Mater Eng Res, 2023, 5(1): 265-278
DOI: 10.25082/MER.2023.01.003

REVIEW

Revolutionizing energy storage: Overcoming challenges and unleashing the potential of next generation Lithium-ion battery technology

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Received: April 23, 2023;
Accepted: June 19, 2023;
Published: July 3, 2023.

Citation: Ahmed MD and Maraz KM. Revolutionizing energy storage: Overcoming challenges and unleashing the potential of next generation Lithium-ion battery technology. *Mater Eng Ress*, 2023, **5**(1): 265-278. https://doi.org/10.25082/MER.2023.01.003

Abstract: Lithium-ion (Li-ion) batteries have become the leading energy storage technology, powering a wide range of applications in today's electrified world. This comprehensive review paper delves into the current challenges and innovative solutions driving the supercharged future of lithium-ion batteries. It scrutinizes the limitations of energy density in existing batteries, exploring advanced electrode materials and designs that promise higher capacity. Safety concerns take center stage, with a focus on cutting-edge thermal management systems and materials. The imperative of sustainable sourcing is addressed, highlighting alternative materials and recycling strategies for a greener supply chain. Transformative breakthroughs, such as solid-state electrolytes and emerging battery chemistries, offer glimpses of the future. The paper also examines the applications and market perspectives of lithium-ion batteries in electric vehicles, portable electronics, and renewable energy storage. It concludes by emphasizing the transformative potential of lithium-ion batteries in accelerating the energy revolution and paving the way for a sustainable energy future.

Keywords: Li-ion battery (LIB), safety for thermal runaway, solid state LIB, next generation LIB, raw material obstacles, recycling strategies

1 Introduction

The world is undergoing an incredible energy revolution, driven by the urgent need for sustainable and clean energy solutions. As renewable energy sources like solar and wind power continue to gain prominence, the demand for effective energy storage systems has skyrocketed [1,2]. In this transformative landscape, lithium-ion batteries have emerged as the leading energy storage technology, playing a crucial role in bridging the energy revolution and paving the way for a future powered by renewable energy.

The energy revolution is fueled by the growing need for energy storage to harness and optimize the intermittent nature of renewable energy sources. While renewable energy offers abundant and environmentally friendly alternatives, their variability poses significant challenges. Reliable and efficient energy storage solutions are therefore essential to capture excess energy during peak production and release it during periods of high demand or when renewable sources are unavailable [3–5]. The global renewable energy capacity has been increasing rapidly, with a forecasted rise of more than 60% from 2020 levels to over 4,800 GW by 2026 [6]. In the next five years, renewable energy sources are projected to contribute to more than 90% of the global electricity expansion. This growth will surpass coal as the leading source of electricity globally, making renewables the largest contributor to the global electricity supply. However, the share of renewable energy in global electricity generation stood at only 28%, indicating a significant gap between potential and actual utilization [7]. In the United States, wind and solar power generation achieved a record high of 8.5% of total electricity generation in 2022, but their intermittent nature led to a combined capacity factor of just 31%. A study revealed that without energy storage, up to 40% of renewable energy in the UK would be curtailed due to generation-demand mismatches. To address this, the US National Renewable Energy Laboratory estimates that the US will require 180-260 GW of energy storage by 2050 [8]. Furthermore, the global energy storage market is expected to reach a staggering 1,095 GW by 2040 [9]. These statistics underscore the pressing need for energy storage systems to bridge the gap between renewable energy generation and power demand, enabling a reliable, stable, and sustainable energy future.

Enter lithium-ion batteries, which have quickly risen to prominence due to their exceptional properties and performance characteristics. Lithium-ion batteries surpass other commercially available rechargeable batteries in terms of both gravimetric and volumetric energy. Figure 1 presents a clear comparison of energy densities among various rechargeable batteries, highlighting the superior performance of lithium-ion batteries in comparison to their counterparts [10, 11]. Due to their exceptional attributes such as high energy density, long cycle life, and fast charging capabilities, lithium-ion batteries have emerged as the preferred choice for a broad spectrum of energy storage applications.

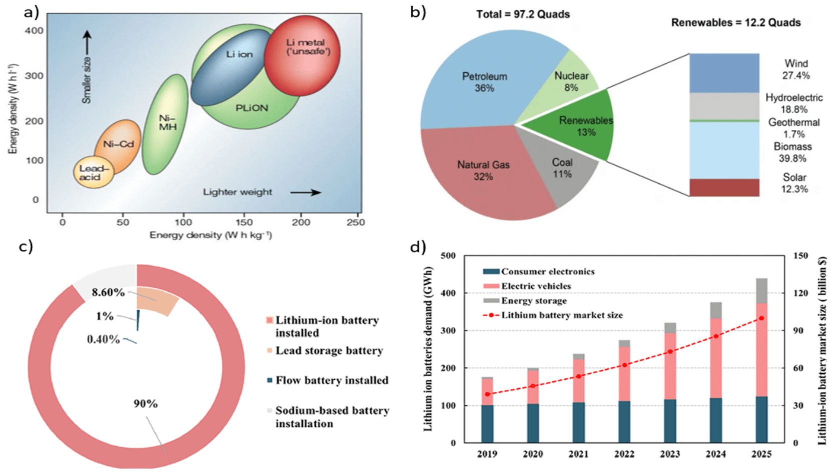


Figure 1 a). Examining the energy densities and specific energy of various rechargeable batteries for comparison purposes [10, 11]; b). U.S. Total and Renewable Energy Consumption by source; c). distribution of installed capacity among different electrochemical energy storage technologies [12]; d). the anticipated demand for lithium-ion batteries across different applications and the forecasted market size from 2019 to 2025 [12].

