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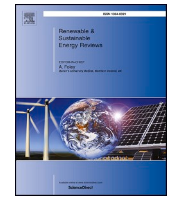

Lithium-ion batteries and the future of sustainable energy: A comprehensive review

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A R T I C L E I N F O

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A B S T R A C T

Lithium-ion batteries (LIBs) have become a cornerstone technology in the transition towards a sustainable energy future, driven by their critical roles in electric vehicles, portable electronics, renewable energy integration, and grid-scale storage. This review provides a comprehensive evaluation of the current state of LIB technology, focusing on recent advancements in electrode materials, electrolytes—including solid-state variants, and separator design. The fundamental electrochemical principles underlying LIBs are discussed alongside engineering innovations that enhance performance, safety, and energy efficiency.

In spite of their widespread adoption, LIBs face several pressing challenges, such as safety concerns, raw material scarcity, environmental impacts, and end-of-life disposal issues. This review not only explores these limitations, but also presents emerging strategies to address them through next-generation materials, advanced recycling technologies, and sustainable design approaches. Unlike previous studies that narrowly focus on performance improvements, this review emphasizes how existing challenges can be transformed into opportunities for industrial innovation, institutional research, and economic development.

This review offers valuable insights into the future of energy storage by evaluating both the technical and practical aspects of LIB deployment. It presents a forward-looking perspective on the role of LIBs in shaping a cleaner, more resilient, and sustainable energy landscape, serving as a roadmap for continued innovation and responsible technology integration.

List of abbreviations

LiBs	Lithium ion Batteries
Ah	ampere-hours
Wh/kg	watt-hours per kilogram
Co	cobalt
LIB	Lithium-Ion Battery
SEI	Solid-electrolyte interphase
NEF	New Energy Finance
DRC	Democratic Republic of Congo
DoD	Deeper discharges
Co	Cobalt ion with a charge of +1/3
Mn	Manganese
O_2	Oxygen
NIB	Nickel-Iron Battery
DESs	Deep eutectic solvents
ILs	Ionic liquids
CRM	Critical Raw Materials
EV	Electric vehicle
CO	Carbon Monoxide
H_2	Hydrogen
US	United States
DOE	Department of Energy

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(*continued*)

TiO_2	Titanium Dioxide
$Li\ Ti_{15}O_{12}$	Lithium titanate
Ni	Nickel ions
Al	Aluminum (aluminum ions)
O	Oxygen (oxygen ions)
Fe	Iron
PO_4	Phosphate
GW	Gigawatt
kWp	Kilowatt-peak
PVW h/kg	Power watt-hours per kilogram
MWh	Megawatt-hour
MW	Megawatt
V2G	Vehicle-to-grid
BMW	Bavarian motors work
RFB	Redox flow battery
CAES	Compressed air energy storage
PHES	Plug-in hybrid electric vehicle
TWh	Terawatt-hour
LCA	Life Cycle Assessment

1. Introduction

Energy storage technologies play a vital role in ensuring sustainable energy systems. Pumped storage hydropower, batteries, thermal energy storage, and compressed air energy storage are all essential components that enable energy storage when needed, reducing the reliance on non-renewable energy sources. The advancement of these technologies is crucial for a sustainable future. By boosting the reliability, flexibility, and efficiency of renewable energy integration, these technologies also support grid stability and cut greenhouse gases. Li-ion batteries have been outstanding for these energy storage systems due to several factors, such as their high energy density, long cycle life, and fast charging capabilities, making them reliable for various applications [1]. The necessity to move away from fossil fuels and diesel-based vehicles to curb their impact on climate change has significantly prompted advancement with electric cars and related battery storage systems to power them. Lithium-ion batteries are genuinely a game-changer when it comes to powering electric vehicles. Their high energy density and long lifespan make them the perfect choice for this application. Also, their ability to be charged and discharged quickly and efficiently makes them even more appealing.

Li-ion batteries are a vital component in pushing toward a more sustainable future. Li-ion batteries are also used to power industrial sensor modules and robots to advance innovative manufacturing as part of the Industry 4.0 implementation across numerous nations worldwide [2]. Li-ion battery packs have been widely used for various applications, including portable electronics like cell phones, iPads, laptops, and television sets. They are essential for storing energy generated from multiple sources, integrating renewable energy from wind, solar, and others to ensure a steady electricity supply to homes, critical facilities like hospitals, and municipal power grid [3]. Lithium-ion batteries have emerged as an appealing option for stationary electrochemical energy storage systems, as well as environmentally friendly automobile power supply backup systems.

Recent progress in Li-ion battery abstraction has centered on new Li-ion cells to improve the performance and sustainability of electrochemical energy storage and alternative chemistries involving anode, cathode, and electrolyte components to provide futuristic Li-ion battery systems and new cell configurations. The electrochemical performance, efficiency, cell balance, and life cycle of Li-ion batteries are considered important benchmarks for their suitability as energy storage devices. Research in these areas has laid the foundation for a promising future for sustainable energy storage technologies. For instance, Stan et al. [4] investigated the Li-ion battery proclivity on the market and its uses in grid support, automotive, as well as backup power and concluded that they are suitable for these applications. Choi et al. thoroughly analyzed the existing situation and difficulties with Li-ion battery energy storage systems for grid use. They noted that numerous administrative and technical issues must be resolved, including material, control chemistry, engineering, manufacturing, testing, standard policy, and safety rules [5]. Several studies have also been reported on Li-ion battery suitability for application in residential solar storage [6], large-scale stationary devices [7], vehicle-to-grid application [8,9], and so more.

Most investigations on Li-ion batteries in the past have mainly focused on their development for performance improvement in novel applications. In contrast, others have concentrated only on their advantages, disadvantages, challenges, and limitations. However, these limitations and challenges with Li-ion batteries bring along several institutional research and economic opportunities, which have yet to be a center of focus from many studies. In this review, we seek to explore the challenges and limitations faced by Li-ion batteries, as well as the educational and economic opportunities these limitations bring. The implications of these limitations are also discussed with a focus on exploring them for better sustainable energy storage and renewable power management.

2. Overview of Li-ion battery and the energy storage system

2.1. The importance of energy storage system in the power grid

Gathering and storing energy for later use is called energy storage. It is critical in sustainable energy systems because it addresses the intermittent nature of renewable energy sources like solar and wind power. These sources often generate energy when demand is low and sometimes fail to provide enough power when demand is high [10,11]. Energy storage aids in the balance of electricity supply and demand. It stores surplus energy from low-demand times for later use during high demand. This guarantees a more steady and dependable energy supply, lowering the need for fossil fuel-based backup power plants. According to a study by Rohit et al. [12], there is a global market for energy storage systems. This market has the potential to be profitable for both end users and producers of renewable energy because it will result in good electricity leverage that promotes economic growth [12].

Droste-Franke and co-workers investigated pertinent issues for integrating energy storage in built environments, their link with demand side management, on-site generating, and energy efficiency measures [13]. The authors acknowledged that the problem of storage in energy systems for sustainability is evident. They need urgent proposals for synergies between supply and demand to minimize their impact on the economy and the environment. Weather-dependent renewable energy sources like solar and wind power require energy storage systems to store extra energy during high-generation periods for usage during no- or low-generation times. This improves the reliability and efficiency of renewable energy integration into the grid. It also reduces the effects of intermittent supply, enables more significant use of renewable energy, and offers flexibility and ancillary services in the electricity supply and demand network [14,15]. Furthermore, energy storage systems provide stability to the electrical grid by regulating and smoothing out fluctuations in energy supply. Thereby responding quickly to changes in grid conditions, such as sudden power outages or surges, and injecting stored energy into the system. This enhances grid resilience and reduces the risk of blackouts [16].

According to a study by Lagrange et al., the energy storage system can increase the resilience benefits of a microgrid in critical facilities like hospitals to an economic value of about $ 440,191, regardless of the increased safety brought by power continuity during surgical procedures and drug storage [17]. Energy storage systems allow for the management of peak electricity demand, to avoid the need for additional power plants that are typically used only during peak demand periods. Teki et al. (2021) reported that peak load shaving could be prevented by integrating renewable energy sources with battery storage, energy control, and management systems [18].

Energy storage systems assist with ancillary services such as voltage control, frequency ordinance, and grid stabilization to the electricity network. These services help maintain the overall reliability and quality of the electricity supply and reduce the need for conventional power plants to provide such services [19]. Energy storage is indispensable for the widespread adoption of electric vehicles. Battery energy provides a means to store and deliver electrical power for transportation, facilitating the integration of electric vehicles into the grid [20]. Table 1 summarizes the key factors that necessitate sustainable storage systems in power generation and supply.

Although a significant focus is on renewable energy sources for sustainable energy storage, all energy generated still needs transportation, storage, and application. Fig. 1 shows substantial energy generation sources, some modes of transport and storage, and general applications. Li-ion batteries play a significant role in energy storage, power transportation, residential homes, critical facilities like hospitals and laboratories, and portable electronics, especially in their rechargeable units [30].

2.2. Li-ion batteries and their potential for energy storage

Li-ion power units are rechargeable energy storage banks with lithium ions as charge carriers. They comprise two electrodes, an electrolyte, and a separator. Lithium ions migrate from the positive electrode to the negative electrode (anode) during charging and in the opposite direction during discharge. Because this reversal process allows for repeated charge-discharge cycles, Li-ion batteries are highly durable [31,32]. Lithium transition metal oxides are common positive electrode materials, and graphite is a typical negative electrode. The separator, usually made of thin polymer, prevents the electrodes from coming into contact and creating a short circuit. Lithium salt in an abiotic solvent is often used as an electrolyte [33]. Currently, several studies are reported with proposed novel materials for application as electrodes for Li-ion batteries [34].

Li-ion batteries are distinguished by their high energy density or the amount of energy they can hold per unit volume. This property permits ample energy storage in a small and lightweight size, making them excellent for portable devices, electric vehicles, and fixed energy storage systems [35]. Fig. 2 shows a cross-sectional view of a standard cylindrical Li-ion cell with annotations of the primary electrodes, coils, and charge movement.

