5	Max. 18.25	Max. 65.10	—
Panasonic	NCR18650BF [18]	Cylindrical	Max. 46.5	Typ. 18.2	Typ. 65.0	—
Panasonic	UR18650GA [19]	Cylindrical	Max. 48.0	Max. 18.50	Max. 65.30	—
Panasonic	UR18650ZY	Cylindrical	Max. 48.0	18.35 ± 0.25	(64.8 − 0.25)–(64.8 + 0.2)	—
Panasonic	UR1865ZM2	Cylindrical	Max. 46.4	18.3 ± 0.2	(65.1 − 0.25)–(65.1 + 0.2)	—
Samsung	ICR18650-26J [20]	Cylindrical	Max. 45.0	Max. 18.4	Max. 65.00	—
Samsung	INR21700-50E [21]	Cylindrical	Max. 69	Max. 20.25	Max. 70.80	—
Samsung	NR18650-15Q [22]	Cylindrical	Max. 48.0	18.15 ± 0.1	64.6 ± 0.5	—
LG Chem	18650HE2 [23]	Cylindrical	Max. 48.0	(18.3 − 0.3)–(18.3 + 0.2)	65.0 ± 0.2	—
LG Chem	ICR18650MF1 [24]	Cylindrical	Approx. 44.0	(18.3 − 0.3)–(18.3 + 0.1)	65.0 ± 0.2	—
LG Chem	INR18650 B4 [25]	Cylindrical	Approx. Max. 48.0	18.29 ± 0.11	≤65.05	—
A123	AMP20m1HD-A [26]	Pouch	496	—	—	Length: 227 Width: 160 Thickness: 7.25
A123	ANR26650m1-B [27]	Cylindrical	76	26	65	—
ATL	902738 [28]	Pouch	—	—	—	Length: Max. 41.3 Width: Max. 27.1 Thickness: fresh max. 9.07; after swelling 9.8
Routejade	SLPB8043128H	Pouch	Max. 84.0	—	—	Length: Max. 128.0 Width: Max. 43.0 Thickness: Max. 7.8
Routejade	SLPB526495	Pouch	Max. 63.2	—	—	Length: Max. 95.5 Width: Max. 64.50 Thickness: Max. 5.20
EEMB	LIR18650 [29]	Cylindrical	46.5 ± 1	Max. 18.4	Max. 65.2	—
EEMB	LIR1632 [30]	Coin	Approx. 1.7 ± 0.3	(16.0 − 0.2)–16.0	3.2–(3.2 + 0.35)	—
GMB	GMB043450S [31]	Prismatic	Approx. 14	—	—	Length: Max. 50.1 Width: Max. 34.0 Thickness: Max. 4.3
VPW	580013 [32]	Prismatic	1.288 kg ± 0.02	—	—	Length: 148 ± 0.15 Width: 101 ± 0.15 Thickness: 39 ± 0.15
VPW	580049 [33]	Pouch	0.415 kg ± 0.02	—	—	Length: 194 Width: 91 Thickness: 11.8
Toshiba	Toshiba-LTO-20AH [34]	Prismatic	515 g	—	—	Length: 116 Width: 106 Thickness: 22
Johnson Controls-SAFT	MP 174865 xlr	Prismatic	~121 g	—	—	Width: 48.0 Height: 65.0 Thickness: 19.0

— This term is not mentioned.

Battery datasheets should specify physical parameters in the following ways. The datasheet should provide the mean and range, useful for a preliminary assessment of the product design and manufacturing process [35]. The process capability can be used to determine if there has been a change in the manufacturing process. In addition, because a pouch cell package will expand (see Figure 1) when gas is generated internally due to cell aging, device manufacturers need to consider the thickness change when designing a product. To prevent the battery swelling from destroying the product in which it is embedded, the battery datasheet is recommended to provide the thickness change of the pouch cell over cell degradation.

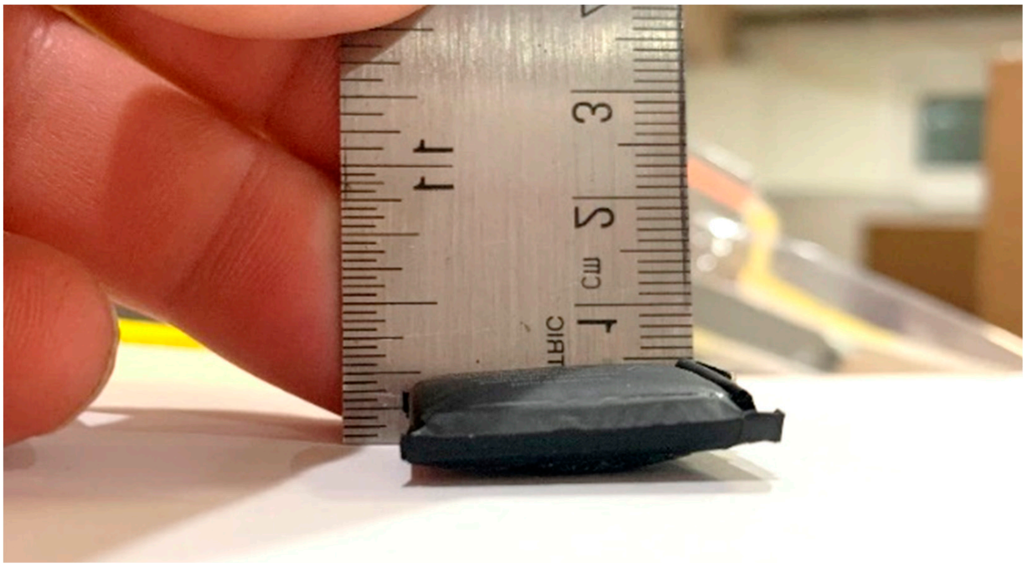

Figure 1. A swollen pouch cell.

3. Electrical Performance and Operating Limits

The electrical performance parameters included in a datasheet are capacity, energy, power, voltage, and resistance. The operating limits guide how to operate batteries safely and reliably.

3.1. Capacity Parameters

Capacity represents the amount of time a fully charged battery can operate for a given loading current and temperature condition. IEC ref 482-03-14 [3] defines capacity as the electric charge a cell can deliver under specified discharge conditions. ANSI C18.2M [36] defines capacity as the quantity of electricity, usually expressed in Ah, which a battery can provide under specified discharge conditions. The International System of Units (SI) for electric charge is the coulomb (1 C = 1 A·s), but in practice, capacity is usually expressed in ampere-hours (Ah).

IEC ref 482-03-15 [3] defines the rated capacity as the capacity value of a battery determined under specified operating conditions and declared by the manufacturer. ANSI C18.2M [36] describes the rated capacity as the quantity of electricity declared by the manufacturer which a single cell or battery can deliver during a 5 h period when charging, storing, and discharge under the conditions specified in the ANSI standard in which the battery datasheets determine the cut-off voltage values. ISO 12405-4 describes the rated capacity [37] as the supplier's specification of the total number of ampere-hours that can be withdrawn from a fully charged battery pack or system for a specified set of test conditions, such as discharge rate, temperature, and discharge cut-off voltage.