The significance of lithium-ion batteries in the energy revolution cannot be overstated. They act as a bridge, connecting renewable energy generation with energy demand, ensuring a stable and reliable energy supply. By enabling the seamless integration of renewable sources, lithium-ion batteries contribute to the reduction of greenhouse gas emissions and facilitate the transition to a low-carbon energy system. Based on a comprehensive analysis of life cycle assessment studies, it has been found that the greenhouse gas (GHG) emissions per kWh of lithium-ion battery cell production can potentially decrease from 41 to 89 kg CO_2 in 2020 to a range of 10-45 kg CO_2 in 2050. This reduction can primarily be attributed to the transition towards low-carbon electricity sources [13–15]. Furthermore, these batteries enhance the resilience and flexibility of the power grid, supporting the development of microgrids and off-grid systems [16].

In this review paper, we aim to explore the challenges faced by lithium-ion batteries and present innovative solutions to overcome these hurdles. Our focus includes increasing energy storage capacity, improving safety features, diversifying raw materials, and enhancing sustainability in battery production and disposal. Additionally, we delve into emerging technologies and future prospects that hold the potential to unlock the full power of lithium-ion batteries and shape the energy landscape of tomorrow.

2 Current challenges: Unveiling the roadblocks

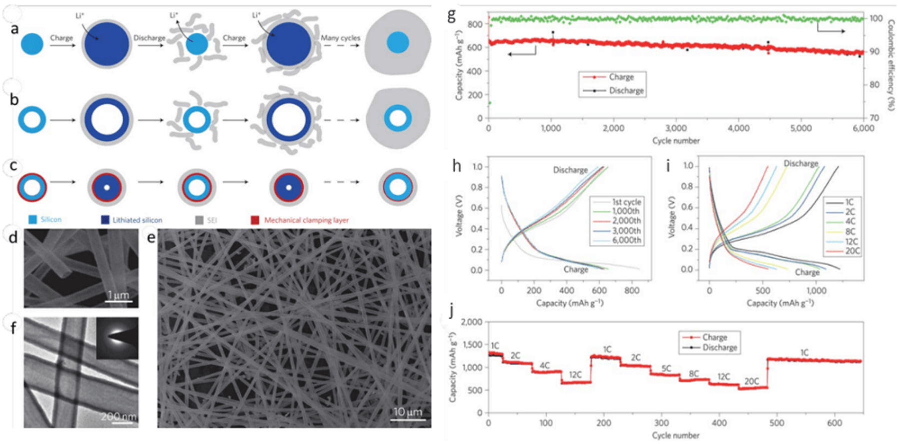
The rapid growth in energy demands calls for the development of energy storage systems having high-energy-density. However, current technologies face challenges in achieving the desired energy density, presenting a significant hurdle.

2.1 Limitations of current energy storage capacity

Despite notable progress in energy storage systems, such as lithium-ion batteries, there are inherent limitations in energy density that impede their overall performance. Traditional electrode materials like graphite have moderate energy storage capabilities, which fall short of meeting the growing demands of various applications. Additionally, factors such as intercalation chemistry, electrolyte composition, separator materials, and cell packaging contribute to the overall energy density limitations [17, 18].

2.1.1 Advanced electrode materials

To address the energy density enigma, researchers are exploring advanced electrode materials that offer higher energy storage capabilities. One such material is silicon, which possesses a high theoretical capacity for energy storage. Silicon-based anodes in lithium-ion batteries show great promise in achieving significantly higher energy densities (up to 4000 mAh/g) compared to conventional graphite-based anodes (372 mAh/g) [19, 20]. However, the challenge lies in mitigating the volume expansion of silicon during cycling, which leads to electrode degradation and performance deterioration. Researchers are actively investigating innovative approaches, including Nano structuring and composite designs, to overcome these challenges and fully exploit the potential of silicon-based anodes [19, 21, 22]. Silicon nanotubes have emerged as a potential solution for improving the performance of lithium-ion battery anodes. Park et al. addressed the limited surface area issue by fabricating silicon nanotubes with a carbon coating, stabilizing the solid electrolyte interphase (SEI) film and enhancing capacity retention [23]. Wu et al. introduced a double-walled structure using a silicon oxide (SiOx) confining layer around the outer wall of the nanotubes. This approach allows lithium ions to pass through the SiOx layer while preventing electrolyte contact with components other than the SiOx layer, preserving the SEI layer and preventing electrode degradation [24]. The double-walled silicon nanotubes (DWSiNT) demonstrate excellent stability, with reversible capacities of around 3200 mAh/g and high-capacity retention of approximately 89% over 200 cycles [23]. The SiOx confining layer in DWSiNT prevents outward expansion during lithiation, maintaining the integrity of the SEI layer and exhibiting a stable voltage profile throughout thousands of cycles. These findings highlight the significant potential of silicon nanotubes in enhancing the performance and lifespan of lithium-ion batteries [21, 23, 24]. (see Figure 2)



Notes: (a-c) illustrates the impact of constant expansion on the solid electrolyte interphase (SEI) layer during multiple charge and discharge cycles for (a) a solid silicon nanowire, (b) a silicon nanotube without a confining layer, and (c) a silicon nanotube with a confining layer. (d,e) SEM images showcase the synthesized double-walled silicon nanotubes (DWSiNTs) at different magnifications, highlighting their uniform hollow structure and smooth tube walls.(f) TEM image provides further insight into the DWSiNTs' unique structure. (g) lithiation/delithiation capacity and coulombic efficiency of the DWSiNTs cycled at a high rate for 6,000 cycles, demonstrating excellent stability. (h) The voltage profiles for the 1st, 1,000th, 2,000th, 3,000th, and 6,000th cycles exhibit consistent behavior over the extended cycling period. (i) Galvanostatic charge/discharge profiles (j) and capacity retention for DWSiNT anodes cycled at different rates from 1C to 20C are also presented. This figure, adapted from references [21, 23, 24], offers valuable insights into the performance and characteristics of DWSiNTs.

