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Perspective

Ten major challenges for sustainable lithium-ion batteries

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SUMMARY

Lithium-ion batteries offer a contemporary solution to curb greenhouse gas emissions and combat the climate crisis driven by gasoline usage. Consequently, rigorous research is currently underway to improve the performance and sustainability of current lithium-ion batteries or to develop newer battery chemistry. However, as an industrial product, batteries follow a linear route of waste-intensive production, use, and disposal; therefore, greater circularity would elevate them as sustainable energizers. This article outlines principles of sustainability and circularity of secondary batteries considering the life cycle of lithium-ion batteries as well as material recovery, component reuse, recycling efficiency, environmental impact, and economic viability. By addressing the issues outlined in these principles through cutting-edge research and development, it is anticipated that battery sustainability, safety, and efficiency can be improved, thereby enabling stable grid-scale operations for stationary storage and efficient, safe operation of electric vehicles, including end-of-life management and second-life applications.

INTRODUCTION

Following the rapid expansion of electric vehicles (EVs), the market share of lithium-ion batteries (LIBs) has increased exponentially and is expected to continue growing, reaching 4.7 TWh by 2030 as projected by McKinsey.[1] As the energy grid transitions to renewables and heavy vehicles like trucks and buses increasingly rely on rechargeable batteries, there is a growing emphasis on conducting sustainability assessments and life cycle assessments (LCAs) of batteries. These assessments aim to evaluate the environmental impact of rechargeable batteries across their entire lifespan, encompassing production usage and end-use management, reflecting the expanding market for such batteries.[2,3]

To date, several efforts have been introduced to improve the sustainability of rechargeable batteries, especially LIBs, considering their widespread market adoption.[2] Obviously, prolonging their operational lifetime is one of the most desirable routes.[4] A strict requirement for EVs is that the state-of-health (SOH) of the LIBs should be >80%, below which the performance of the EVs (especially mileage) is significantly affected.[5,6] A recommendation was to deploy the batteries of SOH <80% for secondary applications such as stationary power storage station, considering that these storage stations allow the batteries to be used further to SOH of 40% or lower.[7,8] Prolonging the operational lifetime of the batteries could effectively delay their delivery for recycling or upcycling. Recycling the components of LIBs is also actively researched to relieve the burden of sourcing new precursor materials during production as well as reducing the amount of critical materials (Li, Co, Ni, Mn, etc.) ending up in landfills.[9] Despite the availability of various LIB recycling

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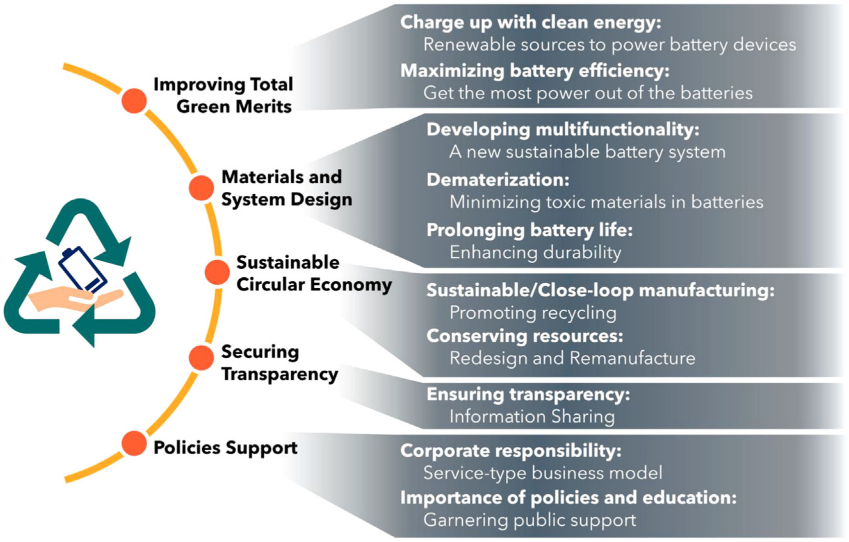

Figure 1. Five main criteria for a sustainable rechargeable battery

Ten principles or development directions to achieve or enhance the sustainability of rechargeable batteries. These principles require synergistic efforts from the public, government, and industries.

techniques[10] and the emergence of battery recycling industries like Southeast Asia's TES B facility in Singapore, the lack of widespread adoption or prominence of such facilities globally remains a concern.[11] One of the main challenges in recycling LIBs is the frequent change in the cathode material choice; the chemistry of recovered cathode material could differ among batches.[12,13] Reducing the cost of recycling LIBs can also help in establishing a recycling industry. Direct cathode recycling stands out as the most effective method, reducing carbon footprint by 17% to 8% and energy use by 6% to 2% compared to alternatives like hydrometallurgical, pyrometallurgical, and electrochemical processes.[14] Nevertheless, to achieve better sustainability for rechargeable batteries, all the negative impacts throughout their life cycle are to be minimized or eliminated. One example is the release of greenhouse gases (GHGs) during the operation, which is mostly neglected as the primary emission is from the power source not from the batteries.

Batteries are often regarded as a green technology when compared to fossil fuels, but they do generate GHG emissions in a direct or indirect way throughout their life cycle, with manufacturing phase (mining and processing raw materials) being a significant contributor to these emissions. Zhao and You's analysis[3] showed higher GHG release during application, particularly with specific cathode materials. Undeniably, securing sustainability in batteries should not focus only on the end of life (EoL) but throughout the life cycle of the batteries. Additionally, the responsibility of establishing circularity in batteries should not depend solely on industries and producers but should involve consumers as well. Policies that promote collaboration and synergy among the public, government, and industries would play a crucial role in this aspect. This led to the establishment of five main criteria and ten principles as outlined in Figure 1. In this perspective article, we have identified five key aspects shaping the entire battery life cycle, informing ten principles covering material design, green merits, circular management, and societal responsibilities. While each principle stands alone, they are interconnected, making assessment complex. Our perspective, outlined in Table 1, recognizes diverse influences on battery sustainability, encouraging broader considerations for improvement.

