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Unlocking the power of second-life: Li-ion batteries for sustainable energy storage and resource management in the Indian context

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Abstract

This review paper examines the second life of Li-ion batteries, its market size, use cases, economics, and environmental impact, with a focus on the Indian context. The study highlights the increasing demand for sustainable energy storage solutions and the projected growth of the second-life battery market. It explores the various applications of second-life batteries, including grid-scale energy storage, residential energy storage, EV charging stations, and telecommunications backup power. The paper discusses the economic benefits of repurposing batteries, such as cost savings compared to new battery systems, and the factors influencing the economics of second-life Li-ion batteries. Furthermore, it emphasizes the importance of government policies and regulations that promote the reuse of batteries, with specific reference to initiatives in India. The environmental impact of second-life batteries is examined, including the reduction in raw material extraction, decreased energy consumption and greenhouse gas emissions during battery production, and the alleviation of waste generated from battery disposal. The challenges in recycling and disposal at the end of the battery's second life are also addressed, emphasizing the need for effective recycling technologies and infrastructure. The paper concludes by highlighting the opportunities for innovation, research, and collaboration in the second-life battery ecosystem, with a call for partnerships among stakeholders to drive advancements in battery management systems, repurposing technologies, and battery chemistry. The findings of this paper contribute to the understanding of the second-life battery industry in the Indian context and provide insights into its potential for sustainable energy storage and resource management.

Keywords: Battery Repurposing; Circular Economy; Battery Recycling and Disposal; Sustainable Energy Storage; Second-Life Batteries

1. Introduction

The rapid adoption of electric vehicles (EVs) and portable electronics has led to an exponential increase in the production and usage of lithium-ion (Li-ion) batteries (Ellingsen, Singh, & Strømman, 2016). As these batteries reach their end-of-life (EOL) in their primary applications, they often still possess considerable capacity, making them suitable for reuse in less demanding, "second life" applications (Zhang, Lv, & Song, 2018). This review paper explores the market size, use cases, economics, and environmental impact of the second life of Li-ion batteries, as well as the challenges and opportunities they present.

1.1. Aim and scope of the review paper

The aim of this paper is to provide a comprehensive understanding of the potential market size, use cases, economic advantages, and environmental impact of second-life Li-ion batteries. Additionally, the paper will identify challenges and opportunities associated with the repurposing and management of Li-ion batteries.

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2. Market Size

2.1. Current market size of second-life Li-ion batteries

The global market size for second-life Li-ion batteries was valued at $3.14 billion in 2020 (Allied Market Research, 2021). The demand for second-life Li-ion batteries is primarily driven by the increasing number of electric vehicles (EVs) reaching end-of-life (EOL) and the need for sustainable energy storage solutions (Serradilla et al., 2020). As the EV market continues to grow and mature, a significant number of batteries will reach their end-of-life in the coming years. These batteries, although no longer suitable for use in EVs, still retain a considerable portion of their capacity and can be repurposed for various applications.

2.2. Market projections for the next decade

The second-life Li-ion battery market is expected to experience significant growth in the next decade. It is projected to grow at a compound annual growth rate (CAGR) of 23.8% from 2021 to 2030, reaching a market size of $38.8 billion by 2030 (Allied Market Research, 2021). This growth can be attributed to several factors.

Firstly, there is a growing emphasis on renewable energy sources and the need for energy storage systems to facilitate their integration into the grid. Second-life Li-ion batteries provide a cost-effective solution for energy storage, as repurposing these batteries reduces the overall investment required compared to new battery systems (Ou, Wang, & Zhang, 2020). The ability to repurpose used batteries for energy storage applications presents a valuable opportunity to enhance the efficiency and reliability of renewable energy systems.

Additionally, the development of efficient recycling technologies plays a crucial role in driving the market growth of second-life Li-ion batteries. Improvements in battery recycling processes enable the extraction of valuable materials, such as lithium, cobalt, and nickel, from EOL batteries, reducing the reliance on primary raw material extraction (Ou et al., 2020). The availability of recycled materials contributes to cost savings and reduces environmental impacts associated with new battery production.

Furthermore, supportive government policies and regulations have a significant influence on the growth of the second-life Li-ion battery market. Initiatives like the European Union's Battery Directive and China's National Sword policy aim to promote the recycling and reuse of batteries, including second-life applications (Zhao et al., 2019). These policies incentivize and regulate the sustainable management of batteries, fostering the development of the second-life battery industry.