The lithium-ion battery was first developed for the consumer electronics industry but eventually found use in other fields, like electric vehicles. The battery is created as an assemblage of separate battery cells that are joined together to form modules or packs and are under the control of a particular electronic circuit. The voltage delivered by the battery and its capacity are determined by the number of cells, the size of each cell, and their arrangement. In the vehicle industry, this is frequently expressed in kilowatt-hours (kWh) [37].

Li-ion batteries are revolutionizing energy storage due to their high density, long cycle life, and fast charging capabilities. As renewable energy sources gain prominence, demand for reliable storage solutions increases. Li-ion batteries can play a significant role in off-grid renewable energy storage due to their superior energy and power densities. A study by Diouf and Pode observed that Li-ion batteries have the potential to fully satisfy the energy storage needs in the electric vehicles industry - still, advancement to match the necessary energy and power densities for the sector [38]. According to a report by Marvin et al., large-scale Li-ion battery energy storage systems are becoming more popular. They may be used in electric networks across Europe, the Middle East, and Africa. The technology's impressive round-trip efficiency, regional economic viability, and ongoing decline in the equable cost of storage all contributed to the increase in its use, facilitating a gradual transition towards decentralized power generation based on renewable resources [39]. All these critical features of Li-ion batteries provide excellent economic opportunities for their energy storage applications and their potential to transform the sustainable energy landscape.

2.3. Key improvements of Li-ion batteries

Li-ion batteries offer several improvements that make them ideal for energy storage applications. Firstly, they have a high energy density, enabling the storage of a significant amount of energy in a compact and lightweight package. This is crucial for limited space applications [40, 41].Furthermore, the extended cycle life and high efficiency of Li-ion batteries contribute to their cost-effectiveness in long-term energy storage applications, particularly grid-scale projects. Their inherent efficiency minimizes energy dissipation during charge-discharge cycles, thereby reducing operational expenditures. Additionally, the low self-discharge rate of Li-ion batteries enables them to retain stored energy over prolonged durations without significant depletion. This feature ensures that the stored energy remains available when needed, making Li-ion batteries reliable for various applications [42]. Moreover, Li-ion batteries are known for their high power density, enabling them to deliver bursts of power quickly. This rapid discharge capability is

Table 1
Factors that necessitate sustainable energy storage systems in the power grid.

Key Factor	Comments	Benefits	Reference
Integration of Renewable Energy	Energy storage systems enable the capture of excess energy during high generation and are used to compensate for low or no generation periods for renewable sources that are variable and weather-dependent	Raise the reliability and efficiency of the power grid; offer flexibility and ancillary services.	Suberu et al. (2014) [21]
Balancing Supply and Demand	Energy generated during low demand is stored and used later when demand is high, ensuring a more stable and reliable power supply and reducing the need for backup power plants that rely on fossil fuels	Very profitable for both end users and power producers; good electricity leverage	Droste-Franke et al. (2012) [22] Rohit and Rangnekar, (2017) [23]
Grid Stability and Resilience	Energy storage systems stabilize the electrical grid by regulating and smoothing supply and demand fluctuations. They can respond quickly to changes in grid conditions, such as sudden power outages or surges, by injecting stored energy into the system.	Enhances grid resilience and reduces the risk of blackouts	Carnegie et al. (2013) [24]. Lagrange et al. (2020) [25]
Peak Load Management	Energy storage allows for the management of peak electricity demand. The stored energy is deployed to alleviate stress on the power grid.	Avoids the need for additional power plants that may be necessary only during peak hours	Teki et al. (2021), [26].
Ancillary Services	Energy storage systems provide various ancillary services to the grid, such as voltage control, frequency regulation, and grid stabilization.	Improves overall reliability and quality of electricity supply; reduces the need for conventional power plants to provide such services	Foley (2021) [27].
Electrification of Transportation	Battery storage enables the charging of electric vehicles, providing a means to store and deliver electrical energy for transportation purposes.	Facilitates the integration of electric vehicles into the power grid; stabilizes and supports renewable energy integration	Rogge et al. (2015) [28] Ahmad et al. (2021) [29]

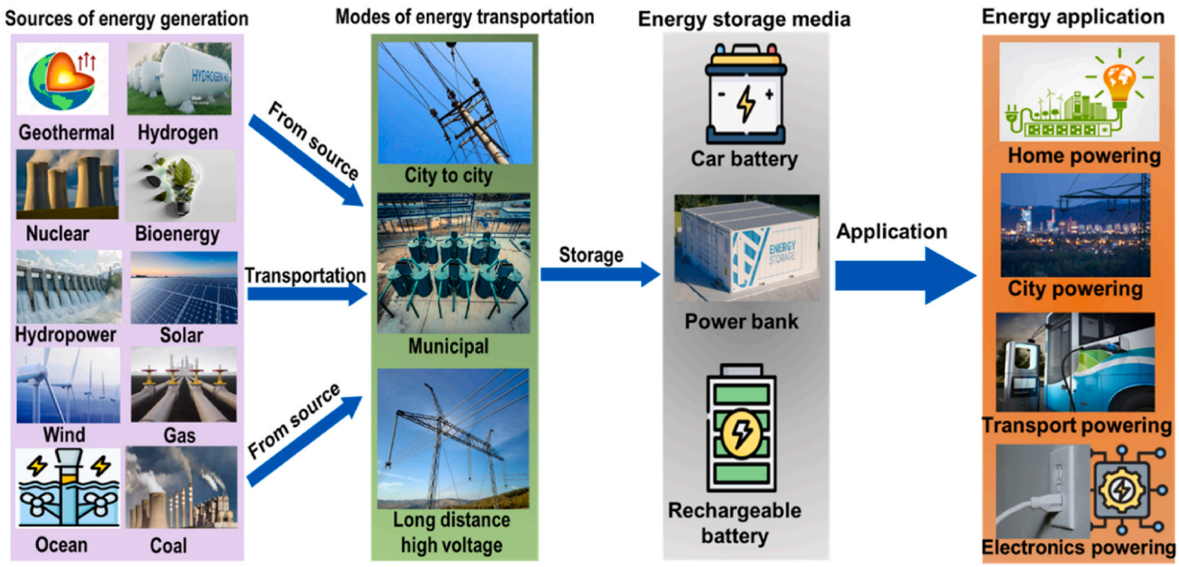

Fig. 1. The different energy sources, transportation modes, storage, and application.

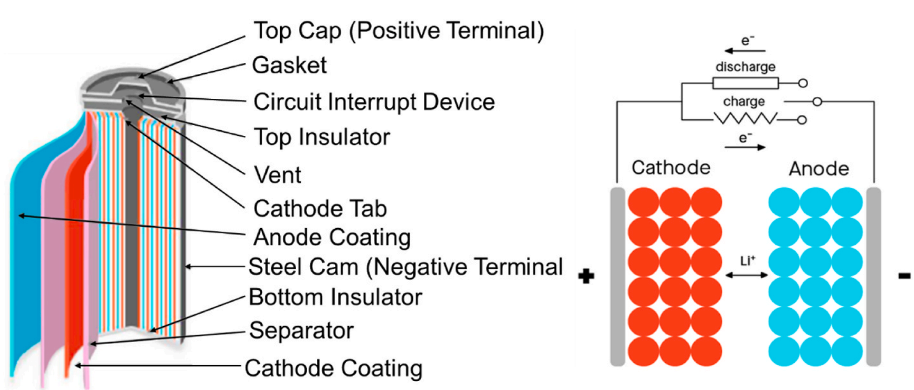

Fig. 2. A cross-section of a typical cylindrical Li-ion unit cell depicting the essential workings of a Li-ion cell and how the electrodes are layered and coiled [36].

essential for high-power output applications, such as electric vehicle acceleration and grid-scale applications with fast response times [43].

2.4. Applications of Li-ion batteries in energy storage systems

Li-ion batteries have been widely used in electronic devices, satellites, and biomedical implants for the past 20 years, offering a steady power source and minimizing weight in exoatmospheric aircraft and pacemakers. [44]. The current focus on Li-ion battery applications is big power storage units and tools. To provide the necessary power, energy density, and safety, novel materials for positive and negative electrodes and electrolytes are being developed [45]. From its many diverse applications, one essential use of Li-ion batteries is the integration of renewable energy sources such as solar and wind into the electrical grid. These renewable sources often generate power intermittently, and Li-ion batteries can store surplus energy during periods of high generation and supply it when demand exceeds supply. This helps to balance the grid and maximize the usage of renewable energy sources [46]. In grid-scale energy storage, Li-ion batteries provide stability and flexibility to the electrical grid. They can respond quickly to power supply and demand fluctuations, helping maintain grid frequency and voltage within acceptable limits [47]. Significant interest has also been paid to creating dependable, affordable, high-energy-density rechargeable Li-ion batteries for use in advanced robotics [48,49]. Fig. 3 illustrates some raw materials from which Li-ion batteries are made, battery cells, battery

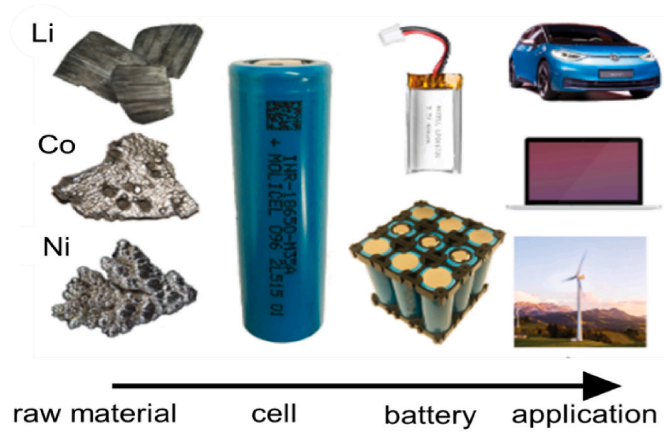

Fig. 3. Raw materials (lithium, cobalt, and nickel) for Li-ion batteries, battery packs, and some desired applications for renewable energy storage [50].

packs, and some application areas.

