

# **Compendium:** Li-ion batteries

Principles, characteristics, laws and standards



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No guarantee can be given for the accuracy, completeness and up-to-dateness of the information due to the ongoing development of lithium-ion battery technology and the related rules and regulations. Read about the current state-of-the-art on the VDE homepage.

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# 1. Foreword

The principle behind the lithium-ion battery dates back to the 1970s. Scarcely anyone now remembers that the first commercial application was in a Hi8 video camera launched by Sony in 1991. Lithium-ion batteries have been used in more and more products ever since – in everything from tiny sensors, mobile phones, tablet and laptop computers, power tools and electric vehicles up to large stationary energy storage units.

Lithium-ion batteries are robust and have high cycle stability and energy density levels. They are the subject of constant technical refinement, and cell production in gigafactories is becoming ever more efficient. This is resulting in falling cell costs coupled with increasing demand and production capacity. In 2018, there were 36 gigafactories worldwide with a production capacity of around 226 GWh. These figures are expected to increase to 66 gigafactories with a production capacity of over 2000 GWh by 2028. Europe has its own lithium-ion battery industry: during this period, European production capacity is forecast to increase from 5.3% to 16.8% of global output. Economies of scale and technical improvements have caused prices for lithium-ion batteries to fall by 20% per year on average since 2010: from 600 euros/kWh in 2010 to 111 euros/kWh in 2020. A price of around 83 euros/kWh is expected for 2025. The extrapolated production turnover for 2028 is set at over 85 billion euros.

The lithium-ion battery is thus the fastest growing battery technology in the world and, most importantly, is the one in which most money is being invested. The VDE Lithium-Ion Batteries Compendium provides an ideal introduction to this technology. It includes an overview of lithium-ion batteries: from the materials used in the most common cell types to the construction of modules and systems. Furthermore, it highlights the key technical and systemic characteristics. These can serve as the basis for procurement decisions on lithium-ion batteries. Finally, the Compendium briefly outlines the current legal regulations and key standards in each application area.

Why consult the VDE? As a technology organisation, the VDE has extensive practical knowledge about lithium-ion batteries. Numerous experts from research and industry work in its committees and specialist groups on standards for the protection, safety and sustainability of lithium-ion batteries and their application in devices and systems. The resulting knowledge is transferred to new test procedures that are applied in the VDE Testlabs worldwide. In addition, the VDE provides both technical and economic advice to companies on suitable energy storage systems.

Ansgar Hinz VDE Chairman of the Board and Chief Executive Officer (CEO)

# 2. Principles of Li-ion batteries

Lithium (Li)-ion batteries and accumulators are to be found in numerous applications all around us – in everything from portable devices and e-bikes (and electromobility in general) through to stationary storage. The following chapter gives an overview of the basic structure and function of Li-ion batteries.

#### 2.1 Primary and secondary batteries

Batteries are electrochemical energy storage devices and are divided into primary and secondary types. Primary batteries are electrochemical power sources in which chemical energy is converted irreversibly into electrical energy. Primary batteries, therefore, are not rechargeable. There are also lithium-based primary batteries in the AA format which is commonly used for NiMh and NiCd cells. These, too, cannot be recharged.

By contrast, secondary batteries – also called accumulators – are rechargeable electrochemical energy storage devices. The chemical reaction which takes place in them is reversible, making them suitable for multiple use. Electrical energy is converted into chemical energy during charging, and from chemical to electrical energy during discharging. A complete charging and discharging process is referred to as a cycle. The life time of a battery is linked to the number of cycles. The life of rechargeable batteries varies depending on the type and application – and on how they are handled.

Most Li-ion batteries are secondary batteries, also called accumulators. They constitute an important storage technology in both mobile and stationary applications due to their numerous advantages over other types of accumulator. The following chapters therefore deal exclusively with this battery type.

#### 2.2 Structure and function

#### 2.2.1 General

The word battery is the generic term for a set of interconnected cells, including the associated peripherals such as cable set and electronics as well as the surrounding battery housing. Cells are galvanic units consisting of two electrodes, electrolyte, separator and cell housing. The individual components of a lithium-ion battery are set out below.

#### 2.2.2 Cell

Each Li-ion cell ( $\Rightarrow$  Figure 1) consists of two different electrodes: a negative electrode (anode) and a positive electrode (cathode). Each electrode is composed of a current conductor (also called a collector) and an active material applied to it. Between the electrodes is the ion-conducting electrolyte, which enables the necessary exchange of charge, and the separator, which separates the electrodes electrically.

### (j)

The terms anode and cathode are basically determined by the oxidation/reduction process. However, the electrode on which oxidation or reduction takes place depends on whether the battery/cell is being charged or discharged. As a result, it has become established practice to use discharging as the defining process for the terms anode and cathode. Thus the anode is the negative, and the cathode the positive pole of the battery.



Figure 1: Structure and functioning of a lithium-ion cell during discharging

The negative electrode of the Li-ion cell consists of a copper foil and a layer of carbon or silicon compounds. Natural or artificial graphite is commonly used as a carbon compound because it has low electrode potential and its volume expands little during charging and discharging. Lithium ions are reduced and intercalated (stored) in the graphite layers during the charging process. Lithium titanate offers a viable alternative for very high performance and safety requirements. Silicon layers are also the subject of research aimed at achieving higher energy density levels.

A potential can be assigned to each electrode (electrochemical series). It is usually expressed in comparison to an electrode made of pure lithium to ensure comparability of the electrode potential of different electrode materials for Li-ion batteries. Pure lithium is set at zero as the initial value. For more details, see  $\rightarrow$  Chapter 3.1.3

The positive electrode consists of mixed oxides applied to an aluminium collector. Transition metal oxides based on cobalt, manganese and nickel or aluminium oxide are the most common compounds. The applied metal oxide layer serves to intercalate the lithium ions when the cell is discharged. Higher proportions of manganese, nickel and aluminium are increasingly being used instead of cobalt. A further material that is used is lithium iron phosphate (LFP). For more details on this and other active materials used in the positive electrode see  $\rightarrow$  Chapter 3.1.3.

