energies

Review

Review on New-Generation Batteries Technologies: Trends and Future Directions

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Abstract: Battery technologies have recently undergone significant advancements in design and manufacturing to meet the performance requirements of a wide range of applications, including electromobility and stationary domains. For e-mobility, batteries are essential components in various types of electric vehicles (EVs), including battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs). These EVs rely on diverse charging systems, including conventional charging, fast-charging, and vehicle-to-everything (V2X) systems. In stationary applications, batteries are increasingly being employed for the electrical management of micro/smart grids as transient buffer energy storage. Batteries are commonly used in conjunction with power electronic interfaces to adapt to the specific requirements of various applications. Furthermore, power electronic interfaces to batteries themselves have evolved technologically, resulting in more efficient, thermally efficient, compact, and robust power converter architectures. This article offers a comprehensive review of new-generation battery technologies. The topic is approached from the perspective of applications, emerging trends, and future directions. The article explores new battery technologies utilizing innovative electrode and electrolyte materials, their application domains, and technological limitations. In conclusion, a discussion and analysis are provided, synthesizing the technological evolution of batteries while highlighting new trends, directions, and prospects.

Keywords: battery roadmap; e-mobility; energy storage; gigafactories; lithium batteries; new generation batteries technologies

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1. Introduction

There is no doubt that the next ten or twenty years will experience a transformation concerning energy storage system technology, especially for batteries and power electronics converters. It concerns not only the manufacturing and commercialization of batteries but also encompasses a supply chain driven by a strong decision of countries or continents to be part of this solid transformation. The electrification of transportation is an undeniable reality. Automotive manufacturers, battery OEMs (Original Equipment Manufacturers), research laboratories, and governmental institutions must adapt according to the new obligations powered by a fast-changing climate, energy and raw materials independence strategies, environmental and health considerations, a substantial presence in the expanding electromobility market, and applied research.

The Paris Agreement [1] seeks to reduce greenhouse gas emissions by encouraging the transition of energy systems within the industrial and transportation sectors. Meanwhile, the European Green Deal [2] is working towards achieving a reduction in net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. In its pursuit of decarbonizing the transportation sector, the European Union (EU) has set the ambitious goal of achieving full decarbonization of its economy and attaining climate neutrality by 2050. To accelerate progress in the battery sector, the European Commission established the European Battery Alliance (EBA) in 2017 and adopted the Strategic Action Plan on Batteries in 2018 [3]. The EU funding programs Horizon Europe and Important Projects of Common European Interest (IPCEI) represent key instruments in this regard. Operating under the umbrella of the European Battery Alliance, their aims are to promote research and innovation, stimulate investment, and foster partnerships among industrial, governmental, and educational institutions. The ultimate objective is to establish cost-effective and environmentally friendly gigafactories on European soil. Similarly, the United Kingdom plans to stop the sale of internal combustion engine vehicles by the end of 2030 [4]. The United States addressed the climate crisis by building a clean and equitable energy economy. Their strategy aims to achieve carbon-pollution-free electricity by 2035 and to reach net-zero emissions no later than 2050 [5]. The investments in energy transition spiked to attain 297 billion dollars in China in 2021, compared to 120 billion dollars spent by the United States [6].

In order to have a share in this important market, stakeholders should secure access to raw and refined materials, discover alternatives for critical materials, and integrate recycled material as part of the circular economy [7].

When considering environmental impact, it is crucial to emphasize that it largely depends on the source of the electricity used to charge the battery. Well-to-wheels (WTW) analysis indicates that battery electric vehicles (BEVs) exhibit favorable environmental performance when powered by electricity generated from nuclear power plants or renewable energy resources [8].

The primary obstacles to the widespread adoption of electric vehicles (EVs) include the high cost of purchase, limited driving range, and a lack of accessible charging stations. A new energy storage technology naturally undergoes a series of transformations aimed at enhancing its performance across several key metrics. These include capacity, gravimetric and volumetric energy (Wh/kg and Wh/L), power (W/kg and W/L), charging time, safety, cycle and calendar life, environmental impact, and ultimately, cost per unit of energy content. Notably, specific energy (or energy density) has shown remarkable progress, increasing from 110 Wh/kg (9 Wh/L) in 2010 to 300 Wh/kg (450 Wh/L) in 2020, with a projected trajectory towards 550 Wh/kg (1200 Wh/L) by 2030 [9–11]. Furthermore, the cost of batteries has declined from \$102/kWh and is expected to reach \$80/kWh by 2030 [12], indicating a significant cost reduction trend.

Nonetheless, it is imperative that research, design, and manufacturing endeavors related to new-generation batteries and their associated power interfaces remain integrated within the framework of a global circular economy. This integration is vital for ensuring the long-term sustainability of the entire process. As an example, the focus is on giving the batteries the experience of a second life through the recycling, reusing, refabricating, and reselling processes.

Within the broader context of the whole system, the role of static power converters, which are based on power electronics semi-conductors-based switches, is to assure the flow of energy between the grid, the batteries, and the power loads, primarily the electric motors. Depending on the battery type, the converters' structures, components, and control systems must ensure a safe and efficient charging and discharging process, while optimizing the efficiency, durability, performance, and cost of the battery and overall system [13].

Another significant hurdle in the widespread adoption of electric vehicles is the time required for charging. To promote broad acceptance, a high-powered charging infrastructure should offer the same convenience as traditional gas and fuel stations. Additionally, there is a need for battery development that allows for rapid energy storage without compromising the battery's health. Charging methods should aim to extend the battery's lifecycle, prevent damage, and reduce charging duration. Authors in [14] proposed a battery charger with variable charging current and automatic voltage compensation. The objective is to reduce circuit complexity for parallel charging. A review of EV fast-charging technologies, their impacts on battery systems, and the associated heat management limitations is provided in [15]. The review also highlights promising new approaches and opportunities for advancing fast-charging systems through power electronic converter topologies.

It is crucial to recognize that new-generation batteries are inherently intertwined with the overall environment, and notably, with power electronics systems. In [16], the authors investigated the power electronics technologies utilized in electric vehicles, such as unidirectional and bidirectional on-board and off-board chargers for the EV battery in its front-end and back-end power stages, in addition to wired and wireless power transfer technologies. Furthermore, from the traction side, the authors focused on the inverter topology according to the type of electric machine and on the unified power converter topology, which includes the grid, the battery, and the electric machine.

The state of the art of power electronics for electric vehicle (EV) traction drives and battery-based EV charging systems has been presented in reference [17]. Three types of charging systems have been discussed: contactless inductive recharging (Wireless Power Transfer, WPT), conductive charging, and battery swapping. Comparative properties of various DC/DC converter charging systems along with soft-switching auxiliary circuits can be found in [18]. Another comparative analysis of resonant converter topologies with a focus on the LLC resonant topology, a configuration that uses two inductances L and one capacitor C, is also addressed by the authors.

The current state of the art of extreme fast charging (XFC) infrastructure using solid-state transformer technology while directly connected to the medium voltage (MV) line is reviewed in reference [19]. Technical considerations, challenges, and improvements in wide-bandgap power devices are also discussed. One significant issue with fast charging of electric vehicles is the decreased performance and lifespan of lithium-ion batteries due to the high current used during charging. A study in reference [20] examines the impact of fast charging on the degradation of lithium-ion batteries under operation profiles from real driving cycles in a Matlab/Simulink©-based platform. The findings showed that Lithium Titanate Oxide batteries (LTO) had the least degradation among the other batteries tested (LFP and NMC).

A general classification of DC-AC power converters is presented in reference [21], starting from a classical topology to a multilevel inverter topology. The issues of power density, switching losses (hard switching vs. soft switching), stresses on devices, and control circuit complexity have been addressed.

A review of the available traction motors and drives for light railways is also provided in reference [22]. Permanent magnet synchronous motors with multiphase windings are evaluated. Wide bandgap semiconductor devices have been introduced for low- and medium-voltage multisource power converters.

Typically, batteries are controlled through a battery management system (BMS). Authors in [23] implemented a real-time battery energy management system carried out on a prototype EV traction system. They proposed two techniques: cascaded fuzzy logic controller (CSFLC) and fuzzy tuned model predictive controller (FMPC) techniques. The primary objective of this system was to minimize battery State of Charge (SOC) and State of Health (SOH) degradation.

Lithium-ion batteries (LIBs) are highly sensitive to operating temperatures. Authors in [13] make a review of the latest advances in thermal management systems for batteries propelling electric vehicles. The authors emphasized the usefulness of solid-liquid phase change material (PCM) for battery thermal management systems (BTMSs). This type of BTMS has several advantages over the cost-effective air-based and the high transfer efficiency of the liquid-based BTMS, such as low energy consumption, small volume change, low noise, and high cooling capacity. Efficient methods of battery thermal management (BTM) are also reviewed in [24].

The functionalities of intelligent battery systems (IBSs) and prerequisites for their implementation have been discussed in [21]. The objective is to improve the reliability, safety, and efficiency of BEVs. These systems should give an accurate and robust determination of cell individual states. The concept of reconfigurable battery systems (RBSs) has also been spotted.

The powertrain system of electric vehicles heavily relies on power converters, which can be split into three categories: AC/DC, DC/DC, and DC/AC (inverters). The performance of these converters is largely determined by the power electronics structures and the semiconductor technology used, with factors such as power density, efficiency, and controllability playing an important role.

Currently, the switches within power electronic converters utilize silicon (Si) semiconductor technology. However, advancements in switching technology have led to the exploration of using wide bandgap (WBG) semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), as an alternative. WBG semi-conductors operate at higher voltages and switching frequencies, enabling high efficiency and power density. For automotive traction applications, Insulated Gate Bipolar Transistors (IGBTs) are commonly used as semiconductor power switches with an operating switching frequency ranging between 5 and 10 kHz [25]. In 2017, Tesla used SiC MOSFETs power switches from STMicroelectronics and Infineon, [26], for the Tesla Model 3 with a switching frequency of hundreds of kHz, adding 18% to efficiency at the high-efficiency zone. On the other hand, and for the purpose of miniaturization, Tesla has recently revealed that its inverters would pass from a 48 SiC MOSFETs to a 12 SiC MOSFETs structure which represents a substantial 75% reduction in the overall usage of SiC within Tesla's inverters [27]. The latest SiC switches offer enhanced reliability, increased efficiency, higher power density, and improved thermal capabilities.

A state-of-the-art review of the current status and opportunities of power electronic converters in electric, hybrid, and fuel cell vehicles can be found in [28,29].

The power density of traction inverters has seen a dramatic increase in the past decade, going from 13.3 kW/L in 2012 [30], to 34 kW/L in 2022 [31]. It is expected to reach as high as 100 kW/L in 2025 [32]. The introduction of wide bandgap technology could further boost efficiency up to 99% [33], extending the vehicle's driving range and enabling high-performance charging and V2X systems. V2X technology enables improved energy management, increased reactivity of the EVs with their surroundings, and better integration of renewable energy into the power grid.

The review paper will take into consideration many influencing external parameters and variables that define the roadmap of new battery technologies. Hereby, the primary role is to provide extensive research and in-depth analyses in the battery field. The work involved a systematic selection of the most critical articles on battery materials and technologies in order to highlight their trends and future directions.

Nowadays, battery applications could intervene in electromobility, stationary energy storage for grid usage, smart cities, and portable electronic utilities. Table 1 shows the share in percentage for each type of application. A great deal of importance should be given to energy storage applications. The implementation of local and international regulations, rules, and agreements aimed at reducing greenhouse gas emissions, promoting carbon neutrality, and ultimately the phasing out of internal combustion engine vehicles in many countries around the world will unquestionably drive the electromobility sector. Specifically, the number of electric vehicles will substantially increase, necessitating a heightened production of electric batteries. Simultaneously, there will be a parallel emphasis on enhancing the energy storage capacity of each battery, reflecting the desire to extend the autonomy of electric vehicles. Consequently, the electromobility sector will indeed become more significant in terms of total energy storage capacity than other sectors like stationary storage systems or portable electronic devices. This does not imply that the energy requirements of the latter two sectors will decrease over the years—quite the contrary. However, the electromobility sector will attract a larger share of the overall stored energy in terms of percentage compared to other sectors. This is what explains the decrease in percentage from 2025 to 2030 for the energy storage and portable electronics sectors.

Table 1. Percentage share of batteries usage applications [34].

	Year		
	2020	**2025**	**2030**
Electric Mobility	81.21%	83.21%	88.94%
Energy Storage	3.55%	10.81%	8.43%
Portable Electronics	15.25%	5.97%	2.63%

Achieving the energy transition goal would involve substantial increases in minerals demands. By 2050, the annual base metal production could increase five- to six-fold (e.g., copper, nickel, aluminum). As for lithium, the demand could reach 100 times its current level.

As shown in Figure 1, according to [35], in order to respond to the battery market demand, the annual production should attain 6700 GWh in 2031.

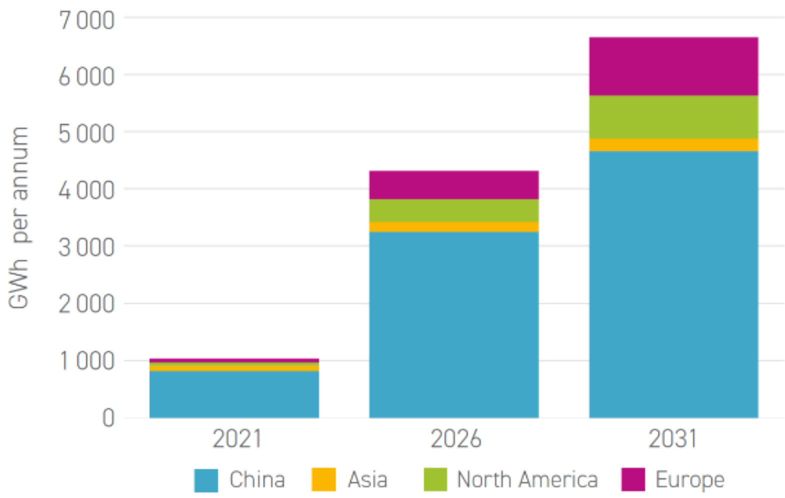

Figure 1. Global battery manufacturing capacity to 2031 [35].

In 2021, China was responsible for approximately 79% of the world's lithium-ion battery manufacturing capacity, while North America and Europe each accounted for about 5% and 7%, respectively.

It is expected that Europe's market share of the global battery supply market will reach 11% by 2026 and 15% by 2031 [35]. Figure 2 illustrates the gigafactories that have been installed and are planned for Europe or a comprehensive overview; a world map displaying the locations of these gigafactories and related data can be accessed on the CIC energiGUNE website [36].