Table 2 summarizes the capacity terms used in the 25 datasheets and the capacity value used to define the 1 C rate for the respective battery types. Other than the rated capacity and nominal capacity, other capacity terms (including minimum capacity, typical capacity, and standard capacity) are also used in the datasheets. There are battery models that specify up to three capacity terms (e.g., Panasonic NCR18650BF). However, not all battery datasheets explain the corresponding measurement condition for each capacity term.

Table 2. Capacity terms used in specifications.

Manufacturer	Model	Rated Capacity (mAh)	Minimum Capacity (mAh)	Typical Capacity (mAh)	Nominal Capacity (mAh)	Standard Capacity (mAh)	1 C (mA)
Panasonic	NCR18650PF	Min. 2700 (20 °C)	2750 (25 °C)	2900 (25 °C)	—	—	—
Panasonic	NCR18650B [15]	Min. 3200 (20 °C)	3250 (25 °C)	3350 (25 °C)	—	—	—
Panasonic	NCR18650BD	2980 | 2910 (20 °C)	3030 | 2935 (25 °C)	3180 | 3080 (25 °C)	—	—	—
Panasonic	NCR18650BF	Min. 3200 (20 °C)	—	—	Min. 3250 Typ. 3350 (25 °C)	—	—
Panasonic	UR18650GA	3300 (20 °C)	3350 (25 °C)	3450 (25 °C)	—	—	—
Panasonic	UR18650ZY	2450 (20 °C)	2500 (25 °C)	2600	—	—	—
Panasonic	UR1865ZM2	—	—	2550	2420 2470	—	—
Samsung	ICR18650-26J	—	—	—	—	Min. 2550	2600
Samsung	INR21700-50E	Min. 4753	—	—	—	Min. 4900	4900
Samsung	NR18650-15Q	1500	—	—	—	145	—
LG Chem	18650HE2	—	—	—	2500	—	—
LG Chem	ICR18650MF1	—	2050	—	2150	—	2150
LG Chem	INR18650 B4	—	2500	—	2600	—	2500
A123	AMP20m1HD-A	—	19.6 Ah	—	—	—	—
A123	ANR26650m1-B	—	2.4 Ah	—	2.5 Ah	—	—
ATL	902738	—	90	92	—	—	—
Routejade	SLPB8043128H	—	—	—	3300	—	3300
Routejade	SLPB526495	—	—	—	3200	—	3200
EEMB	LIR18650	—	2500	2500	2600	—	—
EEMB	LIR1632	25 ± 5	—	—	—	—	—
GMB	GMB043450S	—	530	550	—	—	550
VPW	580013	—	—	75 Ah	—	—	—
VPW	580049	—	—	22 Ah	—	—	—
Toshiba	Toshiba-LTO-20AH	—	—	—	20 Ah	—	—
Johnson Controls-SAFT	MP 174865 xlr	—	—	5.3 Ah	—	—	5.1 A

— This term is not mentioned.

Several battery models (e.g., Panasonic UR1865ZM2 and Samsung INR21700-50E) list the testing condition for each capacity term mentioned in the datasheets, whereas others do not. There are also battery datasheets in which multiple values are specified for the same capacity term. An example is Panasonic NCR18650B, in which the “rated capacity” was measured at 20 °C, whereas the “minimum capacity” and “typical capacity” were measured at 25 °C; however, the “minimum capacity” and “rated capacity” were measured under the same temperature, C-rate, and cut-off condition, which introduces contradictions. For Panasonic NCR18650BD, two values are specified for each capacity term without a clear explanation for variation in these values.

For all the reviewed battery types, except for Panasonic NCR18650BF, the rated capacity and nominal capacity are not used together in a datasheet. No pattern is found for which capacity is used to define 1 C. Only eight out of the 25 datasheets define the electrical current value of 1 C. Without defining each capacity term’s testing conditions and the electrical current value of 1 C, customers have difficulty validating the capacity values specified in datasheets. Besides, none of the 25 datasheets provide the range of the capacity value.

The following conditions are recommended to specify the capacity parameter. First, the datasheet should list each capacity term's measurement condition, including the temperature, charge/discharge C-rate, and cut-off voltage/C-rate. Second, the datasheet should clarify the meanings if more than one value is listed for a single capacity term. Third, the mean and range should be listed for customers to evaluate the production lot variation. Fourth, the current value of 1C should be defined if there is more than one specified capacity term because this helps customers verify the electrical performance and reliability.

3.2. Charge/Discharge Procedures and Limitations

The standard charge consists of charging batteries at a constant current to the upper voltage limit and then at a constant voltage until the charging current has tapered to the cut-off charge current. The charge characteristics are usually plotted in specifications with the parameters mentioned above. The standard discharge consists of discharging batteries at a constant current to the lower voltage limit. While some datasheets plot the discharge characteristics at different C-rates and temperatures, others provide only the charge/discharge capacity values at different temperatures and C-rates.

Table 3 shows the operating parameters and limits for charge and discharge summarized for each battery model. The "standard" current or C-rate does not come from any particular industry standards; it is a term used to define the current or C-rate in the standard charge and discharge cycle in a datasheet.

Table 3. Charge and discharge parameters and limits.