(i)

Especially when metallic lithium is deployed as the anode material, there is a great danger of lithium dendrites<sup>1</sup> forming during recharging. These can pierce the separator. If the dendrites grow towards the cathode, this can result in safety-critical internal short circuiting of the cell. This kinetic phenomenon causes lithium to redeposit not in planar form but to accumulate in needle-like structures in regions with a less pronounced solid electrolyte interphase (SEI) surface layer on the anode. It also leads to a loss of electrochemically usable lithium, and thus to a loss of capacity.

Lithium plating can occur in lithium-ion batteries. During the charging process, lithium ions are deposited as metallic lithium on the surface of the anode and are not intercalated into the electrode structure. This occurs most noticeably during fast charging (high charging currents) and charging at low temperatures. It can result in capacity losses as well as safety-critical events. This is also one of the biggest differences between lithium metal batteries and other lithium ion batteries. In Li-metal batteries, lithium plating supports the functioning of the cell, while in other lithium batteries it is an undesirable process.

As already mentioned, layered materials (instead of metallic lithium) that can absorb lithium reversibly are usually used. During the discharge process ( $\rightarrow$  Figure 1), lithium ions migrate from the anode through the electrolyte and separator to the cathode, where they are reversibly intercalated. Electrons are released by the ongoing oxidation process taking place on the anode. These flow from the negatively charged anode via an external electrical connection to the positive cathode, where a reduction process takes place and electrons are absorbed. Electrical consumers can be powered by the external flow of current. During charging, the reverse process takes place.

The electrolyte acts as an intermediary between the reactions on the electrodes during the charging and discharging processes and serves to transport the Li-ions. It must support high ionic conductivity and be stable in the 0 to 4.5 V voltage range as well as in the temperature range in which the battery is to be operated.<sup>2</sup> Three types of electrolyte are to be found in lithium-ion batteries:

- Liquid: Liquid electrolytes are the most commonly used type in commercial lithium-ion cells. The electrolyte is mostly organic and consists of a conducting salt containing Li-ions added to a non-aqueous solvent. The water content must be as low as possible (< 30 parts per million) in order to reduce harmful side reactions to a minimum.
- Polymer: Most polymer electrolytes have low conductivity compared to liquid electrolytes. They are used in batteries that contain lithium metal anodes, for example. A separator can be dispensed with under certain conditions, depending on the type of polymer electrolyte. Gel-polymer electrolytes are most commonly used. Special additives are incorporated in these in order to lower the operating temperature.
- Solid: The most commonly used solid electrolytes are ion-conducting ceramic compounds. The energy densities of batteries with solid electrolytes are theoretically higher than those containing liquid electrolytes. Furthermore, increased material safety can be achieved by using non-flammable components. At normal temperatures, there is insufficient ionic conductivity and power density<sup>3</sup> for commercial application. This is due to the high interfacial resistance between the electrolyte and the electrolytes, as the current process is designed for liquid electrolytes.

A surface layer, the so-called Solid Electrolyte Interphase (SEI), forms on carbon-based anodes in suitable liquid and polymerised electrolytes. This layer protects the anode from the corroding electrolyte solution yet remains permeable to lithium ions. It is essential for the use of lithium or lithium-ion intercalation compounds in primary and secondary cells. The positive electrode is also referred to here as a conductive interphase. The charging and discharging processes cause the layer, and thus also the resistance in the cell, to grow, thereby reducing the cell voltage under load. This process is accompanied by a loss of electrolyte.

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<sup>1</sup> Pointed, wire-like structures that can form on the electrodes

<sup>2</sup> Hartnig, C.; Schmidt, M. (2013): Handbuch Lithium-Ionen-Batterien – Chapter 6: Elektrolyte und Leitsalze, Springer Vieweg, Heidelberg, pp. 61–62

<sup>3</sup> Specific (W/kg) or volumetric power density (W/l)

The separator separates the two electrodes from each other to prevent a short circuit as the result of direct contact. There are correspondingly high requirements for this component. In most cells, the separator prevents ions from continuing to migrate from the anode to the cathode in the event of a malfunction. Some materials have an additional safety function: there is a loss of ion flow permeability above a certain temperature due to pore closure (melt). This prevents the cell from overheating and subsequently catching fire. Polymer membranes can be used for this. However, these have the disadvantage of having a lower melting temperature (e.g. 165 °C) than ceramic separators. Nonwoven and glass fibre separators are often used due to their ease of processing<sup>4</sup>.

The individual components are usually stacked or wound together to form a cell. The designs are discussed in  $\rightarrow$  Chapter 3.2.4.

#### 2.2.3 Battery

A battery is generally defined as a cell or a combination of cells equipped with the required peripherals for use, such as connections, labels and protective devices. The voltage level of a single cell depends on the combination of the active materials. Today's systems achieve voltages in the range of 2.2 V up to a maximum of 4.2 V per cell. Several cells are connected in series to form a battery, as the voltage (V) delivered by a single cell is not sufficient for practical use in most battery types and applications. A distinction is made between block-type (cell blocks) and modular (modules) lithium-ion batteries.

A cell block is a group of cells connected in parallel which may or may not be connected to protective devices and a monitoring circuit. In a module, a group of cells is connected to each other in series and/or parallel. The modular design consists of a number of (smaller) cell block sub-units which are easier to replace. This design is therefore usually chosen, especially for larger batteries.

The total voltage of a number of cells connected in series is determined by the number of cells multiplied by the cell voltage: a pack of six Li-ion cells of 3.6 V each (nominal) therefore has a nominal voltage of 21.6 V.

Parallel connection, on the other hand, raises the amount of charge (Ah) delivered by the battery while keeping the voltage the same and increasing the maximum charge and discharge current. A certain number of cells or modules are connected in parallel to provide the required capacity for a particular application. The combination of parallel and series connections determines the energy content of the battery in Wh (Ah\*V = Wh).

Cell blocks and modules cannot be used by themselves in a unit because they do not have the necessary housing, connection arrangement and control equipment. All these are added to the assembly of modules or cells to form a battery system that can then be tested and used for an application.

(i)

The available electrical charge of batteries is given in ampere-hours (Ah). An ampere-hour is the amount of charge that flows through a conductor within one hour at a constant electric current of 1A.

4 For more information, see Korthauer, R. (2018): Lithium-ion batteries: Basics and Applications

#### 2.2.4 System

In addition to interconnected cells, modules and battery packs, a battery system (→ Figure 2) consists of a number of carefully harmonised mechanical and electronic components. Key mechanical components include the insulated housing and mounting systems as well as a cooling system.