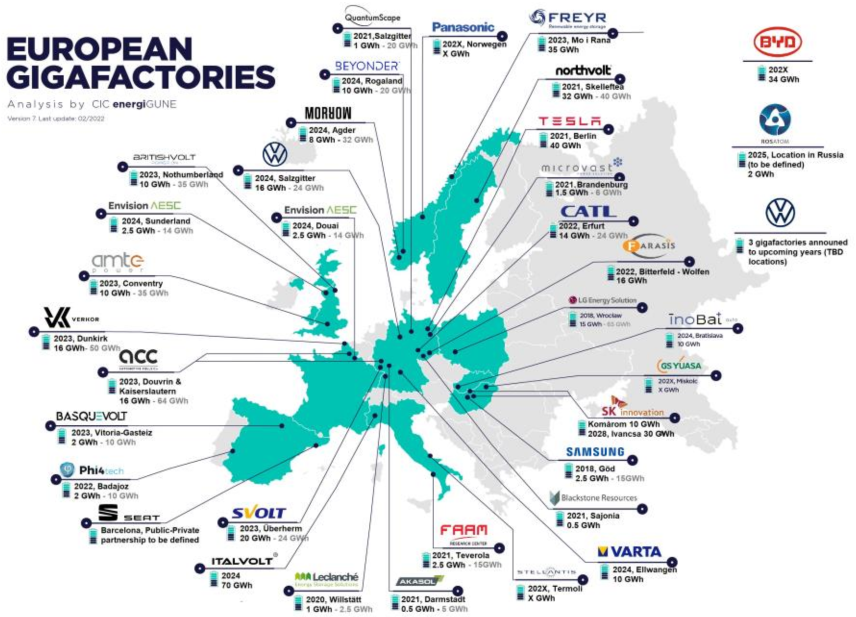

Figure 2. Gigafactories in Europe [37].

Major car manufacturers have committed to transitioning to electromobility, which is being driven by policymakers, promising markets, infrastructure development, societal evolution, and technological innovations [38]. Several considerations lead to original equipment manufacturers (OEMs) and battery manufacturers being located geographically close to each other in order to support just-in-time (JIT) production and minimize lithium-ion batteries transportation, which requires specific safety measures [39].

Lithium-ion batteries (LIBs) have the potential to improve frequency and voltage regulation in grid applications and provide backup power during outages. LIBs can be used in renewable energy plants or smart grids to help stabilize the power system and meet the changing demand for electricity. In addition, batteries can be employed to take advantage of price differences in the energy market, known as energy arbitrage. Specifically, energy is stored during periods when the cost is low and then released when the price is higher, thus providing economic benefits. They can also be used in off-grid settings such as telecom base stations or for household use.

Research efforts for batteries are focused on the materials for the electrodes and electrolytes, the configuration and composition of the electrodes, the arrangement of the cells (in pouch, cylindrical, and prismatic shapes), the material and thickness of the separator, the design of other components such as the pack cover, electronics boards, sensors, and relays, and the cooling system. Eco-friendly design and ways to recycle are also major parts of the research activities.

Nickel manganese cobalt (NMC) batteries are currently the most widely used in electric vehicles (EVs) and are projected to make up approximately 80% of the global market. The popularity of NMC batteries is expected to reach approximately 90% by 2030, as the use of lithium iron phosphate (LFP) and nickel cobalt aluminum (NCA) batteries decreases [40,41]. The cost of silicon based NMC622 batteries is expected to reach a limit of USD 100/kWh, which will impact the overall price of electric vehicles as the battery is the most expensive component. However, this development may also contribute to the wider adoption of electric vehicles due to the reduced cost [42]. High nickel batteries NMC811 and NMC9.5.5 are expected to gain a larger market share due to their increased capacity and reduced material costs compared to NMC622, as indicated in Figure 3.

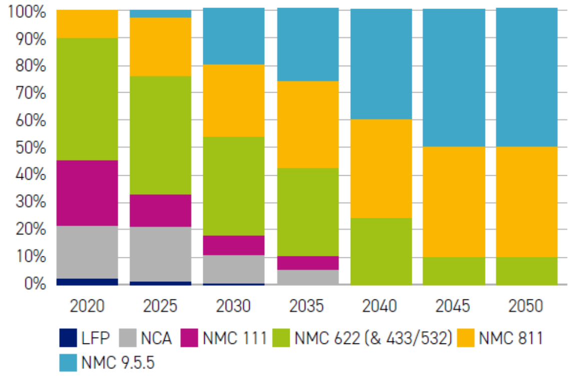

Figure 3. Different cathode types of EV battery chemistries from 2020 to 2050 [41].

Authors in [43] present recent developments in the materials used in the main three LIB components: anode, cathode, and separator/electrolyte. A comparative review of lead-acid, lithium-ion, and ultracapacitor technologies and their degradation mechanisms is well-treated in [44].

For positive electrodes (cathodes) improvement, the goals are to reduce the cobalt content, enhance safety, and increase energy density. The main focus for improving the negative electrodes (anodes) is to enable fast charging even at low temperatures while maintaining safety. It is important for anodes to be able to keep up with the capacity increase of cathodes, explaining the interest of using silicon.

Figure 4 shows a histogram illustrating the distribution of the number of published articles per year used in this paper.

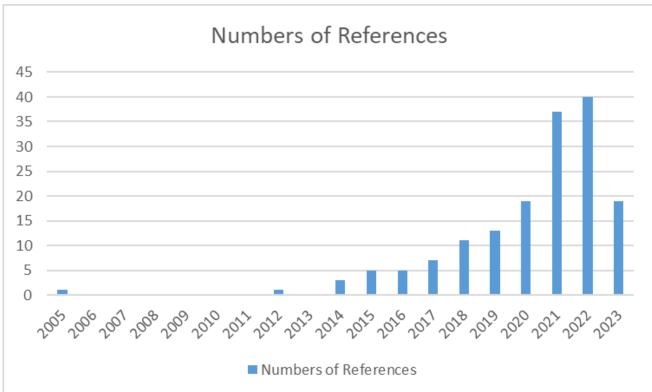

Figure 4. Histogram illustrating the distribution of the number of published articles per year.

The paper is structured as follows: The new generation of batteries is introduced in Section 2. In this section, the components of lithium batteries are described. This is followed by battery technology prior to the development of lithium-ion batteries. Current and future promising battery technologies are then highlighted and detailed. This section also covers the emerging field of solid-state lithium micro batteries, which are becoming increasingly significant in today's technologies, especially in applications such as IoT and wearable electronics. In Section 3, analyses and discussions of various topics are presented, including battery modeling, new manufacturing digital tools for batteries, and other innovative trends such as self-healing, battery passports, and circular economy. The paper concludes with a summary in the Section 4.

2. New Generation Batteries

2.1. Components of a Lithium Battery

2.1.1. Positive Electrode (Cathode)

The ionic conductivity of cathode material is determined by the mobility of the lithium ions, which is in turn defined by the material's structure. Cobalt enhances the chemical and thermal stability of lithium-ion batteries (LIBs). Nickel improves the energy density of the battery and has the advantages of low cost and good conductivity. Manganese is a more affordable alternative to cobalt and nickel for use in LIBs.

The first commercially available electrodes were $LiMn_2O_4$ (LMO) and $LiCoO_2$ (LCO). The $LiMn_2O_4$ material, which has a lattice structure known as a spinel, allows for three-dimensional conductivity for lithium cations. While it offers a good capacity and an affordable cost, it still needs improvement in terms of stability in common electrolyte solutions. $LiCoO_2$ is a layered trigonal crystalline oxide offering two-dimensional mobility. It is known for its high specific capacity, thermal instability, and cost.

A cathode made from a combination of nickel, LMO, and LCO, called $LiNiMnCoO_2$ (NMC), has a longer lifespan and higher energy density. The specific ratio of Ni, Mn, and Co in the mixture determines the properties of the cathode.

There are two main categories of LIBs based on the type of cathode used. The first category includes Lithium-Nickel-Cobalt-Aluminum oxide ($LiNiCoAlO_2$—NCA) and Nickel-Manganese-Cobalt (NMC) batteries, which are widely used in the electric vehicle (EV) industry due to their high voltage and high specific energy. Nickel offers high energy density, but it lowers battery stability. Additionally, while manganese can lower internal resistance and improve specific power, it has lower specific energy. Cobalt is a toxic material that is relatively expensive, and its supply chains pose a significant risk due to the political instability in the major region where it is sourced [41]. Researchers [45] are working towards developing a cobalt-free battery. Increasing the amount of nickel in the battery could be a solution. This leads to higher energy densities, but stability must also be ensured [46].

Three types of battery are commercially available in the NMC-class battery compositions: NMC111, NMC622, and NMC811. These designations are indicative of the proportion of Ni, Co, and Mn on a mole fraction basis. The NMC622 batteries, which are high in nickel content, are gradually replacing NMC111 batteries in EV applications. NMC811 batteries have already been produced and safety concerns are on the rise [47,48]. This does not prevent that $LiNi_{0.9}Mn_{0.05}Co_{0.05}O_2$ (NMC955 or NMC9 $\frac{1}{2}$ $\frac{1}{2}$) batteries, containing less cobalt, are currently in research process [49]. NMC9 $\frac{1}{2}$ $\frac{1}{2}$ is a Ni-rich cathode material having a higher energy density and a limiting cobalt content. However, Ni-rich metal oxides suffer from electrochemical cycling challenging, including substantial capacity fade, severe voltage decay, and higher safety concerns.

The second category is Lithium-Iron-Phosphate (LFP—$LiFePO_4$) batteries, which are popular in the Chinese market and are known for their cobalt-free composition, high cycle life, and low fire risk [50]. The olivine lattice structure of LFP permits linear ion movement in one dimension. However, they offer lower voltage and capacity compared to NCA and NMC batteries. In recent years, NMC batteries have gained more market share and research attention compared to LFP batteries. The prices of raw materials and the availability of mined reserves could also impact the choice of the next generation of battery chemistry.

The NMC (Nickel Manganese Cobalt) layered/spinel technology will be the most widely used for BEV applications ensuring high specific energy and good performances in terms of specific power, lifetime, and safety. The recently introduced NMC811 technology, characterized by 80% nickel, 10% manganese, and only 10% cobalt content, is anticipated to compete with other Ni-rich NMC designs for upcoming EV batteries in 2025 and 2030 [51,52].

2.1.2. Negative Electrode (Anode)

Graphite, having a capacity of 372 mAh/g, is a popular choice for anodes due to its abundance, good electrochemical stability, safety, and low expansion volume during charge and discharge. One way to increase the overall energy density is to include small amounts of metals with high theoretical energy densities, such as silicon (4200 mAh/g). Carbon-coated graphite and graphite-silicon anodes are often considered to be better alternatives because they experience less degradation and can hold more lithium ions. Silicon is considered a potential alternative to graphite as an anode material in lithium-ion batteries. It is considered a safe and reliable option with a sufficient energy density for use in electric vehicles. Despite this, silicon anodes have some downsides, including a volume expansion of up to 300 percent during charge and discharge, which can cause unstable solid electrolyte interphase (SEI) formation, low electrical conductivity, and mechanical grinding of graphite caused by the Si expansion/contraction. To address these issues, researchers are exploring the use of nano-silicon in a composite structure with graphite [53].

Lithium-Titanium oxide anodes ($Li_4Ti_5O_{12}$—175 mAh/g) have the longest cycle life and are used with lithium iron phosphate (LFP) cells [54] and NMC cells [55]. The anode material has an operating voltage of 1.55 V relative to lithium. The formation of lithium plating and a conventional solid electrolyte interphase are not considered problematic. Researchers are exploring alternatives to lithium titanate oxide (LTO), such as niobium titanium oxide (NTO) [56], as potential anode materials. It is expected that replacing anodes with thin lithium metal foils will significantly increase energy density, as long as they can be safely incorporated and stabilized in the system.

2.1.3. Electrolytes

The dissolution of a lithium salt, like lithium hexaflurophosphate (LiPF6) in an organic carbonate, such as ethylene carbonate (EC), dimethyl carbonate (DMC), or diethyl carbonate (DEC), constitutes the electrolyte liquid solution [57]. Fluororalkylphosphates promise advantages for 5 V batteries [58].

Additives could be used for liquid electrolytes to enhance safety, minimize the loss of capacity at the first charge-discharge, avoid oxidation, and prevent gases evolution by electrolysis. To achieve higher voltage cathodes, electrolyte additives will also play the role of stabilizing agents, retarding the thermal decomposition of LiPF6 salt.

In order to decrease the amount of liquid electrolyte, gel/polymer electrolytes (such as $LiN(CF_3SO_2)_2$/LiTFSI) may be potential solutions while focusing on increasing ionic conductivity. In the long term, the goal is to use solid-state electrolytes once they have demonstrated sufficient ionic conductivity and a high level of manufacturability expertise.

There are two main types of solid electrolytes. Inorganic electrolytes are composed of ceramic crystalline materials such as LISICON, NASICON, perovskites, and polymer organic electrolytes [59]. Inorganic electrolytes have high ionic conductivity but present interfacial compatibility limitations. On the other hand, polymer electrolytes have good mechanical and thermal stability, but have lower ionic conductivity.

In terms of safety improvement, enhancing performance and thermal and electrochemical stability even for conventional organic solvent electrolytes is essential.

2.1.4. Separator

The separator, about 25 mm in thickness, consists of a porous membrane wetted with an organic electrolyte solution. Polymers such as polyethylene, polypropylene, or polyvinylidene fluoride (PVDF) are employed [60]. The properties include good permeability, high mechanical resistance, suitable porosity, electrolyte wettability, and good thermal and electrochemical stability. Ceramic coatings [61] are being used more frequently to provide robustness and mechanical strength, preventing short-circuits caused by mechanical damage or dendrite formation.

2.1.5. Current Collectors

Researchers are continuing to work on improving the thickness, hardness, and composition of current collectors to increase their mechanical strength, electrochemical stability, and adhesion with the electrode coating [62].

2.1.6. Anode and Cathode Coatings

In addition to the significant volume expansion during cycling, the observation of low electrical conductivity and the formation of a highly resistive solid electrolyte interphase (SEI) layer are common. In [63], the authors introduce silicon material design approaches and innovative synthesis methods aimed at enhancing the Si anodes properties through improved structural designs.

These volume changes lead to permanent cracking and the separation of the active material from the current collector. In [64], the authors focus on silicon anodes development, emphasizing surface chemistry and the structural integrity of the electrode. They have reported effective strategies for optimizing these anodes.