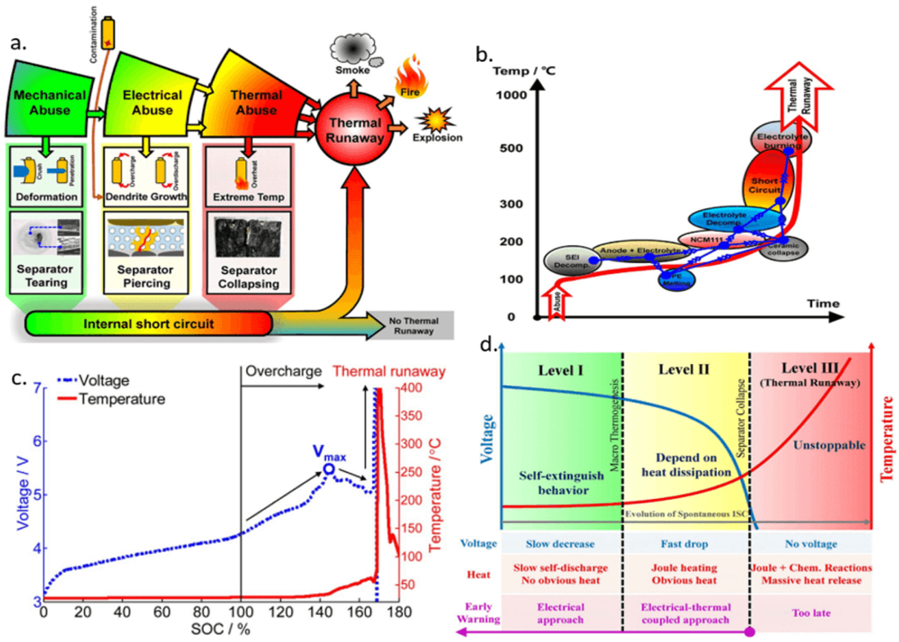
Figure 2 Advanced electrode materials to overcome the current energy storage capacity

In addition to silicon, other materials such as lithium metal, sulfur, and transition metal oxides are also being explored for their ability to enhance energy density. Lithium metal, for instance, exhibits a high specific capacity and has the potential to significantly boost energy density. Sulfur cathodes have shown energy densities of up to 1500 mAh/g, owing to their ability to undergo multiple electron transfer reactions [25]. Transition metal oxides, particularly nickel-rich layered oxide cathodes, have also exhibited promising results in improving energy density due to their high specific capacity and stability during cycling [26, 27].

2.2 Thermal runaway and safety concerns in Lithium-ion batteries

As lithium-ion batteries continue to revolutionize energy storage, ensuring their safety becomes paramount. The potential risks associated with thermal runaway and safety concerns demand comprehensive investigation and advanced mitigation strategies. Thermal runaway, a critical safety issue, occurs when the battery's temperature rises uncontrollably, leading to a self-sustaining and potentially hazardous chain reaction [28]. Factors such as overcharging, external heat sources, manufacturing defects, and mechanical damage can trigger this phenomenon [29].

The release of flammable electrolytes and gases during thermal runaway can cause fires or explosions, posing, risks to both users and the surrounding environment [31, 32]. (see Figure 3)



Notes: a). Incidents associated with the malfunction of lithium-ion batteries, and the corresponding circumstances of misuse b). Qualitative interpretation of the chain reactions during thermal runaway c). Results of overcharge induced thermal runaway for a commercial lithium-ion battery in different state of charge (SOC) d). Three level of the internal short circuit [30].

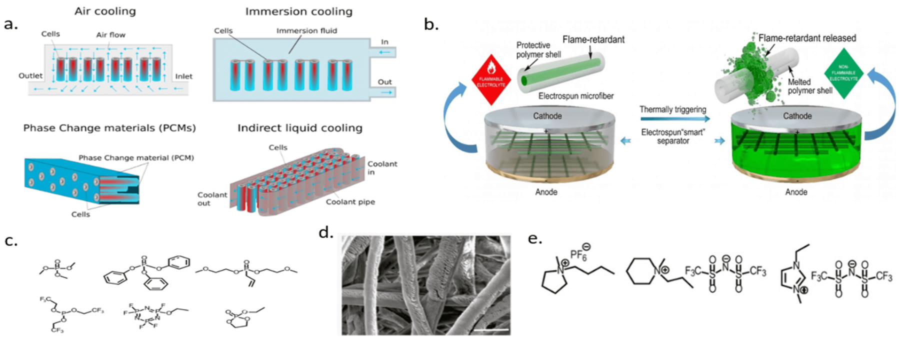
Figure 3 Thermal runaway mechanism of lithium-ion battery

Lithium-ion batteries pose safety concerns due to mechanical, electrical, and thermal abuse. Mechanical abuse can trigger electrical abuse, which can release heat and induce thermal abuse (Figure 3a). Therefore, reliable test approaches are needed to update the test standards and ensure product safety. The internal short circuit (ISC) is a common feature of all types of abuse conditions, and different abuse conditions correspond to different types of ISC [30]. The spontaneous ISC is the most challenging problem to be solved as it evolves throughout the battery's cycle life. There are three levels of ISC, and early detection is crucial before it develops into the third level, *i.e.*, thermal runaway (TR) (Figure 3d). The mechanisms of chain reactions during TR have been reviewed in Figure 3b [30]. Lithium-ion batteries have a high energy density, making them susceptible to hazards such as fast charging, high or low operating temperatures, and mechanical abuse. Therefore, it is essential to develop battery safety standards and regulations to mitigate these hazards.

