Ministry of Physical Infrastructure and Transport

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The comprehensive Management of After-Life Battery Pack Management

2081

A study conducted by

National Road safety Council

ABHIYANTRIKI
ENGINEERING WITH PASSION

Report on “The Comprehensive Management of After-Life Battery Packs from Electric Vehicles

Submitted to Ministry of Physical Infrastructure and Transportation

Acknowledgement

We would like to extend our sincere gratitude to everyone who contributed to the successful completion of the report titled "The Comprehensive Management of After-Life Battery Packs from Electric Vehicles."

First and foremost, we express our deepest appreciation to the **Ministry of Physical Infrastructure and Transportation**, Nepal for their invaluable support and guidance throughout this project. The commitment from MOPT to advancing sustainable energy practices and policies has been instrumental in shaping the direction of our research.

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This report is a testament to the power of collaboration and the shared vision of a sustainable future. We hope that our findings will contribute to the advancement of effective and environmentally friendly practices in the management of after-life battery packs from electric vehicles.

Sincerely,

Abhisek Karki

Abhiyantriki Karmashala Pvt Ltd

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Abbreviations

BEV – Battery Electric Vehicle

BESS – Battery Energy Storage System

BMS – Battery Management System

DfR – Design for Recycling

EIS – Electrochemical Impedance Spectroscopy

EMS – Energy Management System

EoL – End of Life

EPA – Environmental Protection Agency

EPR – Extended Producer Responsibility

ESG – Environmental, Social, and Governance

ESS – Energy Storage System

EU – European Union

EV – Electric Vehicle

GHG – Greenhouse Gas

Gt CO2 – Gigatonnes of Carbon Dioxide

ICE – Internal Combustion Engine

LFP – Lithium Iron Phosphate

LIB – Lithium-Ion Battery

NiMH – Nickel-Metal Hydride

NMC – Nickel Manganese Cobalt

OEM – Original Equipment Manufacturer

R&D – Research and Development

RE – Renewable Energy

SOH – State of Health

SOP – Standard Operating Procedure

STEPS – Stated Policies Scenario

US – United States

V2G – Vehicle-to-Grid

V2X – Vehicle-to-Everything

WTT – Well to Tank

WTW – Well to Wheel

Executive Summary

This report provides an in-depth analysis of the end-of-life (EoL) management and recycling of electric vehicle (EV) batteries, focusing on lithium-ion batteries (LIBs). The study encompasses the history, technological advancements, second-life applications, recycling processes, and environmental impacts associated with EV batteries.

The development of EV technology has seen significant evolution since the late 19th century. Early electric vehicles, powered by lead-acid batteries, were limited in range and performance. The introduction of lithium-ion batteries marked a pivotal advancement, offering higher energy density, longer lifespan, and faster charging capabilities. Recent innovations such as solid-state batteries, silicon anodes, and advanced battery management systems have further enhanced the efficiency, safety, and longevity of EV batteries.

The report highlights the potential for second-life applications of retired EV batteries. These applications include energy storage systems, communication base stations, and powering low-speed vehicles like electric bicycles and urban sanitation vehicles. The success of these applications hinges on the development of technical standards for battery selection, integration guidelines for safety, and efficient battery log data management.

The recycling process for LIBs involves several key steps: batteries are immersed in saline solution to ensure they are fully discharged, preventing accidents during subsequent processes. The discharged batteries are then shredded and crushed into smaller pieces, followed by drying and grinding to remove moisture and reduce the pieces to tiny particles. Various separation techniques (air, gravity, magnetic) are used to isolate valuable materials like black mass (for new battery production), metals (copper, aluminum, iron), and plastics. The KERUI machine process exemplifies an effective industrial approach to battery recycling, converting old batteries into valuable resources for new battery production.

The report underscores the environmental benefits of EVs, particularly in reducing greenhouse gas emissions. EVs produce zero tailpipe emissions, and their lifecycle emissions can be significantly lower than those of internal combustion engine vehicles when powered by renewable energy. However, the short-term increase in emissions due to electricity generation for EVs is noted. Long-term, the electrification of road transport is projected to save approximately 2 Gt CO2 by 2035 on a well-to-wheel basis.