Manufacturer	Model	Charge			Discharge		
		Standard Current/C-Rate	**Max. Current/C-Rate**	**Temperature Range (°C)**	**Standard Current/C-Rate**	**Max. Current/C-Rate**	**Temperature Range (°C)**
Panasonic	NCR18650PF	1375 mA	—	0–45	—	—	−20–60
Panasonic	NCR18650B [15]	1625 mA	—	10–45	—	—	−20–60
Panasonic	NCR18650BD	0.3 C	—	10–45	—	—	−20–60
Panasonic	NCR18650BF	1625 mA	—	0–45	—	—	−20–60
Panasonic	UR18650GA	1475 mA	—	10–45	—	—	−20–60
Panasonic	UR18650ZY	1.75 A	—	0–45	—	Continuous: 5 A	−20–60
Panasonic	UR1865ZM2	1.24 A at 10–45 °C; 0.62 A at 0–10 °C	—	0–45	—	10 A	−20–60
Samsung	ICR18650-26J	1.3 A	—	0–45	520 mA	Continuous: 5.2 A	−10–60
Samsung	INR21700-50E	2450 mA	4900 mA	0–45	980 mA	Continuous: 9800 mA; Non-continuous: 14,700 mA	−20–60
Samsung	NR18650-15Q	750 mA	4 A at 25 °C	5–45	—	18 A at 25 °C	−20–60
LG Chem	18650HE2	1250 mA	4000 mA	0–50	500 mA	Continuous: 20,000 mA	−20–75
LG Chem	ICR18650MF1	0.5 C	1 C	0–45	0.2 C	10 A	−20–60
LG Chem	INR18650 B4	0.5 C	1 C	0–45	0.2 C	−20–5 °C: 0.5 C; 5–45 °C: 2 C; 45–60 °C: 1.5 C	−20–60
A123	AMP20m1HD-A	—	—	−30–55	—	—	−30–55
A123	ANR26650m1-B	2.5 A	—	−30–55	—	Continuous: 50 A; 10 s pulse: 120 A	−30–55
ATL	902738	—	—	0–45	—	1 C	−10–60
Routejade	SLPB8043128H	1 C	2 C	0–45	1 C	Continuous: 20 C; Pulse: 40 C	−10–60
Routejade	SLPB526495	1 C	2 C	0–45	1 C	Continuous: 2 C; Pulse: 3 C	−10–60
EEMB	LIR18650	0.52 A	—	0–45	0.52 A	Pulse: 2.6 A	−20–60
EEMB	LIR1632	0.5 C	1 C	−20–45	—	2 C	−20–60
GMB	GMB043450S	0.5 C	Continuous: 1 C	0–45	0.2 C	Continuous: 1.5 C	−20–60
VPW	580013	—	—	10–45	—	Continuous at 25 °C: 150 A; 60 s Pulse at 25 °C: 300 A	−30–60
VPW	580049	—	—	0–45	—	Continuous at 25 °C: 330 A; 60 s pulse at 25 °C: 660 A	−20–60
Toshiba	Toshiba-LTO-20AH	—	—	−30–50	—	—	—
Johnson Controls-SAFT	MP 174865 xlr	—	5 A	−35–60	C/5	Continuous: 10 A; Pulses: 21 A	−30–60

— This term is not mentioned.

Several battery manufacturers specify the standard charge and discharge current/C-rate for different operating temperature ranges in which the C-rate at lower temperature ranges tends to be lower. In contrast, others do not distinguish the temperature range. Except for Toshiba-LTO-20AH, all other battery datasheets specify the temperature range for both charge and discharge. Not all datasheets specify the maximum charge and discharge C-rates. For the maximum discharge current/C-rate, only the two battery models from VPW specify continuous discharge values, pulse discharge with its length, and the applied temperature range. Others lack 1–3 elements.

Battery manufacturers should recommend charging and discharging C-rates for different temperature ranges, considering the adverse effect of increasing C-rate on battery lifetime due to mechanical stress and side-electrochemical reactions such as lithium plating and gas generation. When specifying the maximum discharge current/C-rate, the datasheet should provide the values for continuous discharge rate, pulse discharge rate with pulse length, the applied state of charge (SOC), and temperature range, such that users know the conditions they can use the battery up to the maximum discharge current.

3.3. Voltage Parameters

The cell voltage is defined by IEC ref 114-03-10 [3] as the voltage between the two terminals of an electrochemical cell. IEC ref 482-03-31 [3] defines the nominal voltage as the suitable approximate value of the voltage used to designate or identify a cell, a battery, or an electrochemical system. However, the way the battery manufacturers determine the nominal voltage is not provided in most datasheets.

Table 4 shows the voltage terms and their values in the 25 battery datasheets. Four battery types (LG 18650HE2, LG ICR18650MF1, EEMB LIR18650, and GMB043450S) specify how the nominal voltage is measured—the average cell voltage during standard discharge. The ATL 902738 datasheet uses typical voltage instead of nominal voltage.

Table 4. Voltage terms used in specifications.

Manufacturer	Model	Nominal Voltage (V)	Typical Voltage (V)	Voltage Range (V)
Panasonic	NCR18650PF	3.6	—	2.5–4.2
Panasonic	NCR18650B [15]	3.6	—	2.5–4.2
Panasonic	NCR18650BD	3.6	—	2.5–4.2
Panasonic	NCR18650BF	3.6	—	2.5–4.2
Panasonic	UR18650GA	3.6	—	2.5–4.2
Panasonic	UR18650ZY	3.7	—	2.75–4.2
Panasonic	UR1865ZM2	3.6	—	2.5–4.2
Samsung	ICR18650-26J	3.63	—	2.75–4.2
Samsung	INR21700-50E	3.6	—	2.5–4.2
Samsung	INR18650-15Q	3.6	—	2.5–4.2
LG Chem	18650HE2	Average for standard discharge: 3.6	—	2.5–4.2
LG Chem	ICR18650MF1	Average for standard discharge: 3.65	—	2.75–4.2
LG Chem	INR18650 B4	3.6	—	2.75–4.2
A123	AMP20m1HD-A	3.3	—	—
A123	ANR26650m1-B	3.3	—	2–3.6
ATL	902738	—	3.7	3–4.2
Routejade	SLPB8043128H	3.7	—	3–4.2
Routejade	SLPB526495	3.7	—	2.7–4.2, but cycle at 3–4.2
EEMB	LIR18650	Average value of the working voltage during the whole discharge process: 3.7	—	2.75–4.2

Table 4. *Cont.*

Manufacturer	Model	Nominal Voltage (V)	Typical Voltage (V)	Voltage Range (V)
EEMB	LIR1632	3.6	—	2.75–4.2
GMB	GMB043450S	Mean operation voltage during standard discharge after standard charge: 3.7	—	2.75–4.2
VPW	580013	3.65	—	2.8–4.2
VPW	580049	3.7	—	3.0–4.2
Toshiba	Toshiba-LTO-20AH	2.4	—	1.5–2.7
Johnson Controls-SAFT	MP 174865 xlr	3.65	—	2.5–4.2

— This term is not mentioned.

The operating voltage range is necessary for developing battery management strategies. Other than A123 AMP20m1HD-A, the remaining 24 datasheets all specify the operating voltage range. Routejade SLPB526495 specifies the voltage range between 2.7 V and 4.2 V but guides customers to cycle the batteries between 3 V and 4.2 V with a decreased usable capacity. This information is misleading because of the discrepancy between the advertised capacity value and the capacity value associated with the recommended voltage range. Thus, the operating voltage range should be specified consistently in a datasheet. It should also specify measured nominal/rated voltage, including the temperature, C-rate, cut-off voltage, and C-rate.

3.4. Impedance/Resistance Parameters

IEC ref 131-12-43 defines the impedance for a passive linear two-terminal element or circuit as the quotient of the phasor U_{AB} (the voltage between the terminals) by the phasor I (the electric current in the element or circuit). The phasor U_{AB} represents the sinusoidal voltage $u_{AB} = v_A - v_B$, and the phasor I represents the sinusoidal electric current. The impedance is equal to $Z = R + jX$, where R is the resistance to an alternating current, and X is the reactance. The coherent SI unit of impedance is ohm, Ω. The battery is not a passive circuit, but its impedance is calculated in the same way.

IEC ref 482-03-36 defines the "internal apparent resistance" of a battery as the quotient of change of voltage as the corresponding change in the discharge current under specified conditions. If the measurement current is direct current (DC), the quotient is mostly called internal resistance or DC resistance; if the measurement current is alternating current (AC), the quotient is called impedance.