2.3. Factors driving the growth of the second-life Li-ion battery market

Several factors contribute to the growth of the second-life Li-ion battery market:

Rapid growth of the electric vehicle market: The increasing adoption of electric vehicles worldwide leads to a larger number of batteries reaching their end-of-life. Second-life applications offer a viable solution for these used batteries, extending their useful life and reducing waste generation (Zubi et al., 2018). The expanding EV market contributes to a sustainable supply of batteries available for repurposing.

Need for sustainable and cost-effective energy storage solutions: The transition towards renewable energy sources requires efficient and affordable energy storage solutions. Second-life Li-ion batteries can play a crucial role in grid-scale and renewable energy applications, providing a more sustainable and cost-effective alternative to new battery systems (Larcher & Tarascon, 2015). These batteries can be integrated into energy storage systems to store excess renewable energy and release it during periods of high demand.

Supportive government policies and regulations: Governments worldwide are implementing policies and regulations that promote the recycling and reuse of batteries, including second-life applications. The Government of India's NEMMP 2020 Aims to promote the manufacturing of advanced batteries, including the repurposing and reuse of lithium-ion batteries, for electric vehicles (Government of India, 2020). Similarly, The European Union's Battery Directive, for example, encourages the reuse and recycling of batteries and sets targets for battery collection and recycling rates (European Commission, 2020) and China's National Sword policy restricts the import of solid waste, including batteries, and promotes domestic recycling (Zhao et al., 2019). These policies create a conducive environment for the growth of the second-life Li-ion battery market by incentivizing battery repurposing and establishing responsible recycling practices.

2.4. Market dynamics and emerging trends

In addition to the driving factors mentioned earlier, several market dynamics and emerging trends contribute to the growth of the second-life Li-ion battery market. These include:

- Technological advancements: Continued advancements in battery technologies, such as improved energy density, longer lifespan, and enhanced safety features, contribute to the viability and performance of second-life Li-ion batteries (Zhang et al., 2020). Ongoing research and development efforts focus on improving the capabilities and efficiency of repurposed batteries, further driving their adoption in various applications.
- Increasing demand for sustainable solutions: The growing awareness and concerns about environmental sustainability drive the demand for sustainable solutions across industries. Second-life Li-ion batteries align with the principles of the circular economy by extending the useful life of batteries and reducing waste generation (Serradilla et al., 2020). Businesses and consumers alike are seeking sustainable alternatives, contributing to the market growth of second-life batteries.
- Energy storage market expansion: The increasing deployment of renewable energy sources and the need for energy storage systems to manage intermittent power generation contribute to the expansion of the energy storage market. Second-life Li-ion batteries offer a cost-effective and sustainable solution for energy storage applications, including grid-scale storage, microgrids, and residential energy storage (Ou et al., 2020). As the demand for energy storage continues to rise, the market for second-life batteries is expected to expand further.
- Collaboration and partnerships: Collaboration among stakeholders in the battery ecosystem, including battery manufacturers, recyclers, energy companies, and government entities, plays a vital role in driving the growth of the second-life Li-ion battery market. Partnerships and collaborations enable knowledge sharing, technology transfer, and the development of efficient value chains for battery repurposing (Bień et al., 2021). These collaborations also facilitate the establishment of standardized processes, quality control measures, and certification programs to ensure the safety and reliability of second-life batteries.

3. Use Cases

3.1. Energy storage systems

Energy storage systems play a crucial role in balancing supply and demand, ensuring grid stability, and integrating renewable energy sources. Second-life Li-ion batteries offer a viable solution for energy storage, contributing to a more sustainable and efficient energy infrastructure.

3.2. Grid-scale energy storage

Second-life Li-ion batteries can be utilized in grid-scale energy storage systems to enhance the overall grid performance (Luo et al., 2015). These systems help to manage fluctuations in electricity generation and consumption, particularly from renewable sources. Notably, the Amsterdam ArenA project in the Netherlands has successfully employed second-life EV batteries for grid-scale energy storage, demonstrating the feasibility of this application (Bloomberg New Energy Finance, 2017).

3.3. Community and residential energy storage

Second-life Li-ion batteries are also well-suited for community and residential energy storage systems. These systems store excess energy generated from solar panels or other renewable sources, allowing homeowners and communities to utilize the stored energy during peak demand periods or grid outages (Barote et al., 2018). By reducing reliance on the grid, second-life batteries enable greater energy independence and contribute to a more resilient and sustainable energy infrastructure.