#### Cell

Battery cells in various shapes (cylindrical, prismatic, pouch) and performance classes

#### Module

A number of cells joined together to form a module. Modules contain a cell control system.

#### **Battery system**



Figure 2: Schematic view of a battery system

The most important electronic component is the battery management system (BMS). In addition to monitoring the calculated State of Charge (SoC)<sup>5</sup> at the cell and system level, it also serves as an interface between the device and the battery during charging and discharging. It uses sensors to measure (and in some cases also to control) the current, voltages and temperatures of the individual cells and the entire system. The BMS thus represents a central safety component. In addition, it can be used for error logging and for switching the system on and off.<sup>6</sup>

The BMS also optimises the usable capacity or energy and the performance of the system through its so-called balancing function.<sup>7</sup> This is necessary because the capacities and internal resistances of individual cells can fluctuate slightly as the result of production and use factors. When several cells are connected, these differences cause the cells to charge and discharge at different rates. Without a suitable control, this can lead to the deep discharging or overcharging of cells which are connected in series, and have a correspondingly strong impact on the life expectancy and safety of the system. Cell balancing inhibits these processes and maximises the usable capacity while increasing the life span.

The housing (and associated cooling system) shields any sensitive active and passive components in the battery system from harmful environmental factors (water, dust, etc.). It is therefore crucial for safe, reliable and long-term operation. For example, the housing of automotive batteries (which are usually located in the underbody of the vehicle) may be exposed to extreme influences such as stone chips, splash water, etc. High-level mechanical stability and corrosion resistance are therefore important.

5 SoC: State of Charge

6 Köhler U. (2013): Handbuch Lithium-Ionen-Batterien – Chapter 8: Aufbau von Lithium-Ionen-Batteriesystemen, Springer Vieweg, Heidelberg

7 Further information on cell balancing: Rothacher T., Schwarzburger H., Timke T. (2018), Stromspeicher für Gewerbe und Industrie

# 3. Characteristics of Li-ion batteries

How suitable a Li-ion battery is for a particular mobile or stationary application depends on many different aspects. Different criteria must be used to select a suitable system based on the requirements and intended use. A number of such criteria are presented in the following chapter.

#### 3.1 Technical properties

#### 3.1.1 Energy density

Energy density is the energy content of a cell or battery per volume or mass. It thus has a direct influence on the range which can be obtained from a purely electric vehicle powered by a traction battery of a given mass or volume. Energy density is expressed as specific [Wh/kg] or volumetric [Wh/l] energy density. The former is the product of specific load density [Ah/kg] and nominal cell voltage [V], and defines the stored energy content per mass. Volumetric load density [Ah/kg] and the nominal cell voltage. The specific energy density is sometimes also referred to as gravimetric energy density on data sheets. A cell with a high energy density requires a combination of two electrode materials with a high load density and potential difference.  $\rightarrow$  Figure 3 shows possible energy densities of different battery types, displayed according to their electrode materials.



Figure 3: Comparison of the volumetric and specific energy densities of present-day commercial batteries and potential chemistries in the future<sup>8</sup>

8 cf. https://battery2030.eu/digitalAssets/860/c\_860904-l\_1-k\_roadmap-27-march.pdf, Retrieval date 02.12.2020

As described, Li-ion batteries cover a wide range of specific energies or energy densities. Roughly 90–250 Wh/kg or 160–650 Wh/I can be achieved at the cell level (depending on the cell chemistry). Energy densities of over 400 Wh/kg are forecast for rechargeable lithium batteries in the future based on Li-sulfur, rising to 800 Wh/I for those based on Li-air. In addition, research is currently being conducted into many types of batteries that can theoretically exceed the very high energy densities of Li-ion cell chemistries, see → Chapter 5.

The energy density is a technical criterion which exerts a strong influence on the battery's own weight and housing volume, making it a decisive factor for the range, especially in mobile applications such as purely battery-driven electric vehicles (BEVs). The greater the energy density, the lighter or smaller the battery can be with the same energy content. Other factors may need to be prioritised for stationary applications.

#### 3.1.2 Power density

Li-ion batteries can be divided into: (i) energy-optimised batteries with high energy densities, low power densities and average discharge currents, and (ii) power-optimised batteries with lower energy densities, high power densities and very high discharge currents over short periods of time. The former are particularly important for BEVs, as the vehicle range depends on the capacity. In contrast, hybrid electric vehicles (HEVs) place very high demands on power density and thus also on high-current capability during charging and discharging. This is particularly true during discharging or when setting off and accelerating, when any additional power peaks need to be accommodated by the electric drive system. The energy stored in the battery must be released very quickly in such cases. During charging, on the other hand, the electrical energy that is converted from kinetic energy by the electric motor and recovered (recuperated) during braking must be stored in the battery within a matter of seconds. The faster the processes take place, the higher the charge or discharge current.

(i)

The specific load density is determined by the molecular weight (or density) of the host material and the number of lithium ions that can be reversibly absorbed into its structure. Specific power density is expressed in watts per kilogram (W/kg), and volumetric power density in watts per litre (W/l).

High-current capability is therefore crucial for high specific power density (W/kg) or volumetric power density (W/l) and fast charging and discharging of the cells or the system (e.g. for rapid charging or acceleration). The C-rate allows the magnitude of the charge and discharge current to be given independently of the capacity of different cells. This is usually lower for charging than for discharging of the battery. C stands for the respective currents which are listed as a fraction or multiple of the nominal capacity given by the manufacturer. The reciprocal of the C-rate thus indicates the number of hours required for charging or discharging.<sup>9</sup> The higher the C-rate, the higher the current and the faster the battery is fully charged.

9 Divide 60 (minutes of an hour) by the given C-rate to obtain the theoretical number of minutes needed for a full charge or discharge.