Table 5 summarizes the impedance/resistance values from the 25 datasheets. Battery impedance will change with the measurement frequency of the sinusoidal excitation. Battery impedance/internal resistance also depends on the battery SOC (see Figure 2) and temperature [38,39]. However, some datasheets define the impedance values without specifying the frequency and SOC of the impedance values (e.g., EEMB LIR18650) or the SOC of the resistance value (e.g., battery model VPW 580013). This ambiguity makes it difficult to validate the specified impedance/resistance values.

Table 5. Impedance/resistance.

Manufacturer	Model	Impedance/Resistance
Panasonic	NCR18650PF	—
Panasonic	NCR18650B [15]	—
Panasonic	NCR18650BD	—
Panasonic	NCR18650BF	—
Panasonic	UR18650GA	—
Panasonic	UR18650ZY	AC impedance at 1 kHz: <100 mΩ
Panasonic	UR1865ZM2	AC impedance at 1 kHz: <40 mΩ
Samsung	ICR18650-26J	AC impedance at 1 kHz: <35 mΩ after standard charge
Samsung	INR21700-50E	AC impedance at 1 kHz: <35 mΩ after standard charge
Samsung	NR18650-15Q	AC impedance at 1 kHz: <25 mΩ after standard charge
LG Chem	18650HE2	—
LG Chem	ICR18650MF1	AC impedance at 1 kHz: <35 mΩ after standard charge
LG Chem	INR18650 B4	AC impedance at 1 kHz: <70 mΩ after standard charge
A123	AMP20m1HD-A	—
A123	ANR26650m1-B	—
ATL	902738	AC impedance at 1 kHz: <300 mΩ at 50% SOC
Routejade	SLPB8043128H	AC impedance at 1 kHz: <5 mΩ after standard charge
Routejade	SLPB526495	AC impedance at 1 kHz: <15 mΩ after standard charge
EEMB	LIR18650	AC impedance ≤70 mΩ
EEMB	LIR1632	—
GMB	GMB043450S	AC impedance at 1 kHz: ≤70 mΩ
VPW	580013	DC resistance ≤1.4 mΩ
VPW	580049	DC resistance ≤2 mΩ
Toshiba	Toshiba-LTO-20AH	—
Johnson Controls-SAFT	MP 174865 xlr	—

— This term is not mentioned.

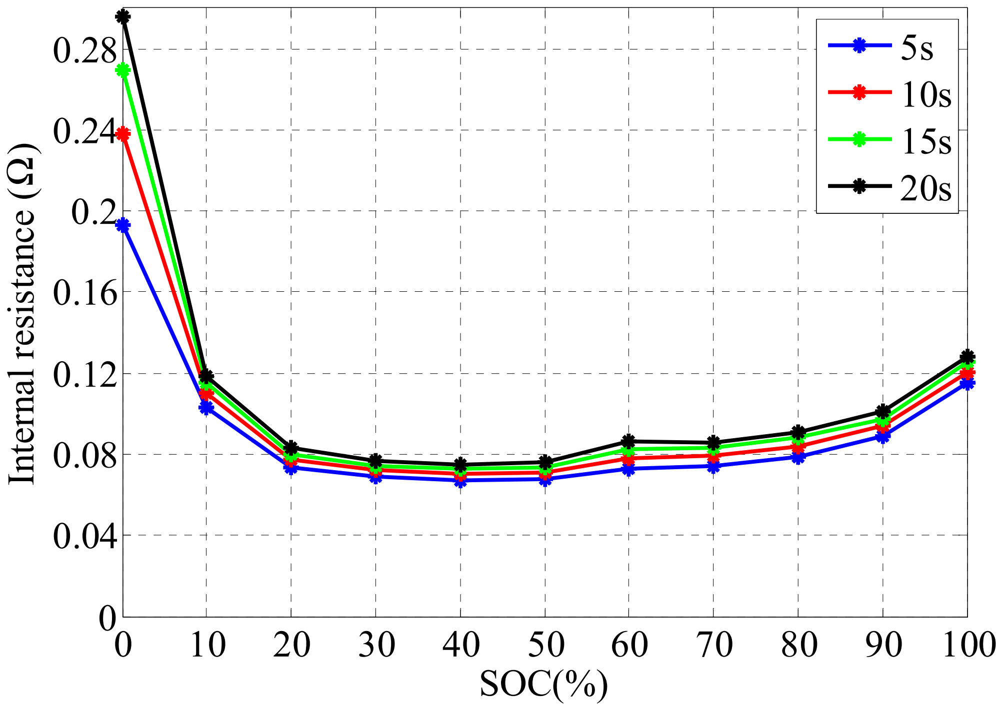

Figure 2. DC resistance measured at different SOCs for $Li(NiCoAl)O_2$ based cells using C/2 discharge.

Increased impedance/resistance can cause the battery terminal voltage to reach the discharge cut-off voltage and terminate the battery's discharge operation, thus decreasing the battery's power capability and deliverable capacity. In addition to the measurement temperature and battery SOC for the resistance/impedance values, battery datasheets should specify the measurement frequency for the impedance values. A comparison of different methods to measure the internal resistance and impedance can be found in [40].

3.5. Energy and Power Parameters

Specific energy, also called gravimetric energy density, is the energy per unit mass stored in a lithium-ion battery/cell. Specific power is the power per unit mass provided by a lithium-ion battery/cell, changing with battery SOC and operating conditions. The specific energy and power are useful in comparing the cost per unit of energy or power among different batteries.

Table 6 shows that ten out of the 25 datasheets provide specific energy or energy density data. However, none of the nine datasheets specify the testing condition for measuring the specific energy or energy density, which can vary significantly with the testing condition, such as the discharge C-rate. Besides, Panasonic NCR18650BD provides two values for the specific energy and two values for the energy density without a distinction. Only A123 ANE26650m1-B provides the specific power with the battery SOC and the testing condition.

Table 6. Energy and power.

Manufacturer	Model	Specific Energy (Wh/kg)	Energy Density (Wh/L)	Specific Power (W/kg)	Power Density (W/L)
Panasonic	NCR18650PF	207	577	—	—
Panasonic	NCR18650B [15]	243	676	—	—
Panasonic	NCR18650BD	217 ǀ 212	630 ǀ 615	—	—
Panasonic	NCR18650BF	248	677	—	—
Panasonic	UR18650GA	224	693	—	—
Panasonic	UR18650ZY	—	—	—	—
Panasonic	UR1865ZM2	—	—	—	—
Samsung	ICR18650-26J	—	—	—	—
Samsung	INR21700-50E	—	—	—	—
Samsung	NR18650-15Q	—	—	—	—
LG Chem	18650HE2	—	—	—	—
LG Chem	ICR18650MF1	—	—	—	—
LG Chem	INR18650 B4	—	—	—	—
A123	AMP20m1HD-A	131	247	2400	—
A123	ANR26650m1-B	—	—	2600, @ 23 °C, 50% SOC, 10 s discharge	—
ATL	902738	—	—	—	—
Routejade	SLPB8043128H	—	—	—	—
Routejade	SLPB526495	—	—	—	—
EEMB	LIR18650	—	—	—	—
EEMB	LIR1632	—	—	—	—
GMB	GMB043450S	—	—	—	—
VPW	580013	213	—	≥1368.8	—
VPW	580049	196	—	≥5884	—
Toshiba	Toshiba-LTO-20AH	—	176	—	—
Johnson Controls-SAFT	MP 174865 xlr	159	371	—	—

— This term is not mentioned.