2.2.1 Advancements in thermal management systems and materials

Advancements in thermal management systems and materials have played a pivotal role in addressing the safety concerns associated with lithium-ion batteries. To mitigate the risks of thermal runaway, significant progress has been made in developing advanced thermal management systems. These systems employ techniques such as active cooling, passive cooling, and thermal insulation to effectively dissipate heat and maintain optimal battery temperature. Liquid cooling, phase-change materials, and heat pipes have emerged as promising methods for efficiently managing battery temperature and mitigating thermal runaway risks (Figure 4a) [33, 34]. A novel electrospun separator for lithium-ion batteries, known for its intelligent features, incorporates thermal-triggered flame-retardant properties. This separator stands independently and consists of microfibers arranged in a core-shell structure, as shown in Figure 4b. The core of the separator contains flame retardant, while the shell is composed of a protective polymer. By encapsulating the flame retardant within the polymer shell, direct exposure and dissolution of the flame retardant into the electrolyte are prevented. This safeguard ensures that the flame retardant does not adversely affect the battery's electrochemical performance. When exposed to heat, the polymer shell undergoes melting, allowing the encapsulated flame retardant to be released into the electrolyte. As a result, the ignition and combustion of the electrolytes are effectively suppressed [33, 35, 36].

Additionally, flame-retardant additives and intumescent coatings have emerged as promising materials to enhance battery safety, addressing the critical issue of thermal runaway. Flame-retardant additives effectively suppress or delay the spread of thermal runaway, while intumescent coatings form protective barriers against heat and flames. These innovative developments provide crucial safeguards, ensuring the ongoing progress of safer and more reliable lithium-ion battery technologies [36, 37]. Furthermore, significant advancements in separator technology, which serves as a vital safety component within lithium-ion batteries, have further contributed to enhancing overall battery safety [38]. Despite these notable achievements, it is important to acknowledge that safety concerns still exist in lithium-ion batteries, and further research and improvements are required in this field.



Notes: a). Different thermal management system b). illustrating the design of an intelligent electrospun separator with flame-retardant properties that are activated by heat for lithium-ion batteries (LIBs) c). Common molecular structure of flame-retardant additives d). SEM image clearly reveals the core-shell structure of the TPP@PVDF-HFP microfibers after etching, with a scale bar indicating a size of 5 μm. e). Typical molecular structures of room temperature ionic liquid used as nonflammable electrolytes for LIBs Figure is adapted from Ref [33, 35, 36]

Figure 4 Thermal management system of Li ion battery

2.3 Sustainable sourcing: Breaking free from raw material constraints

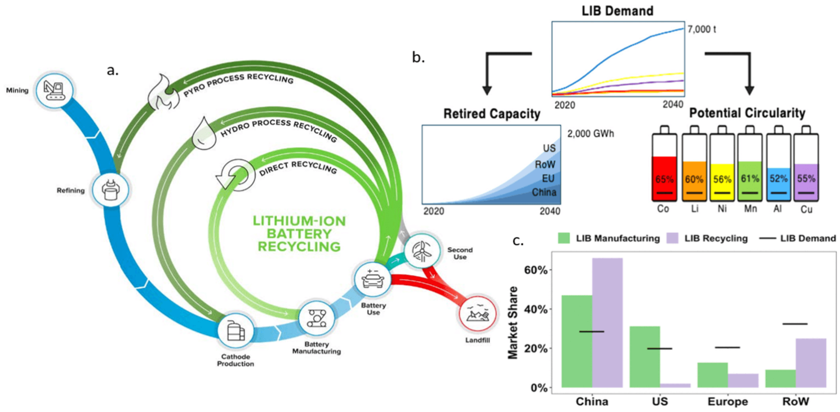
2.3.1 Reliance on scarce materials and geopolitical implications

The production of lithium-ion batteries heavily relies on certain critical raw materials, with cobalt being a primary example. Cobalt is predominantly sourced from regions with geopolitical uncertainties and often involves ethical and environmental concerns. The limited availability and geopolitical risks associated with these materials pose significant challenges to the sustainability and stability of the supply chain. The lithium-ion battery industry heavily depends on the extraction of raw materials and the manufacturing of batteries. Unfortunately, both processes are susceptible to disruptions in the supply chain. Currently, the production of lithium is concentrated in a few countries, namely Chile, Australia, Argentina, and China. This reliance on foreign sources of materials is expected to persist in the coming years, unless there are significant advancements in battery technology that reduce or eliminate the need for rare earth metals [39, 40].

2.3.2 Alternative materials for a sustainable supply chain

Extensive research efforts are currently focused on identifying alternative materials that can mitigate the reliance on scarce resources without compromising the performance of lithium-ion batteries. One promising approach involves minimizing or eliminating the use of cobalt in battery chemistries. Nickel-rich cathode materials, such as nickel-cobalt-aluminum (NCA) and nickel-manganese-cobalt (NMC) chemistries, are emerging as viable cobalt-free or cobalt-reduced options. These cathode materials demonstrate comparable energy density to traditional formulations while offering improved cost-effectiveness and reduced dependence on scarce cobalt resources [36]. In addition to these efforts, other alternatives to lithium-ion batteries, including sodium-ion batteries, silicon-based batteries, magnesium-based batteries, seawater batteries, salt-based batteries, and iron-based batteries, are also being explored. However, it is important to note that these alternative technologies are still in the research and development phase and have not yet reached commercialization [41, 42].