The LIB recycling industry is expanding globally, driven by the increased demand for EVs and the anticipated retirements of EV batteries. Current feedstock sources primarily include consumer electronics and battery manufacturing scrap, with retired EV batteries expected to become the main source in the future. The North American market is notable for its operational facilities and plans for expansion to produce battery-grade materials.

Policies affecting the EoL of EV batteries emphasize extended producer responsibility (EPR), promoting reuse, remanufacturing, and recycling. These policies are crucial for driving design and manufacturing changes to support sustainable battery management. The report concludes that effective EoL management of EV batteries requires coordinated efforts across the supply chain, robust second-life applications, and advanced recycling technologies. The environmental benefits of EVs are substantial, but achieving these benefits necessitates long-term strategies for battery reuse and recycling. Industry stakeholders, including manufacturers, policymakers, and third-party organizations, must collaborate to address the challenges and opportunities in this rapidly evolving field.

Background and the objectives of the study

The rapid growth of green mobility in the form of an electric vehicle (EV) market globally has ushered in a new era of sustainable transportation. As the adoption of electric vehicles increases, so does the volume of lithium-ion battery packs as an energy storage, posing significant environmental and logistical challenges. The increase in the volume of electric vehicle adoption will lead to an increase in the volume of EV batteries reaching end-of-life (EOL) and is projected to grow dramatically in the next 5 to 10 years. Proper management of these EOL battery packs is crucial to mitigate potential environmental hazards and capitalize on the economic value of recyclable materials.

This study, titled "The Comprehensive Management of After-Life Battery Packs from Electric Vehicles," aims to address these challenges by exploring effective strategies for the recycling, repurposing, and disposal of EV batteries. Our research is motivated by an urgency to develop sustainable solutions that align with global environmental goals and support the burgeoning EV industry in Nepal.

Nepal's increasing adoption of electric vehicles and commitment to sustainable practices provides a compelling context for this study. Our unique geographic and economic conditions necessitate tailored approaches to battery management. By focusing on comprehensive management practices approached globally, we aim to inherent global technology well-practised and contribute to Nepal’s environmental sustainability and economic development.

The study encompasses an in-depth research review, analysis of current practices, technological advancements, and innovative approaches adopted in battery recycling and repurposing in the global market. It also evaluates the environmental footprint of various management strategies, emphasizing the importance of a closed-loop system that minimizes waste and maximizes resource recovery.

The goal is to provide depth research report with a better understanding of the potential technical, environmental, energy and cost issues associated with battery recycling and second-life uses that may arise from the expected growth in EVs over the next two decades.

Ultimately, this research seeks to provide actionable insights and recommendations to policymakers, industry stakeholders, and the general public, fostering a sustainable future for electric mobility in Nepal and beyond.

The key objectives of this consulting service are to:

- To assess current practices related to the repurposing, recycling and disposal of EV batteries.
- To assess the environmental impact of different afterlife battery management strategies, including repurposing, recycling and disposal.
- To investigate technological advancement and innovations in battery recycling and repurposing.
- To identify challenges and opportunities associated with afterlife battery management including economic, environmental, social and technological factors.
- To purpose recommendations for optimizing afterlife battery management practices to maximize sustainability and minimize environmental impact.
- Establish protocols for the safe and efficient disassembly, storage and transportation of battery packs to recycling and repurposing facilities.
- To propose actionable recommendations and guidelines for the development of standardized methods for testing and grading of used EV batteries, safe and efficient recycling technologies, and business model for effective management of afterlife EV batteries

Methodology

Our methodology involves a systematic approach to collect, analyze, and interpret data related to the recycling, repurposing, and disposal of EV battery packs.

Research Design: This research-based study employs a mixed-methods research design, combining qualitative and quantitative approaches to ensure a holistic understanding of the subject. This includes a literature review, case studies, stakeholder and expert interviews, and empirical analysis.

1. Literature Review:

   The literature review focuses on:

   - Current practices and technologies approached in EV battery recycling and repurposing in the global market.
   - Environmental and economic impacts of different battery management strategies.
   - Policies and regulations related to EV battery disposal and recycling.
   - Case studies of successful battery management programs globally.