Thus, similar to specifying the capacity, the measurement condition of the specific energy or energy density should be provided. The specific power with battery SOC, temperature, discharge pulse, and pulse duration needs to be listed.

4. Reliability and Recommendations for Storage

The maximum amount of charge that a battery can deliver decreases with usage (cycle life through charge-discharge cycles) and storage (calendar life), known as capacity fade. A lithium-ion battery reaches the end of life when its capacity no longer meets the mission's requirement, described by the end-of-life (EOL) threshold that is predetermined for the mission. The EOL threshold is application dependent. There is also a required number of cycles or time (lifetime requirement) for each mission. That is, the battery capacity should not drop below the EOL threshold until the required lifetime. Lithium-ion batteries with unsatisfactory lifetimes can significantly reduce customer satisfaction and make products inefficient to use in such applications. Thus, the cycle life and storage life are specified in the datasheets.

4.1. Cycle Life

Table 7 summarizes the cycle life parameters in the 25 datasheets in which the cycle life is specified for as low as 200 cycles and as high as 15,000 cycles. The cycling characteristics are usually in the form of plots (capacity vs. cycles) or the capacity retention value after being used for a certain number of cycles in which lithium-ion batteries are cycled at certain environmental and loading conditions for a specific number of cycles. Most of the 25 datasheets provide the cycling characteristics for one testing condition, whereas the A123 ANE26650m1-B datasheet provides the plots for multiple testing conditions.

Table 7. Cycle life characteristics.

Manufacturer	Model	Cycle Life
Panasonic	NCR18650PF	The capacity fade curve for 500 cycles
Panasonic	NCR18650B [15]	The capacity fade curve for 500 cycles
Panasonic	NCR18650BD	The capacity fade curve for 500 cycles
Panasonic	NCR18650BF	The capacity fade curve for 300 cycles
Panasonic	UR18650GA	The capacity fade curve for 500 cycles
Panasonic	UR18650ZY	Discharge time >38 min. at standard discharge conditions after 300 cycles
Panasonic	UR1865ZM2	The capacity fade curve for 1000 cycles
Samsung	ICR18650-26J	≥1785 mAh (70%) after 300 cycles
Samsung	INR21700-50E	≥3802 mAh (80%) after 500 cycles
Samsung	NR18650-15Q	≥870 mAh (60%) after 250 cycles
LG Chem	18650HE2	≥60% after 300 cycles at 10 A discharge or after 200 cycles at 20 A discharge
LG Chem	ICR18650MF1	≥70% after 500 cycles
LG Chem	INR18650 B4	≥80% after 300 cycles
A123	AMP20m1HD-A	The capacity fade curve for 3200 cycles
A123	ANR26650m1-B	The capacity fade curves for three conditions up to 1450 cycles
ATL	902738	—
Routejade	SLPB8043128H	≥2560 mAh after 1000 cycles
Routejade	SLPB526495	≥2640 mAh after 1000 cycles
EEMB	LIR18650	≥2050 mAh after 300 cycles
EEMB	LIR1632	≥80% after 500 cycles
GMB	GMB043450S	≥70% after 500 cycles
VPW	580013	≥80% after 2000 cycles at 25 °C, or after 1200 cycles at 45 °C
VPW	580049	≥80% after 200 cycles
Toshiba	Toshiba-LTO-20AH	The capacity fade curve at 3C, 25 °C up to 15,000 cycles
Johnson Controls-SAFT	MP 174865 xlr	The capacity fade curve at C/2, 20 °C up to 950 cycles

— This term is not mentioned.

The cycle life at multiple testing conditions, such as the operating limit (maximum C-rate and highest and lowest temperature), is recommended for inclusion in the datasheet. In this way, customers understand the cycle life at various loading conditions and predict the lifetime for a targeted application [41,42].

4.2. Storage Life

IEC ref 482-03-47 [3] defines storage life (shelf life) as the duration, under specific conditions, at the end of which a battery has retained the ability to perform a specified function. As shown in the third column in Table 8, out of the 25 datasheets, 21 specify the recommended storage temperature range (ATL, VPW, and Toshiba battery types do not provide information); however, the datasheets do not explain the implications for the storage time associated with each temperature range. For example, the statement "−20–50 °C, less than 1 month" does not reveal the amount of charge and capacity left after the battery is stored for a month at 50 °C.

Table 8. Storage life characteristics.

Manufacturer	Model	Storage Temperature (°C)	Charge Retention	Capacity Retention
Panasonic	NCR18650PF	−20–50	—	—
Panasonic	NCR18650B [15]	−20–50	—	—
Panasonic	NCR18650BD	−20–50	—	—
Panasonic	NCR18650BF	−20–50	—	—
Panasonic	UR18650GA	−20–50	—	—
Panasonic	UR18650ZY	−20–50, less than 1 month −20–40, less than 3 months −20–20, less than 1 year	Discharge time > 30 min (25 °C) after 20 days at 60 °C, 100% SOC	Discharge time > 40 min (25 °C) after 20 days at 60 °C, 100% SOC and being fully charged at 25 °C
Panasonic	UR1865ZM2	20–50, less than 1 month −20–40, less than 3 months −20–20, less than 1 year	—	—
Samsung	ICR18650-26J	−20–60, 1 month −20–45, 3 months −20–23, 1 year	Charge ≥ 2040 mAh (80%) after 30 days at 23 °C, 100% SOC	—
Samsung	INR21700-50E	−20–60, 1 month −20–45, 3 months −20–23, 1 year	Charge ≥ 2040 mAh (80%) after 30 days at 60 °C, 100% SOC	—
Samsung	NR18650-15Q	45–60, 1 month 20–45, 3 months −20–25, 18 months	—	—
LG Chem	18650HE2	−20–60, 1 month −20–45, 3 months −20–20, 1 year	Charge ≥ 90% after 1 month at 23 °C, 100% SOC	Capacity ≥ 80% after 1 week at 60 °C, 100% SOC
LG Chem	ICR18650MF1	−20–60, 1 month −20–45, 3 months −20–20, 1 year	Charge ≥ 90% after 30 days at 25 °C, 100% SOC	Capacity ≥ 80% after 1 week at 60 °C, 100% SOC
LG Chem	INR18650 B4	−20–60, 1 month −20–45, 3 months −20–20, 1 year	Charge ≥ 90% after 30 days at 25 °C, 100% SOC	Capacity ≥ 80% after 1 week at 60 °C, 100% SOC
A123	AMP20m1HD-A	−40–60	—	—
A123	ANR26650m1-B	−40–60	—	—
ATL	902738	—	The cell voltage for long-time storage shall be 3.6–3.9 V at 25 ± 3 °C after 3 months	—
Routejade	SLPB8043128H	40–60 for up to 1 week 25–40 for up to 3 months −20–25 for up to 1 year	Charge ≥ 75% after 1 week at 60 °C, 100% SOC	—
Routejade	SLPB526495	40–60 for up to 1 week 25–40 for up to 3 months −20–25 for up to 1 year	Charge ≥ 75% after 1 week at 60 °C, 100% SOC	—
EEMB	LIR18650	1 month: −5–35 °C; 6 months: 0–35 °C.	Discharge time ≥4 h after 12 months storage at 40–50% SOC at 25 °C, 65 ± 20% RH	—
EEMB	LIR1632	1 month: −20–60 °C 3 months: −20–45 °C 12 months: −20–25 °C	Electricity Charge: 80% after 28 days at 20 °C at 100% SOC	Capacity fade over storage time at 20, 40, 60 °C