3. Limitations of Li-ion batteries in sustainable energy storage systems

Energy storage systems are critical in balancing supply and demand as the globe strives for sustainable energy sources. This section discusses the limitations of Li-ion batteries, which are widely recognized for their exceptional qualities, to enhance their potential for sustainable energy storage applications.

3.1. Limited energy density and capacity

Although Li-ion batteries find applications in diverse sectors, the consensus is that their energy density could be higher. A recent study by Fang Haoyu details factors contributing to the energy density restrictions of Li-ion batteries. It summarizes the drawbacks of each battery component that impact energy density [51]. Energy density, typically expressed as watt-hours per kilogram (Wh/kg), measures how much energy can be held in a given volume or mass of a battery. The total amount of charge a battery can store, measured in ampere-hours (Ah) is referred to as its capacity. Higher energy density and power are essential because they provide more energy storage in a compact and lightweight container, allowing for a broader range of applications [52]. In this review, it has been identified that more research is needed to determine the ideal mass ratio between the battery electrode, capacitor electrode, and electrolyte to get the highest energy density. The following are some factors this review identifies that could affect Li-ion batteries' limited energy density and capacity for sustainable energy storage.

In addition to technical performance, the economic viability of lithium-ion batteries is crucial for their role in future energy systems. One of the most important metrics in this regard is the **Levelized Cost of Storage (LCOS)**, which represents the total lifetime cost of an energy storage system divided by the total electricity it delivers. LCOS provides a standardized way to compare different storage technologies and is especially critical when assessing systems designed to stabilize intermittent renewable energy sources such as solar and wind. Despite the high upfront capital costs, lithium-ion batteries often exhibit competitive LCOS values due to their high efficiency, modularity, and declining costs. However, factors such as cycle life degradation, operational costs, and system design significantly influence LCOS outcomes. As renewable penetration increases, LCOS becomes an essential indicator for evaluating the economic sustainability of energy storage solutions. Therefore, incorporating LCOS into lithium-ion battery assessments is vital for comprehensive energy planning and policy development [53,54].

3.1.1. Electrochemical stability

During charge and discharge cycles, the electrolytes and electrodes in Li-ion batteries undergo chemical reactions and structural changes. These reactions can form a solid-electrolyte interphase (SEI) layer, which hampers battery performance. The SEI layer increases the inner resistance of the battery, reducing its capacity and limiting the maximum voltage at which the battery can operate. Consequently, these electrochemical stability issues restrict Li-ion batteries' energy density and power [55,56].

3.1.2. Material limitations

Li-ion batteries employ lithium compounds as active materials in their electrodes. The properties of these functional materials primarily limit the energy density and capacity of these batteries. For example, lithium cobalt oxide ($LiCoO_2$), commonly used as a cathode material, has a relatively low theoretical specific ability. Similarly, graphite, often used as an anode material, has limitations regarding its lithium storage capacity. These material limitations restrict Li-ion batteries' overall energy density and power, posing a challenge for sustainable energy storage applications [57,58].

3.1.3. Safety concerns

Safety is a critical consideration in battery technology. Li-ion batteries utilize organic electrolytes that are highly flammable, presenting safety risks. Li-ion batteries incorporate safety features such as thermal management systems and protection circuits to mitigate these risks. These safety measures increase the storm's weight and volume and impact its energy density. Balancing safety and energy density is a significant challenge in Li-ion battery design for sustainable energy storage [59,60].

These limitations associated with Li-ion battery applications have significant implications for sustainable energy storage. For instance, using less-dense energy cathode materials in practical lithium-ion batteries results in unfavorable electrode-electrolyte interactions that shorten battery life. [61]. Most critically, limited energy density and capacity directly impact the range and duration of the operation. Electric vehicles with lower energy density batteries require more frequent recharging, restricting their usability for long trips. Similarly, renewable energy systems struggle to reserve surplus energy during phases of high-generation for delayed use during low-generation periods, limiting their effectiveness in providing consistent power [62]. Furthermore, factors contributing to the limited energy density of Li-ion batteries lead to an increased footprint. Larger and heavier battery packs are required to compensate for low energy density and capacity. This increase in size and weight leads to a more significant overall impression of the energy storage system. It poses a challenge in applications where space is limited, such as electric vehicles or residential installations [63]. This offers an economic opportunity to develop more compact battery packs for application in space-restricted areas.

3.2. Cost

Li-ion battery, a key player in energy storage technology, faces high costs due to unpredictable production processes, including chemical, mechanical, and electrical component variations. A study by Nitta et al. [62] observed that price is the principal factor hindering Li-ion batteries from being broadly used in many renewable energy sectors. The study further posited that research into novel electrode materials is imperative to overcome current cost limitations and achieve enhanced power density, improved cycle life, and safety in lithium-ion battery applications. Their conclusion underscored that a reduction in costs would substantially augment the utility of Li-ion batteries and facilitate the realization of new technologies reliant on energy storage [64]. The following are factors that have been identified as currently contributing to the high cost of Li-ion batteries [65].

3.2.1. Raw materials

The high cost of Li-ion batteries is partly attributed to the various expensive raw materials needed for their production. Lithium, cobalt, nickel, and other rare earth metals used in battery chemistries can experience price fluctuations due to limited supply and high demand. Additionally, these materials extraction, refining, and processing can be energy-intensive, further driving up costs [66].

3.2.2. Manufacturing processes

The intricate manufacturing processes involved in producing Li-ion batteries also contribute to their high cost. The fabrication of battery electrodes, the assembly of cells, and the incorporation of safety features require specialized equipment, cleanroom facilities, and skilled labor. The capital-intensive nature of these processes adds to the overall cost of battery production [67,68].

3.2.3. Research and development

The continuous experimentation and development attempts focussed on upscaling Li-ion batteries' performance, safety, and longevity come with significant costs. Battery manufacturers invest substantial resources in research, prototyping, testing, and quality control to enhance battery performance and meet evolving industry standards [69,70].

3.2.4. The scale of production

Economies of scale heavily influence the economics of Li-ion battery production. Large-scale manufacturing facilities can benefit from cost reductions due to higher production volumes, efficient supply chain management, and streamlined processes. However, in the early stages of adoption, when production volumes are relatively low, the high upfront capital investment required to establish manufacturing facilities can contribute to the high cost of Li-ion batteries [71,72].

The high cost of Li-ion batteries affects their use in electric vehicles, raising the purchase price of electric cars and reducing their affordability and market competitiveness. This cost barrier also limits the development of long-range electric cars, making them less competitive with traditional internal combustion engine vehicles [73]. This opens doors for further research into more economically viable and sustainable Li-ion battery production technologies to overcome this challenge. Fig. 4 shows the project prices of Li-ion battery packs from 2010 to 2030, according to Bloomberg New Energy Finance (NEF) data. Bloomberg (NEF) is a significant player in providing information on game-changing technologies and policies on how businesses such as construction, transportation, power generators, and the agricultural sectors can adjust to the energy shift.

3.3. Limited resource availability

Li-ion batteries are a vital technology for sustainable energy storage, aiding in integrating renewable energy sources and shifting to a low-carbon future. However, the limited availability of essential resources for their production presents a major challenge to their scalability and long-term sustainability [75,76]. By understanding the essential resources required for Li-ion battery production, key policies can be developed to manage and sustain these resources for efficient energy storage solutions. The following outlines some of the necessary resources for different parts of Li-ion batteries.

3.3.1. Lithium

Lithium is a crucial component in Li-ion batteries, serving as the active material in the cathode. However, lithium reserves are geographically concentrated, with most global lithium production coming from a few countries. The limited availability of lithium resources raises concerns about potential supply constraints and price volatility, impacting the cost-effectiveness and scalability of Li-ion batteries for sustainable energy storage [77].

3.3.2. Cobalt

Cobalt is another essential resource used in the cathode of specific Li-ion battery chemistries, particularly those with high energy density. Most cobalt production is concentrated in a few countries, including Zimbabwe and the Democratic Republic of Congo (DRC), where concerns about unethical mining practices and human rights issues have been raised. The limited availability of ethically sourced cobalt poses challenges to ensuring a responsible and sustainable supply chain for Li-ion batteries [78,79].

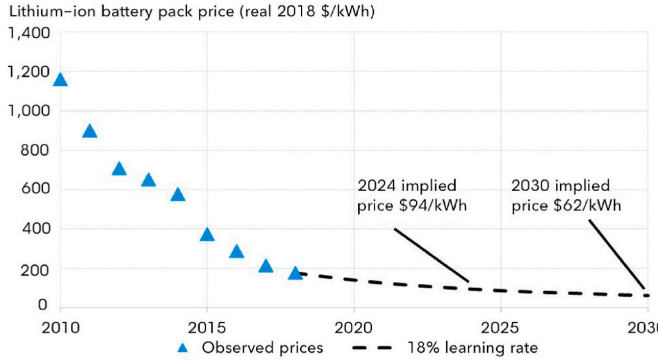

Fig. 4. Lithium-ion battery price outlook from 2010 to 2030 [74].

3.3.3. Nickel

Nickel is a fundamental constituent of Li-ion battery cathodes, particularly in high-energy-density chemistries. Although nickel reserves are relatively abundant globally, there are concerns about the availability of high-quality nickel suitable for battery-grade applications. The growing demand for nickel from other industries, such as stainless steel production, further exacerbates nickel's potential scarcity and price volatility for Li-ion batteries [80,81].

3.3.4. Graphite

Graphite is used as the anode material in Li-ion batteries, providing lithium ions' necessary conductivity and storage capacity. Natural graphite reserves are limited, and a few countries' production capacity is concentrated. Additionally, the high-energy and resource-intensive processes involved in graphite purification and battery-grade graphite production contribute to the environmental impact of Li-ion battery production [82,83]. In addition to the limited resources mentioned, Li-ion battery production relies on various other metals and metal oxides essential for different cell chemistries. Numerous chemistries have been adopted through research to address diverse application needs. The five most popular cell chemistries reported in the literature and their performance trade-offs are shown in Fig. 5. These trade-off values are critical to Lithium-ion battery technology designers [84].