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Table 1. Classification of ten principles based on the five criteria with applicability

Criteria	Principles	Approaches	Initiatives to be taken	Parties involved
Improving total green merits	charge up with clean energy	• integration of renewable energy with power grid	• develop policies favoring renewable energy • strict requirement on carbon footprint and GHG emissions	• policies maker
	maximizing battery efficiency	• design of batteries with high energy density electrodes • battery pack design with efficient battery management system (BMS) and cooling systems	• accessible data on efficiency metrics and cell prototypes	• research communities • manufacturer
Materials and system design	developing multifunctionality	• including multifunctionalities such as piezo, tribo, thermal, light, and biomechanical generators	• explore diverse applications to extend multifunctional batteries • funding to support emerging technologies	• research communities • manufacturer
	dematerialization	• reducing adoption of high performing transition metals through nanotechnology	• funding for nanotechnology research • material choices considering LCA and end-of-life management	• research communities
	prolonging battery life	• optimizing and innovating charging protocols • constant SOH monitoring	• extending lifespan (secondary applications) • implement efficient SOH monitoring practices	• research communities • manufacturer
Sustainable circular economy	sustainable/closed-loop manufacturing	• LCA and inventory analysis • boost recycling efforts	• promoting sustainable practices in manufacturing • efficient recycling techniques	• research communities • manufacturer • policies maker • public
	conserving resources	• optimize resource utilization • design for efficient assembly and disassembly	• incentives for resource conservation • policies supporting recycled batteries	• research communities • manufacturer • policymakers
Securing transparency	ensuring transparency	• disclosure of more information on battery manufacturing	• open research practices • support for standardization and trade regulations • transparency in information sharing and data disclosure • consumers well informed about the LCA of the battery	• research communities • manufacturer • policies maker
Policies support	corporate responsibility	• service-type businesses • extended producer responsibilities	• hold manufacturers and consumers accountable for environmental impacts	• research communities • manufacturer • policies maker • public
	importance of policies and education	• efficient waste collection and management • deposit refund schemes for batteries	• enact policies to regulate battery disposal and recycling • promote sustainable end-of-life management for batteries	• policies maker • public • manufacturer

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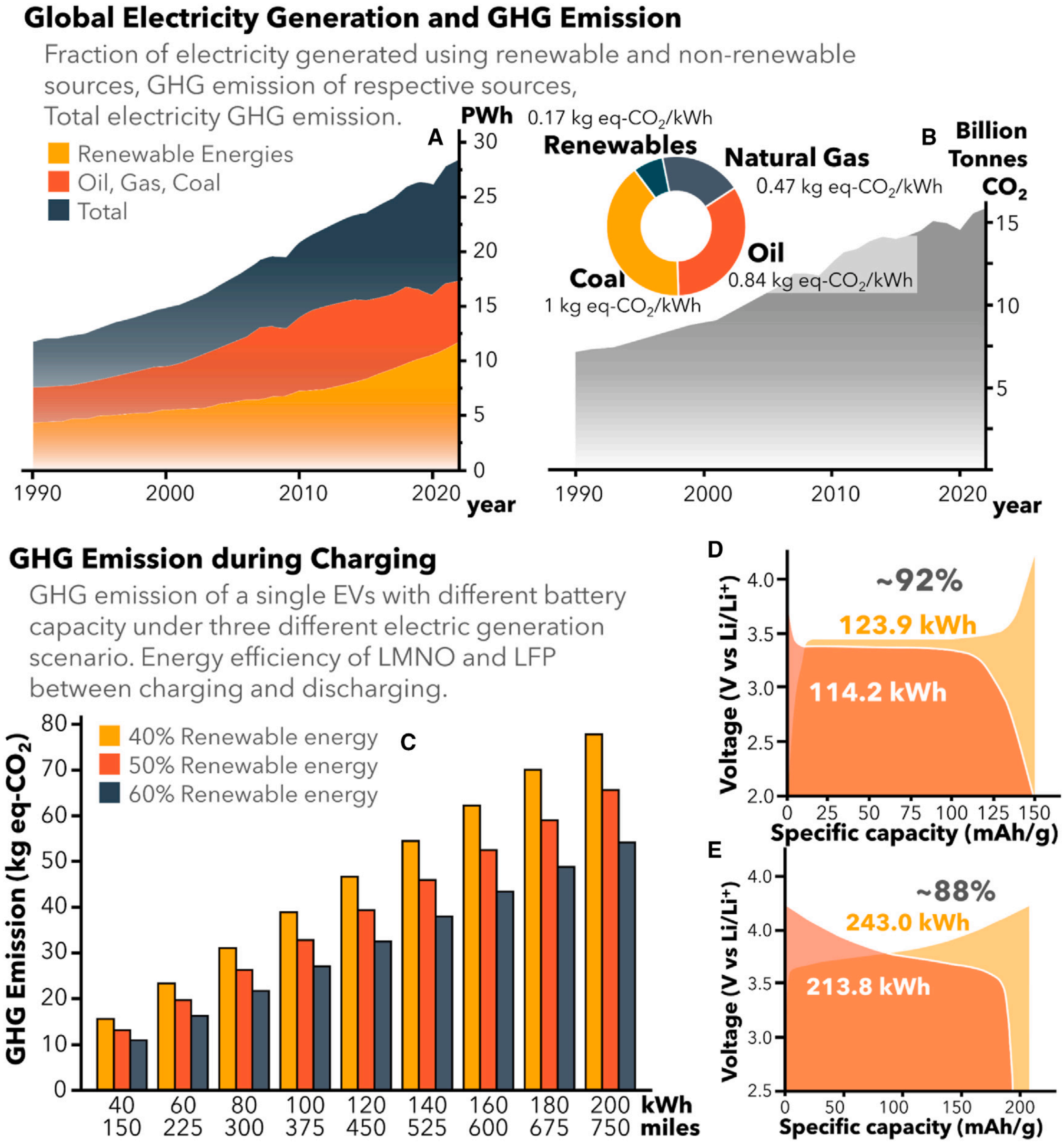