In Figure 5b, the market share of LIB (Lithium-ion Battery) material demand is illustrated by dashes, while the market share of LIB manufacturing and LIB recycling is depicted by columns. This representation provides an overview of the changing market dynamics and the respective shares of these sectors from 2010 to 2040 in the baseline scenario. Utilizing material flow analysis, researchers have made estimations regarding the potential global and regional circularity of various materials found in pack-level components such as lithium, cobalt, nickel, manganese, iron, aluminum, copper, and graphite. These estimations also account for different scenarios, including changes in battery cathode chemistries and the demand for electric vehicles. Under ideal circumstances, it is projected that retired batteries could contribute to 60% of global cobalt supply, 53% of lithium supply, 57% of manganese supply, and 53% of nickel supply by the year 2040. Moreover, if the current trajectory of cathode chemistries continues to favor NMC 811, a low-cobalt chemistry, there is a potential to achieve 85% global circularity of cobalt by the year 2040. Conversely, if the market shifts away from cathodes containing cobalt and leans towards an LFP-dominated market, the importance of cobalt, manganese, and nickel diminishes, resulting in circularity being achieved prior to 2040 [43].



Notes: a). Recycling Strategies of Li ion batteries for a Circular Economy (Image by ReCell Center) b). Circularity of Lithium-Ion Battery Materials in Electric Vehicles c). LIB manufacturing processes versus material demand. This figure is adapted from Ref [43].

Figure 5 Sustainable Sourcing, alternative source of raw materials and recycling strategies of Li-ion batteries

2.3.3 Recycling strategies for a circular economy

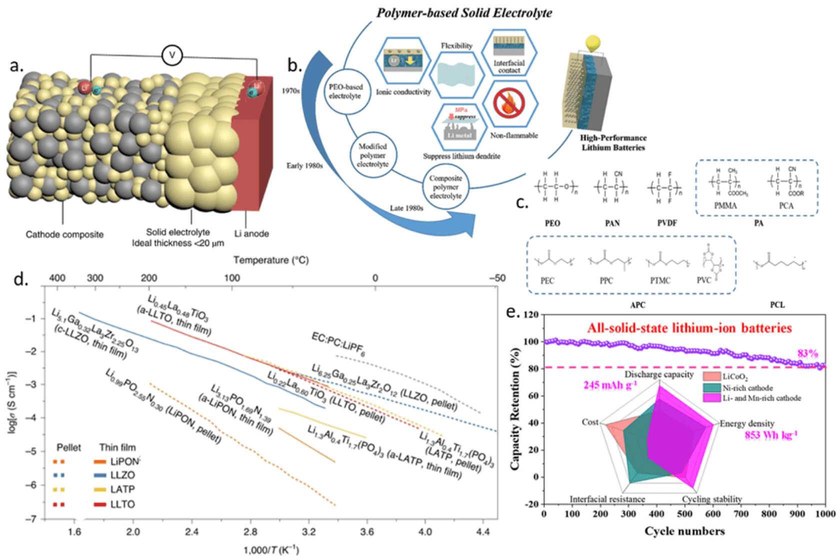
Efficient recycling strategies for lithium-ion batteries are crucial for reducing reliance on primary raw materials and minimizing environmental impacts. Advanced recycling technologies, such as pyrometallurgy, hydrometallurgy, and bio metallurgy (Figure 5a), allow for the recovery of valuable metals like cobalt, lithium, and nickel from spent batteries [44]. This closed-loop approach promotes a sustainable and circular economy by reusing these metals in the production of new batteries [45]. Proper disposal of used batteries is important, and they should be taken to separate recycling or household hazardous waste collection points to ensure safe handling and minimize environmental harm. Circular economy strategies, such as reuse and recycling, can reduce the environmental impacts of battery production and secure regional supplies. Researchers have proposed four potential circular economy strategies for electric vehicle batteries: reduction or elimination of cobalt in batteries, reuse, recycling, and a closed-loop battery recycling system [43]. Recycling battery components is crucial to avoid the discharge of toxic metals and materials from discarded batteries into the environment. By embracing efficient recycling methods, we can contribute to a climate-neutral circular economy and address the increasing demand for sustainable energy storage solutions [46]. Those recycling technologies not only address raw material constraints but also reduce the environmental footprint associated with primary material extraction.

3 Innovations at the frontier: Transforming Lithium-ion batteries

The future of lithium-ion batteries holds immense promise, with innovations at the forefront aiming to transform their performance. One such innovation is the advent of solid-state electrolytes, which offer improved safety and energy density compared to traditional liquid electrolytes [47]. In this article, we delve into the potential of solid-state electrolytes, exploring their role in enhancing battery safety, energy density and challenges associated with the commercialization of solid-state batteries.

3.1 Solid-State revolution: Solidifying the future for enhanced safety and energy density

Solid-state electrolytes have indeed shown great potential in revolutionizing lithium-ion battery technology. They offer numerous advantages, such as improved safety, stability, and compatibility with lithium-ion battery materials [48–50]. Sulfide-based solid-state electrolytes have achieved ionic conductivities exceeding 10 mS/cm, which is comparable to or even surpassing liquid electrolytes [51]. This high ionic conductivity is essential for enabling fast charging and discharging rates in solid-state batteries. Oxide-based solid-state electrolytes also demonstrate high ionic conductivity (10^{-3} to 10^{-4} S cm^{-1}) and good chemical stability against Li metal [52]. Polymer-based solid-state electrolytes (PSEs) are lightweight, flexible, nonflammable, and have high energy density [53, 54]. Solid-state batteries utilizing oxide-based electrolytes have achieved energy densities exceeding 400 Wh/kg, surpassing the energy density of conventional lithium-ion batteries [49]. This makes them suitable for various applications, including electric vehicles and portable electronics. Researchers have also designed a stable, lithium-metal, solid-state battery that can be charged and discharged at least 10,000 times at a high current density, demonstrating the potential for long-lasting solid-state batteries. However, there are still challenges to overcome before solid-state batteries can be commercialized. These challenges include improving the stability of sulfide-based solid-state electrolytes in air and their compatibility with solvents and binders [55]. Additionally, increasing the critical current density of solid-state batteries is crucial for meeting the demands of modern battery applications, such as fast charging for electric vehicles [56]. (see Figure 6)



Notes: a). Typical architecture of a Li metal-based Solid-state battery (SSB) b). Development and main challenges of typical polymer-based solid electrolytes for high-performance lithium batteries c). Common polymers for solid state polymer electrolyte d). Li-ion conductivities of Li-oxide-based solid-state electrolytes in pellet and thin-film form compared with that of the state-of-the-art liquid electrolyte EC: PC: $LiPF_6$ e). benefit of Solid-state Li ion battery in terms of cost, energy density. Cycle stability and safety. This figure is adapted from ref [48, 53, 57].