Combining silicon and silicon oxides offers a solution to tackle these challenges. Silicon monoxides (SiO) and silicon dioxides (SiO_2) can be used as coating material on the silicon-based anode electrodes. This helps stabilize the anode by reducing volume expansion during lithiation, and minimizing contraction that occurs during charge and discharge cycles, thus preventing structural degradation. This, in turn, can improve the overall performance, capacity, and cycle life of lithium-ion batteries [65]. Coating the anode with these materials helps also to prevent direct contact between the electrolyte and the silicon in the anode. Furthermore, nanostructured SiO_x, like silicon oxide nanowires or nanotubes, can be utilized to enhance both the mechanical stability and conductivity of the anode [66]. In addition to presenting progress on SiO- and SiO_2-based anode materials, authors in [67] explore as well non-stoichiometric SiO_x, and Si–O–C-based anode materials.

Chemical and physical characteristics of the cathode influence the performance of the battery. Interactions between cathodes and the electrolyte lead to surface modifications, resulting in degradation. These side-reactions contribute to a decline in battery performance, ultimately diminishing both battery lifespan and power capacity. In [68], the authors conduct an extensive review of advancements in the coating of NMC batteries, exploring multi-functionalities and mechanisms aimed at enhancing their electrochemical properties and overall performance. In [69], the authors discuss the potential of the argyrodite solid electrolyte (ASE) for use in all-solid-state lithium batteries. They propose lithium niobate ($LiNbO_3$, LNO) as a coating material that is compatible with both ASE and cathode active materials (CAM). The study investigates the impact of LNO coating on the electrochemical performance of CAM, specifically assessing capacity, cycling behavior, and rate performance in the context of a nickel-rich cathode (NMC622).

Surface coating of the cathode active material with a thin layer of a protective material enhances the thermal and chemical stability of the cathode, reducing the risk of thermal runaway or detrimental surface reactions with the electrolyte. In [70], an extensive examination of various surface-coating types has been conducted. The study establishes a comparison of electrochemical performance changes between materials with applied coatings and those without. The coating materials assessed include amphoteric oxides (such as ZnO, Al_2O_3, SnO_2, SiO_2, or ZrO_2), rare earth oxides (like cerium oxide, ruthenium oxide), custom preparation of films from a mixture of materials, phosphate-based compounds, glasses, and reduced-carbon materials, as well as other types of preparation methods.

On the other hand, boron nitride (BN) can be applied as a coating for both anode and cathode electrodes. This application enhances electrical conductivity and prevents side reactions with the electrolyte. Authors in [71] conducted investigation on α-Li_3BN_2 as a transition-metal-free cathode material for Li-ion batteries. They demonstrated a specific capacity of 890 mAh/g. In [72], a composite involving a balanced mixture of hexagonal boron nitride, a piperidinium-based ionic liquid, and a lithium salt is proposed. When used in conjunction with conventional electrodes, this composite exhibits stability, enduring over 600 cycles at 120 °C with a total capacity degradation of less than 3%.

2.2. Before the Lithium

Different classifications could exist for battery technologies such as the following:

- lead-acid based: affordable, safe, and sustainable;
- lithium-based: high energy density, low weight;
- nickel-based: long life, reliable (NiMH, NiCd);
- sodium-based: relative low cost; and
- flow batteries [73].

Before lithium batteries, lead–acid batteries were the first to be invented in 1859. Lead-acid batteries still have their place in the starting, lighting, and ignition of vehicles. Gravimetric and volumetric energy are both relatively low and could attain 40 Wh/kg and 90 Wh/L.

The nickel–zinc battery (Ni-Zn) was the second invented, introduced in 1901. However, its relatively short cycle life paved the way for the nickel-metal hydride battery (Ni-MH) to emerge as a dominant choice, becoming the first battery to provide Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs) with gravimetric and volumetric energy densities ranging from 80 to 120 Wh/kg and 140 to 200 Wh/L, respectively.

The lithium battery was discovered in 1912 by Gilbert N. Lewis [74]. Lithium is the lightest metal [75], with a high electrochemical potential and an interesting specific energy per weight [76,77]. In the early 1970s, the first non-rechargeable lithium-metal batteries (LMB) became commercially available. Moli Energy Ltd. marketed the first rechargeable lithium batteries in the 1980s. The batteries failed due to a serious safety risk as the growth of lithium dendrites caused electric shorts, leading to thermal runaway conditions. The results showed the inherent instability of lithium metal, used as anode material, and its incompatibility with the slow discharge and high recharge cycles of portable electronics [78]. The LMB was subsequently replaced by a non-metallic solution utilizing lithium ions, despite having a lower specific energy, due to its significantly enhanced safety characteristics. Figure 5 provides a simplified schematic of an LIB, illustrating the transfer of ions and the direction of current during the charge and discharge processes.

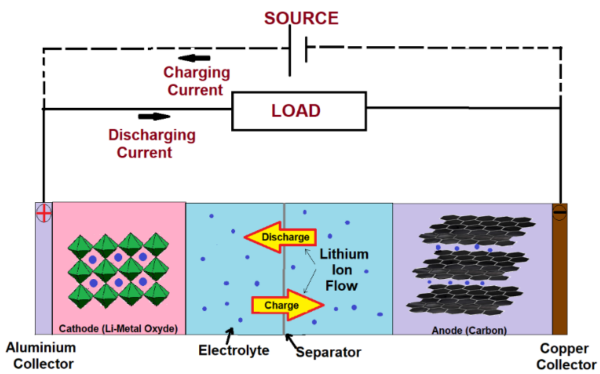

Figure 5. Schematic of the Lithium-Ion battery.

2.3. The Lithium-Ion Battery

Furthermore, the low maintenance, the lack of memory effect, the relatively long cycle life, and the low self-discharge paved the way for Li-ion to be used in electric powertrains [38]. On the other hand, the LIB suffers from cyclic and calendar aging, SEI layer formation, lithium plating, electrolyte degradation, side reaction products, and current collector corrosion. This is the main reason that Li-Ion batteries are always incorporated with a battery management system, ensuring a high degree of protection.

Current trends in battery technology involve the utilization of electrodes with higher capacities, such as sulfur (1675 mAh/g [79]), silicon (4200 mAh/g [80]), and lithium metal

(3863 mA/g [81]), as well as the increase in single-cell voltage. These developments collectively enhance the overall energy density of the battery, consequently extending the vehicle's range. Another significant trend is the adoption of solid-state electrolytes to enhance both safety and energy density within the cell.

Li-ion battery manufacturing will, by far, dominate the market through 2030 and could potentially achieve a production capacity of 6 500 GWh [82]. For an LIB, the work on positive electrodes (NMC, NCA, LFP) is focused on increasing energy density and the batteries' safety while reducing the cobalt content. Higher-capacity cathodes lead to higher-capacity anode utilization (graphite/silicon). From the negative electrodes' point of view, work is much related to safety (fast charging at lower temperature preventing dendrites formation). In order to increase the performance and safety of the battery, flammable electrolytes are replaced by gel/polymer, or solid-state electrolytes.

As mentioned, the LIB has an average density of 300 $Wh \cdot kg^{-1}$ [83]; a fully operational 500 $Wh \cdot kg^{-1}$ battery should be ready by 2025 [84]. Thus, it will have major consequences for reducing the car weight, the raw materials quantities during manufacturing, and expanding drive range. A recent issue has emerged in the UK, as highlighted by the British Parking Association, regarding the weight of electric vehicles parked in multi-story and underground car parks. Many of these facilities were originally designed and constructed with the weight specifications of popular 1976 cars in mind, such as the Ford Cortina, which weighed approximately 960 kg. However, the advent of electric vehicles, particularly best-selling models like the Tesla Model 3, which can weigh up to 2.2 tons due to the substantial battery component, has placed significant stress on the structural integrity of these buildings [85].

A return to lithium metal battery (LMB) technology is a compulsory passage. Various types of LMBs exist, such as lithium-sulfur batteries (LSBs) [86], lithium-air batteries (LiO_2) [87], and solid-state batteries (SSBs) [88]. The latter is based on a lithium metal anode, a layered oxide cathode, and a solid electrolyte (solid polymers or inorganic solids). Research focuses on the safety, life cycle, fast charging, and cost requirements of these batteries.

2.4. Current and Future Promising Technologies

2.4.1. Generation 3

Battery generations are classified according to the cathode material, anode material, type of electrolyte, and cell chemistry. The forecast market deployment of new battery generations is shown in Table 2. For the next decade, the LIB will still be the most commercialized.

A roadmap for 2030 primarily focuses on lithium-based technologies that use modified nickel cobalt manganese oxide (NMC) materials. The optimized NMC811 has a higher nickel content and a lower cobalt content, in combination with carbon/silicon composite materials that have a high capacitive anode.

To enhance energy density, the primary approach is to elevate the cell's voltage to 5 V by incorporating high-voltage electrode materials (as current materials typically reach 4.2 V), such as the 3D oxide-structured 5 V spinel. However, achieving a stable electrolyte for sustained cycling poses a significant challenge. An alternative is to increase the storage capacity of the battery in terms of weight or volume, which can be achieved by increasing the faradic capacity of the electrodes (mAh/g).

Despite ongoing research into lithium-metal batteries (particularly solid-state batteries) and post-lithium technologies, it is evident that lithium-metal batteries (LMBs), particularly solid-state batteries (SSBs), represent a highly promising technology capable of significantly enhancing energy density.

Lithium-sulfur batteries (lower environmental impact, better depth of discharge) and sodium-ion batteries are serious alternatives to lithium-ion batteries. Metal-air batteries (such as lithium-air batteries) promise theoretically specific energy comparable to gasoline.

Thus, some technological challenges are yet to be overcome, such as insufficient cycle life. Figure 6 shows the specific energy/energy density of the mentioned battery technologies:

Table 2. Prediction of the evolution of battery technology [89]—adapted.

Battery Generation	Technology/Electrode Active Materials	Cell Chemistry/Type	Implementation Date/Forecast Market Deployment
Gen 1	Cathode: NFP, NCA, LCO	Lithium-Ion	1991
	Anode: Carbone/Graphite		
Gen 2a	Cathode: NMC111, LMO		1994
	Anode: Carbone/Graphite		
Gen 2b	Cathode: NMC532, NMC622		2005
	Anode: Carbone/Graphite		
Gen 3a	Cathode: NMC622, NMC 811		2020
	Anode: Graphite + 5/10% Si		
Gen 3b	Cathode: High Energy NMC, High Voltage Spinel—5 V	Optimized Lithium-Ion	2025
	Anode: Silicon/Carbon		
Gen 4a	Cathode: NMC	Solid State Lithium-Ion	2025
	Anode: Silicon/Carbon		
	Solid Electrolyte		
Gen 4b	Cathode: NMC	Solid State Lithium-Metal	>2025
	Anode: Lithium metal		
	Solid Electrolyte		
Gen 4c	Cathode: High Energy NMC, High Voltage Spinel	Advanced Solid State	2030
	Anode: Lithium metal		
	Solid Electrolyte		
Gen 5	LiO_2 Li-Air/Metal-Air	Metal-Air	>2030
	Li-Sulphur	LiS	
	New ion-based systems (Na, Mg, Zn or Al)	New ion-based insertion chemistries	

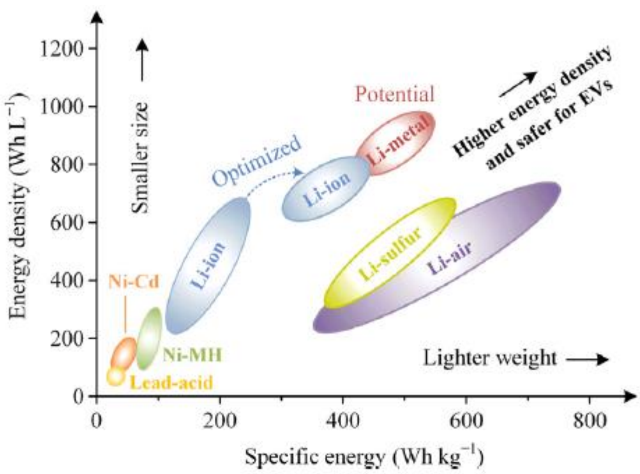

Figure 6. Specific energy and energy density of lithium-based batteries [34].

2.4.2. Generation 4

Liquid electrolytes of LIBs consist of a lithium salt dissolved in a combination of several organic solvents. This configuration may induce serious safety hazards due to the electrolyte's toxicity, leakage, and flammability [90]. The advantages of solid-state batteries in comparison to liquid electrolyte cells are quite numerous. We could enumerate higher energy density, enhanced safety, absence of liquid electrolyte, lower manufacturing cost, and excellent shelf life. The passage from a Si/C anode (Gen. 4a) to a lithium metal anode (Gen. 4b and 4c) could improve the specific energy from 400+ Wh/kg, 800+ Wh/L to 500+ Wh/kg, 1000+ Wh/L [91]. Perpetual efforts to replace these types of electrolytes with solid-state batteries are facing challenges such as power limitation due to poor ionic conductivity, high interfacial resistance, poor interface contacts, chemical instabilities at interfaces, and surely the need to update manufacturing processes.

Li-metal technology combines lithium metal with the negative electrode, insertion materials with the positive electrode, and a solid electrolyte (such as extruded polyethylene oxide, PEO, [92]). The primary advantage of lithium metal lies in its higher energy density compared to the graphite used in lithium-ion batteries, with 3860 mAh/g vs. 372 mAh/g, respectively.

However, these batteries have a limited operating temperature in order to assure sufficient ionic conductivity. The PEO electrolyte may be unstable at voltages higher than 4 V, which restricts its use to lithium iron phosphate (LFP) cathodes. When combined with a graphite anode, the LFMP (lithium-iron-manganese-phosphate) battery cell can be charged up to 4.25 V. This allows for high power capability while also enhancing thermal stability and safety. Additionally, the LFMP battery exhibits excellent cyclability and storage performance [93,94].

The French manufacturer Blue Solutions, a subsidiary of the Bolloré Group, utilizes lithium-metal-polymer (LMP) technology, which employs a dry polymer electrolyte and a negative lithium electrode. This battery functions effectively at temperatures exceeding 60 °C, requiring battery heating during extended stops. Due to these characteristics, Blue Solutions promotes this technology for buses and stationary storage applications, which are better suited to managing thermal considerations (Figure 7).

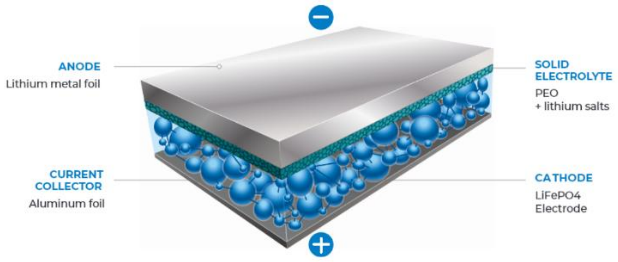

Figure 7. Blue Solutions' LMP® battery [95].