Figure 2. Improving the green metric of rechargeable batteries

Reducing the GHG emissions for the power grid used to charge the batteries is critical in enhancing overall sustainability of rechargeable batteries.

(A) Sources of energy generation for the power grid around the globe where non-renewable energy sources occupied a huge fraction.

(B) The total global GHG emissions during energy generation, where most originated from non-renewable energy sources.

(C) Projection of GHG emissions when the fraction of renewable energy in the power grid is increased to 60%.

(D and E) The energy efficiency for $LiFePO_4$ (D) and $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ (E) cathode material, respectively.

THE TEN PRINCIPLES

Charge up with clean energy

Clean electrification via batteries also involves charging from clean sources. Charging batteries from the power grid entails drawing power generated from a mixed source, where most of this power is generated from non-renewable sources, as shown in Figure 2A. The GHG emissions of these sources are summarized in Figure 2B, with the annual total GHG emissions for the power grid. In brief, generating energy from non-renewable sources such as oil, natural gases, and coal will generate

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GHGs of 1.11, 0.44, and 1.03 kg eq-CO_2, respectively.[15] In other words, the claims that batteries are fossil-fuel-free during operation are unacceptable. In Figure 2C, we estimated the reduction in GHG emissions of battery modules charged through a 60% renewable energy generation power grid during daily operation. Based on the current technologies, an EV with a 40- and 100-kWh LIB module could drive for 150 and 375 miles, respectively,[16] a mileage-to-capacity ratio of 3.75. Charging a 40-kWh LIB module is estimated to release ~15.6 kg eq-CO_2, where increasing the contribution of renewable energies in electricity to 60% is expected to reduce the GHG emission to ~10 kg eq-CO_2. The estimated value was derived from a single EV and could be an underestimation when compared to the actual GHG emissions. Nevertheless, such a prediction shows the significance of promoting a fossil-fuel-free power grid to further reduce the GHG emission of LIBs during operation. The continuous cost reduction for power generation using renewable technologies could also lower the overall operational cost of LIBs.[17] Besides, from promoting renewable energies in the power grid, the operational and EoL GHG emissions of LIBs can also be further reduced through either improving the energy efficiency during charging/discharging or promoting multifunctionality within the LIBs and utilizing renewables for battery recycling. Transparency in renewable energy sourcing aids stakeholder trust and market differentiation, while challenges include costs, supply chain complexity, regulatory burdens, greenwashing risks, and technological constraints. Government policies supporting renewables and disclosing related technology specifications without revealing proprietary information could aid in long-term planning.

Maximizing battery efficiency

The disproportion between the charge stored during charging and discharging is commonly referred to as Coulombic efficiency.[18–20] Different from Coulombic efficiency, energy efficiency offers information on the energy lost during the charging process. To demonstrate the energy efficiency of LIBs, the charge/discharge behavior of the two most widely deployed cathode materials, namely $LiFePO_4$ and $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$, are compared in Figures 2D and 2E. The area under the charging or discharging curve corresponds to the energy consumed (released) during charging (discharging). An energy efficiency of ~92% and ~88% was calculated for $LiFePO_4$ and $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$, respectively. While exhibiting notable energy efficiency, an 8% to 12% energy loss occurs during operation, equating to operational GHG emissions of approximately 1.6 kg eq-CO_2 for a 40-kWh battery capacity. In the case of an anode, substituting the graphite anode (~250 Wh/kg) with lithium, the specific energy can be increased to about 450 Wh/kg in Li-LMO cells, and Li-S and Li air systems can further elevate this to ~650 Wh/kg and ~950 Wh/kg, respectively. However, challenges including volume changes and dendrite formation encountered in designing Li metal full cells lead to repeatability issues. While Si-carbon-based anode materials provide benefits like high capacity, high open circuit voltage (~4 V), and eco-friendliness, they face obstacles in commercialization due to issues such as poor conductivity and electrode degradation upon cycles.[21] In a practical scenario, the structural pack design utilizing the 2,170 and 4,680 cells in the Tesla Model Y has shown significant improvements in manufacturing, with 50% lower capital expenditure and a 66% smaller environmental footprint. Over a 2-week period, the 2,170 cells in the Model 3 may discharge by approximately 14%.[22,23] Considering the energy saved, increasing the energy efficiency of LIBs could result in a more sustainable and cost-effective power system. Energy efficiency can be further enhanced through (1) material design and engineering, (2) battery operation management and monitoring, as well as (3) device innovation. Incorporating sacrificial organic lithium salt as an additive in the cathode could form a stable

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Table 2. Metrics to be considered while designing cells and for LCA analysis