Example: Li-ion cell with a nominal capacity of 2 Ah		
C-Rate	Time (theor.)	Power
1 C	1 hour	2 A
0.5 C	2 hours	1 A
2 C	30 minutes	4 A
30 C	2 minutes	60 A

Table 1: C rates of a 2 Ah Li-ion cell in relation to time and current

High currents are also associated with high heat generation. Suitable cell chemistry and sufficient cooling capacity are therefore required for reliable operation. If there is insufficient cooling capacity, the resulting temperatures and associated cell reactions will have a negative impact on the cycle stability and life span of the battery.<sup>10</sup>

#### 3.1.3 Cell voltage

The cell voltage is sometimes expressed as the open-circuit voltage. This is the cell voltage when no current is flowing and no charging or discharging process is taking place. If there is a flow of current, the actual cell voltage will deviate from this value.

The electrode potentials of the respective active materials are used to determine the theoretical open-circuit voltage. In order to compare the potential of different electrode materials for Li-ion batteries, the materials are measured against a standard electrode made of metallic lithium whose potential is fixed at zero and thus serves as the basic reference. Examples of the electrode potential of different compounds are shown in  $\rightarrow$  Figure 4.

If two of these materials, such as  $LiMn_2O_4$  and graphite, are combined in a Li-ion cell, the resulting cell voltage is the difference between these electrode potentials (i.e. approx. 3.7 V in the example). The difference between the potentials of the materials should be as large as possible in order to achieve the maximum open-circuit voltage.

The final charge voltage is approx. 4.2 V for cells with a carbon-based anode (e.g. graphite) and metal oxide cathode (e.g. NMC). The corresponding final discharge voltage is typically 2.7-3.0 V. Overcharging or deep discharging can cause irreversible damage and loss of capacity. The BMS is responsible for avoiding such safety-critical events ( $\rightarrow$  Chapter 2.2.4).

10 Linden, Kirby W. Beard; Thomas B. Reddy. (2019): Handbook of Batteries, 5th edition



Figure 4: Overview of the electrode potentials of different active materials

#### 3.2 Systemic aspects

#### 3.2.1 Life time

The life time of a Li-ion battery is defined as the period between the time of delivery (beginning of life, BoL – characterised by properties typically defined in the specifications) and the time at which these properties fall below a previously defined value due to ageing (end of life, EoL). The EoL for batteries in electric vehicles is usually reached when the storage capacity falls below 80% of the nominal capacity. The defined value for the EoL depends to a great extent on the application.

In the measurement of life span, a distinction is made between

- cycle life or cycle stability and
- calendar life.

In practice, the total life expectancy of a battery is influenced by the combination of both service life specifications. The calendar life refers to the battery in the absence of cyclisation, i.e. when the system is not in use in the respective application, or is in storage. It is expressed in the number of expected years of use. In the unused state, interactions between electrolyte and active materials as well as decomposition processes take place in the cell which have an impact on the life span. Extreme external temperatures, charging conditions, the composition of the electrolyte and the quality of the manufacturing process are other factors that can accelerate ageing.<sup>11</sup>

<sup>11</sup> Korthauer, R. (2018): Lithium-ion batteries: Basics and Applications

Ageing is the deterioration of the electrochemical properties (for example, lower capacity, higher internal resistance, etc.). This is largely due to the energy throughput or cyclisation. High power requirements during charging and discharging of the battery give rise to high internal heat production. This can irreversibly damage the electrode materials and directly influence and accelerate the ageing of the cell or system. The capacity decreases over time, and there is an increase in internal resistance and a corresponding decrease in power. Secondary reactions in the electrolyte that take place during charging, such as expansion processes in the active materials or the resulting mechanical working of the active masses, also have an effect on ageing. The use of a number of different materials which are in contact with each other means that a variety of reactions is possible. Furthermore, external temperature factors also influence the possible life span. The higher the temperature, the faster these processes take place and the shorter the expected life span. Active cooling may therefore be necessary, depending on the application and conditions.

The cycle life is the number of possible cycles of a cell or system, through use or cyclisation, until EoL. A single process consisting of charging and discharging is referred to as a cycle. A distinction is made between full and partial cycles. A full cycle is discharging to a charge of 0% followed by charging to 100%. In contrast, an incomplete discharge is referred to as a partial cycle. Key parameters for the cycle life include the depth of discharge (DoD) and the state of charge (SoC). DoD and SoC are specified in relation to the total capacity of the battery and are expressed as a percentage. The usable capacity can be limited, thereby allowing the battery to be operated in partial cycles in order to increase battery life.



Figure 5: Life span in different applications with and without DoD limitation

The usable battery capacity is defined by the manufacturer. It is determined by the planned service life of the unit ( $\rightarrow$  Figure 5). This results in a life span of a few years or up to 500 cycles for some applications. One criterion here is the conditions under which these devices are used. The life span can be significantly increased by limiting the SoC to approx. 80–90% of the total capacity, as this submits the electrode materials to less strain. Cyclic ageing is therefore dependent not only on the number of charging and discharging processes (cyclisation), but also on the SoC and DoD. Other factors influencing the cyclic life include the temperature, the level of current applied and the speed of charging and discharging.<sup>12</sup>

#### 3.2.2 Safety

Lithium-ion batteries combine materials with a high energy content and flammable electrolytes. Safety-critical situations can be triggered in the event of extreme external influences such as short circuits, high temperatures or mechanical deformation. These must be taken adequately into account in the risk assessment undertaken during the design phase. Various internal and external safety features can be integrated into a lithium battery to minimise risks.

A key aspect is the reaction when cells are overcharged. This can lead to uncontrollable heating and, in the worst case, to a "thermal runaway"<sup>13</sup>. A thermal runaway that starts in a single cell can spread to other cells as a slow chain reaction caused by the powerful release of heat and/or the ignition of gaseous electrolyte, which can lead to fire and trigger an explosion in the cells. Deep discharges that can result in lithium plating should also be avoided. In order to check for these and other reactions, the cells must be subjected to electrical and mechanical safety tests before being placed on the market. The behaviour during rapid charging and discharging with high currents is also tested. Furthermore, tests must be carried out under extreme environmental conditions. More detailed information on standards relating to the corresponding safety tests can be found in  $\rightarrow$  Chapter 4.