Li-ion batteries' reliance on scarce resources and geopolitical factors can lead to supply chain vulnerabilities, impacting sustainable energy storage and production affordability [86,87]. A comparative study by Chayambuka et al. [86] on Sodium ions and Li-ion batteries acknowledges that limited resources available for Li-ion battery production have profound pricing implications. The limited availability of critical resources and increasing demand can result in price volatility. The geographically uneven distribution and the price volatility associated with raw material deposits crucial for Li-ion batteries, such as lithium and cobalt, significantly impact the Li-ion battery value chain. Consequently, this necessitates the development of alternative energy storage chemistries to ensure sustainable energy storage solutions [88]. The development of alternative energy solutions will again open doors for research, economic opportunities, job creation, and the sustainability of energy storage systems.

3.4. Limited cycle life

Despite having a better life cycle than lead-acid batteries and other storage options, Li-ion batteries still need improvements to be more sustainable. Their limited cycle life restricts their broader use in electric vehicles and renewable energy systems applications [89,90]. Several factors contribute to the limited life cycle of Li-ion batteries. Understanding these limitations is essential for developing more durable and reliable energy storage solutions.

3.4.1. Electrochemical reactions

Life cycle appraisal of Li-ion batteries has become crucial for its application in sustainable energy storage systems. In their study to quantify the various factors that can influence a battery pack designer's choice, Hehenberger, and Akasapu [91] found that electrochemical reactions could shorten the life of batteries if they weren't correctly set up. Li-ion batteries experience gradual degradation due to electrochemical reactions during charging and discharging. Side reactions, such as forming solid-electrolyte interface layers and electrolyte decay, can reduce capacity and increase internal resistance. These cumulative

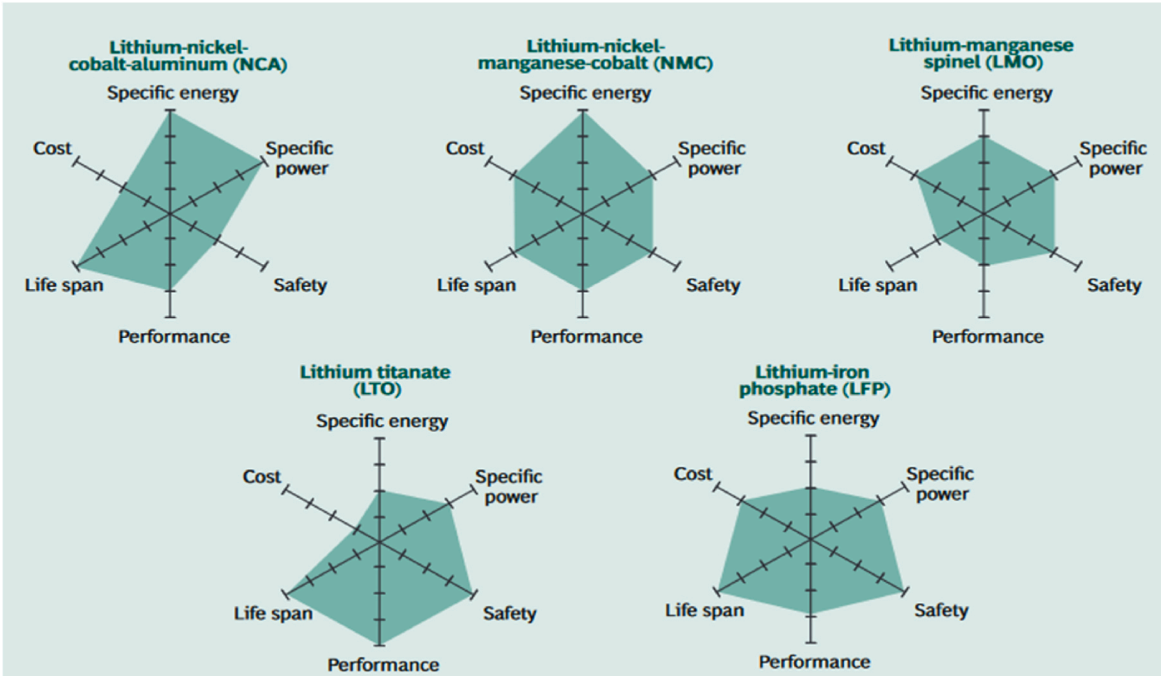

Fig. 5. The five principal Li-ion battery technologies and their trade-offs [85].

effects over multiple cycles contribute to the limited life span of Li-ion batteries [92]. To increase electrochemical performance, Li and Tang, inserted Mn_3O_4 grains into metal-organic framework-derived nitrogen-doped highly porous carbon fibers made via electrospinning. Sufficient open-void areas can support volume change while maintaining high Li + flux throughout the Li + intercalation/deintercalation process. The solid 1D structure, along with the high electrical conductivity of nitrogen-doped highly porous carbon fibers, creates more efficient routes for ions and electrons to transport quickly. The high electrochemical performance, environmental compatibility, simple synthesis technique, and low cost of manganese-based materials demonstrate the potential of Mn_3O_4/NPCFs-1.4 composites for practical applications [93].

3.4.2. Mechanical stress and structural changes

Li et al. investigated how internal stress and external pressure affected battery performance and lifespan. The researchers discovered that Li-ion batteries experience significant dendritic development, poor Coulombic efficiency, and electrolyte side effects, mainly when using liquid electrolytes [94]. Repeated expansion and contraction of electrode materials during cycling can result in mechanical stress, leading to electrode cracking, particle detachment, and loss of active material. The gradual structural changes and loss of electrode integrity contribute to capacity fade and performance degradation over time.

In the work of Zheng et al., a new electrochemical model was developed to evaluate how electrode-level cracks impact Li-ion battery performance and impedance. The study quantified the effects of crack geometry, length, orientation, and position on energy, capacity, and impedance, providing insights for improving battery design and durability. [95]. Zhang et al. studied the fracture behavior of bi-layer electrodes in Li-ion batteries caused by diffusion-induced stress. They developed an analytical model to analyze how cracks initiate and propagate during galvanostatic intercalation and deintercalation.Higher tensile stress during lithium extraction is predicted to cause more cracks, but their growth could halt as they enlarge due to reduced stress intensity [96].

3.4.3. Temperature effects

High operating temperatures and temperature variations during charging and discharging accelerate the aging process of Li-ion batteries. A study by Zhu et al. showed that elevated temperatures promote side reactions, accelerate electrode degradation, and accelerate electrolyte decomposition, reducing the cycle life of Li-ion batteries [97].

3.4.4. Depth of discharge (DoD)

The depth of discharge, or the extent to which a battery is discharged during a cycle, can impact the cycle life. Deeper discharges and higher DoD levels increase the stress on the battery, leading to accelerated degradation and reduced cycle life. The main causes of cell capacity loss during continuous cycling were solid electrolyte interface development and crack-reforming mechanisms, according to a model developed by Deshpande and Uddin [98] for estimating Li-ion battery cycle life. Li-ion batteries experience reduced capacity over time as they go through charging and discharging cycles. This decline affects their energy storage capabilities, leading to shorter ranges, lower efficiency in electric vehicles, and limited storage in renewable energy systems, ultimately impacting their performance and reliability [99]. The relatively short cycle life characteristic of lithium-ion batteries mandates a higher frequency of maintenance and replacement procedures, which consequently elevates the overall cost of ownership. This is especially pertinent for large-scale energy storage installations and electric vehicles, where it can negatively influence their economic feasibility and long-term sustainability. [100]. Li-ion batteries' short lifespan raises environmental concerns due to their creation, disposal, resource extraction, energy consumption, and carbon emissions from manufacturing operations [101,102]. Proper disposal and recycling of spent batteries is crucial for environmental impact reduction while carefully handling the Li-ion battery supply chain can also offer resource recovery opportunities. Fig. 6 shows the critical factors affecting the Li-ion battery supply chain.

3.5. Environmental concerns

Over the past ten years, there has been an exceptional rise in the clamor for Li-ion batteries, which is predicted to continue. As a result,

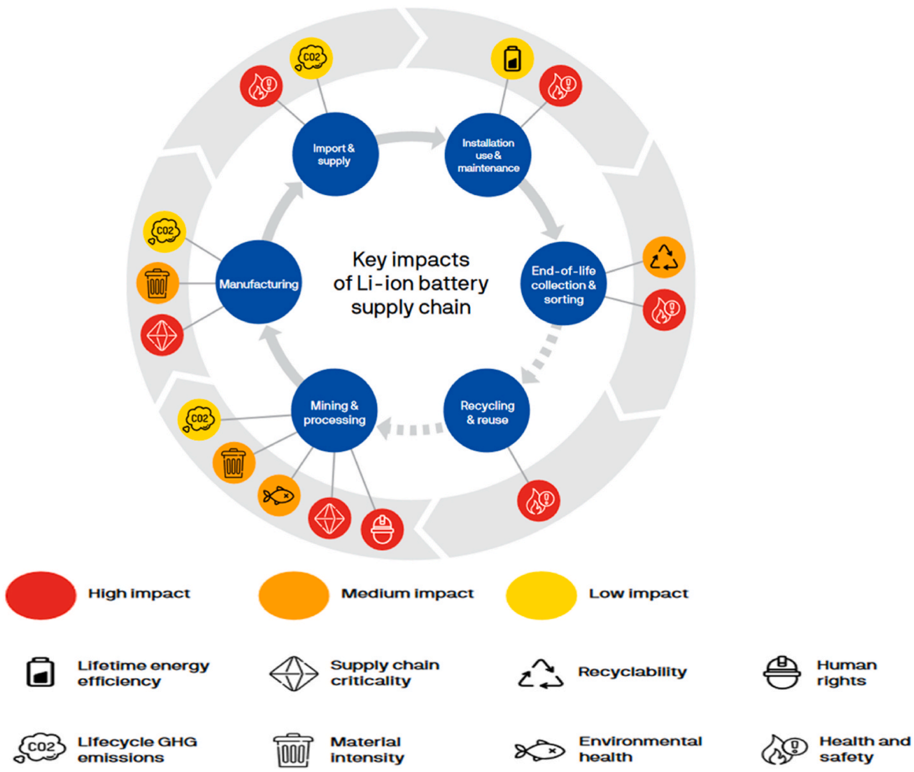

Fig. 6. Key factors affecting the Li-ion battery supply chain [103].

mining raw materials necessary for manufacturing Li-ion batteries, such as cobalt and lithium, has significantly increased to keep up with the rising market demands, where Li-ion batteries account for about 40 % of the market share [104]. For the foreseeable future, Li-ion batteries will continue to be the most popular option for energy storage [105]. Consequently, even with successful attempts for reuse, repair, and remanufacturing, enormous numbers of batteries will unavoidably be thrown away [106].Environmental issues from increased mining and battery waste could impede widespread Li-ion battery adoption, highlighting the need for sustainable energy storage.