Table 8. *Cont.*

Manufacturer	Model	Storage Temperature (°C)	Charge Retention	Capacity Retention
GMB	GMB043450S	Less than 1 year: −20–25 Less than 3 months: −20–40	—	—
VPW	580013	—	—	—
VPW	580049	—	—	—
Toshiba	Toshiba-LTO-20AH	—	—	The capacity fade over float storage time at 25, 35 and 45 °C, 2.7 V
Johnson Controls-SAFT	MP 174865 xlr	Recommended: 10–30 Allowable: −40–60	—	—

— This term is not mentioned.

Nine datasheets specify the amount of charge left in a battery after being stored at 100% SOC. Five datasheets specify the capacity retention after storage. Particularly, EEMB LIR1632 provides the capacity fade over storage time at three different temperatures. ATL 902738 specifies the cell voltage after storage. Toshiba provides the capacity fade over float storage at 2.7 V at three different temperatures.

5. Safety and Safety Caution

Lithium-ion batteries are classified under UN category 9 as dangerous goods because they are thermally and electrically unstable if subjected to certain harsh environmental conditions or are mishandled during transportation, storage, and usage [43]. Battery hazards include electrolyte leakage, heat production, venting of gases, thermal runaway leading to fire and explosions.

Frequent lithium-ion battery fires increase the safety concerns in customer electronics, vehicles, and large commercial aircraft. Severe environmental conditions, such as external heating, can lead to thermal runaway by triggering a series of exothermic chemical reactions inside the battery [44]. Electrical mishandling, such as overcharging, can lead to gas generation, lithium metal plating on the anode, and electrode fracture [45]. At elevated battery voltage during overcharging, the cathode crystal structure will collapse due to excessive delithiation, and the electrolyte will be oxidized, both generating a significant amount of gas. Lithium plating may cause an internal short circuit by piercing the separator or growing dendrite through the separator's pores. Mechanical damage, such as crush or penetration, may cause an internal short circuit, leading to rapid heating and thermal runaway [46].

Table 9 summarizes lithium-ion batteries' behavior under different environmental, electrical, and mechanical conditions. The tests are performed at the cell level without any external protection component. Thirteen datasheets specify safety in various examinations.

The three LG battery datasheets provide the safety behavior in nine tests, the highest number of tests among the 25 battery models. The two Routejade battery models were tested per the UL1642 standard. The safety tests for Samsung INR21700-50E and ICR18650-26J batteries followed the IEC 62133 standard, UN transportation regulation (UN38.3), and the UL1642 standard. The A123 AMP20m1HD-A batteries were tested per EUCAR 3. The testing procedures can be found in the corresponding standards.

The testing procedures should be specified in detail for the safety tests that do not follow a standard test methodology. However, EEMB LIR 1632 batteries did not mention the circuit resistance used in the short-circuit test [47].

Table 9. Safety.

Manufacturer	Model	Environmental				Electrical			Mechanical				
		Thermal Shock	Heating	Low Temperature	Low Pressure	Overcharge	External Short-Circuiting	Over-Discharge	Impact	Drop	Vibration	Crush	Nail Penetration
Panasonic	NCR18650PF	—	—	—	—	—	—	—	—	—	—	—	—
Panasonic	NCR18650B [15]	—	—	—	—	—	—	—	—	—	—	—	—
Panasonic	NCR18650BD	—	—	—	—	—	—	—	—	—	—	—	—
Panasonic	NCR18650BF	—	—	—	—	—	—	—	—	—	—	—	—
Panasonic	UR18650GA	—	—	—	—	—	—	—	—	—	—	—	—
Panasonic	UR18650ZY	—	—	—	—	—	—	—	—	√	—	—	—
Panasonic	UR1865ZM2	—	—	—	—	—	—	—	—	—	—	—	—
Samsung	ICR18650-26J	—	√	—	—	√	√	√	—	√	√	—	—
Samsung	INR21700-50E	—	√	—	—	√	√	√	—	√	√	—	—
Samsung	INR18650-15Q	—	√	—	—	√	√		—	√	√	—	—
LG Chem	18650HE2	√	√	—	—	√	√	√	√	√	√	√	—
LG Chem	ICR18650MF1	√	√	—	—	√	√	√	√	√	√	√	—
LG Chem	INR18650 B4	√	√	—	—	√	√	√	√	√	√	√	—
A123	AMP20m1HD-A	—	√	—	—	√	√	√	—	—	—	√	√
A123	ANR26650m1-B	—	—	—	—	—	—	—	—	—	—	—	—
ATL	902738	—	—	—	—	—	—	—	—	—	—	—	—
Routejade	SLPB8043128H	—	√	—	—	—	√	—	√	—	—	—	—
Routejade	SLPB526495	√	√	—	√	√	√	—	—	—	—	—	—
EEMB	LIR18650	√	—	√	—	√	√	—	√	√	√	—	—
EEMB	LIR1632	—	√	√	—	√	√	—		√	√	—	—
GMB	GMB043450S	—	—	—	—	—	√	√	√	—	—	√	√
VPW	580013	—	—	—	—	—	—	—	—	—	—	—	—
VPW	580049	—	—	—	—	—	—	—	—	—	—	—	—
Toshiba	Toshiba-LTO-20AH	—	—	—	—	—	—	—	—	—	—	—	—
Johnson Controls-SAFT	MP 174865 xlr	—	—	—	—	—	—	—	—	—	—	—	—

— This term is not mentioned; √ this term is specified.