Parameter	NCA graphite	NMC graphite	LFP graphite	LFP LTO
Cell-level specific energy (Wh/kg)	150–200	150–180	120–150	100–120
Nominal voltage	3.6–3.9 V	3.6–4.2 V	3.2–3.3 V	2.3–2.5 V
Cycle life	500–1,000	1,000–2,000	2,000–3,000	5,000+
Shelf life	3–5 years	3–7 years	5–10 years	10+ years
Operating temperature	−20°C–60°C	−20°C–65°C	−20°C–45°C	−20°C–55°C
Thermal runaway	150°C–200°C	160°C–210°C	200°C–250°C	270°C–300°C
Price per kWh rating	\$150–\$250	\$120–\$200	\$100–\$150	\$200–\$300
Primary use cases	EVs grid storage	EVs grid storage	power tools consumer electronics	energy storage EVs electric buses
Manufacturers	Panasonic LG Chem Samsung SDI	Panasonic LG Chem Samsung SDI	BYD CATL CALB	BYD Lishen Kokam
Environmental impact (CO_2 eq/kWh)	100–200	80–180	50–150	30–100
Energy efficiency	85%–90%	85%–92%	80%–85%	90%–95%
Material toxicity	moderate	moderate	low	low
Manufacturing footprint (kWh/kg)	200–300	180–280	150–250	120–200
Resource depletion	high	high	moderate	low
Recycling rate	10%–20%	15%–25%	20%–30%	30%–40%
Social impacts	moderate	moderate	low	low
Supply chain transparency	low	low	moderate	moderate
Economic factors (\$/kWh)	150–250	130–220	100–200	80–150
Policy and regulations	stringent regulations	stringent regulations	moderate regulations	limited regulations

The values provided are based on Lai et al., Porzio and Scown, Arshad et al., and Wang et al.[2,27–29] and may vary depending on various factors such as region, manufacturing processes, and inventory used.

interface while significantly reducing the parasitic lithium consumption during charging-discharging while improving the electrochemical performance of the battery.[24,25] Other than material engineering, the capability of the battery management system in adjusting the operating conditions of the battery (i.e., thermal management, charge-discharge rate, etc.) is also crucial in maximizing the energy efficiency of the battery.[26] Last but not least, manufacturing of the battery needs to be fine-tuned to achieve a device with the lowest possible internal resistance while pursuing reduced volume or weight (for higher volumetric and gravimetric energy density). In battery management systems, air cooling provides cost-effective temperature-control solutions for LIB packs in EVs alongside liquid cooling and phase-change material solutions. When commercializing new battery designs and improvements in efficiency, standardizing the reporting of energy efficiency metrics outlined in Table 2 supports transparency for sustainability reporting and assessments.

Developing multifunctionality

Thus far, LIBs have been used solely to store charges; however, efforts to increase the multi-functionality of LIBs, as shown in Figure 3A are currently underway.[30,31] Contemporary research includes energy generation capability within the LIBs through device component modification. The capability to generate and simultaneously store charges within a single device was reported to be the next possible development of self-rechargeable energy storage technology.[32] Utilizing photovoltaic electrode materials, piezo-electric separator, tribo-electric electrodes, and redox-active electrolyte would result in photo-, piezo-, tribo-, thermo-, and bio-electrochemical batteries.[33] Among them, piezo-, tribo-, thermo-, and bio-electrochemical batteries have the potential to harvest ambient energies from body movements, heat, and bodily fluids. While they offer opportunities for self-powered wearables or

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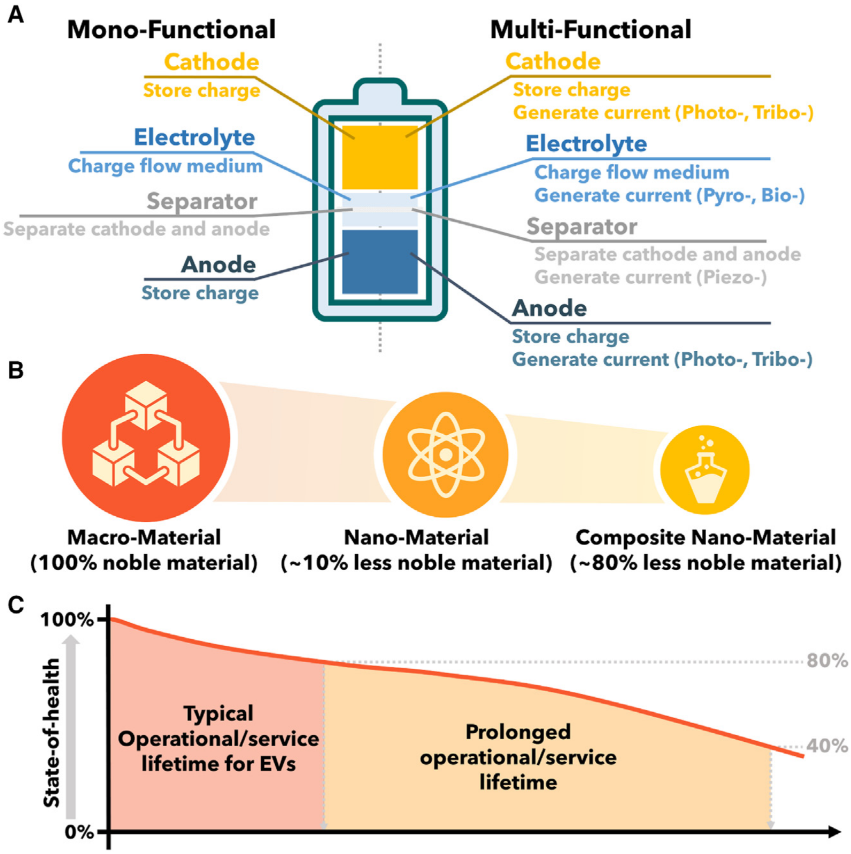

Figure 3. Material design for improved electrochemical performance

Careful selection of materials could serve as a catalyst in further enhancing the functionality and performance of the energy storage devices.