3.5.1. Raw material extraction

Extraction of raw minerals for lithium-ion batteries, such as lithium, cobalt, and nickel, can have serious environmental consequences. Mining operations can cause deforestation, habitat degradation, soil disintegration, and water contamination. Additionally, some mining practices in regions with weak environmental regulations can result in human rights abuses and social conflicts [107]. In a study, Koyamparambath and colleagues examined the risk of supply for a few raw materials used in batteries from 2000 to 2018 from the perspectives of the European Union, Australia, the United States, Canada, and some Asian nations. They found that policies to secure raw materials while protecting the environment still need to be fully implemented [108].

3.5.2. Energy exhaustion and carbon emissions

The energy-intensive processes in battery production contribute to carbon emissions and global warming potential. The uprooting, refining, and processing of raw materials and the manufacturing and assembly of batteries require substantial energy inputs. The reliance on fossil fuels for electricity generation further increases the carbon footprint of battery production [109].

3.5.3. Water consumption and contamination

Battery manufacturing processes, including the purification of raw materials, electrode fabrication, and cell assembly, often require significant water consumption. Water scarcity and contamination can occur in regions where battery production is concentrated, exacerbating environmental concerns and impacting local communities [110,111].

3.5.4. Hazardous materials and waste

Li-ion batteries contain hazardous materials, including toxic chemicals and heavy metals such as lithium, nickel, and cobalt. Inadequate disposal or recycling of spent batteries can lead to environmental contamination and threaten human health. The current lack of standardized recycling infrastructure and practices further exacerbates the environmental impact of battery waste [112,113].

3.5.5. Supply chain transparency and ethics

Li-ion batteries' complex global supply chains pose challenges in ensuring transparency and ethical sourcing. Concerns regarding child labor, unsafe working conditions, and human rights violations have been raised, particularly in the mining and processing of cobalt in certain regions [114,115]. Ensuring responsible supply chains is crucial for addressing environmental and social concerns associated with battery production.

The improper management of environmental limitations in Li-ion battery production can significantly impact sustainable energy storage systems.Given the promise of lithium-ion batteries, a comprehensive life cycle assessment (LCA) of battery storage is essential. Sadhukhan and Christensen performed an LCA on Li-ion batteries to assess and minimize their environmental footprint. Their findings indicated that lithium-ion batteries have a global warming potential of 1.7, 6.7, and 8.1 kg CO_2 eq kg^{-1}, with and without recycling credit, based on a whole-system LCA approach [116]. This is because the fabrication of lithium-ion battery cathodes is resource-intensive. To compete with fossil fuels and other renewable sources, improvements are required to reduce recycling and fossil emissions, increase energy density, lengthen longevity, and improve recyclability. Arshad et al. conducted a life cycle assessment of lithium-ion batteries to evaluate and mitigate the environmental impacts of their manufacturing processes, aiming to establish a consensus on the environmental sustainability of these batteries. The study reviewed various estimates of the environmental effects of lithium-ion battery production and identified essential criteria for assessing both current and next-generation batteries. The authors emphasized the need for new chemistries to meet sustainability demands and recommended that energy demand modeling in future LCA studies should account not only for production and battery lifespan but also for internal battery efficiency [117].

Implementing energy efficiency and transitioning to renewable energy sources can mitigate these concerns [118,119]. Other efforts to upscale the sustainable sourcing of raw materials for Li-ion batteries include promoting responsible mining practices, investing in recycling technologies, and exploring alternative battery chemistries that require fewer scarce or environmentally sensitive materials [120].

Reusing materials from old lithium-ion batteries, especially cathodes, helps reduce the need for critical raw materials and mitigates heavy metal contamination issues from traditional disposal. Maider et al. [121] developed a life-cycle assessment methodology for nine hydrometallurgical recycling processes of Li-ion battery cathodes, focusing on environmental impacts like global warming. They found that recycling $LiNi_{1/3}Co_{1/3}Mn1/3O_2$ cathodes, which are prevalent in electric vehicles, enhances the long-term viability of these batteries, though further process improvements are suggested. Fig. 7 summarizes these elements, known as the Circular Economy concepts.

4. Opportunities for Li-ion batteries for sustainable energy storage

Li-ion battery technology has revolutionized energy storage systems, making sustainable energy storage essential for modern society. Since 1991, Li-ion batteries have been used in fixed grid systems, portable electronics, and electric vehicles. Integrating renewable energy and large-scale lithium-ion batteries presents numerous opportunities for sustainable storage.

4.1. Advancements in electrode material development

Researchers are hard at work exploring other abandoned NIB technologies and other electrode materials to investigate their potential as a supplement to lithium-ion batteries in light of the growing worry about the sustainability of Li sources and their uneven distribution. Advanced electrode material research and commercialization now have excellent opportunities because of this [122,123]. Studies are currently optimizing silicon and black/red phosphorus in high-energy Li-ion battery negative electrodes to enhance material conductivity, lower polarization, and improve anode's chemical and thermal stabilityThis constant requirement for electrode material optimization has led the road for fiscally accessible electrode materials for lithium-ion batteries [124,125].

4.2. Novel approaches to electrolyte design

When it comes to lithium-ion batteries, the electrolyte of choice is crucial. These decisions will affect the electrolyte's charging rate and cell life in real-time applications. Pushing the limits of Li-ion cells' rate capability is one of the leading research goals for Li-ion batteries. Ever faster charging speeds are particularly wanted in the electric vehicle sector, where it is thought that charging rates that begin to match the time it takes for internal combustion engines to refuel will reduce the range time and encourage the mainstream adoption of electric vehicles. Recently, it has been shown that highly concentrated electrolyte solutions can be used to increase rate capability. This has created a huge commercial opportunity for research and design of electrolytes for Li-ion batteries [126,127].

Recent progress in lithium-ion battery technology has led to considerable improvements in performance, stability, and sustainability, attributed to advancements in materials science and cell design. As an example, solid-state electrolytes (SSEs) signify a significant evolution from traditional liquid electrolytes, providing enhanced safety characteristics by diminishing the likelihood of leakage and flammability, and concurrently offering the prospect of increased energy density. [128]. Various SSE types, such as sulfides, oxides, and polymer-based electrolytes, are being actively studied, each with unique benefits and challenges [129]. Sulfide-based electrolytes demonstrate high ionic conductivity but require careful handling due to air sensitivity, whereas oxide-based electrolytes offer excellent chemical stability but face interfacial resistance issues [130]. High-capacity cathode materials, such as nickel-rich layered oxides (e.g., NCM 811) and lithium-rich materials, have shown considerable promise for increasing energy density. Nickel-rich cathodes offer improved capacity but require innovations in thermal stability and degradation mitigation. In contrast, lithium-rich materials show high capacity and cycling stability yet suffer from voltage fading issues [131–133].

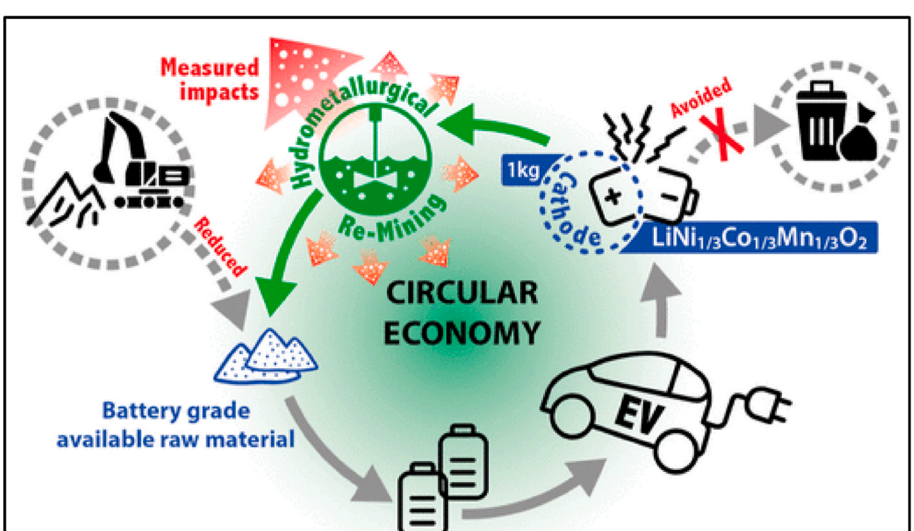

Fig. 7. Illustration of the possibility for circularity and hydrometallurgical recycling of Li-ion battery with $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ as cathodes.

4.3. Innovative battery architectures and designs

The escalating demand for rechargeable lithium-ion batteries exhibiting enhanced capacity and tailored geometries underscores the necessity for innovative battery topologies, materials, and manufacturing methodologies. Manufacturing advancements such as 3D printing, two-step facile synthesis, interlaced architecture, and honeycomb structural modification represent key innovations driven by the pursuit of improved Li-ion battery energy storage performance. [134,135]. These have created massive research and economic opportunities.

4.4. Recycling and reuse of battery materials

As Li-ion batteries become more widely used, the amount of battery scrap generated during production and at the limit of its life also increases, which needs to be recycled for environmental and economic reasons. This potential for recycling returns has paved the way for developing recycling plants and processes. Currently, pyrometallurgical and hydrometallurgical processes are the most common types of battery recycling. These processes have created several job opportunities and commercial values [136,137]. Fan et al. analyzed battery usage and recycling in terms of commercial profitability, safety, technology, and environmental impact to improve on the tremendous efforts already made [125]. Many emerging technologies require electrode materials, electrolytes, and separators that can be used to support the development of energy storage devices, including carbon-free electricity, electric vehicles, and electrochemical energy storage [138].