Several solutions were proposed by using additives to improve the solid electrolyte interphase (e.g., vinylene carbonate, and methyl cinnamate) [96], or some flame-retardant additives (e.g., trifluoropropylene carbonate, hexamethoxycyclotriphosphazene, trimethyl phosphate, triethyl phosphate) [97].

Researchers are developing new solid-state electrolytes with high ionic conductivity, good electrochemical performances, and high thermal stability. The low resistance electrolyte/electrode interface is a critical issue for the next generation of SSBs.

As noted, solid-state electrolytes could be made from the following:

- inorganic materials such as the sulfide-based inorganic electrolytes, β-Alumina electrolytes, and NASICON electrolytes [97,98],
- organic polymer electrolytes, gel polymer electrolytes, and plastic crystal electrolytes [99], or
- a combination of both inorganic and organic (hybrid) solid-state electrolytes [100].

Research is being conducted on all these electrolytes. Performance issues, interfacial stability, and mechanical constraints are the main challenges.

2.4.3. Generation 5

a. Metal-Air Battery

The metal-air battery utilizes the electrochemical principle that involves a metal negative electrode (Zn, Al, Li, Mg, Ca, etc.) and an oxygen-reducing cathode made of mesoporous carbon. Metal-air batteries have a high amount of energy stored in relation to their weight. Besides the lithium-air type, with a nominal voltage of 2.91 V, the metal-air batteries could include zinc-air, aluminum-air, magnesium-air, and calcium-air. While lithium-air batteries have a specific energy of 13.2 kW/kg (similar to gasoline), aluminum-air batteries tend to have a more stable performance. Figure 8 shows the theoretical specific energy of metal-air batteries. Researchers are trying to improve the short lifespan and high internal resistance within the battery, which are major drawbacks due to the low specific power and carbonation of alkaline electrolytes.

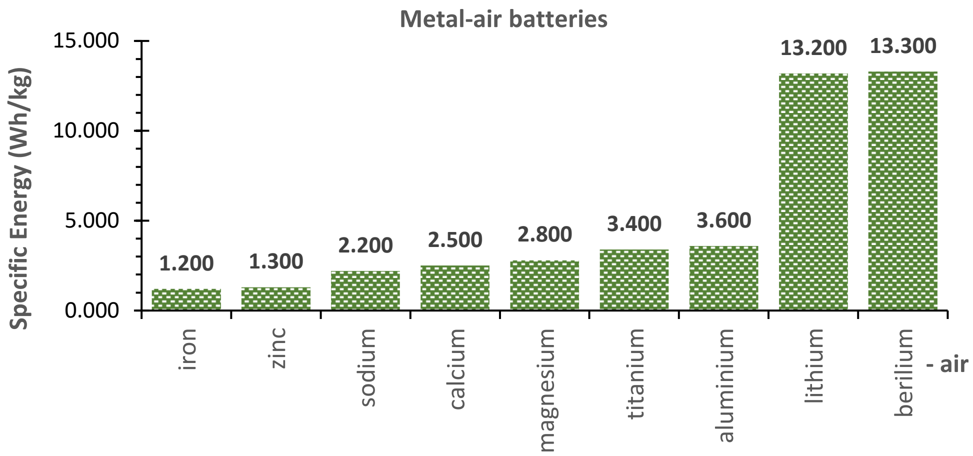

Figure 8. Theoretical specific energy of metal-air batteries [101].

Several disadvantages are identified, such as the dendrite formation and corrosion of the negative electrode, the operation of the positive electrode ideally in an aqueous environment, and the precipitation of the oxidized products in the positive electrode, which alters the reversibility of the system.

b. Lithium Sulfur Battery

Lithium-sulfur batteries (LiSBs) use lithium metal as an anode, sulfur composite as a cathode, and organic liquid as an electrolyte. They exhibit high theoretical gravimetric capacity (1675 $mAh \cdot g^{-1}$) and high theoretical specific energy (2600 $Wh \cdot kg^{-1}$) [102,103]. Furthermore, the low cost, high abundance of sulfur, and absence of critical materials make LiS batteries a promising option for future energy storage applications. This type of battery has less environmental impact, as well as sulfur may be sourced from recycled materials. The nominal voltage of an LiSB cell is 2.1 V. The battery has the potential to have a deeper depth of discharge than the LIB, with the LiSB reaching 100% compared to LIB's 80%. Another advantage of the LiSB is its long lifespan estimated at 10 years [104]. It is estimated that LiSBs could be ready to enter the market with a density energy of 500 Wh/kg [105]. By then, solutions should have been found for the problems of limited cycle life, poor electrode conductivity, high volumetric expansion during charging and discharging cycles, corrosion of the negative electrode, lithium dendrites formation, and poor stability at higher temperatures [106]. The use of a sulfur-based electrode could lead to the emission of specific toxic gases (e.g., H_2S, SO_2, COS, CS_2) in the event of thermal runaway [107]. A reliable battery management system is highly advised in order to optimize the battery's operation.

In addition to sulfur's low conductivity and volume changes during cycling, the LiS suffers from the shuttle effect, which involves the undesired migration of lithium polysulfides between the cathode and anode. This phenomenon reduces the capacity, energy efficiency, and shortens the cycle life of the battery. To address these challenges, the authors in [86] propose four strategies: the design of carbon/sulfur composite cathodes for the next-generation sulfur cathode, the introduction of kinetic promoters, the design of specific ion-solvent complexes in the electrolyte, and the protection of the lithium metal anode through electrolyte regulation, artificial coatings, and pretreatment methods. The encapsulation of sulfur cathodes in carbon host materials is also discussed in [108]. The LiS is considered by [106] among the most commercially mature next generation batteries. The authors have developed an extensive research roadmap that analyzes primary challenges for these types of batteries and proposed strategic solutions aimed at their mitigation. A set of the near-future research directions for both the liquid and solid-state LSBs are proposed in [109]. Authors highlighted that solid LSBs are expected to replace the liquid current LSBs in the coming decade.

c. Batteries beyond Lithium

The goal is to eventually replace lithium battery technologies with more affordable and sustainable light metals such as sodium. However, the significant challenge is developing durable and stable electrodes with high energy density and fast charge/discharge rates.

Among various chemistries (sodium, magnesium, zinc based), the sodium-ion battery (SIB) [110] has gained attention due to its low cost, the abundance of sodium on earth, and its similar chemistry to LIBs. However, it has a lower energy density of 90 $Wh{\cdot}kg^{-1}$ [111]. The Chinese manufacturer CATL aims to reach 200 $Wh{\cdot}kg^{-1}$ [112].

The operating principle of sodium-ion batteries (NIBs) is similar to that of Li-ion batteries. Sodium resources are inexpensive and widespread; it is considered the 4th most prevalent element on the planet. NIBs suffer from a fast decrease in capacity and a lower cycle life (relatively to LiBs) due to the difficult insertion of sodium ions into the anode and cathode [113].

The state of the art of sodium-based batteries consists of high temperature operating batteries, commercialized since 2022. It consists of a liquid and an ion-conducting ceramic solid electrolyte. The aim of raising the temperature is to keep the sodium-based electrode in a liquid state and enhance the conductivity of the solid electrolyte. Sodium-Nickel-Chloride NaCl (resp. Sodium-Sulfur NaS) operates between 270 °C and 350 °C (resp. 300 °C and 340 °C) and has an energy density of 120 Wh/kg (resp. 220 Wh/kg) with a nominal voltage of 2.58 V (resp. 2 V). Even with the high lifecycle (4500 cycles) and long calendar life (over 15 years), these batteries still have some drawbacks, such as the need for high temperatures, thermal losses, and low efficiency. A new technology for room temperature sodium-ion batteries is under development, with expectations for commercialization of high-density sodium-ion batteries at room temperature after 2025. The commercialization of all solid-state sodium-ion room temperature batteries is projected to occur after 2030. The anticipated energy density of this technology is expected to range from 380 Wh/kg to 700 Wh/kg, with an estimated calendar life exceeding 30 years. Additionally, it is expected to achieve a full cycle efficiency ranging between 6000 and 12,000 cycles.

The magnesium-ion battery (MIB) presents high specific energy and specific power [114], low cost, superior safety, and environmental friendliness. However, the technology is yet to be approved.

d. Solid-State Li-Ion Micro-Batteries

While the market for micro-batteries [115] may be comparatively smaller than that dedicated to electromobility and stationary power-grid applications, the importance of lithium-ion micro-battery technology span a vast array of applications. Anticipated growth forecasts indicate an ascent from a 2023 valuation of 0.5 billion USD to reach 1.3 billion USD by the year 2028 [116].

Multiple sectors are engaged, encompassing healthcare devices, environmental monitoring, wearable personal electronics, IoT (Internet of Things) with smart and connected miniaturized sensors [117], as well as microelectronics (in smart packaging, smart cards, etc.), and radiofrequency identification systems, thus requiring high flexibility and ultra-thin design. Another sector also emerges, which falls within the domain of micro-drones and/or micro-robots known as insectoids [118], Figure 9. Nonetheless, the challenge of designing and manufacturing efficient micro-storage devices to ensure the energy autonomy of these systems persists. In facts, micro-batteries continue to face challenges related to their relatively sizable physical dimensions and suboptimal electrochemical performance per unit area due to the loose electrode structure.

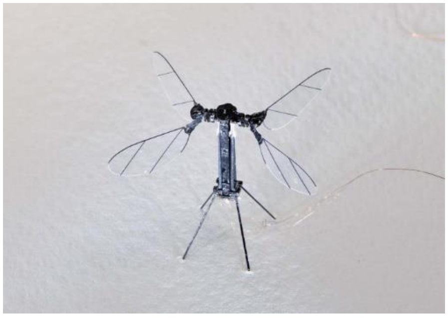

Figure 9. Miniature robot with insect-like flight capabilities, [119].

Three-dimensional (3D) rechargeable microbatteries, with partially lithiated silicon at the anode, were developed in [120], having a 3 mm × 3 mm footprint, an areal capacity of 1.8 mAh/cm^2 (5.2 mWh/cm^2)), a current density of 0.66 mA/cm^2, and a potential lifespan of 200 cycles at 0.5 mAh/cm^2 (1.6 mWh/cm^2).

Authors in [121] developed a compact aqueous K-ion micro-battery in order to realize a small footprint and high areal capacity, ensuring an areal capacity of 5.1 mAh/cm^2 and an energy density of 4.78 mWh/cm^2.

Table 3 shows examples of solid-state Li-ion micro-batteries. The EFL700A39, for instance, is a rechargeable lithium battery with a thin film design. It incorporates a LiCoO2 cathode, a LiPON ceramic electrolyte, and a lithium anode. In contrast, the CR1216 is a non-rechargeable coin cell battery using manganese dioxide as its cathode material.

Table 3. Examples of solid-state Li-ion micro-batteries.

Manufacturer	ITEN	ST Micro	MURATA
Product number	ITX121005B	EFL700A39	CR1216
Type	thin-film solid-state	thin-film solid-state	coin cell
Footprint	3.2 mm × 2.5 mm	25.7 × 25.7 mm	12.5 mm ∅
Thickness (µm)	600 mm	220 mm	1600 mm
Capacity (µAh)	50 µAh	700 µAh	30,000 µAh
Voltage (V)	2.5 V	3.9 V	3.0V
Operating temperature range	−40 °C/+85 °C	−20 °C to 60 °C	−30 °C to 70 °C
Reference	[122]	[123]	[124]

3. Analyses and Discussions on Future Batteries Challenges

3.1. Modeling and Components

By gaining a deeper understanding of the intricate and varied internal physical and chemical reactions that occur within a battery, manufacturers can make targeted improvements to materials and manufacturing processes. This will allow them to increase the capacity retention of the battery over its lifetime and reduce the rate of aging and degradation. To accurately model the interfacial structures between the electrolyte and the electrode active particles and metastable material states in a battery, it is necessary to use realistic computational resources that can model the battery at different levels of granularity (stochastic, mechanistic, or machine learning). Figure 10 illustrates various modeling methods for generating electrode mesostructures. The stochastic approach utilizes experimental particle size distributions, formulation, and porosity as inputs. The mechanistic model predicts electrode mesostructures based on manufacturing process parameters. In addition, the machine learning approach is employed to forecast the impact of manufacturing parameters on both electrode mesostructure and performance properties.

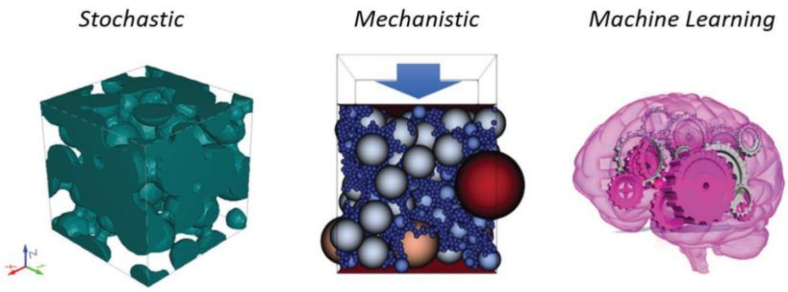

Figure 10. Various modeling methods of the battery [125].

3.2. Battery Degradation

Over time and with use, lithium-ion batteries experience aging, which manifests as capacity fade, or a loss of lithium inventory and active materials and degradation of the electrolyte.

The main factors contributing to the aging of lithium-ion batteries can be summarized as follows: the development of a solid electrolyte interphase (SEI) layer on the anode, leading to a depletion of the lithium content; the infiltration of solvent molecules into the electrode material, resulting in structural damage and obstructing further lithium intercalation; electrolyte decomposition; alterations in the electrode material's structure during charge and discharge cycles; and lithium plating due to elevated temperatures, overcharging, or high current during charging or discharging (see Figure 11).

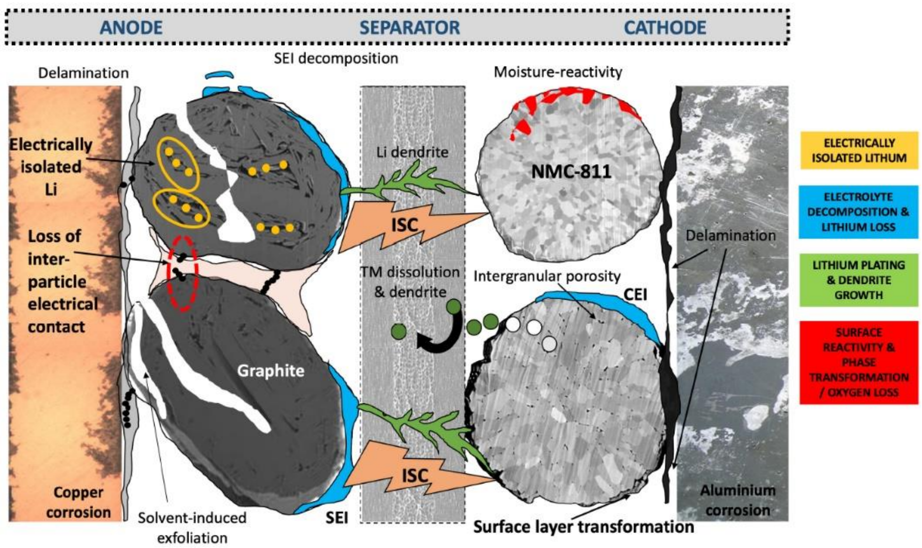

Figure 11. Degradation effects of an LIB [126].