(A) Promoting multifunctionality in rechargeable batteries through replacing specific components with current-generating properties. The batteries can be charged simultaneously during operation (despite the low charging efficiency from current technologies).

(B) Dematerialization of electrode materials through nanostructuring could reduce the amount of resources (ecological impact can be minimized) while maintaining the electrochemical performance of the energy storage devices.

(C) Prolonging operational lifetime of rechargeable batteries through repurposing or reusing the discarded batteries. The operational lifetime of the battery can be extended significantly by repurposing the discarded batteries for other applications.

small gadgets in portable electronic devices, their relevance for EV batteries is limited due to differences in scale, efficiency, and requirements. Further, tribo and piezo energy harvesting typically generates energy in pulses or intermittent surges rather than providing a continuous and steady supply of electrical energy, limiting their commercial usage. One suitable example is regenerative braking, already employed in EVs but in need of enhanced efficiency. This system recharges the battery by harnessing the friction energy produced during braking operations. Other than these approaches, sacrificial materials can also be included into a battery to induce charging through chemical oxidation reaction.[34,35] Despite the poor cycling capability (or reusability) of this technique, further research could enable complete recovery of the oxidized material, allowing for continuous and repetitive rechargeability. The self-power characteristic could also prolong the operation duration of the batteries while reducing the needs for charging through the power grid, further reducing the operation GHG emission of LIBs. Unfortunately, the energy harvesting efficiency of the "generators" in tandem with LIBs is lower than their standalone "generators" counterpart.[32,36] Therefore, materials, protocols, and devices to convert photo-, thermo-, piezo-, tribo-, and bio-electrochemical energies as well as chemical redox reaction into electrical charges and storing them with high energy efficiency must be intensively researched for commercialization with open research practices.

Dematerialization

Dematerialization in batteries aims to store more energy using fewer materials, achieved through advances like solid-state electrolytes and additive manufacturing, resulting in lighter, more efficient cells with reduced waste while improving recycling methods to recover critical materials efficiently. Toxicity of materials is a critical issue during materials processing, device fabrication, and end-use management. Thanks to the advancement of packaging technologies, toxicity and leakage do not pose significant threats during their operation. Present-day batteries use heavy metals with lower environmental sustainability, such as lead, cobalt, nickel, and phosphorus. Their irresponsible disposal could pose a slow poison to living beings. All living organisms store energy in their tissues for later use, signifying that developing biofriendly materials and protocols for energy storage is possible. Other than material toxicity, scarcity of raw materials also poses significant obstacles in manufacturing low-cost LIBs. Rare elements such as cobalt and high-grade lithium are location specific and subject to geopolitical conflicts that would further increase the production cost of LIBs. One of the most widely adopted strategies in tackling the scarcity drawback is dematerialization, which can be defined as reducing the amount of material used during fabrication. Nickel-rich layered cathode materials are the best example of reducing the content of cobalt while preserving its electrochemical performance.[37,38] Adopting nanotechnology (Figure 3B) is also in line with the dematerialization strategy, where only a minimum amount of material is used for a required device functionality. One such example would be the nanoparticle silicon-graphite anode composite in LIBs, which aids in alleviating volume expansion of silicon nanoparticles as well as enhancing the overall performance of the anode.[39–42] However, the up-scaling and commercialization of nanotechnologies remain a hurdle due to its low yield and cost as well as time-consuming processing.

Prolonging battery life

Enhancing the durability of the batteries has always been the focus of recent research to put the device to work before ending up in landfill. Strategies aimed at extending the lifespan of current commercial LIBs in EVs involve optimizing charging protocols, enhancing thermal management, improving battery monitoring systems, and adopting smart charging practices. Operational battery life is influenced by chemistry, materials, and environmental factors. SOH efficiency measures a battery's current condition relative to its original capacity, influenced by factors like internal resistance and voltage suppression. Strategies for extending battery life include optimizing charging protocols and employing predictive maintenance. Monitoring SOH is crucial for predicting performance and scheduling maintenance, with implications for sustainable energy storage practices. Besides, batteries with longer operating duration (Figure 3C) would also increase the return of investment (ROI), which is beneficial in convincing the public to adopt batteries.[43]

Various methods are available for assessing the SOH, each serving specific purposes. Electrochemical impedance spectroscopy monitors internal resistance, capacitance changes, and voltage response across frequencies.[44] Cycling performance tests under constant current (galvanostatic) and constant voltage (potentiostatic) modes assess capacity retention, voltage stability, and cycle efficiency. Magnetic techniques, including magnetic resonance imaging and magnetic susceptibility measurements, allow non-invasive internal examination to detect structural abnormalities in solid-state batteries.[45] Certain non-destructive methods, such as eddy currents, for inspecting conductive materials while others like strain gauges and fiber Bragg gratings are adaptable to composite electrode materials. Acoustic emission techniques identify fatigue damage, albeit requiring precise capture of damage progression, especially in thin electrodes.[46] Ultrasonic guided waves offer detailed structural coverage with minimal signal loss, generated and detected using piezoelectric wafer active sensors for contact-based damage detection, suitable for *in operando* monitoring.[47,48] Electromagnetic acoustic transducers, air-coupled-ultrasonic sensors, and laser-based ultrasonic sensors are other non-contact options. Low-frequency ultrasound waves (<100 kHz) penetrate deeper, ideal for monitoring major structural flaws, while high-frequency waves (MHz) offer sharper detail for early detection of minor defects.[49] Additionally, machine learning techniques are applied to guided-ultrasonic-wave-based structural health monitoring (SHM) for predictive damage localization and quantification, using uncertainty quantification frameworks, probabilistic Bayesian approaches, and neural networks.[50]