4.4.1. Methods of recycling Li-ion batteries

Recycling lithium-ion batteries is crucial for environmental sustainability and resource recovery. With the growing demand for these batteries in electric vehicles and renewable energy systems, efficient recycling methods are vital for reducing environmental impact and conserving essential materials.

4.4.1.1. Mechanical and hydrometallurgical recycling techniques. Mechanical and hydrometallurgical recycling techniques are used to recover valuable metals from Li-ion batteries, with hydrometallurgical leaching offering high recovery rates for lithium, cobalt, and nickel. A study by Kovačević et al. outlines advancements focused on hydrometallurgical recycling of Li-ion batteries using eco-friendly ionic liquids (ILs) and deep eutectic solvents (DESs). These solvents offer benefits like superior selectivity, low energy consumption, and reduced environmental impact compared to traditional solvents. The work highlights recent progress in using ILs and DESs for CRM recovery from Li-ion batteries [139].

Iloeje et al. conducted an in-depth study on developing hydrometallurgical processes to close the electric vehicle Li-ion battery value chain loop. The work goes beyond investigating new solvents, reagents, and conditions that optimize material recovery and reduce environmental Pan and Shen reported a novel recycling method that uses pyrolysis impact and improves the overall sustainability of the recycling process [140].

4.4.1.2. Pyrometallurgical recycling initiatives. Pyrometallurgical recycling is a method that involves high-temperature smelting of battery materials to recover metals, particularly cobalt, nickel, and copper, despite being energy-intensive. to simultaneously process spent Li-ion batteries and organic wastes. Organic wastes are transformed into reducing agents like hydrogen, carbon monoxide, and char through carbothermal and gas thermal reduction. This approach reduces both costs and energy consumption compared to traditional roasting methods and facilitates the valorization of organic wastes [141]. A study by Holzer et al. developed a sustainable recycling process using hydromechanical preparation, flotation, and pyrometallurgical treatment. The process achieved high-purity Li-ion battery active materials, reduced carbon content, and produced a Li-free metal alloy [142].

4.4.1.3. Advanced direct recycling techniques. Direct recycling of lithium-ion batteries is an emerging method to address traditional recycling techniques' limitations. This approach focuses on efficiently recovering and restoring active electrode materials while maintaining their electrochemical performance. Compared to conventional pyrometallurgy and hydrometallurgy, direct recycling offers cost-effectiveness, energy efficiency, and sustainability by preserving the material structure and reducing the recycling process duration [143]. Recent advancements in direct recycling, including battery sorting, pretreatment, and regeneration, and discussed challenges in scaling to industrial scale, strategies, and industry trends are covered in the work of Holzer et al. [144].

4.4.2. Case studies and successful Li-ion batteries recycling initiatives

Several industrial-scale initiatives have demonstrated the practical application of advanced recycling methods. For example, Fortum, a Finnish energy company, has developed a proprietary hydrometallurgical process that recovers over 80 % of the materials from lithium-ion batteries. Their facility in Finland illustrates how large-scale recycling can be both economically viable and environmentally sustainable [145]. The study by Karlsson and Lindström found that while traditional manufacturing strategies can be applied to battery recycling, unique challenges like uncertain inflow of discarded products, varying battery chemistries, and the need for flexible processes must be addressed. Key recommendations from the study include simplifying battery disassembly, developing intelligent labeling systems, and promoting industry standards to improve recycling efficiency. [146]. Sloop et al. conducted a case study on cathode-healing in battery recall, demonstrating an industrial model for recycling lithium-ion batteries that applies to both consumer electronics and electric vehicles. The recycling process includes several stages: electrolyte extraction using carbon dioxide, industrial shredding, electrode harvesting, froth flotation, cathode-healing™, and assembling new cells with recycled cathodes and anodes. The full cells produced from directly recycled materials showed effective performance. Insights from recycling this prototype chemistry are being preliminarily applied to chemistries relevant to electric vehicle batteries [147].

The development of more efficient and environmentally friendly recycling processes is critical for the future sustainability of Li-ion batteries. By leveraging advanced techniques and learning from successful case studies, the industry can significantly reduce its environmental footprint and ensure a steady supply of critical materials for future battery production.

4.5. System-level optimization for improved performance and safety

In grid applications using Li-ion batteries, the system must generally be modified to include the capability to manage energy, control temperature, and power auxiliary electronics. To warrant the safety and reliability of Li-ion batteries, thermal management systems must be used for sustainable energy storage applications to keep the temperature constant [148]. To achieve high heating efficiency, Li-ion battery thermal energy management systems today require external heating approaches, such as heat convection, electrothermal elements, current excitation methods, and self-healing. Several other objectives, such as those of the US Advanced Battery Consortium for electric vehicle applications, include designing batteries that are capable of surviving non-operational conditions, provide a higher level of energy, have a long service life of over 15 years, and charge to 80 % in less than 15 min. All these goals with Li-ion batteries bring about significant economic and research opportunities in renewable energy and sustainable energy storage sector [149,150].

5. Global allocation of lithium reserves according to its purity and capacity

The Andean highlands of Chile, Bolivia, and Argentina are currently reported to contain the highest lithium reserves, with Chile possessing almost 8.6 million tons. And though Chile includes the largest lithium reserves globally and is known for its high-quality lithium carbonate production, Australia is still the largest producer of lithium in the world. It has significant lithium reserves and produces high-quality lithium concentrate and carbonate [151]. Also, Peru recently declared it would start extracting pegmatite in the Falchani region. Canada is reported to have significant lithium resources, particularly in Quebec. The country is working on expanding its lithium production capacity to meet the growing demand for lithium-ion batteries for electric vehicle supply in its Great Lakes region [152]. China does not possess as high lithium reserves as Australia and Chile but remains a leading producer of lithium-ion materials. It has a significant presence in the lithium industry and produces various lithium compounds, including lithium carbonate and hydroxide. Australian lithium is transported as spodumene concentrates to China, Korea, or Japan, where it is further processed chemically and added to supply chains for lithium-ion batteries. Eventually, this mineral will act as an energy storage media for powering electric cars, grids, and houses [153]. Argentina is known for its lithium reserves, particularly in the "Lithium Triangle" region, which it shares with Chile and Bolivia. The country has been developing its lithium production capacity and is emerging as a critical player in the industry. Another country with lithium reserves and is actively involved in lithium extraction and production is the United States. It aims to strengthen its domestic lithium supply chain to support the electric vehicle industry's growth.

The largest known lithium deposit in the US and one of the most outstanding lithium deposits in the world is located in Humboldt County, Nevada. It is the subject of a lithium clay mining development project called the Thacker Pass Lithium Mine. Since 2007, Thacker Pass has undergone extensive investigation. Elon Musk, the CEO of Tesla, declared during his "battery day" in the fall of 2020 that his business would continue vertically integrating the whole EV supply chain by obtaining the rights to lithium extracted from clay resources in Nevada [154,155]. Zimbabwe has been found to have substantial lithium deposits and has been trying to develop its lithium industry. The country aims to attract investment in lithium mining and processing to capitalize on its resources [156]. The DRC is known for its vast mineral wealth and is estimated to hold significant lithium deposits, primarily in the southern part of the country. However, the current focus in the DRC is associated mainly with producing other minerals, such as cobalt and copper, which are crucial for manufacturing lithium-ion batteries. While lithium production in the DRC is less prominent than in some other countries, its lithium resources have the potential for future development as the demand for lithium-ion batteries continues to grow. As much as 70 % of the global cobalt supply is produced in the DRC, making it the world's top producer [157]. The various nations having lithium reserves are depicted in Fig. 8 by their capacity, quality, and output.

5.1. *Some associated projects of Li-ion battery applications for sustainable energy storage*

The upcoming grid system, which is intricate but crucial for energy delivery in the modern day, is predicted to include a significant role in battery energy storage devices. Li-ion batteries are, at this stage, the most extensively used energy-holding devices for various grid services. This section overviews the current Li-ion battery applications for sustainable energy storage from different research perspectives based on actual projects. Although significant resources are expended during installation, only system owners who precisely predict the lifetime costs and installation-related hazards can now assess the performance and dependability of the various energy storage systems. Each project is considered a learning curve for the future development of sustainable energy storage systems. According to the official hub for Global Energy Storage Data by the United States Department of Energy (DOE), 1364 energy storage projects using 174 GWs of energy were operational across the globe as of December 2021, with additional 334 energy storage projects with a combined rated power of 18 GWs already announced to be contracted and built [159,160]. Among the various battery energy storage systems, the Li-ion battery alone makes up 78 % of those currently in use [161].

The need for next-generation Li-ion batteries is rising quickly to satisfy the needs of developing applications like electric vehicles and large-scale energy storage systems at a significantly reduced cost as global warming, and environmental pollution become critical global challenges. Xu et al. carried out a project to develop a Li-ion battery with anatase TiO_2 as the anode and $LiFePO_4$ cathodes to supplement stationary energy storage systems for renewable energy sources like solar and wind power. The study compared the battery's performance with other anode materials and found minimal lattice distortion and volume change during lithium-ion insertion and extraction on $LiFePO_4$ and anatase TiO_2 or $LiTi_{15}O_{12}$ electrode materials. The $LiTi_{15}O_{12}$ or TiO_2 anodes demonstrated a promising electrode combination for stationary applications and will offer affordable, secure, and stable cycling performance [162]. The structure of the Li-ion battery cell with anatase TiO_2 as cathode material is shown in Fig. 9. In another battery design project for practical application, Crawford et al. performed a lifecycles comparison of a Li-ion battery based on $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ and

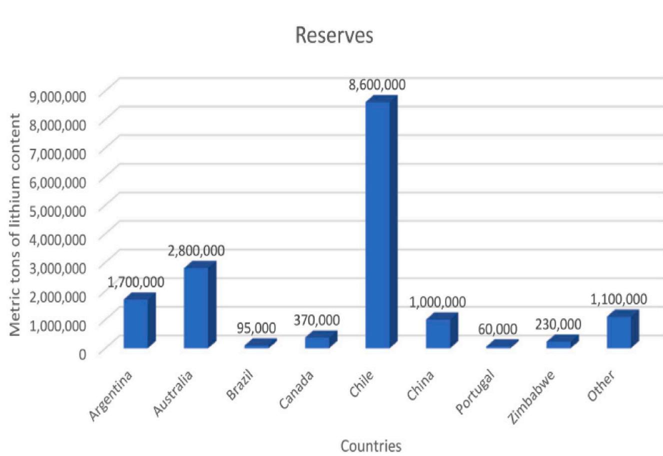

Fig. 8. Various nations with large lithium reserves. Data obtained via USGS report [158].