This aging is caused by the internal degradation of electrochemical processes due to reactions at the interfaces. The loss of lithium is caused by the continuous growth of a solid electrolyte interphase (SEI) layer or dendrites (fractal-like structures of metallic lithium) on the anode surface. These factors are influenced by temperature, usage patterns, and the construction of the battery pack.

3.3. Lithium-Ion Battery Manufacturing

The LIB production process involves the preparation of electrodes, the assembling of cells, and the activation of battery electrochemistry. Electrodes preparation involves the preparation of a slurry mixture to be coated on a current collector (aluminum for cathode and copper for the anode). The slurry is composed of active materials, solvent, conductive additive, and binder. A first drying process is then activated in order to evaporate and recover the solvent, considered as toxic for the cathode part. A calendaring process allows the physical properties adjustment of the electrodes (bonding, conductivity, density, porosity, etc.). After slitting, the electrodes are taken to a vacuum oven to dry out, and then transferred to a dry room for cell production. Once the enclosure is filled with electrolytes and sealed, the electrochemistry activation of the battery (formation and aging) can begin, a long energy-consuming process. Manufacturing contributes about 20% of the cost of LIBs [127].

The different steps' impact on the manufacturing process of LIBs, such as cost, energy consumption, and throughput, are explained in [128]. The model was based on a 67-Ah $LiNi_{0.6}Mn_{0.2}$-$Co_{0.2}O_2$ (NMC622)/graphite cell. The authors concluded that the formation and aging process is the costliest, followed by the coating and drying process. In addition, formation and aging contribute the most to the production time followed by the vacuum drying process. In terms of energy consumption, electrode drying/solvent recovery and dry room processes are the most energy consuming. The same conclusions, concerning the energy consumption parts, are highlighted in reference [129,130]. In [129], the case study was taken for a 2 GWh producing prismatic NMC333 cells. A manufacturing energy analysis of a 24-kWh battery pack with 192 prismatic LMO-graphite LIB packs was reported in [130]. Data collection and modeling were performed at each manufacturing process from real industrial processes.

The near future for battery production will be dominated by optimized LIBs and surely solid-state battery manufacturing. Prospects on giga-scale manufacturing of solid-state batteries are treated in [131]. The authors highlighted the state-of-the-art solid-state battery manufacturing approaches and the importance of utilizing conventional battery manufacturing approaches for achieving price parity in the near term. Controlled microstructure, interfaces, and thickness are essential prerequisites for achieving extended lifetimes, efficient processing, the integration of high-energy-dense anodes, cost-effectiveness, and scalability.

The authors in [132] presented the process parameters and requirements, quality features, challenges, and technology alternatives for each manufacturing steps for an all-solid-state battery. Two alternatives of electrode and electrolyte production were taken into consideration. The first was presented as a continuous extrusion process (suitable for sulfide-based all-solid-state batteries); the second presented a physical vapor deposition (PVD) process. In each step, the rate transferability of lithium-ion battery cell manufacturing expertise is noted.

Battery cell manufacturing should focus on reducing energy, costs, and scrap output production. In order to minimize environmental impact, it should also comply with legal frameworks and regulations in terms of air and water quality, CO_2 emissions, chemical substance, and waste management [133].

Implementing intelligent control processes could improve the efficiency of plants. Sustainability, customization, high quality product, short design and delivery time, and smart manufacturing lead to adapting the Industry 4.0 approach [125,134]. Throughout the different manufacturing processes, this approach allows a real-time WIP (Work In Progress) control, simulation, and optimization, production traceability (RFID embedded, field communication, QR code laser printing), and inter-machines communication. It includes several digital technologies such as the Internet of Things (IoT), cloud computing and analytics, artificial intelligence, and the deployment of Automatic Guided Vehicles (AGVs) and Digital Twins (DTs) as a part of the Industry 4.0 concept. Figure 12 shows the different stages of manufacturing a cylindrical lithium-ion cell illustrated on the website of the French battery manufacturer, VERKOR.

The concept of Industry 4.0 consists of a digital representation of the manufacturing processes facilitating the digital transformation of the battery manufacturing plants, with the aim to achieve the required targets in reducing costs and promoting sustainability. DT would help the future transfer of LIBs to solid-state battery manufacturing requiring flexible adaptation of the production lines. Scrap material from production can be a significant source for recycling as 5% to 10% of the production capacity ends up as production scrap. Production scrap will be the main feed for LIB recycling plants [135].

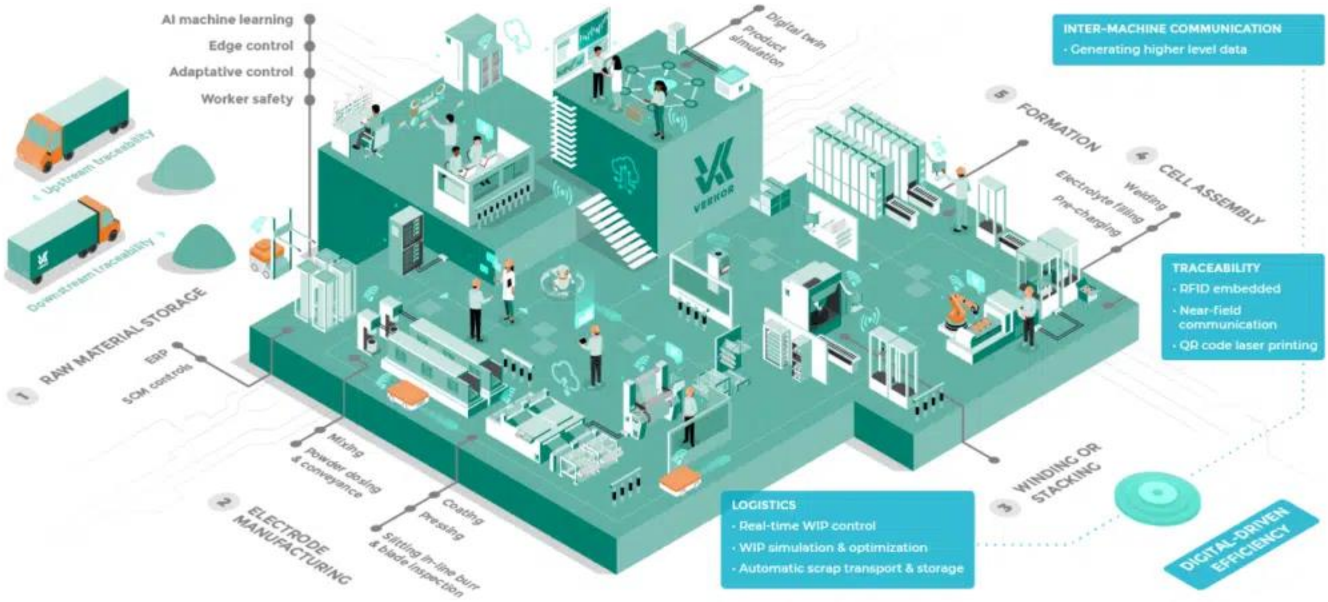

Figure 12. Diagram showing the different stages of manufacturing a cylindrical lithium-ion cell [136].

3.4. Self-Healing

Self-healing is a new area of research in which the goal is to restore batteries to their original condition and functionality by reversing unwanted chemical changes that occur within the cell during use. The focus of self-healing is to restore the conductivity of the damaged electrodes, regulate the transport of ions, and minimize the effects of side reactions [137,138].

3.5. Battery Passport

The Global Battery Alliance of the European Commission has decided to implement a Battery Identity Global Passport (BIGP) by 1 January 2026, with the aim of establishing traceability throughout the entire lifecycle of batteries, from production to recycling or subsequent treatment within a circular economic model [139]. It will also ensure the compliance of the battery with the approved regulations. The Battery Passport is a sort of a digital asset accompanying the battery throughout its life in order to improve interoperability and allow the sharing and logging of the battery specific information (chemistry, capacity, origin, etc.), and history and current states key technical indicators. This will be helpful to reuse or repurpose batteries, or to direct the battery to the appropriate recycling process, all as part of the circular economy process [140].

3.6. Mining of Critical Materials for Battery Applications

The primary active materials used in LiBs are lithium, cobalt, nickel, and manganese. However, it is worth noting that the extraction methods for lithium and cobalt demand significant energy and water inputs, resulting in air and water pollution, land degradation, and the potential for groundwater contamination [141]. Responsible and sustainable sourcing of battery raw materials is assessed in the technical report in [142]. In fact, in order to extract one metric ton of lithium, a staggering 2.2 million liters of water are required [143]. Argentina, Bolivia, and Chile, collectively known as the 'Lithium Triangle', as well as Australia, possess extensive lithium reserves. In contrast, cobalt reserves are primarily concentrated in the Democratic Republic of Congo. The cost of cobalt, along with the harsh and hazardous conditions associated with its mining, has prompted a growing interest in cobalt-free battery technologies. The principal nickel reserves can be found in Indonesia, Australia, Brazil, Russia, and Philippines, while the primary manganese reserves are located in South Africa, Ukraine, Brazil, and Australia [144]. Although lithium, nickel, and manganese are relatively abundant in nature, their availability is constrained, their access is limited, and geopolitical factors also exert significant influence over the supply chain. From the anode side, graphite is considered a critical element for LiBs, with most flake graphite ores being primarily extracted from mines in China [145]. In the study referenced in [146], a classification of 17 minerals critical for the green energy transition was conducted. Notably, cobalt, graphite, and lithium, crucial minerals for batteries, exhibited the lowest availability index values. Nickel also registered low indices. The study foresaw demand and supply scenarios for these minerals in accordance with a 2050 projection, highlighting a significant degree of uncertainty. Integration of circular economy is a most for attaining sustainability sourcing as discussed in the next section.

Raw materials, in Figure 13, should meet the expectations of the market and its needs by developing new technological routes to optimize and foster the circularity of the sector.

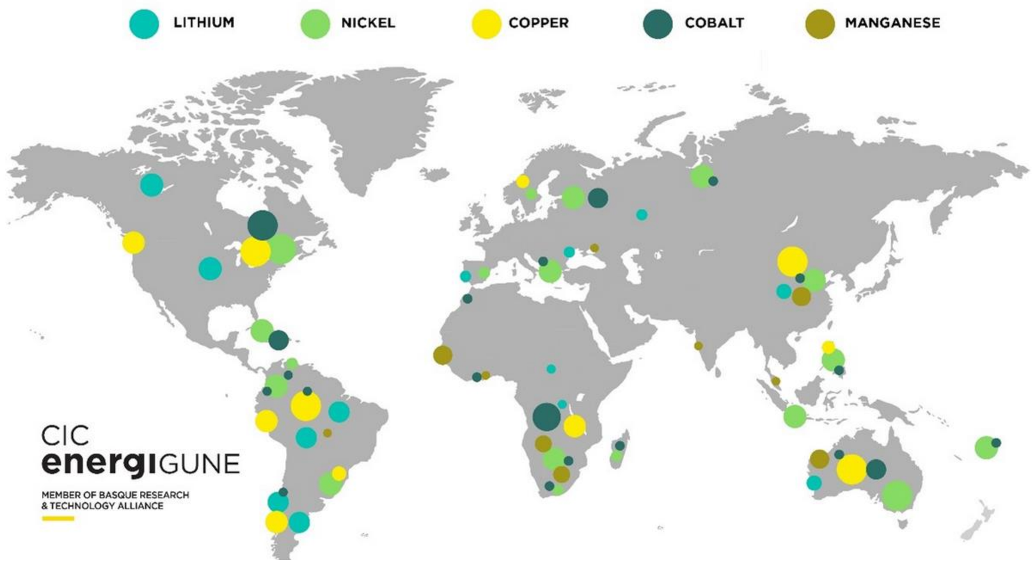

Figure 13. Battery raw materials sources [147].

3.7. Second Life—Remaining Useful Life—Recycling

According to a recent study conducted by IDTechEx, it is estimated that over 6 million battery packs will reach the end of their useful life (EUL) by 2030 [148]. By 2030, the supply of second-life batteries for stationary applications has the potential to surpass 200 GWh [149].

The concept of giving batteries a second life, or repurposing them for additional use, is a relatively new area of research. Once the state of health (SoH) of a battery attains 80%, it might integrate the 4R process (Reuse, Repair, Remanufacture, and Recycle). This raises the needs to develop accurate SoH estimation and life prediction techniques [150,151].

These "second-life" batteries can be utilized in a variety of applications, including renewable energy and smart grid systems, charging infrastructure, and low power e-mobility system [152,153].

A regulatory structure, appropriate standards, industry investments, and a supportive legal environment are necessary for creating a circular economy that is sustainable and efficient.

The knowledge of the battery state according to several measurements applied to battery cells is quite important. Smart-sensing technology, [154,155], will help users predict the performance of the battery and prevent any unwanted behavior or, at least, be prepared for this type of situation.

Consequently, battery state estimation, management system, and estimation of the remaining useful life (RUL) have become a topic of interest for researchers. Considering this, appropriate battery data acquisition and proper information on available battery data sets may be required. This review paper is mainly focused on three parts. The first one is battery data acquisitions with commercially and freely available Li-ion battery data set information. The second is the estimation of the states of battery with the battery management system. And the third is the battery remaining useful life (RUL) estimation.

Regarding recycling, there are set targets for material recovery of lithium. By the year 2027, the goal is to achieve a 50% recovery rate, which is expected to further increase to 80% by 2031 [156,157]. The recovery of nickel, cobalt, and lithium will also be fully commercially viable in future [158,159]. Nickel-based batteries have a long life and are very reliable. Recycling efficiency should increase from the current 79% (active materials at 50%) to 80–85% (active materials at 55–60%) by 2030 to reach a break-even business model [160].

4. Conclusions

This paper has concerned a review on new-generation batteries technologies with the scope of trends and future directions. A review on new-generation batteries dealt with an exhaustive and graduated approach. Beginning with an exploration of batteries before lithium, the review then extensively covers contemporary lithium-ion battery technologies, followed by an in-depth examination of both existing and promising future battery technologies. In particular, there is a focus on Generations 3, 4, and 5. The next part ends with a section on analyses and discussions on future batteries challenges, covering in particular modeling and battery degradation issues, manufacturing challenges, and the problematics of second life, remaining useful life, and recycling.