### (i)

Safety is frequently prescribed for electrical systems and equipment in terms of functional safety, and is defined in standards as follows:

- Safety: Freedom from unacceptable risk
- Risk: Combination of the probability of occurrence of harm and the severity of that harm
- Harm: Physical injury or damage to the health of people, or damage to property or the environment.
- In practice: A cell or battery which is deemed safe has a lower probability of developing faults which could cause damage (e.g. overheating, release of gas) than other cells or batteries, or causes less damage if faults do arise. In the case of cells, the likelihood of faults occurring is largely dependent on the manufacturing quality (e.g. material purity, homogeneity of the electrodes). In the case of batteries, it is mostly influenced by the design.

Further information:

- DIN EN 61508-4, para. 3.1.11, 3.1.6 and 3.1.1
- ISO/IEC Guide 51:1999, Definition 3.1, 3.2 and 3.3
- International Electrotechnical Vocabulary, IEV ref 903-01-19, 903-01-07 and 903-01-07

<sup>12</sup> Korthauer, R. (2018): Lithium-ion batteries: Basics and Applications

<sup>13</sup> A state in which a battery heats up during charging or discharging and self-destructs due to internal heat generation caused by excessive overcharge or overdischarge current or other improper conditions. Linden, Kirby W. Beard; Thomas B. Reddy. (2019): Handbook of Batteries, 5th edition

As already mentioned, measures can be taken to minimise risks at all levels in a battery system. A selection of examples is given below:

Action	Description
Electrolyte additives	Addition of flame retardant additives to flammable organic electrolyte solutions
Shutdown separators	Micropores of the separator are closed through the action of heat to prevent further ion transport and to interrupt the flow of current
Redox shuttle	Electrochemically active substances added to the electrolyte. When the charging voltage is increased, these oxidise on the positively charged electrode and then migrate to the negative electrode, where they return to their original state through a reduction reaction. The excess charge is thus dissipated in a controlled process.
Shutdown additives	The additives to the electrolyte either release gases when the cell is overcharged, causing a pressure-sensitive switch to interrupt the current flow, or they impede the flow of ions in the electrolyte. <sup>14</sup>
Fuse	The fuse integrated in the circuit melts in the event of excessively high currents resulting in high increases in temperature

Table 2: Examples of risk minimisation measures

Any measures designed to minimise risk always have other effects on the battery, such as increasing module costs or lowering energy densities etc.

At the system level, the BMS is the most important component for ensuring safe and reliable operation of the battery ( $\Rightarrow$  Chapter 2.2.4), besides the mechanical installations themselves. The battery must not be recharged if the BMS does not prevent such irreversible damage from occurring, e.g. if the battery leaves its operating window. Otherwise, the damage could continue to grow within the operating window itself and trigger a safety-critical event.  $\Rightarrow$  Table 3 summarises further measures to increase safety at the cell and system level.

14 Korthauer, R. (2018): Lithium-ion batteries: Basics and Applications

Action	Description
Crash safety	Encasing the battery in a corrosion and crash-proof housing containing fire-retardant materials
	Valves for venting the reaction gases in the event of a fault
	Controlled discharge reaction of the battery in the event of the separator being destroyed
Operating safety	Microcontroller-based cell monitoring, automatic shutdown of the battery before safety-critical limit values are exceeded
	Thermal management (e.g. cold start behaviour)
	Overcharge protection, cell balancing (equalisation of voltages)
Service safety	Clear labelling of all high-voltage cables
	Contact protection in the form of insulation and special plugs that prevent contact with live parts
	Division of the battery into several modules connected via a safety switch

Table 3: Overview of further battery safety measures<sup>15</sup>

#### 3.2.3 System stress

Depending on the application, Li-ion batteries are exposed to various hazard-related stresses, most of which have already been addressed in the criteria presented above. The following table summarises the most important aspects and presents some recommendations:

Type of stress	Description
Mechanical	Stress and expansion processes during intercalation of the Li-ions in the electrode materials can cause the electrode to crack and break apart and thus change its volume.
	Collision-related mechanical deformations can lead to short circuits.
Electrical	The higher the charging and discharging currents, the greater the stress on the cell chemistry and the more heat is generated. Especially in combination with high states of charge, this can negatively affect the life of the battery by reducing the capacity and raising the internal resistance.
Thermal	The temperature during use has a great influence on the life span in terms of loss of capacity and usable capacity.
	Outdoor temperatures of 10–25 °C and operating temperatures of 20–40 °C are ideal for normal operation.
	Temperatures outside the ideal temperature range can influence the life span.
	Internal heat production accelerates possible (side) reactions in the materials used, which can lead e.g. to increased internal resistance and thus influence the life span and possibly also safety.
	The available capacity decreases as the temperature drops.

Table 4: Type of battery stress

<sup>15</sup> Wallentowitz, H.; Freialdenhoven A. (2011): Strategien zur Elektrifizierung des Antriebsstranges-Technologien, Märkte und Implikationen, 2nd revised edition, Vieweg+Teubner, Wiesbaden, p. 112

#### 3.2.4 Structural form

Lithium-ion cell manufacturers focus on three structural forms, each of which has its corresponding advantages and disadvantages. The cylindrical cell is a widely used battery cell design. A common size in the industry is the 18650 cell, which is 18 mm in diameter and 65 mm tall. It is easy to produce and is mechanically comparatively stable. However, its shape means that it has poor heat dissipation and that high volumes are required to form large packs. The cell chemistry of this battery is integrated into a stable round housing ( $\rightarrow$  Figure 6). The cell has a cavity along the cylindrical axis. This allows the battery to "breathe" in under load (heating) but not to expand. Another typical round cell format is the 27100 cell.



Figure 6: Structure of cylindrical, prismatic and pouch cells based on LMO

The structure of a prismatic cell is similar to that of a cylindrical cell. The components are folded into a flat coil to pack them into a solid prismatic housing in the following sequence: anode – separator – cathode – separator. The flat rectangular shape permits better volume utilisation and heat dissipation than the cylinder design. Disadvantages, however, include the more complex cell production and assembly.

The pouch (coffee bag, laminate) cell is another version of the prismatic cell. Plastic-coated aluminium films are usually used instead of the solid housing. The anode – separator – cathode sequence is usually stacked during production. These stacks are either made from pre-cut components or laminated and die-cut from the roll. Clear advantages of this cell shape are its superior cooling properties, its good scalability and very good heat dissipation. In addition, high energy densities can be obtained at relatively low production costs. The low mechanical stability of the cell and its possible inflation due to increased internal pressure in the event of uncontrolled gas development must be taken into account<sup>16</sup>.