Figure 6 Evaluation of solid-state Li ion battery for enhancing safety and energy density

Solid-state electrolytes, including sulfide-based, oxide-based, and polymer-based electrolytes, have shown promising characteristics for the next generation of batteries. Their improved safety, stability, and compatibility with lithium-ion battery materials make them strong candidates for various applications. However, further research and development are needed to address the remaining challenges and enable the commercialization of solid-state batteries.

3.1.1 Progress and challenges in commercializing solid-state batteries

Solid-state batteries hold immense potential for energy storage, but their commercialization poses significant challenges. Achieving high ionic conductivity in solid-state electrolytes is crucial for optimizing battery performance. Researchers are continuously working on developing novel solid-state electrolyte compositions and structures to enhance ionic conductivity. Additionally, ensuring good interfacial stability between the solid-state electrolyte and electrode materials is crucial for long-term battery performance. Furthermore, scaling up the production of solid-state batteries and reducing manufacturing costs remain significant hurdles. The synthesis and fabrication processes for solid-state electrolytes and electrodes need further optimization to achieve cost-effective mass production. Ensuring the long-term reliability and cycle life of solid-state batteries is another aspect that requires extensive research and development efforts [58, 59].

3.2 Next generation battery: Emerging battery chemistries

The future of lithium-ion batteries lies not only in optimizing existing technologies but also in exploring alternative battery chemistries that offer enhanced performance and capabilities.

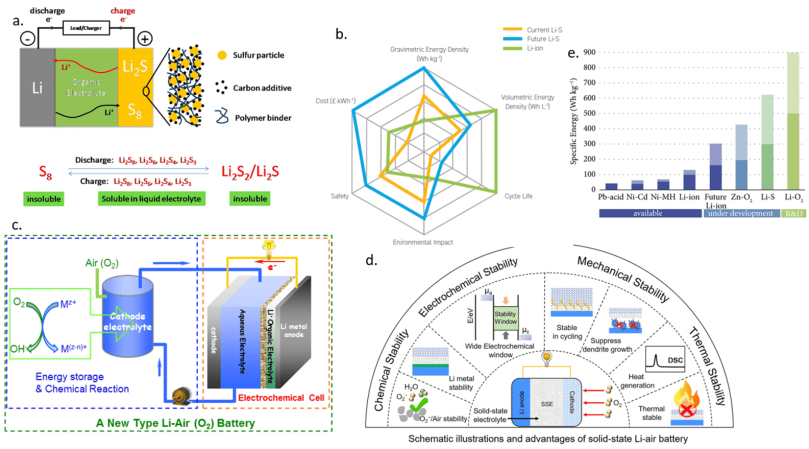
Emerging battery chemistries, such as lithium-sulfur (Li-S) and lithium-air (Li-Air) batteries, have the potential to revolutionize energy storage due to their high energy densities and the use of abundant, low-cost materials [60, 61]. These next-generation technologies could significantly extend the range of electric vehicles and increase the runtime of portable electronic devices.

3.2.1 Lithium-Sulfur (Li-S) batteries

Lithium-sulfur batteries have gained significant attention due to their high theoretical energy density, which surpasses that of conventional lithium-ion batteries. The combination of a lithium anode and a sulfur cathode enables a reversible electrochemical reaction, resulting in the storage and release of large amounts of energy. Li-S batteries also benefit from the abundance and low cost of sulfur as a raw material [62].

3.2.2 Lithium-Air (Li-Air) batteries

Lithium-air batteries, also known as lithium-oxygen batteries, represent another promising next-generation technology. These batteries utilize a lithium anode and an air cathode, with oxygen from the air participating in the electrochemical reactions. Li-Air batteries have the potential to achieve significantly higher energy densities compared to lithium-ion batteries, as they utilize oxygen as the cathode material instead of transition metal oxide [63]. (see Figure 7)



Notes: a). Typical mechanism of Li-S battery: Charging and discharging b). benefit of Li-S battery over LI ion battery c). recent mechanism of new Li-air battery e). energy density comparison of Li-S and Li-air battery over market available batteries. This figure is adapted from ref [63–65].

Figure 7 Next generation of Li-ion battery: Advantage of Li S and Li air battery

3.2.3 Advantages and technical hurdles

Lithium-sulfur and lithium-air batteries offer several advantages over conventional lithium-ion batteries. Their high energy densities hold the potential to significantly extend the range of electric vehicles and increase the runtime of portable electronic devices. Moreover, the abundant and low-cost nature of sulfur and the use of air as a cathode material make these technologies economically attractive. However, both Li-S and Li-Air batteries face significant technical hurdles that hinder their commercialization. For Li-S batteries, challenges include the dissolution of polysulfides in the electrolyte, which leads to capacity fading and limited cycling stability. Additionally, the low electrical conductivity of sulfur and the volume expansion during cycling pose mechanical integrity and electrode stability issues. In the case of Li-Air batteries, one major challenge is the formation and decomposition of lithium peroxide (Li2O2) during discharge and charge cycles, which can lead to irreversible reactions and decreased performance. Additionally, the sluggish oxygen reduction and evolution reactions at the cathode require efficient catalysts and air electrode designs.