The battery datasheets instruct customers about handling lithium-ion batteries to avoid unsafe events leading to fire or bodily injury; these rules also exempt the manufacturer from liability if customers violate any stated precautions in the datasheet. For example, the customers shall not expose the battery to extreme heat or flame, shall not immerse the battery in water, and shall not subject the battery to external mechanical shocks. The warranty ranges from 6 to 18 months from the date of shipment. The malfunctioning cells will be replaced within the warranty period if cell manufacturing defects cause the issue, which may lead to an unsafe event or a rapid performance decay. Battery manufacturers typically set the safety test pass criteria to include no explosion or fire in the mentioned safety tests. Still, no statement clarifies the manufacturer's responsibility once an unsafe event occurs due to manufacturing or other defects out of customers' control.

It is recommended that the datasheets specify the battery's behavior under extreme environmental, electrical, or mechanical conditions that possibly occur during transportation, storage, or usage. The safety may be defined individually or combinedly, i.e., transportation, storage, or usage, but needs to be clearly defined and stated for the respective stage. If the batteries are not tested per an industry standard where the specific testing procedures and conditions are given, each safety test should provide the testing condition for customers to verify the safety, such as the battery SOC, environmental temperature, the circuit resistance, and the short-circuit time in the short-circuit test.

6. Discrepancies in Datasheets for the Same Battery Model

For Panasonic NCR18650B cells, three different datasheets are found online [13–15]. The specified capacity and nominal voltage are the same; however, the physical parameters, charge/discharge characteristic curves, and cycling characteristics curves are all different. Figure 3 compares the charge curves. The charging C-rate is 0.5 C in "The Charge Characteristics for NCR18650B" Plot [13] and "Charge Characteristics" Plot [15] and 0.3 C in "TYPICAL CHARGE CHARACTERISTICS" plot [14].

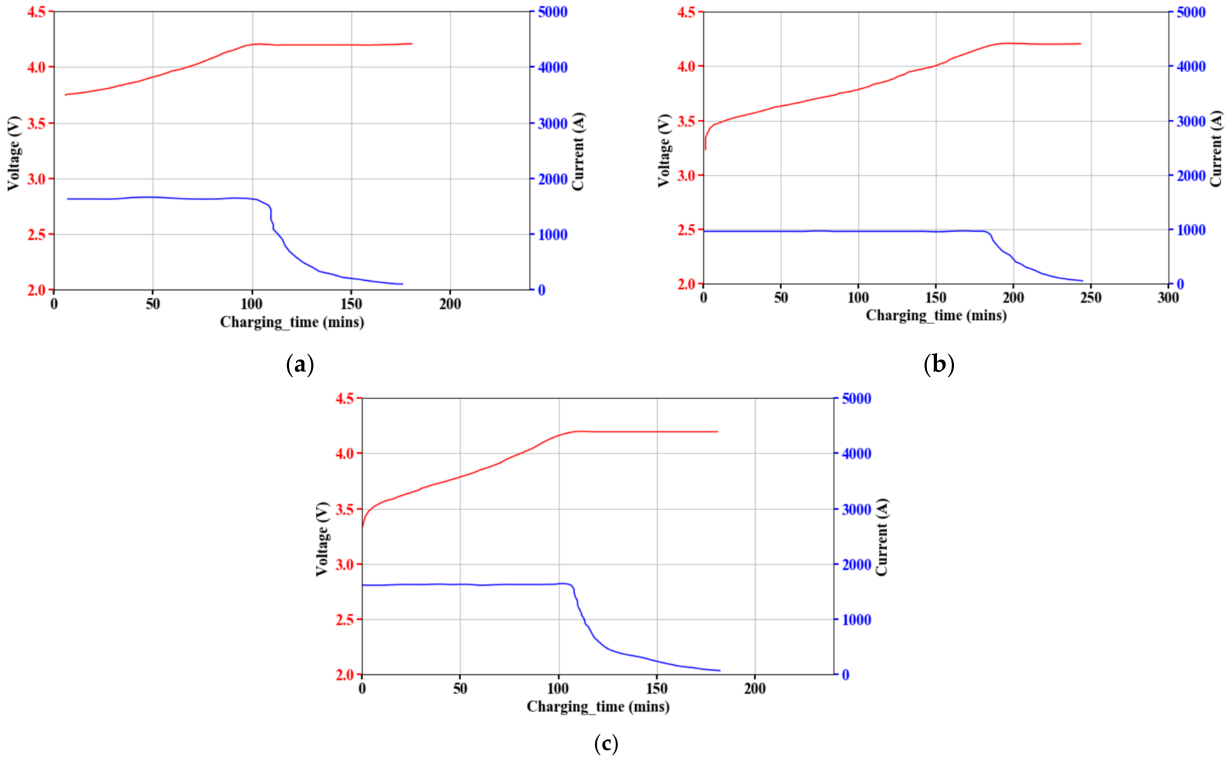

Figure 3. Observed inconsistent charge characteristics from different sources for Panasonic NCR18650B cells: (**a**) [13]; (**b**) [14]; and (**c**) [15].

Figures 4 and 5 shows that compares that the discharge characteristic curves are inconsistent with each other at the same discharge C-rate and temperature. The discharge curves have significant variation. This may be due to a change in the electrode and electrolyte properties or variation in the manufacturing batch. These should be clarified in the datasheet so customers can select the right product for their targeted application.

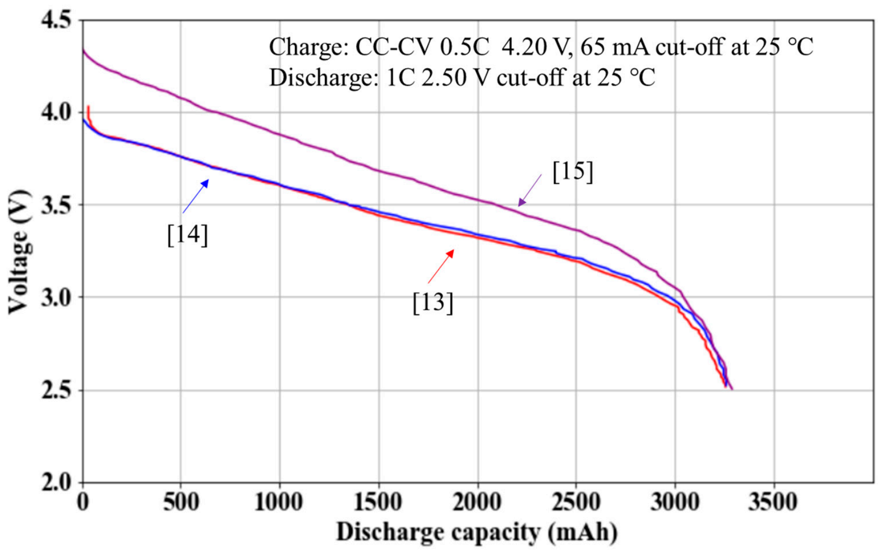

Figure 4. Observed inconsistent discharge characteristics at 25 °C, 1 C from different sources for Panasonic NCR18650B cells.