### (j)

#### Important

Both non-rechargeable (primary) and rechargeable batteries (accumulators or also secondary batteries) come in the same sizes and shapes.

Before charging a battery, please read the safety instructions on both the battery and the charging device. If in doubt, do not charge the battery under any circumstances!

16 battprod.vdma.org/documents/7411591/15357859/Produktion+LIB-Zelle/f53063de-1469-ed58-9b34-b8d7fc9f7f3f, Retrieved on 02.12.2020

### 4. Legal regulations and standards for Li-ion batteries

There is a confusing array of legal requirements and standards for the handling of lithium-ion batteries in different application areas. The following chapter is therefore intended to provide a brief overview to people and institutions who/which are new to dealing with lithium-ion batteries.

#### 4.1 Legal regulations and binding agreements

Important legal regulations for batteries can be found in the current version of the Battery Act (BattG). "BattG" is the German implementation of the European Battery Directive. The Battery Act regulates the placing on the market, return and environmentally compatible disposal of batteries. It applies to all types of batteries, regardless of their shape, size, mass, material composition or use (with the exception of military applications). The specifications apply even if the batteries are installed in devices. Environmental aspects are increasingly being taken into account in the latest revisions of the specifications.

These are supplemented by the regulations of the ADR (Accord européen relatif au transport international des marchandises **D**angereuses par **R**oute), which is the European agreement on the international carriage of dangerous goods by road. There are different regulations depending on the mode of transport. Air, rail, water and road transport are covered in detail. The regulations for road transport address packaging, labelling and the securing of dangerous goods loads. The ADR is updated regularly, with the latest version always coming into force after a transitional period of one year. The Dangerous Goods Ordinance for Road, Rail and Inland Navigation (GGVSEB) applies the ADR to transport within Germany, supplementing it with national regulations.

With few exceptions, lithium batteries must meet the requirements of section 38.3 of the UN Manual of Tests and Criteria (UN 38.3 Transport Test) to ensure the safety of lithium-ion batteries during transport. This test therefore simulates the conditions to which lithium batteries can be subjected during transport, such as crushing, falling, pressure and temperature fluctuations, and even impact. Different testing requirements apply for lithium batteries depending on their weight, energy content and other factors. This test must be passed for the transport of production quantities of lithium batteries > 100 pieces. Smaller quantities can be transported in accordance with ADR special provision 310.

Batteries as products also fall under the Product Safety Act (ProdSG), which must therefore be observed additionally. It regulates the safety of products on the market and can be fulfilled in part by complying with existing standards.

These legal regulations and binding agreements are supplemented by various standards, primarily covering safety aspects and their testing. They are examined in more detail in the following section. However, the application of standards is not legally binding.

#### 4.2 Important standards by type of use

The standards for lithium-ion batteries are divided according to application, as different requirements have to be considered and tests carried out depending on the use. Below is a list of some (but not all) important standards and application rules for lithium-ion batteries. For specific details, the currently valid version must be used in each case.

Portable batteries	
DIN EN 62133-2 (VDE 0510-82)	Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable equipment Part 2: Lithium systems
	This standard specifies requirements and tests for the safe operation of portable sealed lithium secondary cells and batteries. The main focus is on testing the cells and batteries for their intended use and for reasonably foreseeable misuse.
Stationary batteries	
DIN EN 62619 (VDE 0510-39)	Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries, for use in industrial applications
	This standard specifies the requirements and tests for the safe operation of secondary lithium cells and batteries (accumulators) in industrial (including stationary) applications. Stationary applications include uninterruptible power supplies, electrical energy storage systems and emergency power systems. Mobile applications include forklifts, golf carts, automatic guided vehicles and other mobile applications other than road vehicles. This standard applies to various industrial applications and specifies common minimum requirements. It is supplemented by applications.
DIN EN 62620 (VDE 0510-35)	Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for use in industrial applications
	This standard specifies the performance testing of primary and secondary lithium-ion batteries. The purpose of this standard is to set out a basic general test methodology that can be used for the general primary testing of lithium-ion primary and secondary batteries in various battery installations.
DIN EN 63056 (VDE 0510-56)	Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems
	This standard specifies requirements and tests for the product safety of secondary lithium cells and batteries used in electrical energy storage systems up to a maximum (nominal) voltage of 1,500 V DC. This standard also applies to uninterruptible power supplies. Portable systems supplying less than 500 Wh are excluded.

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VDE-AR-E 2510-50	Stationary energy storage systems with lithium batteries – Safety requirements
	This VDE application guide specifies safety requirements for battery energy storage systems (BESSs) based on lithium batteries in conformity with the Product Safety Act. Complete energy storage systems are the main focus of attention. It contains requirements designed to ensure the safety of the storage units throughout their life cycle: Warehouse storage, transport, installation, operation, maintenance, disassembly and recycling. This application guide thus contains verification procedures in the form of visual inspections, document checks and practical type and routine tests. The scope of AR 2510-50 is limited to BESSs that are accessible to, and can be operated by, non-professionals (e.g. in private and small-scale commercial use). The requirements do not apply in full to battery storage systems in electrical operating facilities and medical areas, where further standards must be applied.
Electric road vehicles	
DIN EN IEC 62660-1 (VDE 0510-33)	Secondary lithium-ion cells for the propulsion of electric road vehicles Part 1: Performance testing
	This part of IEC 62660 specifies the procedures for testing the performance and life span of secondary lithium-ion cells used to power electric vehicles, including battery electric vehicles ( <i>BEVs</i> ) and hybridelectric vehicles ( <i>HEVs</i> ). The objective of this standard is to define the test methods for determining the essential characteristics of lithium-ion cells for vehicle propulsion in terms of their capacity, power density, energy density, storage life and cyclic life.
DIN EN IEC 62660-2 (VDE 0510-34)	Secondary lithium-ion cells for the propulsion of electric road vehicles Part 2: Reliability and abuse testing
	Part 2 of DIN EN 62660 specifies the procedures for testing the reliability and abuse behaviour of secondary lithium-ion cells and cell blocks used to power electric ve- hicles, including battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs). The purpose of this document is to set out standardised methods and conditions for testing the basic properties of lithium-ion cells intended to power battery and hybrid electric vehicles. These tests are crucial for gathering essential data on the reliability and abuse behaviour of lithium-ion cells for various battery system and battery pack designs. This document provides a standard classification of the description of test results to be used in the design of battery systems and battery packs.
DIN EN 62660-3 (VDE 0510-49)	Secondary lithium-ion cells for the propulsion of electric road vehicles Part 3: Safety requirements
	This part of DIN EN 62660 specifies the procedures and acceptance criteria for testing the reliable operation of secondary lithium-ion cells and cell blocks used to power electric vehicles (EVs), including battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs). This international standard serves to determine the basic safety of cells used in battery packs and systems; both in terms of intended use and in foresee-able abuse or failure during normal operation of electric road vehicles. The cell safety requirements in this standard are based on the assumption that the cells are used as intended in a battery pack and system within the voltage, current and temperature limits (cell operating range) specified by the cell manufacturer. Assessment of the safety of cells during transport and storage is not covered by this standard.