4 Applications and market perspectives: Powering the world

Lithium-ion batteries have become increasingly pivotal in the transition towards clean and sustainable energy, particularly in the applications of electric vehicles (EVs) and renewable energy storage. The adoption of EVs is a crucial step towards reducing carbon emissions and achieving sustainable transportation. Lithium-ion batteries play a vital role in powering EVs, offering high energy density, long cycle life, and fast charging capabilities [66, 67]. However, widespread adoption of EVs faces challenges related to infrastructure. The establishment of a robust charging infrastructure network is essential to alleviate range anxiety and promote EV adoption. Moreover, the limited availability of fast-charging stations and the time required for recharging pose hurdles for EV users. Disruptive technologies, such as solid-state batteries and fast-changing technologies, hold the potential to address these challenges by significantly reducing charging times and increasing the convenience of EV ownership [66–68].

In addition to EVs, lithium-ion batteries are also utilized for efficient and reliable integration of renewable energy sources, focusing on grid-scale applications and advancements in energy management systems [16, 69]. The role of batteries in the context of renewable energy is particularly significant due to the variable nature of sources like solar and wind power, which generate varying amounts of energy. Batteries play a crucial role in storing electricity during times when there is no wind, the sun is obscured by clouds, or during nighttime, enabling continuous operation. Lithium-ion batteries, in particular, possess the capability to safely store substantial amounts of energy, ensuring stable and predictable electricity flows even in decentralized and stationary applications.The integration of battery storage assists renewable generators in seamlessly connecting with existing power grids by storing excess generation and facilitating smoother energy distribution. Batteries can store surplus solar and wind power, subsequently distributing it when needed. As more battery installations are established, electrical grids become better equipped to accommodate higher levels of renewable energy, surpassing the demand for grid electricity on exceptionally sunny or windy days. This is made possible as batteries enable the long-term storage of energy, allowing for a more balanced and reliable energy supply [16, 66–70]. Overall, lithium-ion batteries have become a critical pillar for building a fossil fuel-free economy. (see Figure 8)

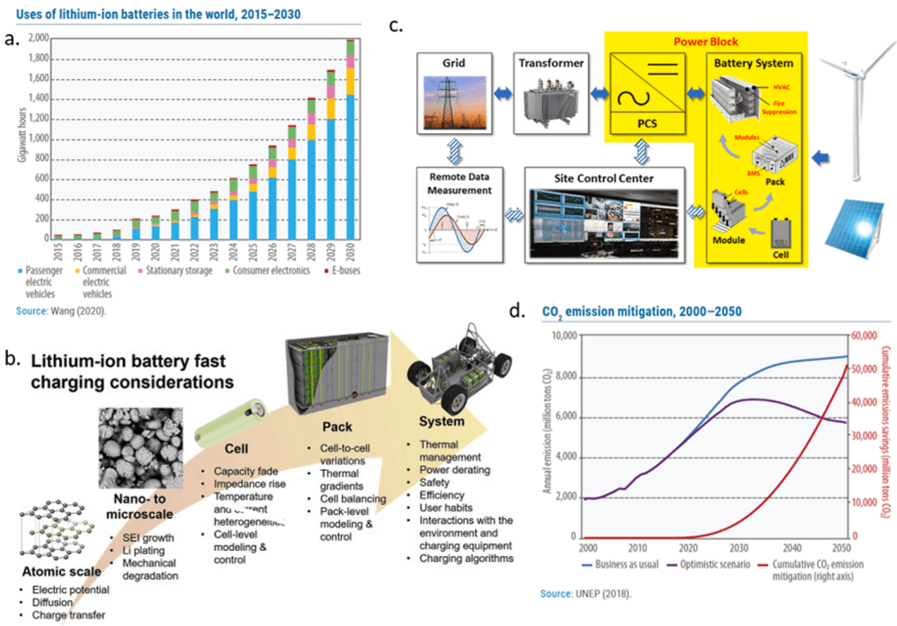


Figure 8 Current market of LIB. a). LIB most used in electric vehicles (EVs) b). advancement of Fast charging process of LIB c). Li-ion battery technology for grid application d). Reduction of CO_2 emission due to EVs. This figure is adopted from ref [66, 69].

The continuous advancement of lithium-ion battery technology has resulted in improved driving ranges and enhanced performance, contributing to the growing popularity of EVs. Moreover, the utilization of lithium-ion batteries for efficient and reliable integration of renewable energy sources has become increasingly important in the transition towards clean and sustainable energy.

5 Future Outlook: Accelerating the energy revolution

The future of lithium-ion batteries is expected to witness significant advancements and breakthroughs across various fronts. Researchers and scientists are actively exploring novel electrode materials, such as silicon, lithium-sulfur, and lithium-air, to enhance energy density, extend battery life, and improve overall performance [71]. Advances in nanotechnology and material engineering are enabling the development of new electrode architectures and interfaces, further pushing the boundaries of lithium-ion battery capabilities. Moreover, the quest for safer batteries continues, with a particular focus on solid-state electrolytes. Solid-state batteries offer enhanced safety, improved energy density, and wider operating temperature ranges [72]. Ongoing research aims to overcome technical challenges related to electrolyte conductivity, interfacial stability, and scalability, paving the way for the commercialization of solid-state batteries. (see Figure 9)