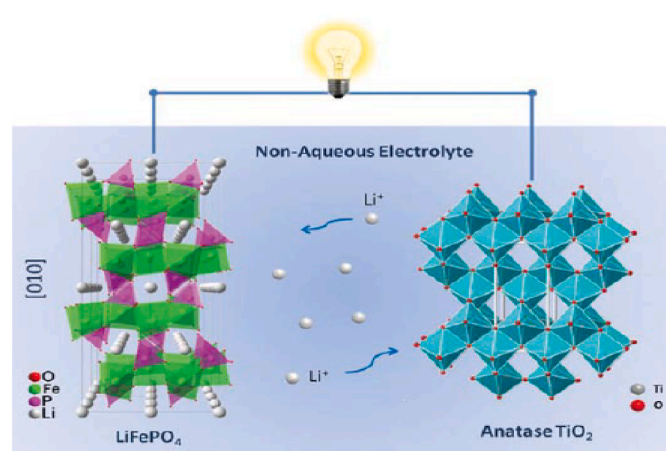

Fig. 9. Li-ion battery cell with $LiFePO_4$ anode and anatase TiO_2 as cathode material for immobile energy storage application (Adapted from Ref. [164]).

$LiFePO_4$ electrodes for electric vehicle grid storage. They tested the network duty cycles for recurrence control and peak shaving to appreciate the degradative impact of grid service for typical electric vehicle use patterns. The authors observed that second-life energy grid storage applications, repurposed Li-ion batteries with eight years of electric vehicle service could provide up to ten years of extra service, depending on the chemistry and use profile [163].

The feasibility of automating Li-ion battery assembly for electric vehicles was carried out by D'Zousa et al. (2020). The proposed design addressed existing capacity needs in the electric vehicle industry and unmet needs for the long-term sustainability of lithium-ion power packs by providing a novel strategic capability that is modular, scalable, and sustainable to the electric vehicle original electric equipment manufacturing sector. The study gave Li-ion assembly systems vendors a solid alternative offering to pitch to electric vehicle original electric equipment manufacturers and more excellent details on volume plans, specs, and requirements for assembly and disassembly [165].

Off-grid energy systems are becoming increasingly common as a self-sufficient source of energy to meet the needs of individual households for electricity, especially in undeveloped countries where the primary grid is either underdeveloped or expanding the grid would be economically unviable due to the location's remoteness. Fig. 10 shows the overall configuration of a macroscale Li-ion battery energy depository system, including the battery handling system, the grid connection, and the coupling system.

In the US Northwest Power Pool system, Viswanathan et al. [166] discovered that Li-ion batteries would be more affordable than natural gas to support 15 GW of wind energy. Universities, military bases, and numerous tourist attractions are all benefiting from microgrid energy storage [167]. On the Dutch island of Bonaire, a burned-out power plant was renovated in 2009 using a hybrid wind-diesel facility coupled with a 3 MW Li-ion battery to provide the starting power and the reinforcement required to maintain energy quality. If wind turbine output drops, the Li-ion batteries provide energy for 2 min to enable diesel start-up [168]. On the Japanese island of Miyakojima, 25 homes with four kWp of consumer-side PV were outfitted with 8 kWh of Li-ion battery storage in 2010. Based on the weather, the PV power output storage capabilities fluctuated up to 3 MW in minutes. Still, this impact on the grid was reduced by adopting Li-ion battery storage systems [169].

Lithium-ion batteries are an electrochemical energy storage option that is gaining popularity for off-network, mini, and mini-grid projects. Lithium-ion batteries have long been the preferred choice for performance because their elevated specific energy can vary from 75 W h/kg to 125 W h/kg. Some cutting-edge Li-ion technologies can provide up to 15,000 complete cycles, efficiency between 90 and 95, and self-discharge of around 5 % monthly, increasing their prospects of becoming the storage centers for community-scale grids in underdeveloped countries [170].

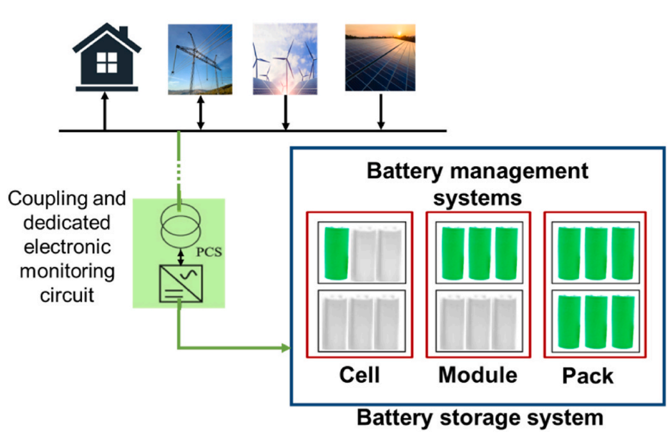

Fig. 10. Depiction of a macroscale Li-ion battery energy storage system.

California's Moss Landing Energy Storage Facility has opened the world's most extensive lithium-based energy storage system. In December 2020, the successful project started storing energy and was connected to the electrical grid. It is presently the world's most significant energy storage system, powered by lithium-ion batteries, with a 300 MW/1200 MWh capacity. It offers emission-free electricity, complies with California's sustainability regulations and goals, considerably helps the neighborhood, and eventually gives consumers affordable electricity [171]. Lithium-ion batteries are an excellent choice for small off-grid energy storage applications in developing countries because of their high energy density and long lifespan. Still, their high cost prevents them from being employed in these circumstances. Birki et al. created a modular converter system employing used Li-ion batteries for low-cost off-grid energy storage because they are less expensive and still have good capacity and cycle life. However, a robust power management system is required to govern the converters to safely and effectively use such cells. Their study offered a revolutionary design that allowed the building of an electrical storage device using repurposed Li-ion cells of varied types and capacities. This design also included a system to account for variations in cell voltages and abilities as well as the failure of individual cells [172].

The expansion of the electric vehicle market offers another chance for using Li-ion batteries for grid storage. Companies like Toyota, BMW, Nissan, and Tesla have already built grid-connected storage facilities for their electric vehicle batteries. However, the investigation is still ongoing on their performance and competing technologies standing [173,174]. Other ongoing projects involve reusing electric car batteries once their capacity decreases. Several manufacturers are taking these batteries for reuse in stationary electricity storage, where they can be utilized to power buildings or even a whole neighborhood during power outages. Thereby maximizing the use of low-carbon energy generated by solar power plants and wind turbines. Vehicle-to-grid (V2G) technology, which Mobilize is developing in the Netherlands, is a good example. This technology directly reintroduces the low-carbon electricity from an electric car into the grid. When plugged into a terminal, a car's battery can be energy storage. The complete steps of assembling Li-ion battery packs for electric vehicle applications are shown in Fig. 11.

To improve Li-ion battery storage's wider acceptance for more application areas, such as shipping, air travel, and space travel, ongoing research, and development are expanding quickly and pose challenges to developing effective battery thermal management systems, rigorous testing protocols, safety considerations, and certification standards. Most all-electric and plug-in hybrid vehicles on the road today use Li-ion batteries, even though the specific chemistry frequently differs from that of consumer electronics batteries.

Due to the absence of vibration, external weather conditions, weight and volume restrictions, and irregular driving cycles, stationary electricity grid utility applications are often less demanding than electric vehicle applications. Li-ion is a good contender for battery storage system applications because of its long cycle life and adaptable charging/discharging capabilities. Batteries manufacturers continually pursue better cell chemistry, higher energy densities, and smaller, more compact designs for better integration into various applications.

6. Comparative analysis of Li-ion batteries with alternate energy storage technologies

Most portable consumer electronics, such as mobile phones and laptops, today use Li-ion batteries because of their high energy per mass compared to alternative electrical energy storage technologies. They also work well at high temperatures, have a high power-to-weight ratio, are very energy-efficient, and have less self-discharge. Numerous energy storage systems are competitive with Li-ion batteries in terms of their suitability for large-scale storage, energy efficiency, energy per unit mass, power-to-weight ratio, high-temperature performance, discharge rate, and cost. These technologies include pumped hydro storage,

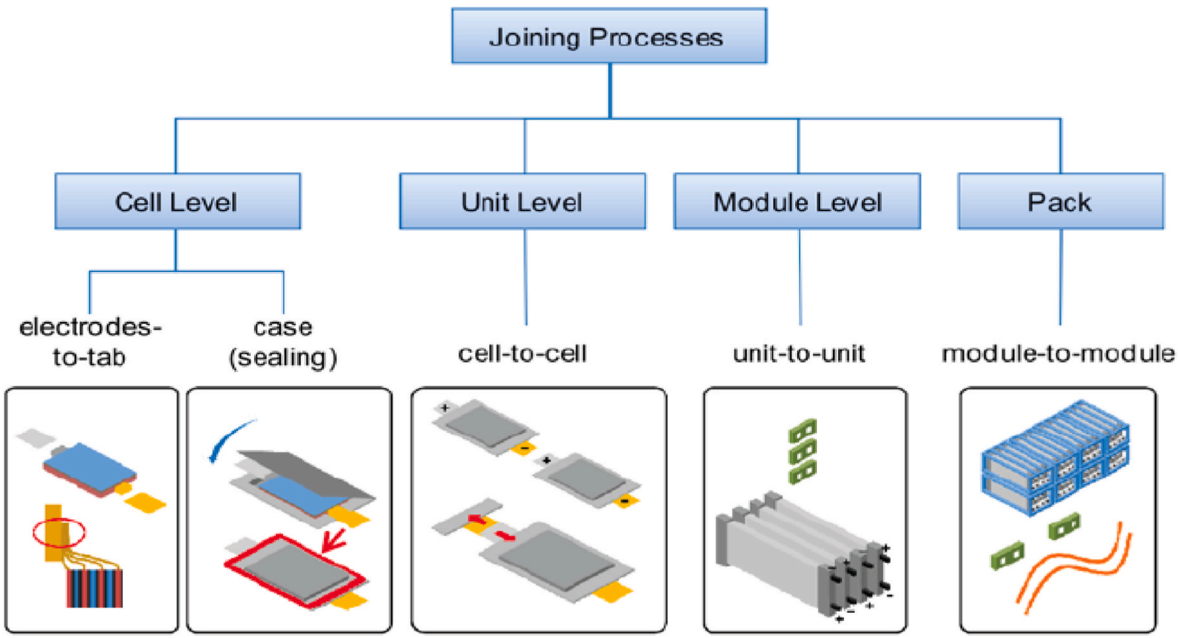

Fig. 11. The process of assembling Li-ion batteries for electric vehicles' use [175].

sodium sulfide, compressed air energy storage, flow batteries, and thermal energy storage.