3.4. Electric vehicle charging stations

Second-life Li-ion batteries can be effectively utilized at electric vehicle (EV) charging stations to optimize their operation and enhance their sustainability. By employing these repurposed batteries, charging stations can reduce peak power demand and optimize electricity usage (Zhang et al., 2020). This not only helps to balance the load on the grid but also lowers operational costs for charging station operators.

3.5. Telecommunications backup power

The second life of Li-ion batteries presents an opportunity for their use in telecommunications backup power solutions. During grid failures or unstable power supply situations, repurposed Li-ion batteries can provide reliable power to ensure uninterrupted communication services (Chaturvedi et al., 2017). This application is critical for maintaining communication networks during emergencies or natural disasters.

3.6. Remote and off-grid power solutions

In remote and off-grid areas with limited access to electricity, second-life Li-ion batteries can serve as a valuable solution for storing and delivering power. These batteries can power lighting systems, small-scale appliances, and even support microgrids in rural communities, contributing to improved energy access and sustainability (Wang et al., 2020).

3.7. Emerging applications and potential future use cases

The second-life Li-ion battery market continues to evolve, with emerging applications and potential future use cases. Electric bikes, wearable devices, and smart home systems are among the emerging applications that can benefit from second-life batteries (Lopez-Linares et al., 2020). These batteries can provide energy storage for electric bikes, extending their range and usability. Furthermore, research is ongoing to explore the utilization of second-life batteries in stationary storage for renewable energy sources, such as wind and solar farms (Lopez-Linares et al., 2020). This application can contribute to the integration of renewable energy into the grid and enable more efficient utilization of clean energy resources.

4. Economics

4.1. Cost savings from repurposing Li-ion batteries

One of the significant advantages of second-life Li-ion batteries is the potential for cost savings compared to new battery systems. Repurposing used batteries significantly reduces the upfront investment required, making energy storage solutions more economically viable (Zubi et al., 2018). The cost savings can vary depending on factors such as battery condition, capacity degradation, and the specific application.

Numerous studies have investigated the cost savings associated with the repurposing of Li-ion batteries. For example, a study by Bień et al. (2021) assessed the business models and economic benefits of second-life Li-ion batteries in household energy storage systems. The findings showed that utilizing repurposed batteries led to significant cost reductions compared to new battery systems, making them a more affordable option for residential energy storage.

In another study, Zhao et al. (2019) conducted an economic and environmental assessment of second-life Li-ion batteries for grid-scale energy storage. The results indicated that repurposed batteries offered cost savings ranging from 40% to 70% compared to new batteries, depending on battery condition and performance. These cost savings made second-life batteries an attractive option for large-scale energy storage projects.

Furthermore, research by Zhang et al. (2020) reviewed the second-life applications of Li-ion batteries, focusing on their cost, safety, and electrochemical performance. The study emphasized that repurposing used batteries can significantly reduce the overall cost of energy storage systems, enabling the deployment of more affordable and sustainable energy solutions.

It is worth noting that the extent of cost savings can vary depending on factors such as battery condition and capacity degradation. Batteries that have undergone higher levels of degradation may offer lower cost savings compared to those with better performance. Additionally, the specific application and requirements of the energy storage system can also influence the cost savings achieved through battery repurposing.

Here is an illustration to demonstrate the dynamics of repurposed battery capacity, battery degradation, and illustrates the benefits in terms of dollars per ampere-hour (Ah) capacity and dollars per kilowatt-hour (kWh) with assumed numbers:

- Cost of a new Li-ion battery system: $10,000
- Cost of a second-life Li-ion battery system: $6,000
- Repurposed battery capacity: 70% of original capacity
- Battery degradation rate: 1% per year
- Battery lifespan: 10 years

Table 1 Illustration of Benefits of Repurposed Li-ion Batteries

Year	Battery Capacity (Ah)	Battery Capacity (kWh)	New Battery Cost	Repurposed Battery Cost	Benefit ($/Ah)	Benefit ($/kWh)
1	300	75	$10,000	$6,000	$13.33	$80.00
2	297	74.25	$10,000	$6,000	$13.47	$80.81
3	294	73.5	$10,000	$6,000	$13.61	$81.62
4	291	72.75	$10,000	$6,000	$13.76	$82.44
5	288	72	$10,000	$6,000	$13.89	$83.33
6	285	71.25	$10,000	$6,000	$14.04	$84.21
7	282	70.5	$10,000	$6,000	$14.18	$85.11
8	279	69.75	$10,000	$6,000	$14.31	$86.02
9	276	69	$10,000	$6,000	$14.49	$86.96
10	273	68.25	$10,000	$6,000	$14.64	$87.91

In this example, it is assumed that the battery capacity decreases by 1% per year due to degradation. The battery capacity is measured in ampere-hours (Ah) and converted to kilowatt-hours (kWh) for comparison. The benefit per Ah and per kWh is calculated by subtracting the repurposed battery cost from the new battery cost and dividing it by the corresponding capacity.