The primary objective and contribution of the review paper lie in the widespread and exhaustive research carried on, involving extensive bibliographical in-depth analyses. The paper synthesizes the major trends and future directions in battery materials and technology, ensuring a comprehensive understanding of the current state of the field and its implications.

In summary, the paper provided an overview of the evolving landscape of new-generation battery technologies, with a particular focus on advancements in material research. The adopted analysis emphasizes the increasing significance of material innovation as a key factor influencing the development of next-generation batteries. As the field of battery technology continues to progress, it is evident that future research directions should emphasize and explore novel materials, their synthesis methods, and their impact on enhancing battery performance and sustainability. In fact, cathodes have a lower storage capacity for lithium than anodes, and to address this limitation, researchers are exploring new materials. The original LIB cathodes were based on cobalt, and whilst it is still used, there are notable industry efforts to lower the amount of cobalt in cathode materials. This is driven by its toxicity, but also due to the risky supply chains of cobalt, associated with the geo-political instability of its provenance. As researchers continue to develop cobalt-free materials, there will be a range of new higher voltage chemistries in this domain. These are mainly based on higher-nickel-content materials and related chemistries termed “lithium excess”. These cathodes will have an inherent higher voltage and capacities but will require stabilization, as they are sensitive to moisture and prone to degradation.

Electrolytes improvements to the thermal and electrochemical stability of conventional organic solvent electrolytes are still required if safety is to be maximized. Electrolyte additives with higher voltage stability will enable the uptake of higher voltage cathodes for use with organic electrolytes.

Moving forward, solid-state systems are the Holy Grail, and will continue to be researched intensively to achieve the required ionic conductivity. Research on solid-state batteries is hindered by high interfacial resistance caused by poor wetting between the lithium and solid electrolyte. As discussed, one potential solution is the use of polymer-based solid electrolytes, which have been shown to have better lithium wetting than ceramic-based electrolytes, which are typically preferred for their higher ionic conductivity. Hybrid polymer/ceramic composites, which are adaptable to large-scale manufacturing, may also be a viable option. Another challenge in the development of solid-state batteries is the formation of dendrites, which can inhibit the growth and propagation of dense microstructures in high-power applications.

For separators, protective ceramic coatings are increasingly being used to add robustness and mechanical integrity. This increases the safety of the batteries by mitigating short circuits through mechanical damage.

To advance and improve current collectors, scientists continue to research properties such as their thickness, hardness, composition, surface coating layers, and their basic structure. Improvements are desired through increasing their mechanical strength, chemical and electrochemical stability, and adhesion quality with the electrode coating.

Several key limitations to this study should be noted:

- Technological limitations: The review is influenced by the current technological landscape in battery materials, including constraints related to the reliability, efficiency, and autonomy of battery systems.
- Societal and policy limitations: Societal acceptability, economic factors, and political decisions, such as the governmental decisions to implement gigafactories, play a significant role in shaping the future of batteries and their adoption.
- Cost, material, and environmental limitations: The study is also bounded by the limitations associated with the cost of materials, considerations related to the circular economy, and the environmental footprint of battery technologies.

On the other hand, the integration of the Internet of Things (IoT), cloud computing, Application Programming Interfaces (APIs), open standards, artificial intelligence (AI), and digital reality technologies are rapidly transitioning from abstract concepts to tangible realities that cannot be overlooked in electromobility and smart-grid domains. The intertwining relationship between energy and data is becoming increasingly inseparable, with energy and data acting as mutualistic twins, inherently interconnected. Batteries must efficiently store energy, while power electronics assume a vital role in ensuring the efficient conversion of energy. Embracing transformative technologies has the power to unlock the full potential of energy as a shared resource, shaping a future where energy is accessible, adaptable, and consistently integrated into the overall ecosystem.

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References

1. Schleussner, C.; Rogelj, J.; Schaeffer, M.; Lissner, T.; Licker, R.; Fischer, E.; Knutti, R.; Levermann, A.; Frieler, K.; Hare, W. Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Clim. Chang.* **2016**, *6*, 827–835. [CrossRef]
2. Sikora, A. European Green Deal—Legal and financial challenges of the climate change. In *Era Forum*; Springer: Berlin/Heidelberg, Germany, 2021.
3. Mathieu, C. *The European battery alliance is moving up a gear. The European Battery Alliance is Moving up a Gear*; Edito de l'Ifri: Paris, France, 2019.
4. Shale-Hester, T. UK 2030 Petrol and Diesel Ban: What Is It and Which Cars Are Affected? Available online: https://www.autoexpress.co.uk/news/108960/uk-2030-petrol-and-diesel-ban-what-it-and-which-cars-are-affected (accessed on 8 June 2023).
5. Register, F. Tackling the Climate Crisis at Home and Abroad. Presidential Documents, United States of America, Federal Register/Vol. 86, No. 19, Monday. 1 February 2021. Available online: https://downloads.regulations.gov/EPA-HQ-OPPT-2021-0202-0012/content.pdf (accessed on 1 July 2023).
6. BloombergNEF; BloombergPhilanthropies. *Energy Transition Factbook*; Clean Energy Ministerial: Paris, France, 2021.
7. Granholm, J. *National Blueprint for Lithium Batteries 2021–2030*; U.S. Department of Energy: Washington, DC, USA, 2021.
8. Van Mierlo, J.; Messagie, M.; Rangaraju, S. Comparative environmental assessment of alternative fueled vehicles using a life cycle assessment. *Transp. Res. Procedia* **2017**, *25*, 3435–3445. [CrossRef]
9. Field, K. BloombergNEF: Lithium-Ion Battery Cell Densities Have Almost Tripled Since 2010. 19 February 2020. Available online: https://cleantechnica.com/2020/02/19/bloombergnef-lithium-ion-battery-cell-densities-have-almost-tripled-since-2010/ (accessed on 1 June 2023).
10. Vehicle Technologies Office. Volumetric Energy Density of Lithium-Ion Batteries Increased by More than Eight Times between 2008 and 2020. 18 April 2022. Available online: https://www.energy.gov/eere/vehicles/articles/fotw-1234-april-18-2022-volumetric-energy-density-lithium-ion-batteries (accessed on 1 July 2023).
11. Cao, W.; Zhang, J.; Li, H. Batteries with high theoretical energy densities. *Energy Storage Mater.* **2020**, *26*, 46–55. [CrossRef]
12. Gordon, D. Battery Market Forecast to 2030: Pricing, Capacity, and Supply and Demand. 15 March 2022. Available online: https://www.esource.com/report/130221hvfd/battery-market-forecast-2030-pricing-capacity-and-supply-and-demand (accessed on 1 June 2023).
13. Yue, Q.; He, C.; Wu, M.; Zhao, T. Advances in thermal management systems for next-generation power batteries. *Int. J. Heat Mass Transf.* **2021**, *181*, 121853. [CrossRef]
14. Liu, P.; Chen, T.; Yang, H. A Li-Ion Battery Charger With Variable Charging Current and Automatic Voltage-Compensation Controls for Parallel Charging. *IEEE J. Emerg. Sel. Top. Power Electron.* **2021**, *10*, 997–1006. [CrossRef]
15. Collin, R.; Miao, Y.; Yokochi, A.; Enjeti, P.; Von Jouanne, A. Advanced electric vehicle fast-charging technologies. *Energies* **2019**, *12*, 1839. [CrossRef]
16. Afonso, J.; Cardoso, L.; Pedrosa, D.; Sousa, T.; Machado, L.; Tanta, M.; Monteiro, V. A review on power electronics technologies for electric mobility. *Energies* **2020**, *13*, 6343. [CrossRef]
17. Amry, Y.; Elbouchikhi, E.; Le Gall, F.; Ghogho, M.; El Hani, S. Electric Vehicle Traction Drives and Charging Station Power Electronics: Current Status and Challenges. *Energies* **2022**, *15*, 6037. [CrossRef]
18. Habib, S.; Ehsan, F.; Liu, H.; Nadeem, M.; Abbas, F.; Numan, M. A Comprehensive Topological Assessment of Power Electronics Converters for Charging of Electric Vehicles. In *Flexible Resources for Smart Cities*; Springer: Cham, Switzerland, 2021; pp. 133–183.
19. Ronanki, D.; Kelkar, A.; Williamson, S. Extreme fast charging technology—Prospects to enhance sustainable electric transportation. *Energies* **2019**, *12*, 3721. [CrossRef]
20. Al-Saadi, M.; Olmos, J.; Saez-de-Ibarra, A.; Van Mierlo, J.; Berecibar, M. Fast Charging Impact on the Lithium-Ion Batteries' Lifetime and Cost-Effective Battery Sizing in Heavy-Duty Electric Vehicles Applications. *Energies* **2022**, *15*, 1278. [CrossRef]
21. Komsiyska, L.; Buchberger, T.; Diehl, S.; Ehrensberger, M.; Hanzl, C.; Hartmann, C.; Hölzle, M.; Kleiner, J.; Lewerenz, M.; Liebhart, B.; et al. Critical review of intelligent battery systems: Challenges, implementation, and potential for electric vehicles. *Energies* **2021**, *14*, 5989. [CrossRef]
22. Polater, N.; Tricoli, P. Technical Review of Traction Drive Systems for Light Railways. *Energies* **2022**, *15*, 3187. [CrossRef]
23. Abdelaal, A.; Mukhopadhyay, S.; Rehman, H. Battery Energy Management Techniques for an Electric Vehicle Traction System. *IEEE Access* **2021**, *10*, 84015–84037. [CrossRef]
24. Mahamud, R.; Park, C. Theory and Practices of Li-Ion Battery Thermal Management for Electric and Hybrid Electric Vehicles. *Energies* **2022**, *15*, 3930. [CrossRef]
25. Yamamoto, M.; Kakisaka, T.; Imaoka, J. Technical trend of power electronics systems for automotive applications. *Jpn. J. Appl. Phys.* **2020**, *59*, SG0805. [CrossRef]
26. Shi, B.; Ramones, A.; Liu, Y.; Wang, H.; Li, Y.; Pischinger, S.; Andert, J. A review of silicon carbide MOSFETs in electrified vehicles: Application, challenges, and future development. *IET Power Electron.* **2023**. [CrossRef]
27. AEHR Test System. Aehr Comments on Recent Tesla Statements on Silicon Carbide and Reiterates its Annual Guidance. Press Release. 2 March 2023. Available online: https://www.globenewswire.com/news-release/2023/03/02/2619726/11245/en/Aehr-Comments-on-Recent-Tesla-Statements-on-Silicon-Carbide-and-Reiterates-its-Annual-Guidance.html (accessed on 11 June 2023).

28. Maroti, P.; Padmanaban, S.; Bhaskar, M.; Ramachandaramurthy, V.; Blaabjerg, F. The state-of-the-art of power electronics converters configurations in electric vehicle technologies. *Power Electron. Devices Compon.* **2022**, *1*, 100001. [CrossRef]
29. Kumar, S.; Adil, U. A review of converter topologies for battery charging applications in plug-in hybrid electric vehicles. In Proceedings of the 2018 IEEE Industry Applications Society Annual Meeting (IAS), Portland, OR, USA, 23–27 September 2018; pp. 1–9.
30. Wen, H.; Xiao, W.; Wen, X.; Armstrong, P. Analysis and Evaluation of DC-Link Capacitors for High-Power-Density Electric Vehicle Drive Systems. *IEEE Trans. Veh. Technol.* **2012**, *61*, 2950–2964.
31. Zhang, C.; Srdic, S.; Lukic, S.; Sun, K.; Wang, J.; Burgos, R. A SiC-Based Liquid-Cooled Electric Vehicle Traction Inverter Operating at High Ambient Temperature. *CPSS Trans. Power Electron. Appl.* **2022**, *7*, 160–175. [CrossRef]
32. Ding, C.; Lu, S.; Zhang, Z.; Zhang, K.; Nguyen, T.; Ngo, K.; Burgos, R.; Lu, G. Double-Side Cooled SiC MOSFET Power Modules with Sintered-Silver Interposers for a 100 kW/L Traction Inverter. *IEEE Trans. Power Electron.* **2023**, *38*, 9685–9694. [CrossRef]
33. Das, S.; Marlino, L.; Armstrong, K. *Wide Bandgap Semiconductor Opportunities in Power Electronics*; Oak Ridge National Lab.(ORNL): Oak Ridge, TN, USA, 2018.
34. Liu, W.; Placke, T.; Chau, K. Overview of batteries and battery management for electric vehicles. *Energy Rep.* **2022**, *8*, 4058–4084. [CrossRef]
35. Gifford, S. *The Gigafactory Boom: The Demand for Battery Manufacturing in the UK*; FARADAY INSIGHTS; The Faraday Institution: Cambridge, UK, 2022.
36. CIC energiGUNe. World Map of Gigafactories. 21 October 2021. Available online: https://cicenergigune.com/en/blog/world-map-gigafactories (accessed on 7 January 2023).
37. Ortiz, S.; Careaga, I. Gigafactories: Europe's Major Commitment to Economic Recovery through the Development of Battery Factories. 7 April 2021. Available online: https://cicenergigune.com/en/blog/gigafactories-europe-commitment-economic-recovery-battery-factories (accessed on 7 January 2023).
38. Itani, K.; De Bernardinis, A. Management of the Energy Storage Hybridization in Electric Vehicles. In *Encyclopedia of Electrical and Electronic Power Engineering*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 542–562.
39. Sutcliffe, E. Electric Vehicle Fires on Ships & Ferries—EV Fire Safe. 14 September 2022. Available online: https://www.evfiresafe.com/post/electric-vehicle-fires-on-ships-ferries (accessed on 7 January 2023).
40. Booth, S.; Nedoma, A.; Anthonisamy, N.; Baker, P.; Boston, R.; Bronstein, H.; Clarke, S.; Cussen, E.J.; Daramalla, V.; De Volder, M.; et al. Perspectives for next generation lithium-ion battery cathode materials. *Appl. Mater.* **2021**, *9*, 109201. [CrossRef]
41. Gifford, S. Lithium, Cobalt and Nickel: The Gold Rush of the 21st Century. *Changes* **2022**, *2050*, 6–500.
42. Berckmans, G.; Messagie, M.; Smekens, J.; Omar, N.; Vanhaverbeke, L.; Van Mierlo, J. Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030. *Energies* **2017**, *10*, 1314. [CrossRef]
43. Barbosa, J.; Gonçalves, R.; Costa, C.; Lanceros-Mendez, S. Recent advances on materials for lithium-ion batteries. *Energies* **2021**, *14*, 3145. [CrossRef]
44. Van Mierlo, J.; Berecibar, M.; El Baghdadi, M.; De Cauwer, C.; Messagie, M.; Coosemans, T.; Jacobs, V.; Hegazy, O. Beyond the state of the art of electric vehicles: A fact-based paper of the current and prospective electric vehicle technologies. *World Electr. Veh. J.* **2021**, *12*, 20. [CrossRef]
45. Kim, Y.; Seong, W.; Manthiram, A. Cobalt-free, high-nickel layered oxide cathodes for lithium-ion batteries: Progress, challenges, and perspectives. *Energy Storage Mater.* **2021**, *34*, 250–259. [CrossRef]
46. Lee, S.; Manthiram, A. Can cobalt be eliminated from lithium-ion batteries? *ACS Energy Lett.* **2022**, *7*, 3058–3063. [CrossRef]
47. Lima, P. CATL's NCM 811 Battery Cells Are Problematic. 28 September 2020. Available online: https://pushevs.com/2020/09/28/catl-ncm-811-battery-cells-are-problematic/ (accessed on 9 June 2023).
48. SMM. Tragedy of Electric Car Catching Fire Immediately After Collision in China's Hangzhou City Renews Concerns Over Safety of Nickel-Manganese-Cobalt (NMC 811) Battery. 7 June 2023. Available online: https://news.metal.com/newscontent/102243830/tragedy-of-electric-car-catching-fire-immediately-after-collision-in-china%E2%80%99s-hangzhou-city-renews-concerns-over-safety-of-nickel-manganese-cobalt-nmc-811-battery (accessed on 9 June 2023).
49. Xia, M.; Lin, M.; Liu, G.; Cheng, Y.; Jiao, T.; Fu, A.; Yang, Y.; Wang, M.; Zheng, J. Stable cycling and fast charging of high-voltage lithium metal batteries enabled by functional solvation chemistry. *Chem. Eng. J.* **2022**, *442*, 136351. [CrossRef]
50. Mao, N.; Gadkari, S.; Wang, Z.; Zhang, T.; Bai, J.; Cai, Q. A comparative analysis of lithium-ion batteries with different cathodes under overheating and nail penetration conditions. *Energy* **2023**, *278*, 128027. [CrossRef]
51. Adham, S.; Jackson, M.D.C.; Laugharne, A. Navigating the Rapidly Evolving EV Battery Chemistry Mix. CRU Group. February 2023. Available online: https://www.crugroup.com/knowledge-and-insights/insights/2023/navigating-the-rapidly-evolving-ev-battery-chemistry-mix/ (accessed on 22 October 2023).
52. Adham, S. The Next-Generation Cobalt-Free EV Battery Is Just Around the Corner. 27 May 2021. Available online: https://lmc-auto.com/wp-content/uploads/2021/05/The-next-generation-cobalt-free-EV-battery-is-just-around-the-corner.pdf (accessed on 22 October 2023).
53. Müller, J.; Abdollahifar, M.; Doose, S.; Michalowski, P.; Wu, N.; Kwade, A. Effects of carbon coating on calendered nano-silicon graphite composite anodes of LiB. *J. Power Sources* **2022**, *548*, 232000. [CrossRef]
54. Yi, S.; Wang, B.; Chen, Z.; Wang, R.; Wang, D. A study on LiFePO 4/graphite cells with built-in Li_4 Ti_5 O_{12} reference electrodes. *RSC Adv.* **2018**, *8*, 18597–18603. [CrossRef] [PubMed]