Efforts to further increase the specific energy of LIBs have seen the adoption of alloying-type silicon as anode, offering a specific capacity of 2,000–3,000 mAh g^{-1}.[51,52] However, the extreme volume expansion of silicon particles during lithiation ($\sim$400 vol %) subjected the anode to severe fragmentation and poor cycling stability.[53] Despite recent efforts in enhancing the cycling stability of such anodes,[54,55] the durability of alloying-type materials is inferior compared with typical graphite. Advanced manufacturing techniques, such as 3D printing, stereolithography, and laser printing, can help to produce battery cells with a more precise and consistent structure.[56] This can improve their performance and durability by reducing the likelihood of defects and inconsistencies in the electrode manufacturing process. Proper charging and the maintenance practices can significantly impact battery lifespan. Using a high-quality battery charger with voltage and charge compatibility that limits the amount of overcharging helps prevent damage to the battery cells, for instance CTEK's Charge Strom sustainable EV charging stations. Also using a battery management system to monitor the SOH of the stationary LIBs and ensuring that they are not subjected to extreme temperatures or other adverse conditions can help to extend their lifespan.

Sustainable/closed-loop manufacturing

Despite been labeled as green technologies, LIBs have a high-carbon footprint from their production; a whopping 89 eq-CO_2/kWh emission during the processing of electrode materials.[57] Closed-loop production, also known as circular production, involves recovering and reusing materials in a closed-loop system, rather than extracting and discarding them, as in Figure 4. In a recent study, a sustainable direct recycling method used low-temperature lithium relithiation to recover $LiFePO_4$ cathodes, employing a low concentration of lithium salt and eco-friendly reducing agent (N_2 and H_2O_2), achieving performance comparable to pristine $LiFePO_4$. LCA analysis indicated a significant reduction in energy usage ($\sim$80%–90%) and GHG emissions ($\sim$75%). This method addresses anti-site defects in $LiFePO_4$, where incorrect iron atom placement in the $LiFePO_4$ crystal structure reduces the electrochemical performance, which has been mitigated through low-temperature treatment and eco-friendly reducing agents.[58] Recycling techniques that consume less energy are also highly favorable in ensuring sustainable material processing.[59] Table 3 shows the comparison of different recycling methods, their benefits, limitations, and

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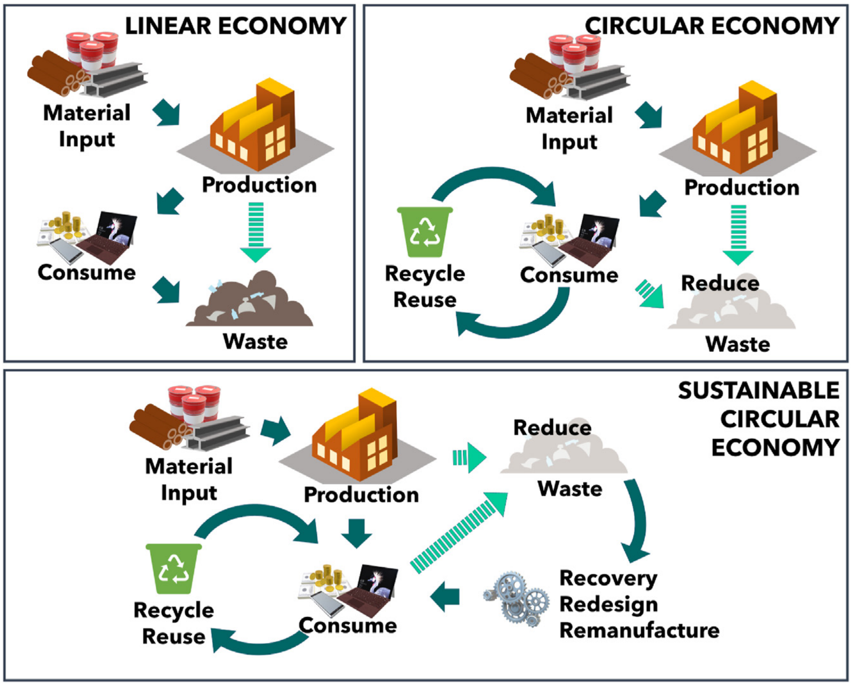

Figure 4. Promoting a circular economy
Waste generation can be significantly reduced through adopting a sustainable circular economy where all the waste generated throughout the life cycle of a product can be recovered and reused.

challenges. The capability to recover precious metals such as lithium, cobalt, nickel, etc., could also circumvent the geopolitical concerns while securing the source of raw materials. It should be noted that the supply and demand economy will drive the cost of LIBs to a new high if encountered with shortage of raw materials. EV batteries, with their large size and capacity, have significant environmental impacts during the manufacturing phase, while AAA and coin cells also pose resource extraction and waste management challenges.[27] Battery LCAs are often designed based on specific applications, aiding comparisons of metrics like efficiency and cycle life, and involve complexities in making a unified framework for individual use cases. Yet, some studies overlook the battery use phase, especially for newer technologies.[60] In non-specific EV analyses, researchers adjust parameters and configurations to match applications, possibly setting boundaries at the module assembly stage. Cradle-to-grave LCAs cover the battery life cycle, including recycling; however, recycling methods range from specialized to variable approaches, targeting effective material recovery.[2] Concerns persist over the limited availability of critical materials (lithium and cobalt), along with the risks of production concentration in specific geographic regions. Supply chain risks, like geopolitical instability or price fluctuations, are sometimes confused with resource depletion.[2] Additionally, the ecological impacts of raw material extraction and processing, like mining, are inconsistently evaluated. Furthermore, the battery assembly process lacks comprehensive evaluation, leading to potential environmental and operational challenges and inconsistencies.[28] Comparative LCA, material flow analysis, carbon footprint assessment, and circular economy assessment are among the LCA models utilized for individual electrode and EV life cycle analysis.[10] Table 2 provides generic use phase parameters and metrics for EVs based on individual electrode chemistry. Apart from the metrics listed in Table 2, battery life cycle analysis encounters uncertainties such as raw material availability impacted by geopolitics and other use cases, as