As shown in above Table, the benefit in terms of $/Ah capacity ranges from $13.33 to $14.64 over the 10-year lifespan. Similarly, the benefit in terms of $/kWh capacity ranges from $80.00 to $87.91. These values demonstrate the cost advantages of using repurposed Li-ion batteries compared to new battery systems.

4.2. Factors influencing the economics of second-life Li-ion batteries

Several factors influence the economics of second-life Li-ion batteries. These factors play a crucial role in determining the economic viability and profitability of repurposing used batteries.

- Initial battery cost: The initial cost of the battery affects the economics of its second life. Lower initial battery costs provide a more favorable starting point for repurposing, as the cost savings compared to new battery systems can be more significant (Serradilla et al., 2020). However, it is important to consider the balance between initial cost and the remaining capacity of the battery.
- Condition and remaining capacity: The condition and remaining capacity of the battery impact its suitability for repurposing and the potential revenue streams it can generate. Batteries with higher remaining capacities can offer greater value in terms of energy storage or other applications (Serradilla et al., 2020). The assessment of battery condition and capacity is crucial in determining the economic feasibility of repurposing.
- Cost of refurbishment or repackaging: The cost associated with refurbishing or repackaging the batteries for their second life influences the overall economics. Refurbishment costs may include activities such as testing, repairing, or replacing individual battery cells, as well as repackaging the batteries for specific applications (Serradilla et al., 2020). Minimizing refurbishment costs while maintaining quality and performance is essential to maximize the economic benefits.
- Potential revenue streams: The availability and profitability of revenue streams from the use of second-life Li-ion batteries are critical for their economic viability. The revenue streams can vary depending on the specific applications, such as grid-scale energy storage, residential energy storage, or other sectors (Serradilla et al., 2020). Identifying and capitalizing on the most lucrative applications is key to optimizing the economic returns.

Moreover, factors such as the duration of the second life and the market demand for repurposed batteries also influence the economics of second-life Li-ion batteries. The longer the duration of the second life, the higher the potential returns on the initial investment in repurposing (Majeau-Bettez et al., 2019). Additionally, the market demand for repurposed batteries, driven by factors like government policies, regulations, and industry trends, affects the economic prospects of second-life battery business models (Majeau-Bettez et al., 2019).

Table 2 Factors Influencing the Economics of Second-Life Li-ion Batteries

Factors	Description
Initial battery cost	The cost of the battery when new
Condition and remaining capacity	The overall condition and capacity of the battery
Cost of refurbishment or repackaging	The cost associated with refurbishing or repackaging the batteries for their second life
Potential revenue streams	The availability and profitability of revenue streams from the use of second-life Li-ion batteries
Duration of the second life	The duration for which the battery can be utilized in its second life
Market demand	The demand for repurposed batteries driven by policies, regulations, and industry trends

4.3. Government policies and regulations promoting the reuse of batteries

Government policies and regulations play a crucial role in shaping the economics of second-life Li-ion batteries. Incentives, subsidies, and supportive frameworks can encourage investment in battery repurposing and foster the growth of the second-life battery industry.

The Government of India (GOI) has taken significant steps to promote the repurposing and reuse of batteries through its policies and regulations. The GOI's India's National Electric Mobility Mission Plan (NEMMP) 2020, Aims to promote the manufacturing of advanced batteries, including the repurposing and reuse of lithium-ion batteries, for electric vehicles (Government of India, 2020). These policies emphasize the importance of a circular economy and sustainable resource management. some additional measures that government policies can include to promote the repurposing and reuse of batteries:

Research and development grants: Governments can provide grants and funding opportunities for research and development initiatives focused on battery repurposing and reuse. This support encourages innovation, advances in technology, and the development of efficient and cost-effective processes for repurposing batteries.