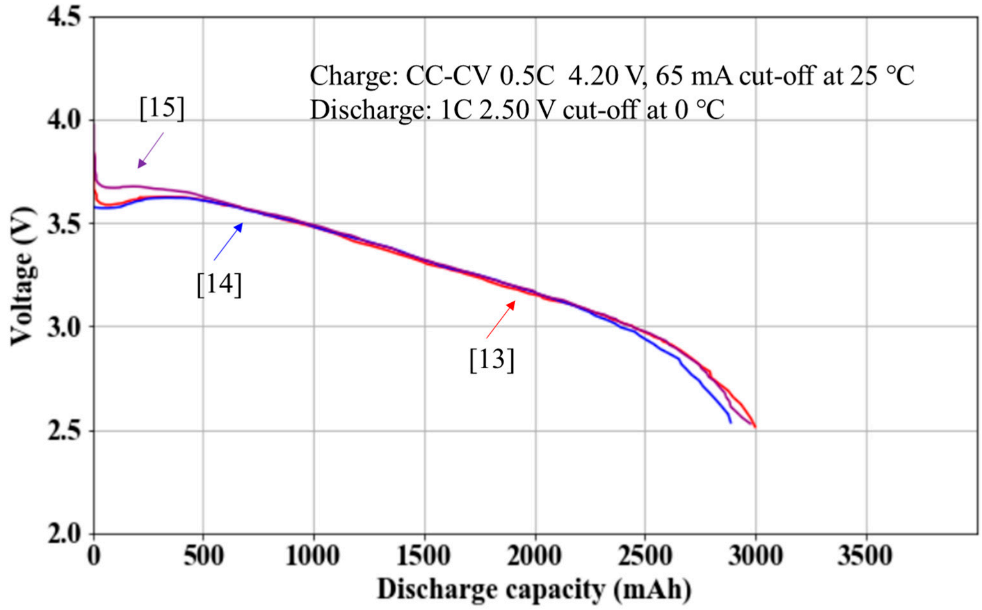

Figure 5. Observed inconsistent discharge characteristics at 0 °C, 1 C from different sources for Panasonic NCR18650B cells.

Figure 6 shows there is a distinct difference between the cycling performance in the two data sheets [14,15]. This all results in confusion for low-volume battery customers who do not have direct communication access with battery manufacturers. Thus, battery manufacturers should provide the official datasheet for clarification for commercial-off-the-shelf battery models sold on various third-party sales websites. The battery manufacturer should confirm the credentials of distributors and third-party sales websites.

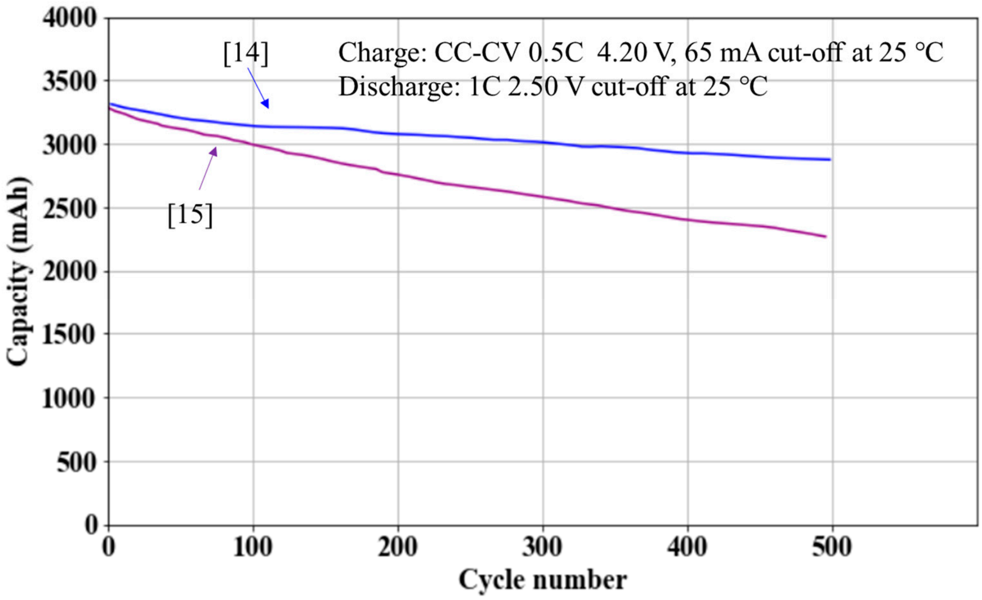

Figure 6. Inconsistency observed in the cycle characteristics from different sources for Panasonic NCR18650B cells.

7. Conclusions

In this paper, datasheets from 25 different lithium-ion battery types from eleven major battery manufacturers are evaluated regarding the way present information related to physical parameters, electrical performance parameters, and operating limits, reliability, and safety is made available to the end-users. It is recommended that the battery manufacturer supply sufficient and clear information to end-users through the following practices.

The datasheet should provide the mean and range for physical parameters and capacity/impedance for customers to evaluate the production lot variation. To prevent the battery swelling from damaging the product in which it is embedded, the datasheet should provide the thickness change in the pouch cell over cell degradation.

For electrical parameters, the electrical current value of 1 C should be defined. The datasheets need to list the measurement conditions for each capacity term, specific energy, and nominal/rated voltage, including the temperature, charge/discharge C-rate, and cut-off voltage/C-rate. When indicating the specific power, they also need to provide the measurement conditions for battery impedance/resistance, including SOC, measurement frequency, temperature, pulse amplitude, and pulse duration. The datasheet should clarify the meanings of the differences if more than one value is listed for a single term, such as capacity, power, or energy. The maximum discharge current/C-rate needs to be specified with additional information: continuous discharge, pulse discharge (length), and the applied temperature and SOC range.

As a recommendation, this work proposes a well-defined datasheet, including cycle life at multiple testing conditions such as at the operating limit (maximum C-rate and highest/lowest temperature), for users to make cycle life predictions for various applications. The datasheet should specify the storage temperature range and describe the implications of the storage time associated with each temperature range. Information, including charge retention and capacity retention over the storage time, should be included possibly at multiple storage conditions (e.g., at the limit of the specified SOC and temperature range). The datasheets are recommended to provide any resources to locate the reliability characteristics, if available.

Further for safety parameters, the datasheets should report battery behavior under all abusive thermal, electrical, or mechanical conditions that possibly occur during transportation, storage, and usage or as per required compliance standards. Each safety test should either mention the specific standard per which they conduct the safety testing or provide the testing condition for customers to verify battery safety.

Finally, to benefit the customers and end-users, it is recommended that battery manufacturers authenticate the correct datasheet version for the battery under consideration and confirm the credentials of distributors and third-party sales websites. Implementing the recommended suggestions and changes to the datasheets will enable customers to procure suitable battery types for their required applications and develop appropriate battery management systems for enhanced reliability and safety, hence benefitting a wide spectrum of battery users' communities.

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