Batteries made of lithium have a low weight and a high operating voltage due to their low density and substantial standard electrode potential. Li-ion batteries offer one of the finest energy-to-mass ratios, no memory effect, and minimal self-charge, making them the primary energy storage option for portable gadgets like mobile phones, iPads, and televisions [176]. However, Li-ion batteries are expensive to maintain and have several safety concerns. Table 2 contains numerical values for several parameters of Li-ion batteries and compared with alternate energy storage technologies. Flow batteries are now competitive options for generating and storing sustainable energy because of their adaptive modular layout and functioning, long cycle life, moderate maintenance cost, and high stability. Flow batteries are observed to be best suited for high-power rechargeable storage because of their comparatively large redox flow capacity. This has made them very attractive for grid energy storage. However, flow batteries are unlikely to offer workable large-scale energy storage options in the current environment [177,178]. Pumped hydro storage provides the highest storage capacity and efficiency of about 70–85 % compared to other energy storage technologies. The technology is in high demand since it can deliver high power and ability. However, due to its immobile nature and geographic limitations, it is not very attractive [179].

Large-scale renewable energy systems have successfully incorporated compressed air storage technologies [181,182]. Compressed air storage systems have several benefits, such as fewer maintenance procedures, the capacity to function better even in adverse environmental circumstances, and longer lifespan. The major drawback of this technology is its low energy efficiency, mainly caused by heat lost during the compression process.

Compared to other storage technologies, thermal energy storage systems are relatively cost-effective and have minimal negative environmental impact. Large buildings can store energy effectively using the method. The technology was previously only utilized on a limited scale for heating and hot water. Still, it is currently gaining pace for usage in large-scale electrical energy production as a sustainable energy storage technique [183].

Li-ion batteries are often regarded as safe when used in rechargeable applications, with a charge threshold of eighty percent made possible. They are likely to explode if overcharged due to an increased temperature during the charging process and because Li-ion batteries are far denser than other batteries. On the other hand, raw materials for Li-ion batteries, such as cobalt, lithium, and copper, are less hazardous and abundant in nature. However, the risks associated with recycling used Li-ion batteries are substantial due to dangerous metals like nickel and manganese, which are detrimental to the ecosystem and natural water sources. Li-ion batteries are also fire hazards compared to other renewable energy storage technologies and thus must be properly disposed of or handled with care when recycling [184].

7. Future outlook for Li-ion batteries in sustainable energy storage systems

Due to their suitability for use in electric vehicles and the need to combat climate change through radical energy transition, Li-ion batteries will continue to be in high demand worldwide. The Li-ion battery chain, from mining to recycling, could expand by more than 30 % yearly from 2022 to 2030, reaching a market size of 4.7 TWh and a value of more than 400 billion dollars, based on a 2022 estimate by McKinsey Battery Insights team. If not appropriately managed, this growth could bring many social benefits, but with severe environmental impacts.

As the demand for Li-ion batteries increases, so will the need for raw material extraction; the risk of lithium scarcity will impact the economy and the environment due to excessive mining. Thus, effective industrialization and friendly environmental procedures for sustainable decarbonization will be needed. The future disposition of used Li-ion batteries poses another environmental challenge; therefore, recycling is recommended. Governments and legislators should create programs and subsidies that would support Li-ion battery recycling to save the environment and lessen the cost of resource extraction. Lithium technology must be combined with other energy sources to deliver sustainable energy storage solutions and ease resource restrictions efficiently. Recycling must be strictly regulated, especially in underdeveloped nations with lenient environmental laws and affordable labor.

Furthermore, manufacturers should develop a better approach to balance decreased material usage, economic growth, and prolonged product life. Significant policy modifications should carefully govern take-back procedures and subsequent recycling procedures. In the interim, stakeholders can contribute to preserving resources other than lithium by engaging in wise consumer behavior: Consider purchasing

Table 2
Energy storage technology comparison table adapted from [180].

Storage System	Output Device	Power [MW]	Device Capacity [MWh]	Storage Period	Specific Energy [kWh/ton]	Energy Density [kWh/m^3]	Efficiency [%]	Lifetime [#cycles]	Energy Cost [$/kWh]	Power Cost [$/kW]	LCOS [$/MWh]	Maturity
LIB	Electric	0.001–0.1	0.25–25	Day–Month	75–200	300	85–100	1000–4500	500–2500	175–4000	120–200	Commercial
RFB	Electric	0.03–7	<10	Day–Month	10–30	25–35	75–85	12,000	150–1000	600–1500	150–300	Demo/Early Commercial
CAES	Electric	5–300	≤250	Day	30–60	2–6 (at 70–200 bar)	60–79	8000–12000	50–100	1250	60–150	Demo/Early Commercial
PHES	Electric	<3100	Small: ≤5000Large: ≤140000	Day–Month	~0.28 (at 100m head)	~0.28 (at 100m head)	65–82	10,000–30,000	80–200	600–2000	30–100	Mature

eco-friendly products and rethinking how often you should replace your car, mobile phone, laptop, and digital camera or their Li-ion batteries.

Effective cathode, anode, and electrolyte materials that can improve their life cycle should be developed at the lab-scale and commercial levels to manage Li-ion batteries' raw material scarcity. Consumer education will also be necessary for the sustainability of the Li-ion batteries. Vendors should be considered part of the value chain, and consumers should know when it is right to replace the batteries of their mobile phones, laptops, and other electronic and electric vehicle batteries, as well as and their proper disposal. Finally, energy intensive operations should choose the essential energy mix for their service for better environmental impact and energy efficiency.

8. Conclusions

Lithium-ion batteries play a crucial role in pursuing sustainable energy storage, offering significant potential to support the transition to a low-carbon future. Their high energy density, efficiency, and versatility make them an essential component in integrating renewable energy sources and stabilizing power grids. However, the widespread adoption of Li-ion batteries also presents challenges, including concerns about resource availability, environmental impact, and safety. Addressing these challenges requires continued innovation in battery technology, improvements in recycling and resource management, and the development of alternative materials. Furthermore, policy support and investment in research are crucial to overcoming these hurdles and unlocking the full potential of Li-ion batteries. By navigating these challenges, Li-ion batteries can play a central role in achieving global sustainability goals, making them a vital element in the future of energy storage. In this article, the multifaceted landscape of Li-ion batteries has been presented, emphasizing their critical importance in the transition towards a cleaner and more sustainable energy future. After a comprehensive analysis of the latest developments, challenges, and opportunities, the main finding is that as the demand for sustainable energy storage increases, and Li-ion batteries remain at the forefront, positioned to play a pivotal role in integrating renewable energy sources, enhancing grid stability, and reducing carbon emissions. Li-ion batteries are a versatile and reliable energy storage technology. Their widespread adoption in portable electronics, electric vehicles, and renewable energy systems underscores their adaptability and indispensability in modern society. Key findings from this review show that solid-state batteries and recycling strategies are promising pathways for enhancing sustainability and reducing environmental burdens. In addition, electrolyte formulation is central to improving the lifespan and operational safety of Li-ion batteries, and high-capacity electrode materials such as silicon-based anodes and layered oxide cathodes show strong potential for next-generation Li-ion batteries. As researchers and policymakers continue to push the boundaries of Li-ion battery technology, we move closer to achieving a more sustainable and electrified future that is a reliable, and efficient, as well as an eco-friendly energy storage system.

9. Recommendations for future research

The integration of Li-ion batteries with other energy storage technologies, such as supercapacitors or flow batteries, in future studies to create hybrid systems that offer enhanced energy density, longer life cycle, and improved performance. Additionally, researchers working in this field should investigate using nanomaterials, such as nanowires, nanotubes, or nanocomposites, in Li-ion batteries to improve energy storage capacity, charge-discharge rates, and overall performance.

While Li-ion batteries are currently the most dominant energy storage technology, it is essential to explore alternative battery chemistries. Research efforts should be directed towards technologies like solid-state batteries, lithium-sulfur batteries, and beyond-Li-ion chemistries to diversify energy storage options and address potential limitations of Li-ion batteries. A comprehensive life cycle assessment to evaluate the environmental impact of Li-ion batteries throughout their entire life-cycle, from raw material extraction to manufacturing, use, and disposal, is also proposed for future research in the field.

Author contributions

All authors contributed to the study's conception and design. Mr. Kitalu R. Ngoy wrote the first draft. Mr. Valantine Takwa Lukong provided the structural design, data collection, and final draft. Mr. John Beya and Mr. Christopher Chukwuati contributed to the preliminary review and editing. Dr. Kelvin Yoro and Dr. Orevaoghene Eterigho-Ikelegbe contributed to reviewing, editing and redrawing all the figures and tables as well as revising the manuscript. Dr Kingsley Ukoba and Prof. Tien-Chien Jen supervised the project. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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