Tax incentives: Governments can offer tax incentives to companies and individuals involved in the repurposing and reuse of batteries. These incentives can include tax credits, exemptions, or reductions on equipment purchases, refurbishment costs, or revenue generated from the sale of repurposed batteries.

Regulatory frameworks for safe handling and disposal: Governments can establish regulations and guidelines for the safe handling, transportation, and disposal of used batteries. These frameworks ensure that repurposed batteries meet safety standards and minimize environmental impact during the repurposing process and at the end of their useful life.

Collaboration and partnerships: Governments can facilitate collaboration and partnerships among industry stakeholders, research institutions, and technology providers to promote knowledge sharing, standardization, and the development of best practices in battery repurposing. These collaborations help foster a supportive ecosystem for the second-life battery industry.

Public procurement policies: Governments can incorporate sustainable procurement policies that prioritize the purchase of products and services that align with circular economy principles. This includes the procurement of repurposed batteries for various government applications, such as energy storage systems or backup power solutions.

It is important to note that the specific measures implemented by governments may vary depending on regional policies, priorities, and industry dynamics.

4.4. Business models for the second-life battery industry

Various business models have emerged in the second-life battery industry, driven by the goal of optimizing the use of repurposed batteries, maximizing revenue potential, and minimizing financial risks associated with battery repurposing.

One such business model is battery leasing, where customers lease batteries instead of purchasing them outright. This model allows customers to access the benefits of energy storage without the high upfront costs of buying new batteries (Bień et al., 2021). Companies offering battery leasing services can acquire second-life batteries at a lower cost and provide them to customers through flexible leasing arrangements. This model benefits both customers and companies, as it reduces upfront investment and ensures the efficient utilization of repurposed batteries.

Battery-as-a-service (BaaS) is another emerging business model in the second-life battery industry. Under this model, companies provide end-to-end battery solutions, including the supply, installation, operation, and maintenance of repurposed batteries (Bień et al., 2021). Customers pay for the energy storage services provided by the batteries rather than owning the batteries themselves. BaaS models enable customers to access energy storage without the need for significant upfront capital investment and allow companies to efficiently manage and monetize the use of repurposed batteries.

Partnerships between battery manufacturers, electric vehicle (EV) companies, and energy storage providers have also emerged as successful business models. Battery manufacturers can collaborate with EV companies to repurpose batteries that have reached the end of their useful life in electric vehicles. These repurposed batteries can then be used for stationary energy storage applications (Bień et al., 2021). Such partnerships leverage the expertise and resources of multiple stakeholders, optimizing the value chain and maximizing the economic and environmental benefits of second-life batteries.

Table 3 Business Models for the Second-Life Battery Industry

Business Models	Description
Battery leasing	Customers lease batteries instead of purchasing them outright, reducing upfront costs and ensuring efficient utilization of repurposed batteries
Battery-as-a-service (BaaS)	Companies provide end-to-end battery solutions, offering energy storage services without customers owning the batteries
Partnerships	Collaborations between battery manufacturers, EV companies, and energy storage providers to repurpose and use second-life batteries

5. Environmental Impact

5.1. Reduction in raw material extraction

The second life of Li-ion batteries contributes to the reduction of raw material extraction by extending the useful life of batteries before their final disposal. This reduction in raw material extraction has significant environmental benefits, as it conserves natural resources and reduces the environmental impact associated with the extraction and processing of raw materials used in battery production (Larcher & Tarascon, 2015).

By reusing batteries in various applications, the demand for new battery production is reduced. This decreased demand directly translates into a reduction in the extraction of raw materials, such as lithium, cobalt, nickel, and other critical metals used in Li-ion batteries. These metals are often mined through processes that have environmental consequences, including habitat destruction, water pollution, and carbon emissions (Amnesty International, 2017).

Decreased energy consumption and greenhouse gas emissions during battery production

Battery production is associated with significant energy consumption and greenhouse gas emissions. However, by extending the life of Li-ion batteries through second-life applications, the overall energy consumption and greenhouse gas emissions related to battery production can be reduced. This reduction contributes to the environmental benefits of second-life batteries.

The production of new batteries involves several energy-intensive processes, such as raw material extraction, refining, cell manufacturing, and assembly. These processes require substantial energy inputs and contribute to greenhouse gas emissions (Majeau-Bettez et al., 2019). However, when batteries are repurposed and reused, the need for manufacturing new batteries is reduced, resulting in energy savings and decreased emissions.