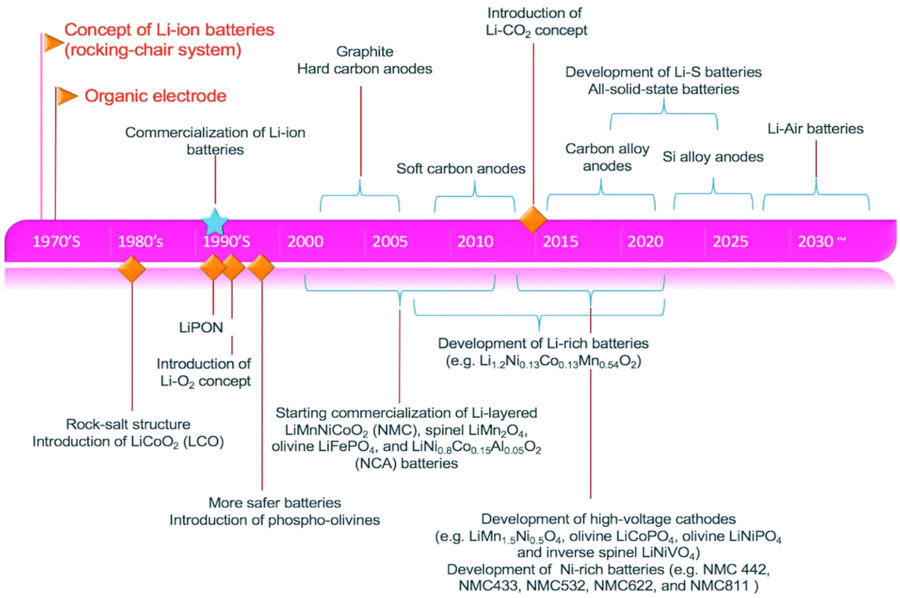


Figure 9 The growth and advancement of lithium-ion battery technology over time. Figure is adopted from ref [73]

5.1 Policy considerations, investment trends, and potential hurdles

The widespread adoption of lithium-ion batteries requires a supportive policy landscape and substantial investments. Governments worldwide are recognizing the importance of energy storage and implementing policies to incentivize the development and deployment of advanced battery technologies. These policies include research funding, tax incentives, and regulations promoting clean energy adoption. Investment trends also play a vital role in shaping the future of lithium-ion batteries. The increasing demand for electric vehicles, renewable energy integration, and portable electronics is driving significant investments in battery manufacturing capacity and technology development. Collaborations between battery manufacturers, research institutions, and governments are fostering innovation and accelerating the scale-up of production [74, 75].

Despite the positive outlook, several potential hurdles remain. The reliance on raw materials, such as lithium, cobalt, and nickel, raises concerns about resource availability and ethical sourcing. Efforts to diversify the materials used in lithium-ion batteries, improve recycling technologies, and develop alternative battery chemistries are essential for long-term sustainability. Additionally, challenges related to safety, cost reduction, and charging infrastructure must be addressed to achieve mass adoption. Continuous improvements in battery safety, such as early detection of thermal runaway and the development of robust safety mechanisms, are crucial. Cost reduction through economies of scale, advancements in manufacturing processes, and materials innovation will contribute to making lithium-ion batteries more affordable for various applications. Furthermore, expanding the charging infrastructure network and developing fast-changing technologies will alleviate range anxiety and enhance the convenience of electric vehicles [76–78].

6 Conclusion

Unleashing the potential of lithium-ion batteries is crucial for bridging the energy revolution and paving the way towards a supercharged future. This review paper has highlighted the transformative capabilities of lithium-ion batteries in shaping our energy landscape, while also addressing the challenges and innovative solutions needed to overcome them. Energy density remains a significant challenge, with current lithium-ion batteries having energy densities ranging from 100-265 Wh/kg. Novel electrode materials and designs are required to transcend the limitations of current energy storage capacity and unlock the full potential of renewable energy sources and electric vehicles. Safety concerns, such as thermal runaway events, must not be overlooked. Advancements in thermal management systems and materials are paramount to ensuring the wider adoption of lithium-ion batteries and mitigating the risk of fires and explosions. Sustainable sourcing is an ethical obligation that must be embraced. The scarcity of raw materials like cobalt calls for the exploration of alternative materials and recycling strategies. By doing so, we can forge a sustainable supply chain that mitigates environmental impact and fosters a greener energy future. Solid-state batteries offer enhanced safety and energy density, revolutionizing the lithium-ion battery landscape. Overcoming commercialization hurdles is essential to bring this promising technology to the forefront. Additionally, exploring beyond lithium, such as lithium-sulfur and lithium-air batteries, unveils a world of possibilities, albeit accompanied by technical challenges that demand our attention and ingenuity. Adopting a green by design approach, eco-friendly electrode materials, and electrolytes demonstrate our commitment to sustainability Applications in electric vehicles, portable electronics, and renewable energy storage illustrate the transformative impact of lithium-ion batteries in powering the world.

However, infrastructure challenges and the emergence of disruptive technologies call for continuous innovation and collaboration to fully realize their potential. Looking towards the future, a collective effort encompassing policy considerations, investment trends, and overcoming potential hurdles is essential. By doing so, we can propel the energy revolution forward, accelerating the adoption of lithium-ion batteries and witnessing the dawn of a new era in energy storage. In conclusion, the journey towards unleashing the potential of lithium-ion batteries is fraught with challenges, but it is through innovative solutions that we can overcome these hurdles. With their transformative capabilities, lithium-ion batteries stand at the forefront of the energy revolution, poised to shape a sustainable and supercharged future. Let us embark on this transformative path, empowering the energy revolution and embracing the boundless possibilities that lie ahead.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We would like to express our sincere appreciation and gratitude to the University of Tennessee, Knoxville, USA and the Institute of Radiation and Polymer Technology, Bangladesh Atomic Energy Commission, Dhaka, Bangladesh for their invaluable resources and unwavering support throughout the course of this research.

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