55. da Silva Lima, L.; Wu, J.; Cadena, E.; Groombridge, A.; Dewulf, J. Towards environmentally sustainable battery anode materials: Life cycle assessment of mixed niobium oxide (XNO™) and lithium titanium-oxide (LTO). *Sustain. Mater. Technol.* **2023**, *37*, e00654.
56. Tian, T.; Lu, L.; Yin, Y.; Li, F.; Zhang, T.; Song, Y.; Tan, Y.; Yao, H. Multiscale designed niobium titanium oxide anode for fast charging lithium ion batteries. *Adv. Funct. Mater.* **2021**, *31*, 2007419. [CrossRef]
57. Mehta, J. A Review of Temperature Effects on Varying Li-Ion Cell Chemistries for Electric Vehicle Applications. SSRN 4254130. 16 September 2022. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4254130 (accessed on 1 July 2023).
58. Kurzweil, P.; Garche, J. Overview of Batteries for Future Automobiles. In *Lead-Acid Batteries for Future Automobiles*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 27–96.
59. Zheng, F.; Kotobuki, M.; Song, S.; Lai, M.; Lu, L. Review on solid electrolytes for all-solid-state lithium-ion batteries. *J. Power Sources* **2018**, *389*, 198–213. [CrossRef]
60. Costa, C.; Lanceros-Mendez, S. Recent advances on battery separators based on poly (vinylidene fluoride) and its copolymers for lithium-ion battery applications. *Curr. Opin. Electrochem.* **2021**, *29*, 100752. [CrossRef]
61. Chen, X.; Chen, S.; Lin, Y.; Wu, K.; Lu, S. Multi-functional ceramic-coated separator for lithium-ion batteries safety tolerance improvement. *Ceram. Int.* **2020**, *46*, 24689–24697. [CrossRef]
62. Kim, S.; Song, Y.; Wee, J.; Kim, C.; Ahn, B.; Lee, J.; Shu, S.; Terrones, M.; Kim, Y.; Yang, C. Few-layer graphene coated current collectors for safe and powerful lithium ion batteries. *Carbon* **2019**, *153*, 495–503. [CrossRef]
63. Ashuri, M.; He, Q.; Shaw, L. Silicon as a potential anode material for Li-ion batteries: Where size, geometry and structure matter. *Nanoscale* **2016**, *8*, 74–103. [CrossRef]
64. Gonzalez, A.F.; Yang, N.; Liu, R. Silicon anode design for lithium-ion batteries: Progress and perspectives. *J. Phys. Chem. C* **2017**, *121*, 27775–27787. [CrossRef]
65. Ashuri, M.; He, Q.; Shaw, L. Silicon oxides for Li-ion battery anode applications: Toward long-term cycling stability. *J. Power Sources* **2023**, *559*, 232660. [CrossRef]
66. Peng, C.; Chen, H.; Li, Q.; Cai, W.; Yao, Q.; Wu, Q.; Yang, J.; Yang, Y. Synergistically reinforced lithium storage performance of in situ chemically grown silicon@ silicon oxide core—Shell nanowires on three-dimensional conductive graphitic scaffolds. *J. Mater. Chem. A* **2014**, *2*, 13859–13867. [CrossRef]
67. Liu, Z.; Yu, Q.; Zhao, Y.; He, R.; Xu, M.; Feng, S.; Li, S.; Zhou, L.; Mai, L. Silicon oxides: A promising family of anode materials for lithium-ion batteries. *Chem. Soc. Rev.* **2019**, *1*, 48. [CrossRef]
68. Shaw, L.; Ashuri, M. Coating-A potent method to enhance electrochemical performance of Li (NixMnyCoz) O2 cathodes for Li-ion batteries. *Adv. Mater. Lett.* **2019**, *10*, 369–380. [CrossRef]
69. Hassan, E.; Amiriyan, M.; Frisone, D.; Dunham, J.; Farahati, R.; Farhad, S. Effects of Coating on the Electrochemical Performance of a Nickel-Rich Cathode Active Material. *Energies* **2022**, *15*, 4886. [CrossRef]
70. Kaur, G.; Gates, B. Surface Coatings for Cathodes in Lithium Ion Batteries: From Crystal Structures to Electrochemical Performance. *J. Electrochem. Soc.* **2022**, *169*, 043504. [CrossRef]
71. Emani, S.; Liu, C.; Ashuri, M.; Sahni, K.; Wu, J.; Yang, W.; Németh, K.; Shaw, L. Li3BN2 as a Transition Metal Free, High Capacity Cathode for Li-ion Batteries. *ChemElectroChem* **2019**, *6*, 320–325. [CrossRef]
72. Rodrigues, M.; Kalaga, K.; Gullapalli, H.; Babu, G.; Reddy, A.; Ajayan, P. Hexagonal boron nitride-based electrolyte composite for Li-ion battery operation from room temperature to 150 C. *Adv. Energy Mater.* **2016**, *6*, 1600218. [CrossRef]
73. Soloveichik, G. Flow batteries: Current status and trends. *Chem. Rev.* **2015**, *115*, 11533–11558. [CrossRef]
74. Lewis, G.N.; Keyes, F.G. The potential of Lithium Electrode. *J. Am. Chem. Soc.* **1913**, *35*, 340–344. [CrossRef]
75. Hanusa, T.P. *The Lightest Metals: Science and Technology from Lithium to Calcium*; John Wiley & Sons: Hoboken, NJ, USA, 2015.
76. Diouf, B.; Pode, R. Potential of lithium-ion batteries in renewable energy. *Renew. Energy* **2015**, *76*, 375–380. [CrossRef]
77. Gao, J.; Shi, S.-Q.; Li, H. Brief overview of electrochemical potential in lithium ion batteries. *Chin. Phys. B* **2015**, *25*, 018210. [CrossRef]
78. Jarrat, E. New Lessons from the Epic Story of Moli Energy, the Canadian Pioneer of Rechargeable Lithium Battery Technology. September 2020. Available online: https://electricautonomy.ca/2020/09/18/moli-energy-lithium-battery-technology/ (accessed on 5 January 2023).
79. Zhu, K.; Wang, C.; Chi, Z.; Ke, F.; Yang, Y.; Wang, A.; Wang, W.; Miao, L. How far away are lithium-sulfur batteries from commercialization? *Front. Energy Res.* **2019**, *15*, 123. [CrossRef]
80. Wu, F.; Chu, F.; Xue, Z. Lithium-Ion Batteries. In *Encyclopedia of Energy Storage*; Cabeza, L.F., Ed.; Elsevier: Oxford, UK, 2022; pp. 5–13.
81. Xu, W.; Wang, J.; Ding, F.; Chen, X.; Nasybulin, E.; Zhang, Y.; Zhang, J. Lithium metal anodes for rechargeable batteries. *Energy Environ. Sci.* **2014**, *7*, 513–537. [CrossRef]
82. Jennifer, L. Lithium-ion Battery Capacity to Reach 6.5 TWh in 2030, Says S&P Global. Carbon Credits. 18 July 2023. Available online: https://carboncredits.com/lithium-ion-battery-capacity-to-reach-6-5-twh-in-2030-says-sp-global/ (accessed on 1 July 2023).
83. Li, Q.; Yang, Y.; Yu, X.; Li, H. A 700 W· h· kg− 1 Rechargeable Pouch Type Lithium Battery. *Chin. Phys. Lett.* **2023**, *40*, 048201. [CrossRef]

84. Gipson, L. NASA's Solid-State Battery Research Exceeds Initial Goals, Draws Interest. 7 October 2022. Available online: https://www.nasa.gov/aeroresearch/nasa-solid-state-battery-research-exceeds-initial-goals-draws-interest (accessed on 5 June 2023).
85. Walters, I.; Hull, R. Weight of Electric Vehicles Could Cause 'Catastrophic' Damage and 'Lead to Car Parks Collapsing': Engineers Warn Britain's Parking Facilities Were Not Designed for Hulking Battery Cars. 19 December 2022. Available online: https://www.dailymail.co.uk/news/article-11550269/Weight-electric-vehicles-cause-catastrophic-damage-lead-car-parks-collapsing.html (accessed on 27 December 2022).
86. Zhao, M.; Li, B.; Zhang, X.; Huang, J.; Zhang, Q. A perspective toward practical lithium–sulfur batteries. *ACS Cent. Sci.* **2020**, *6*, 1095–1104. [CrossRef]
87. Aurbach, D.; McCloskey, B.; Nazar, L.; Bruce, P. Advances in understanding mechanisms underpinning lithium–air batteries. *Nat. Energy* **2016**, *1*, 16128. [CrossRef]
88. Lim, H.; Park, J.; Shin, H.; Jeong, J.; Kim, J.; Nam, K.; Jung, H.; Chung, K. A review of challenges and issues concerning interfaces for all-solid-state batteries. *Energy Storage Mater.* **2020**, *25*, 224–250. [CrossRef]
89. Salgado, R.M.; Oliveira, J.C.R.E.; Braga, H. *Intelligence in Mobile Battery Applications Desk Research Report. Alliance for Batteries Technology, Training and Skills*; The European Commission: Brussels, Belgium, 2020.
90. Kalhoff, J.; Eshetu, G.; Bresser, D.; Passerini, S. Safer electrolytes for lithium-ion batteries: State of the art and perspectives. *ChemSusChem* **2015**, *8*, 2154–2175. [CrossRef]
91. European Commission. Batteries Europe. December 2021. Available online: https://energy.ec.europa.eu/system/files/2021-12/vol-3-008-2.pdf (accessed on 6 June 2023).
92. Wu, X.; Chen, K.; Yao, Z.; Hu, J.; Huang, M.; Meng, J.; Ma, S.; Wu, T.; Cui, Y.; Li, C. Metal organic framework reinforced polymer electrolyte with high cation transference number to enable dendrite-free solid state Li metal conversion batteries. *J. Power Sources* **2021**, *501*, 229946. [CrossRef]
93. Xu, H.; Ye, W.; Wang, Q.; Han, B.; Wang, J.; Wang, C.; Deng, Y. An in situ photopolymerized composite solid electrolyte from halloysite nanotubes and comb-like polycaprolactone for high voltage lithium metal batteries. *J. Mater. Chem. A* **2021**, *9*, 9826–9836. [CrossRef]
94. Park, J.; Park, D.; Go, S.; Nam, D.; Oh, J.; Han, Y.; Lee, H. Malonatophosphate as an SEI-and CEI-forming additive that outperforms malonatoborate for thermally robust lithium-ion batteries. *Energy Storage Mater.* **2022**, *50*, 75–85. [CrossRef]
95. B.S.B. Group. Battery Technology. 2023. Available online: https://www.blue-solutions.com/en/battery-technology/ (accessed on 20 August 2023).
96. Trofimov, B.; Myachina, G.; Oparina, L.; Korzhova, S.; Doo, G.N.S.; Cho, M.; Kim, H. Triethyl 2-(1, 3-oxazolidin-3-yl) ethyl orthosilicate as a new type electrolyte additive for lithium-ion batteries with graphite anodes. *J. Power Sources* **2005**, *147*, 260–263. [CrossRef]
97. Aziam, H.; Larhrib, B.; Hakim, C.; Sabi, N.; Youcef, H.; Saadoune, I. Solid-state electrolytes for beyond lithium-ion batteries: A review. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112694. [CrossRef]
98. Yamauchi, H.; Ikejiri, J.; Tsunoda, K.; Tanaka, A.; Sato, F.; Honma, T.; Komatsu, T. Enhanced rate capabilities in a glass-ceramic-derived sodium all-solid-state battery. *Sci. Rep.* **2020**, *10*, 9453. [CrossRef]
99. Bhat, M.; Hashmi, S. Mixture of non-ionic and organic ionic plastic crystals immobilized in poly (vinylidene fluoride-co-hexafluoropropylene): A flexible gel polymer electrolyte composition for high performance carbon supercapacitors. *J. Energy Storage* **2022**, *51*, 104514. [CrossRef]
100. Fan, L.; Wei, S.; Li, S.; Li, Q.; Lu, Y. Recent progress of the solid-state electrolytes for high-energy metal-based batteries. *Adv. Energy Mater.* **2018**, *8*, 1702657. [CrossRef]
101. Alliance for Batteries Technology, Training and Skills. In *Desk Research and Data Analysis for Sub-Sector IMBA—ALBATT*; The European Commission: Brussels, Belgium, 2021.
102. Li, M.; Jafta, C.; Belharouak, I. Progress of nanotechnology for lithium-sulfur batteries. *Front. Nanosci.* **2021**, *19*, 137–164.
103. Kim, S.; Chart, Y.; Narayanan, S.; Pasta, M. Thin Solid Electrolyte Separators for Solid-State Lithium–Sulfur Batteries. *Nano Lett.* **2022**, *22*, 10176–10183. [CrossRef]
104. McAlpine, K. 1,000-Cycle Lithium-Sulfur Battery Could Quintuple Electric Vehicle Ranges. 12 January 2022. Available online: https://news.umich.edu/1000-cycle-lithium-sulfur-battery-could-quintuple-electric-vehicle-ranges/ (accessed on 6 June 2023).
105. Bi, C.; Zhao, M.; Hou, L.; Chen, Z.; Zhang, X.; Li, B.; Yuan, H.; Huang, J. Anode material options toward 500 Wh kg^{-1} lithium–sulfur batteries. *Adv. Sci.* **2022**, *9*, 2103910. [CrossRef]
106. Robinson, J.; Xi, K.; Kumar, R.; Ferrari, A.; Au, H.; Titirici, M.; Parra-Puerto, A.; Kucernak, A.; Fitch, S.; Garcia-Araez, N.; et al. 2021 roadmap on lithium sulfur batteries. *J. Phys. Energy* **2021**, *3*, 031501. [CrossRef]
107. Abert, M. Analysis of gases emitted in safety events. Electrochemical Powers Sources: Fundamentals, Systems, and Applications. In *Li-Battery Safety*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 196–215.
108. Seh, Z.; Sun, Y.; Zhang, Q.; Cui, Y. Designing high-energy lithium–sulfur batteries. *Chem. Soc. Rev.* **2016**, *45*, 5605–5634. [CrossRef] [PubMed]
109. Sun, J.; Wang, T.; Gao, Y.; Pan, Z.; Hu, R.; Wang, J. Will lithium-sulfur batteries be the next beyond-lithium ion batteries and even much better? *InfoMat* **2022**, *4*, e12359. [CrossRef]