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ISO 12405-4	Electrically propelled road vehicles – Test specification for lithium-ion traction battery packs and systems Part 4: Performance testing
	This document specifies test procedures for the basic characteristics of performance, reliability and electrical functionality for the battery packs and systems in either heavy duty or high-energy applications. Typical applications for heavy duty battery packs and systems are hybrid electric vehicles (HEVs) and one type of fuel cell vehicle (FCV). Typical applications for high-energy battery packs and systems are battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and some types of fuel cell vehicles (FCVs). Testing at the cell level is specified in the DIN EN 62660 series.
ISO 6469-1	Electrically propelled road vehicles – Safety specification Part 1: Rechargeable Energy Storage Systems (RESS)
	This document specifies safety requirements for rechargeable energy storage systems (RESSs) in electrically propelled road vehicles for the protection of persons. It does not provide comprehensive safety information for manufacturing, maintenance and repair personnel. The requirements for motorbikes and mopeds are specified in ISO 13063 and ISO 18243.
Light Electric Vehicles	s (LEVs)
DIN EN 50604-1 (VDE 0510-12)	Secondary lithium batteries for light electric vehicle applications Part 1: General safety requirements and test methods
	This standard specifies test methods and requirements for the safe use of secondary lithium batteries in light electric vehicles including EPACs (pedelecs). The objective is to increase the safety of battery packs containing lithium battery technologies for use in light electric vehicles. This standard is not intended to assess the safety of storing battery packs/systems, of vehicle manufacture, repair or maintenance, nor does it apply to:
	<ul> <li>lithium cells (testing at cell level is covered in the IEC 62660 series of standards);</li> <li>batteries other than lithium-ion batteries;</li> <li>primary batteries (including lithium batteries)</li> </ul>

Table 5: Standards for lithium-ion batteries, by application

Other topics where normative documents are currently in the pipeline include modular battery systems, the "seconduse" of traction batteries and standardised information on the characteristic values of stationary storage systems. In addition, ecological issues are increasingly coming to the fore, also in response to political demands.

## 5. Outlook

The German government's climate protection plan aims to reduce annual greenhouse gas emissions by up to 95 per cent by 2050 (compared to 1990 levels). Restructuring of the German energy supply system and zero-emission mobility are important areas for achieving this alongside industry, buildings and agriculture. As more use is made of renewable energy, the intention is to gradually replace the fossil fuels currently used for energy and transport, thus creating an environmentally-friendly energy supply. A key factor in the transformation process for meeting these goals is battery technology. Battery storage systems are used, among other things, in stationary applications for storing electrical energy from renewable power generators, and for supplying energy in vehicles. In order to achieve this goal, it is now essential to take measures such as developing the relevant electrochemical competence as well as enhancing current battery systems and their performance.

#### 5.1 Future battery technologies

Research is being conducted into aspects such as

- higher energy density
- shorter charging times
- improved temperature characteristics
- reduced costs
- increased safety
- greater environmental compatibility and
- longer life span.

Researchers worldwide are faced with the challenge of combining as many of these aspects as possible to create a more effective technology. The greatest potential for optimising the batteries lies in the materials themselves. Experiments are being carried out on new materials and on alternative combinations of existing materials. The aim of the research is to discover more effective compositions than those found in the lithium-ion batteries commonly used at present. The following section provides an overview of some of the battery chemistries that are the subject of intensive research. So far, a number of challenges still lie in the way of successful commercialisation.

#### Solid-state battery

In solid-state batteries, an electrolyte made of solid material is used instead of a liquid electrolyte. Intensive research is being conducted into solid electrolytes, as they can achieve much higher specific energy densities of around 500 Wh/kg. The solid structure of solid state batteries slows down the growth of dendrites, which is why they are considered the most likely option for the industrial implementation of secondary Li-metal batteries. Initial successes have already been achieved in the laboratory with solid electrolytes, but cycle stability remains a common problem in their industrialisation to date.

#### Metal-sulfur batteries

The metal-sulfur battery is an example of an alternative cell material, and the most prominent representative of this battery type is the lithium-sulfur battery. Sulfur is a cheap raw material which is available in large quantities as a waste product created during the separation of hydrogen sulfide from natural gas and crude oil. The combination of lithium and sulfur theoretically offers a high specific energy density of up to 860 Wh/kg. The raw material costs of a metal-sulfur battery are lower than those of a comparable lithium-ion system offering the same capacity.

#### Metal-air and metal-oxygen batteries

Research is also being conducted not only on metal-sulfur but also on metal-air and metal-oxygen batteries. Electrical energy is released in such systems by means of a chemical reaction between metals and oxygen. Of particular interest here is oxygen, because this can be obtained from the ambient air via the electrode and not held in the battery as in other systems. In theory, metal-air and metal-oxygen batteries can achieve a higher volumetric energy density (approx. 850–900 Wh/I) than other types. Lithium can also be used as the basis.

#### Sodium-ion batteries

Sodium-ion batteries are an attractive alternative to lithium-ion batteries. This is because sodium is readily available – in the oceans and also in the earth's crust, for example. Furthermore, it is cheaper to extract than lithium. The established manufacturing methods can also be used to produce sodium-ion batteries. However, both the specific and volumetric energy densities of sodium-ion batteries are lower than those of lithium-ion batteries.