Table 4 Reduction in Energy Consumption and Greenhouse Gas Emissions through Second-Life Batteries

Environmental Impact	Description
Decreased energy consumption	The reuse of Li-ion batteries through second-life applications reduces the overall energy consumption of battery production.
Reduced greenhouse gas emissions	Battery reuse contributes to a reduction in greenhouse gas emissions compared to the production of new batteries.

A study conducted by Majeau-Bettez et al. (2019) assessed the environmental impact of second-life electric vehicle (EV) batteries compared to the production of new batteries. The study found that the reuse of batteries can significantly reduce energy consumption and carbon emissions. In particular, the authors noted that battery reuse can lead to a 60-70% reduction in greenhouse gas emissions compared to the production of new batteries.

An illustration of the benefits of second-life batteries in the Indian context, considering assumptions and numbers is as below:

- CO2 equivalent emissions per kilowatt-hour (kWh) of electricity in India: 0.82 kg CO2-eq/kWh (source: Central Electricity Authority, 2021).
- CO2 equivalent emissions per kilowatt-hour (kWh) of battery production: 150 kg CO2-eq/kWh (assumed value).
- Battery lifespan: 10 years.
- Repurposed battery capacity retention: 70% of original capacity.
- New battery production avoided: 1,000 kWh.

Table 5 Benefits of Second-Life Batteries in the Indian Context

Parameter	Calculation	Result
CO2 Emissions Reduction	(CO2 emissions per kWh of battery production - CO2 emissions per kWh of electricity) * New battery production avoided	-68,000 kg CO2
Energy Consumption Reduction	New battery production avoided	1,000 kWh

In the Indian context, assuming CO2 equivalent emissions per kilowatt-hour (kWh) of electricity to be 0.82 kg CO2-eq/kWh, and CO2 equivalent emissions per kilowatt-hour (kWh) of battery production to be 150 kg CO2-eq/kWh (assumed value), we can calculate the benefits of second-life batteries.

Using the assumption that 1,000 kWh of new battery production is avoided by repurposing batteries, the reduction in CO2 emissions can be calculated by multiplying the difference in CO2 emissions per kWh of battery production and CO2 emissions per kWh of electricity by the new battery production avoided. In this case, it results in a reduction of 68,000 kg of CO2 emissions.

Additionally, the energy consumption reduction is simply the amount of new battery production avoided, which in this case is 1,000 kWh.

5.2. Extended battery life cycle and reduced waste generation

The second life of Li-ion batteries extends their overall life cycle, resulting in a reduction in the amount of waste generated from battery disposal. Repurposing batteries plays a crucial role in alleviating the environmental burden associated with managing end-of-life (EOL) batteries, thereby minimizing the need for landfilling or incineration and promoting a more sustainable waste management approach (Ou, Wang, & Zhang, 2020).

Battery disposal, especially when not managed properly, can pose environmental risks due to the presence of hazardous materials. Landfilling or incineration of batteries can lead to the release of toxic substances into the environment, potentially causing soil and water contamination (Chaturvedi et al., 2017). By repurposing batteries, their useful life is extended, and the need for immediate disposal is reduced.

Table 6 Benefits of Second-Life Batteries in Waste Management

Environmental Benefit	Description
Reduced waste generation	The second life of Li-ion batteries reduces the amount of waste generated from battery disposal.
Alleviated environmental burden	Repurposing batteries minimizes the need for landfilling or incineration, reducing associated environmental risks.
Sustainable waste management	Second-life batteries contribute to a more sustainable waste management approach.

5.3. Challenges in recycling and disposing of batteries after their second life

While the second life of Li-ion batteries offers environmental benefits, challenges persist in the recycling and disposal of batteries at the end of their second life. These challenges arise due to battery chemistries, designs, and varying levels of degradation, which can hinder the development of efficient and cost-effective recycling processes (Ellingsen et al., 2016). Addressing these challenges is crucial to ensure the proper management of batteries at the end of their second life and to mitigate potential environmental risks.

Li-ion batteries consist of various materials, including metals, electrolytes, and plastics, which require specialized processes to separate and recover. The diverse chemistries and designs of Li-ion batteries contribute to the complexity of recycling processes (Ellingsen et al., 2016). Additionally, the degradation of batteries over time affects their composition and performance, further complicating the recycling process.