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Table 3. Techniques to recover electrode materials

Method	Benefits	Limitations involved in the technique	Challenges and research focus
Hydrometallurgy	• high recovery rate • targeted metal recovery • low energy consumption • less gas emission • high selectivity of metal	• generate tremendous amounts of wastewater • time-consuming process	• wastewater treatment • optimization of the separation process
Pyrometallurgy	• simple operation and workflow • no limitation on the size of inputs • high efficiency	• Li and Mn are not recovered • high energy consumption • low recovery efficiency • emit tremendous amount of GHG • high cost for waste gas treatment • depends on hydrometallurgy for further metal separation	• reduce energy consumption • reduce pollution emissions and environmental hazards • constant supply of LIBs and continuous recycling operation
Direct physical recycling	• short recovery route • low energy consumption • high recovery rates • environmentally friendly	• high operational and equipment requirements • incomplete recovery of electrode • knowledge on electrode materials	• reduce recovery cost • enhance recovery efficiency • transparency of battery information
Electrochemical	• effective recovery of Li • targeted metal recovery • environmentally friendly • low energy consumption	• repetitive separation requires to extract each metal • less effective in extracting individual metal • product mostly phosphate ($FePO_4$)	• currently limited to lab scale • investigation focused on LFP electrode
Bio-metallurgy	• eco-friendly • low energy consumption	• limited applicability to certain metal recoveries • requires specific conditions for microbial activity; thus, cannot be standardized for all microbes • limited metal solubilization and recovery rates	• lack of standardized processes and scalability • management of microbial contamination and waste products

Five most widely utilized techniques to recover metals from wasted LIBs.

listed in Table 4. Labor costs, transportation emissions, and recycling efficiency are variable due to market conditions and regulations.[28] Challenges also arise in inventory data of EoL disposal, market demand, and depend on supply chain disruptions, underscoring the necessity for a comprehensive tool to specifically assess the environmental impact.

Conserving resources

A complete circular economy not only relies on recycling and recovering of the batteries' materials or components but also redesigning and remanufacturing the used batteries for other purposes. Redesigning and remanufacturing batteries involves testing the batteries for their remaining capacity and then repurposing them for another use, such as powering low-drain devices or building battery packs. For example, LIBs in EVs are mostly disposed when the capacity retention is at 80% after repetitive charge/discharge.[2,18] Repurposing the residual 80% lifetime of LIBs for other applications would significantly extend the lifespan of the battery, reducing the need for new batteries to be manufactured. This requires the battery module to be deconstructed into its individual cells and remanufactured into a new product (e.g., for a smart power grid energy storage station), without total dismantling of LIBs. However, it is important to note that reusing batteries does have some limitations. Batteries that have been heavily used or damaged may not be suitable for reuse. Additionally, certain types of batteries, such as LIBs, require specialized equipment such as a thermal imaging camera, profilometer, and spot welder and knowledge to test and repurpose safely. Certainly, more options for redesigning and remanufacturing batteries systems are required. Further, the commercial LIBs' high modularity and scalability requirements, especially in EVs, increase design complexity, necessitating careful evaluation of pack dimensions and space allocation. Automation and rapid assembly

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Table 4. Environmental impact contribution of different phases of battery life cycle for specific applications

Life cycle phase	Environmental impact contribution	Battery lifetime	Battery efficiency	Battery capacity requirements
Electric vehicles				
Raw material extraction	high	high (10–15 years)	high (>90%)	30 kWh to 200 kWh
Manufacturing	moderate to high			
Use	moderate			
End of life	moderate to high			
Grid storage				
Raw material extraction	high	high (>15 years)	high (80%–90%)	very high (1,000 kWh)
Manufacturing	high			
Use	high			
End of life	moderate			
Electronics				
Raw material extraction	moderate	moderate (<5 years)	moderate (>80%)	low (50–100 kWh)
Manufacturing	moderate			
Use	low			
End of life	low to moderate			
Lab scale R&D				
Raw material extraction	low	low (2–5 years)	low to high (70%–95%)	very low (10–50 kWh)
Manufacturing	low			
Use	low			
End of life	low			

processes can help reduce manufacturing costs. Designs for assembly and disassembly are key for cost reduction in both production and EoL scenarios, especially considering that disassembly costs can be significant if not planned in advance. Moreover, government support like access to comprehensive data on resource availability by geographic location might aid battery manufacturers in informed decision-making and strategic planning.

Ensuring transparency

Material disclosure is an important aspect of transparency, where manufacturers disclose the materials used in their batteries and their sources. Companies can disclose information about the suppliers and manufacturers they partner with to ensure that the materials and components used in batteries are ethically and sustainably sourced. Inscription of materials and production history in the devices through blockchain technology ensures the reliability and authenticity of a product.[61] Auditing and certification ensure manufacturers adhere to transparency, sustainability, and environmental standards. ISO standards like ISO 14001 and ISO 26000 assess sustainability and accountability. Transparent battery module design is preferable for redesigning and remanufacturing; however, the lack of knowledge on module design hinders automation during dismantling.[62] The dismantling works are mostly performed through manual labor, subjecting workers to electric shock and other hazards. Standardizing the module design could be another step toward automation recycling, considering that corporates could be reluctant to share information that is considered a trade secret. However, such efforts can only be achieved through the support of governmental policies.