110. Nayak, P.; Yang, L.; Brehm, W.; Adelhelm, P. From lithium-ion to sodium-ion batteries: Advantages, challenges, and surprises. *Angew. Chem. Int. Ed.* **2018**, *57*, 102–120. [CrossRef]
111. Abraham, K. How comparable are sodium-ion batteries to lithium-ion counterparts? *ACS Energy Lett.* **2020**, *5*, 3544–3547. [CrossRef]
112. Hu, Y.; Li, Y. Unlocking sustainable Na-ion batteries into industry. *ACS Energy Lett.* **2021**, *6*, 4115–4117. [CrossRef]
113. Zhao, C.; Lu, Y.; Li, Y.; Jiang, L.; Rong, X.; Hu, Y.; Li, H.; Chen, L. Novel Methods for Sodium-Ion Battery Materials. *Small Methods* **2017**, *1*, 1600063. [CrossRef]
114. Guo, Q.; Zeng, W.; Liu, S.; Li, Y.; Xu, J.; Wang, J.; Wang, Y. Recent developments on anode materials for magnesium-ion batteries: A review. *Rare Met.* **2021**, *40*, 290–308. [CrossRef]
115. Kyeremateng, N.; Hahn, R. Attainable energy density of microbatteries. *ACS Energy Lett.* **2018**, *3*, 1172–1175. [CrossRef]
116. MARKETS AND MARKETS. Micro Battery Market. July 2023. Available online: https://www.marketsandmarkets.com/Market-Reports/micro-battery-market-25755945.html?gclid=EAIaIQobChMIg670_fqugQMV4BkGAB3hIAF6EAAYASAAEgJ0VfD_BwE (accessed on 5 September 2023).
117. Xia, Q.; Zan, F.; Zhang, Q.; Liu, W.; Li, Q.; He, Y.; Hua, J.; Liu, J.; Xu, J.; Wang, J.; et al. All-Solid-State Thin Film Lithium/Lithium-Ion Microbatteries for Powering the Internet of Things. *Adv. Mater.* **2023**, *35*, 2200538. [CrossRef]
118. Jafferis, N.; Helbling, E.; Karpelson, M.; Wood, R. Untethered flight of an insect-sized flapping-wing microscale aerial vehicle. *Nature* **2019**, *570*, 491–495. [CrossRef] [PubMed]
119. Vaughan, O. RoboBee breaks free. *Nat. Electron.* **2019**, *2*, 265. [CrossRef]
120. Hur, J.; Smith, L.; Dunn, B. High areal energy density 3D lithium-ion microbatteries. *Joule* **2018**, *2*, 1187–1201. [CrossRef]
121. Han, Y.; Dai, C.L.J.; Liu, F.; Ma, H.; Wang, Y.; Lu, B.; Shao, C.; Guo, Q.; Jin, X.; Zhang, X. A compact aqueous K-ion Micro-battery by a Self-shrinkage assembly strategy. *Chem. Eng. J.* **2022**, *429*, 13229. [CrossRef]
122. ITEN. Available online: https://www.iten.com/en/micro-batteries (accessed on 5 September 2023).
123. ST. EFL700A39. June 2014. Available online: https://www.st.com/resource/en/datasheet/efl700a39.pdf (accessed on 5 September 2023).
124. MURATA. CR1216. Available online: https://www.murata.com/products/productdata/8808560951326/CR1216-DATASHEET.pdf?1617161448000 (accessed on 6 September 2023).
125. Ayerbe, E.; Berecibar, M.; Clark, S.; AA, F.; Ruhland, J. Digitalization of battery manufacturing: Current status, challenges, and opportunities. *Adv. Energy Mater.* **2022**, *12*, 2102696. [CrossRef]
126. Loveridge, M.; Dowson, M. *Why Batteries Fail and How to Improve Them: Understanding Degradation to Advance Lithium-Ion Battery Performance*; The Faraday Institution, Warwick Manufacturing Group, University of Warwick: Coventry, UK, 2021.
127. International Energy Agency. *Global EV Outlook 2023—Catching up with Climate Ambitions*; IEA: Paris, France, 2023.
128. Liu, Y.; Zhang, R.; Wang, J.; Wang, Y. Current and future lithium-ion battery manufacturing. *IScience* **2021**, *24*, 102332. [CrossRef] [PubMed]
129. Jinasena, A.; Burheim, O.; AH, S. A flexible model for benchmarking the energy usage of automotive lithium-ion battery cell manufacturing. *Batteries* **2021**, *7*, 14. [CrossRef]
130. Yuan, C.; Deng, Y.; Li, T.; Yang, F. Manufacturing energy analysis of lithium ion battery pack for electric vehicles. *CIRP Ann.* **2017**, *66*, 53–56. [CrossRef]
131. Hatzell, K.; Zheng, Y. Prospects on large-scale manufacturing of solid state batteries. *MRS Energy Sustain.* **2021**, *8*, 33–39. [CrossRef]
132. Heimes, H.; Kampfer, A.; Hemdt, A.; Schön, C.; Michaelis, S.; Rahimzei, E. *Production of All Solid-State Battery Cells*; German Mechanical Engineering Industry Association—RWTH Aachen University: Aachen, Germany, 2018.
133. European Commission. *Questions and Answers on Revised EU Rules on Industrial Emissions*; European Commission: Brussels, Belgium, 2022.
134. Cooke, P. Gigafactory logistics in space and time: Tesla's fourth gigafactory and its rivals. *Sustainability* **2020**, *12*, 2044. [CrossRef]
135. Brückner, L.; Frank, J.; Elwert, T. Industrial recycling of lithium-ion batteries—A critical review of metallurgical process routes. *Metals* **2020**, *10*, 1107. [CrossRef]
136. VERKOR. Everything You Need to Know about Lithium-Ion Batteries. 14 December 2021. Available online: https://verkor.com/en/everything-you-need-to-know-about-lithium-ion-batteries/ (accessed on 5 June 2022).
137. Xu, J.; Ding, C.; Chen, P.; Tan, L.; Chen, C.; Fu, J. Intrinsic self-healing polymers for advanced lithium-based batteries: Advances and strategies. *Appl. Phys. Rev.* **2020**, *7*, 031304. [CrossRef]
138. Narayan, R.; Laberty-Robert, C.; Pelta, J.; Tarascon, J.; Dominko, R. Self-Healing: An Emerging Technology for Next-Generation Smart Batteries. *Adv. Energy Mater.* **2022**, *12*, 2102652. [CrossRef]
139. European Commission. *Regulation of the European Parliament and of the Council Concerning Batteries and Waste Batteries, Repealing Directive 2006/66/EC and Amending Regulation (EU) No 2019/1020*; European Commission: Brussels, Belgium, 2020.
140. Global Battery Alliance. *A Vision for a Sustainable Battery Value Chain in 2030: Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation*; World Economic Forum: Geneva, Switzerland, 2019.
141. Zhengh, M. The Environmental Impacts of Lithium and Cobalt Mining. EARTH.ORG. 31 March 2023. Available online: https://earth.org/lithium-and-cobalt-mining/ (accessed on 21 October 2023).

142. Mancini, L.; Eslava, N.; Traverso, M.; Mathieux, F. *Responsible and Sustainable Sourcing of Battery Raw Materials*; Publications Office of the European Union: Luxembourg, 2020.
143. Campbell, M. In pictures: South America's 'Lithium Fields' Reveal the Dark Side of Our Electric Future. Euronews. Green. 1 February 2022. Available online: https://www.euronews.com/green/2022/02/01/south-america-s-lithium-fields-reveal-the-dark-side-of-our-electric-future (accessed on 21 October 2023).
144. Luong, J.; Tran, C.; Ton-That, D. A Paradox over Electric Vehicles, Mining of Lithium for Car Batteries. *Energies* **2022**, *15*, 7997. [CrossRef]
145. Tsuji, K. *Global Value Chains: Graphite in Lithium-ion Batteries for Electric Vehicles*; Office of Industries, US International Trade Commission: Washington, DC, USA, 2022.
146. Nate, S.; Bilan, Y.; Kurylo, M.; Lyashenko, O.; Napieralski, P.; Kharlamova, G. Mineral policy within the framework of limited critical resources and a green energy transition. *Energies* **2021**, *14*, 2688. [CrossRef]
147. Careaga, I. Raw Material Shortage: The New Big Challenge for the Battery Industry. CIC energiGUNE. 29 June 2022. Available online: https://cicenergigune.com/en/blog/raw-material-shortage-new-big-challenge-battery-industry (accessed on 5 January 2023).
148. Jiao, N. *Second-Life Electric Vehicle Batteries 2020–2030*; IDTechx: Tokyo, Japan, 2020.
149. Engel, H.; Hertzke, P.; Siccardo, G. Second-Life EV Batteries: The Newest Value Pool in Energy Storage. 30 April 2019. Available online: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage (accessed on 20 May 2023).
150. Huang, S.; Tseng, K.; Liang, J.; Chang, C.; Pecht, M. An online SOC and SOH estimation model for lithium-ion batteries. *Energies* **2017**, *10*, 512. [CrossRef]
151. Oji, T.; Zhou, Y.; Ci, S.; Kang, F.; Chen, X.; Liu, X. Data-driven methods for battery soh estimation: Survey and a critical analysis. *IEEE Access* **2021**, *10*, 126903–126916. [CrossRef]
152. Illa Font, C.H.; Siqueira, H.V.; Machado Neto, J.E.; Santos, J.L.F.D.; Stevan, S.L., Jr.; Converti, A.; Corrêa, F.C. Second Life of Lithium-Ion Batteries of Electric Vehicles: A Short Review and Perspectives. *Energies* **2023**, *16*, 953. [CrossRef]
153. Hossain, E.; Murtaugh, D.; Mody, J.; Faruque, H.; Sunny, M.; Mohammad, N. A comprehensive review on second-life batteries: Current state, manufacturing considerations, applications, impacts, barriers & potential solutions, business strategies, and policies. *IEEE Access* **2019**, *7*, 73215–73252.
154. Wei, Z.; Zhao, J.; He, H.; Ding, G.; Cui, H.; Liu, L. Future smart battery and management: Advanced sensing from external to embedded multi-dimensional measurement. *J. Power Sources* **2021**, *489*, 229462. [CrossRef]
155. Wei, Z.; Hu, J.; He, H.; Yu, Y.; Marco, J. Embedded distributed temperature sensing enabled multistate joint observation of smart lithium-ion battery. *IEEE Trans. Ind. Electron.* **2022**, *70*, 555–565. [CrossRef]
156. European Commission. Green Deal: EU Agrees New Law on More Sustainable and Circular Batteries to Support EU's Energy Transition and Competitive Industry. 9 December 2022. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7588 (accessed on 25 May 2023).
157. Halleux, V. *New EU Regulatory Framework for Batteries*; European Parliamentary Research Service: Brussels, Belgium, 2023.
158. Gaines, L. Lithium-ion battery recycling processes: Research towards a sustainable course. *Sustain. Mater. Technol.* **2018**, *17*, e00068. [CrossRef]
159. Duan, L.; Cui, Y.; Li, Q.; Wang, J.; Man, C.; Wang, X. Recycling and direct-regeneration of cathode materials from spent ternary lithium-ion batteries by hydrometallurgy: Status quo and recent developments: Economic recovery methods for lithium nickel cobalt manganese oxide cathode materials. *Johns. Matthey Technol. Rev.* **2021**, *65*, 431–452. [CrossRef]
160. EUROBAT. *Battery Innovation—Roadmap 2030*; Version 2.0; EUROBAT: Brussels, Belgium, 2022.