Developing effective recycling technologies is essential to enable the recovery of valuable materials from end-of-life batteries. These technologies aim to extract and purify metals and other valuable components while minimizing environmental impacts. Innovations such as hydrometallurgical and pyrometallurgical processes have been explored for battery recycling, but further advancements are needed to improve efficiency and cost-effectiveness (Ellingsen et al., 2016).

Table 7 Challenges in Recycling and Disposal of Second-Life Batteries

Challenges	Description
Battery chemistries and designs	The diverse chemistries and designs of Li-ion batteries pose challenges in developing efficient recycling processes.
Varying levels of degradation	Battery degradation over time affects composition and performance, making recycling more complex.
Efficient and cost-effective recycling	Developing effective recycling technologies and processes for the recovery of valuable materials.
Infrastructure for end-of-life management	Establishing proper infrastructure and systems for the recycling and disposal of batteries.

6. Challenges and Opportunities

Technical challenges in repurposing Li-ion batteries

The repurposing of Li-ion batteries for second-life applications presents technical challenges that need to be addressed to ensure safe and efficient use.

Safety concerns related to Li-ion batteries, such as thermal runaway and fire hazards, require careful monitoring and management in second-life applications (Zhang et al., 2018). As batteries age and undergo degradation, their internal components may become less stable, increasing the risk of potential safety incidents. Therefore, robust safety measures, including thermal management systems and monitoring technologies, are essential to mitigate these risks and ensure the safe operation of repurposed batteries.

The degradation of battery performance over time also poses a challenge in determining their suitability for specific applications (Zubi et al., 2018). As batteries are used and reach the end of their first life, their capacity, power output, and overall performance may decline. This degradation affects their ability to meet the requirements of certain applications. Accurate assessment and sorting processes are necessary to evaluate the remaining capacity and performance characteristics of repurposed batteries, ensuring that they are suitable for the intended second-life applications.

6.1. Safety concerns and performance degradation

Ensuring the safe operation of second-life Li-ion batteries is crucial to mitigate potential risks. Aging and degradation of batteries can lead to safety concerns, and therefore, proper testing, monitoring, and quality control procedures are necessary (Chaturvedi et al., 2017). Additionally, managing the performance degradation of batteries and matching their capabilities with appropriate applications is essential for their optimal utilization.

As Li-ion batteries undergo multiple charge-discharge cycles and experience aging, their performance may decline, resulting in reduced capacity and power output. Proper testing procedures, such as capacity testing, internal resistance measurements, and thermal stability analysis, are important to assess the health and safety of second-life batteries (Chaturvedi et al., 2017).

Monitoring the performance and condition of second-life batteries during their operation is also critical. Advanced battery management systems (BMS) can be employed to monitor parameters such as voltage, temperature, and state of charge, ensuring safe and efficient operation. Regular inspections and maintenance activities can help identify potential risks and address issues promptly (Chaturvedi et al., 2017).

Matching the capabilities of second-life batteries with appropriate applications is crucial to optimize their utilization. Detailed characterization of the battery's performance and considering factors such as capacity fade, power limitations, and voltage profiles are necessary to ensure safe and effective integration into various applications, including energy storage systems and electric vehicle charging infrastructure (Chaturvedi et al., 2017).

6.2. Standardization and compatibility issues

Standardization and compatibility across different battery chemistries and form factors are crucial for facilitating the repurposing and integration of second-life batteries. Developing common protocols, interfaces, and systems can enhance the efficiency and scalability of second-life battery applications (Zhang et al., 2020).

Li-ion batteries come in various chemistries and form factors, each with its own specifications and characteristics. Achieving standardization and compatibility enables seamless integration and interchangeability of batteries, promoting their broader utilization in different applications.

Standardization efforts can focus on several aspects, including:

- Battery interfaces: Defining common interfaces and communication protocols that enable plug-and-play compatibility between batteries and various devices or systems. This ensures that repurposed batteries can be easily integrated into different applications without the need for extensive modifications.
- Battery management systems (BMS): Establishing standard protocols for battery management systems that monitor and control the performance, state of charge, and health of batteries. Standardized BMS protocols enable efficient management and optimization of repurposed batteries, irrespective of their chemistries or form factors.
- Safety and testing standards: Developing standardized safety and testing procedures to ensure the quality, reliability, and safety of repurposed batteries. This includes standardized methods for evaluating the remaining capacity, health, and safety of second-life batteries before their integration into new applications.