Corporate responsibility

A service-type business model involves a company providing a service to its customers rather than selling a physical product. This can include services such as consulting, education, maintenance, repair, or entertainment. Service-type businesses often rely on the skills and expertise of their employees to deliver the service

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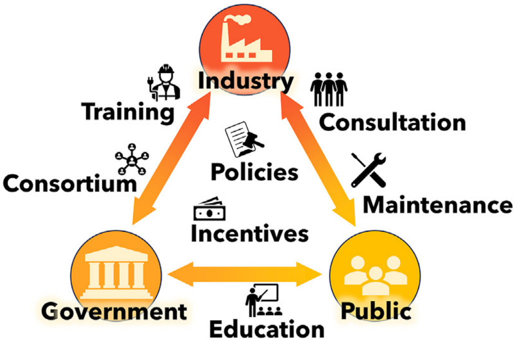

Figure 5. The public-government-industry relations in promoting sustainability
The promotion of a circular economy in rechargeable batteries requires efforts from all parties.

to the customers. These types of businesses may have a more variable revenue stream, as the demand for their services may fluctuate. They may also have higher operating costs, as they may need to continuously train and invest in their employees to maintain the quality of their service. Despite these challenges, service-type businesses can be successful if they are able to effectively market their services and meet the needs of their customers. Producers, distributors, and merchants who produce or sell items are held accountable for the economic effects of their commodities throughout their life cycles under a concept known as extended producer responsibility (EPR). This covers the gathering and preparation of raw materials, the creation and sale of the goods, as well as the product's eventual disposal or recycling.[63] Under an EPR system, producers are required to take responsibility for managing the EoL disposal or recycling of their products, either individually or through an industry-funded organization. This can include setting up take-back programs for products that are returned by consumers at the end of their useful life or working with recycling facilities to ensure that their products are properly processed and disposed of. EPR is intended to internalize the environmental costs of product production and disposal so that these costs are reflected in the price of the product. This can encourage producers to design products that are more environmentally friendly and to adopt more sustainable business practices throughout the life cycle of their products.[63]

Importance of policies and education

Recycling programs such as EPR schemes for batteries, as discussed above, can reduce waste and demand for raw materials. Effective collection and transportation systems, proper material separation, investing in advanced recycling technologies, public education, and government policies should be taken into concern. Policies that support recycling can include recycling targets, financial incentives, and penalties for non-compliance. To implement such policies, a multifaceted approach is required, as shown in Figure 5, which includes education programs to inform the public on the importance of proper management of battery systems during and after their operation. The public needs to be well informed on information related to recycling, i.e., collection points for battery disposal, proper handling or battery waste, detection of mal-functioning batteries, etc. This information is preferable in ensuring all the batteries are recollected for reprocessing, considering that rechargeable batteries in portable electronics are mostly disposed of irresponsibly by the public. Besides, supporting policies that instill involvement of the public in recycling batteries should also be enforced. For example, deposit refund schemes for plastic can encourage proper disposal and recycling of used plastic, which can help to reduce its environmental impact. Identical deposit refund schemes can also be applied for battery systems, such that consumers can be incentivized to return their used batteries to a designated collection point to receive their deposit back. Returning used batteries to a designated collection point could also help alleviate logistic challenges from manufacturers, encouraging corporations to practice their social responsibility.

Conclusions and outlook

Undoubtedly, continuous advancement of both market and research on rechargeable energy storage technologies without careful planning on their overall sustainability could eventually thwart the effort of achieving zero emission. The development of a sustainable and circular economy for batteries is crucial for addressing the environmental and economic challenges posed by the production and disposal of batteries besides the sustainability of charge-storing technology for various energy needs. Most efforts had been placed on reducing the GHG emissions as well as environmental impacts of battery manufacturing through recycling disposed of devices. However, the daily operation of batteries also contributes to such emission, which is largely disregarded by both the vendor as well as the public. Besides, recycling and recovering the degraded batteries have proved to be difficult, mostly due to logistical issues, lack of supporting policies, and low ROI. Out of the five main proposed criteria, two criteria (materials and system design; sustainable circular economy) can be easily done within the energy storage communities, while the other three (improving total green merits; securing transparency; policy support) require external motion. It is crucial to note that a well-planned supporting policy from the government could push the sustainability of rechargeable batteries to a new height. A lesson learnt from the successful drive of EVs to replace petrol-based vehicles through strict policy implementation and government assistance could speed up the promotion of sustainability of rechargeable batteries, especially in terms of recycling and recovering of degraded devices. Other than that, improving the total green metric of batteries by charging using green energies can only be done through increasing the fraction of renewable energies in the national grid, which needs governmental policies to minimize or eliminate coal-based power generation. Besides, a well-planned supporting policy could also increase the confidence of financial investors, driving more investment toward developing waste management industries or financing research activities that would boost the sustainability of rechargeable batteries. Nevertheless, public education would also play a crucial role, considering the effect of consumerism in promoting once-used-then-throw (linear economy). Consumers need to be taught to hold responsibility for the waste they generate. Once again, supporting policies are required to ensure that the public is encouraged to recycle or recover the degraded batteries. Exciting policies have been in place for other merchandise. One of the possible examples to make mention of is the deposit refund scheme for plastic recycling. Undeniably, promoting sustainability of rechargeable batteries requires the involvement of all parties, be it researchers proposing new ideas on eco-friendly materials or recycling techniques, investors supporting new battery recycling industries, governments providing sustainable-friendly policies, and the public taking up responsibility in proper disposal of degraded batteries. Only then can rechargeable batteries be truly sustainable.

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AUTHOR CONTRIBUTIONS

B.R. conceptualized and wrote the original draft. J.K.L. visualized and edited the draft. J.R. and S.R. supervised and secured funding. All authors have reviewed the final draft for submission.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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