#### 5.2 Carbon footprint and recycling

The Federal Ministry for Economic Affairs and Energy's theses on industrial battery cell production in Germany and Europe place additional focus on the "sustainable and environmentally compatible production and disposal conditions, e.g. low CO<sub>2</sub> emissions during production [...] in the entire battery manufacturing value chain [...]<sup>\*17</sup>. Many companies are striving to reduce their emissions as a consequence of the German government's climate protection goals and the growing importance of climate protection. The most important ways of achieving the climate targets include the consistent use of renewable energies, increased energy efficiency and new production processes.<sup>18</sup>

A study by the World Economic Forum (WEF) estimates that a battery-electric vehicle has the potential to reduce emissions by 50% compared to a conventional vehicle if a circular battery value chain can be established.<sup>19</sup>

"The CO<sub>2</sub> footprint is reduced in cases where a high proportion of renewable energy is used in production, for example in the form of self-generated electricity from solar plants or through the purchase of green electricity. Other starting points are the supply chains, subcontractors and raw material extraction. A further solution is adopting a circular economy approach for batteries, based for example on the collection of data which is verified and traceably linked to the battery. Recycling can be used, for example, to help reduce CO<sub>2</sub> emissions in the extraction of raw materials. As the number of electric cars increases, so does the demand for the disposal of traction batteries. The German government still has time to develop a regulatory framework. Lithium-ion batteries are characterised by their long life span (depending on usage patterns), meaning that it will be several years before the first major wave of batteries is due for recycling. The end of the "first life" is considered to have been reached when the available capacity has fallen to 70-80% of the nominal capacity, depending on the application. This does not, however, mean that the battery has to be recycled immediately. There is then the possibility of a "second life". Here the "state of health" of the battery is examined at the end of the initial application. If this meets the second life requirements, the battery can be used in an application with a lower capacity requirement, for example as a stationary energy storage device. Only at the end of the second life is the battery submitted to the recycling process. German car manufacturers and the Federal Ministry for Economic Affairs and Energy are aiming for a 90% recycling rate. Initially, pilot plants are to be set up which will eventually be converted into industrial-scale plants in the long term. Recycling enables valuable raw material resources such as cobalt, copper and nickel to be recovered and fed back into the recyclable material process."20

<sup>17</sup> https://www.bmwi.de/Redaktion/DE/Downloads/S-T/thesen-zur-industriellen-batteriezellfertigung-in-deutschland-und-europa.pdf?\_\_blob=publicationFile&v=5, Retrieved on 11.10.2020

<sup>18</sup> Logistics, Energy and Mobility 2030. Meta-study for the BMWi ICT for Electromobility Technology Programme. Office of the Accompanying Research ICT for Electromobility, December 2020

<sup>19</sup> https://www.plattform-zukunft-mobilitaet.de/wp-content/uploads/2020/10/20201020-NPM-Bericht-AG6-RoadmapNachhaltigeMobilitaet-V2-wrz.pdf

<sup>20</sup> Logistics, Energy and Mobility 2030. Meta-study for the BMWi ICT for Electromobility Technology Programme. Office of the Accompanying Research ICT for Electromobility, December 2020

#### 5.3 Regulatory framework for the recycling and sustainability of batteries

The National Platform for the Future of Mobility (NPM) has published a roadmap on "Sustainable Mobility – Standards and Norms" (in German). We refer to this below.<sup>21</sup>

Regulatory framework for batteries		
Chemicals Regulation 2006/1907/EC (REACH)	The Chemicals Regulation 2006/1907/EC (REACH) has regulated the registration, evaluation, authorisation and restriction of chemicals within the EU since 2007. This affects numerous raw materials that are incorporated in the batteries themselves or used in the production process.	
EU Regulation 493/2012	EU Regulation 493/2012 regulates the calculation of recycling efficiencies of the recycling processes of waste batteries and accumulators.	
Directive (EU) 2018/849	Directive (EU) 2018/849 regulates the amendments to Directives 2006/66/EC (batteries and accumulators), 2000/53/EC (end-of-life vehicles), 2012/19/EU (waste electrical and electronic equipment).	

Table 6: Regulatory framework for the recycling and sustainability of batteries

Current and planned standards		
Environmental aspects		
DIN EN IEC 63218 (VDE 0510-218)	Secondary cells and batteries containing alkaline and other non-acid electrolyte – Secondary Lithium ion, Nickel Cadmium, and Nickel Metal Hydride cells and batteries for portable applications – Guidance on environmental aspects	
Labelling		
DIN EN IEC 62902 (VDE 0510-902)	Secondary cells and batteries – Marking symbols for identification of their chemistry	
Reuse		
IEC 63330 (in development)	Requirements for reuse of secondary batteries	
IEC 63338 ED1 (in development)	General guidance for reuse of secondary cells and batteries	
IEC 62933-4-4 (in development)	Electrical energy storage (EES) systems Part 4-4: Environmental requirements for BESS using reused batteries in various installations and aspects of life cycles	
VDE pre-standard (in development)	Stationary use of lithium-ion automotive batteries	

Table 7: Current and planned standards

21 https://www.plattform-zukunft-mobilitaet.de/wp-content/uploads/2020/10/20201020-NPM-Bericht-AG6-RoadmapNachhaltigeMobilitaet-V2-wrz.pdf

# Listings

#### Abbreviations

ADR Accord européen relatif au transport international des marchandises Dangereuses par Route (European Agreement concerning the International Carriage of Dangerous Goods by Road) Ah Ampere-hour BattG Battery Act BEV Battery Electric Vehicle BMS Battery Management System BMWi Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy) BoL Beginning of Life C-rate Charge or discharge rate, current in relation to nominal battery capacity DoD Depth of Discharge End of Life EoL GGVSEB Gefahrgutverordnung Straße, Eisenbahn und Binnenschifffahrt (Ordinance on the Transport of Dangerous Goods by Road, Rail and Inland Waterways) Hybrid Electric Vehicle HEV Li Lithium LCO Lithium cobalt oxide LFP Lithium iron phosphate LMO Lithium manganese oxide NCA Lithium nickel cobalt aluminium oxide NMC Lithium nickel manganese cobalt oxide PHEV Plug-In-Hybrid Electric Vehicle SoC State of Charge SEI Solid Electrolyte Interphase

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