6.3. Regulatory challenges

Regulatory frameworks must evolve to support and incentivize the repurposing of Li-ion batteries. Policies addressing safety, quality assurance, and environmental concerns need to be developed and implemented to ensure the sustainable growth of the second-life battery industry (European Commission, 2020).

In the Indian context, several initiatives and regulations have been implemented to support the repurposing of Li-ion batteries and ensure their safe and sustainable management.

Table 8 Regulatory Frameworks Supporting Li-ion Battery Repurposing in India

Regulatory Initiatives	Description
The Central Pollution Control Board (CPCB) Guidelines	The CPCB has issued guidelines for the environmentally sound management of electronic waste, including Li-ion batteries (CPCB, 2018).
Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016	These rules govern the management, handling, and transboundary movement of hazardous waste, including Li-ion batteries (MoEFCC, 2016).
Bureau of Indian Standards (BIS) standards	BIS has established standards for safety, performance, and quality of batteries, including Li-ion batteries, to ensure their safe use and repurposing (BIS, n.d.).

6.4. Public awareness and perception of second-life batteries

Educating the public about the benefits and safety aspects of second-life batteries is crucial for fostering acceptance and trust. Addressing concerns regarding the performance, reliability, and safety of repurposed batteries can contribute to the wider adoption of second-life applications (Zhang et al., 2018).

6.5. Opportunities for innovation and collaboration in the second-life battery ecosystem

The second-life battery industry presents opportunities for innovation, research, and collaboration among stakeholders. Developing advanced battery management systems, refining repurposing technologies, and establishing partnerships between battery manufacturers, recyclers, and end-users can drive the growth and sustainability of the second-life battery market (Bień et al., 2021). Collaborative efforts can lead to the development of standardized testing methods, quality assurance protocols, and efficient battery repurposing processes.

Furthermore, research and development in battery chemistry and engineering can enhance the performance, safety, and longevity of second-life Li-ion batteries. Advancements in battery diagnostics, state-of-health monitoring, and predictive analytics can optimize the utilization and lifespan of repurposed batteries (Zhang et al., 2020). Collaborative projects between academia, industry, and government organizations can accelerate innovation and enable the exploration of new use cases for second-life batteries.

Table 9 Regulatory Frameworks Supporting Li-ion Battery Repurposing in India

Opportunities	Description
Advanced battery management systems	Development of systems for efficient monitoring, control, and optimization of second-life batteries.
Refining repurposing technologies	Advancements in repurposing processes to improve efficiency, cost-effectiveness, and quality of repurposed batteries.
Partnerships and collaborations	Collaborative efforts between stakeholders, including battery manufacturers, recyclers, end-users, and research institutions.
Battery chemistry and engineering	Research and development to enhance performance, safety, and longevity of second-life batteries.

In the Indian context, collaborations and partnerships between academia, industry, and government organizations can drive innovation in the second-life battery ecosystem. These collaborations can lead to the development of standardized testing methods, quality assurance protocols, and efficient battery repurposing processes tailored to Indian conditions. Research and development efforts in battery chemistry and engineering can contribute to enhancing the performance, safety, and longevity of second-life Li-ion batteries.

7. Conclusion

The second life of Li-ion batteries offers substantial opportunities for repurposing used batteries, contributing to a more sustainable and circular economy. The market size for second-life Li-ion batteries is growing, driven by the increasing demand for energy storage and the emergence of new applications. Economically, repurposing batteries can result in cost savings compared to the production of new batteries, while also reducing the environmental impact associated with raw material extraction and battery manufacturing.

The use cases for second-life Li-ion batteries span diverse sectors, including energy storage systems, electric vehicle charging stations, telecommunications backup power, and off-grid power solutions. These applications contribute to a more efficient and sustainable energy infrastructure.

However, challenges related to safety, performance degradation, standardization, and regulatory frameworks need to be addressed to maximize the potential of the second-life battery industry. Collaborative efforts among stakeholders are essential to develop effective recycling technologies, establish safety standards, promote public awareness, and create supportive regulatory frameworks.

By embracing the second life of Li-ion batteries, we can harness their remaining value and contribute to a more sustainable and circular approach to energy storage. Continued research, innovation, and collaboration will be crucial to unlock the full potential of second-life Li-ion batteries and drive the transition towards a greener and more sustainable future.

Compliance with ethical standards

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By submitting this Declaration of Interest Statement, we confirm our commitment to upholding the highest standards of research integrity and ensuring transparency in the publication process.

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