2. Data Collection:

   Primary Data:

   - Conducting Interviews with key stakeholders, including industry experts, policymakers, and environmentalists.
   - Conducting surveys by distributing questionnaires to EV suppliers, battery pack suppliers to gather insights on current practices, challenges, and perceptions.

   Secondary Data:

   - Analyzing reports from automotive and battery industries.
   - Consulting peer-reviewed articles on battery technologies, EOL battery uses and recycling methodologies.

3. Case Studies: In depth case studies of existing battery management systems in global market are conducted to identify best practices and innovative solutions. Each case study includes:
    - Description of the management system.
    - Technological approaches used for recycling and repurposing.
    - Economic and environmental outcomes.
    - Lessons learned and applicability to the Nepali context.
4. Stakeholder Engagement

   Engaging stakeholders through direct meetups, phone calls and through an online interviews to:
    - Collect and validate findings and gather additional insights.
    - Discuss potential barriers and enablers for implementing recommended practices.
    - Foster collaboration among government agencies, industry players, and environmental groups.
5. Policy Analysis

   Analyzing existing global policies and regulations to identify gaps and opportunities for policy improvements. This involves:
    - Studying and reviewing global regulations related to battery disposal and recycling.
    - Identifying incentives and support mechanisms for sustainable battery management practices.
6. Reporting and Recommendations

The research based study findings into a comprehensive report that includes

- Analysis of current practices and technological advancements.
- Assessment of the environmental and economic impacts of different afterlife battery pack management strategies.
- Recommendations for policymakers, industry stakeholders, and the recycling/ repurposing startups to enhance the management of after-life EV battery packs.

Electric Vehicles

Electric vehicle (EV) technology has undergone significant evolution since the first electric cars were developed in the early 19th century [1]. The initial wave of EVs, powered by lead-acid batteries, offered limited range and performance compared to internal combustion engine (ICE) vehicles. However, the advent of lithium-ion battery technology in the late 20th century marked a turning point, providing a much higher energy density, longer lifespan, and faster charging capabilities [1], [2].

Technological Advancements:

- **Lithium-ion Batteries**: The development and continuous improvement of lithium-ion batteries have been critical to the success of modern EVs. Innovations such as solid-state batteries, silicon anodes, and improved battery management systems have further enhanced the efficiency, safety, and longevity of EV batteries [2], [3], [4].
- **Electric Drivetrains**: Advances in electric motors and power electronics have significantly improved the performance and efficiency of EVs. Technologies such as regenerative braking and advanced motor controllers have contributed to increased range and better energy utilization [5].
- **Autonomous Driving and Connectivity**: The integration of autonomous driving technologies and vehicle-to-everything (V2X) communication has not only enhanced the functionality of EVs but also contributed to the broader vision of smart transportation systems and connected mobility.

Environmental Impact:

- **Reduced Emissions**: One of the primary motivations for the adoption of EVs is their potential to reduce greenhouse gas emissions and air pollutants. EVs produce zero tailpipe emissions, which is a significant advantage over traditional ICE vehicles. When powered by renewable energy sources, the lifecycle emissions of EVs can be substantially lower than those of ICE vehicles [6].

- **Energy Efficiency**: EVs are generally more energy-efficient than ICE vehicles. Electric drivetrains convert a higher percentage of energy from the battery to the wheels, whereas ICE vehicles lose a significant portion of energy as heat [7].

Today the global leading car manufacturers include Tesla, VW group, and BYD, which have production facilities and abilities to design and manufacture Ev. While some automobile manufacturers have dedicated their product portfolios to electric vehicles, others adapt popular conventional assembly plants for their electric models. The focus of EV manufacturing among a limited number of OEMs is due to the intense competitiveness of the auto industry where with constant innovation driving improvements in the systems of EVs and its market segment.

EV Battery

Batteries used in EV have several attributes that are important for the operations and increasing popularity of EV. One of such precedent is energy density, which shows how much energy is stored in a vehicle per unit of volume or mass and thus affects the range directly. Power density is equally important because acceleration and, collectively, driving characteristics also depend on it. Number of charge discharge cycle, which conveys how many cycles a battery is capable of withstanding, elaborates the duration. As with charging speed, temperature and further safety options are also critical, so the effective and reliable charging process occurs. However, one of the most important sources of cost concern connected with electric vehicles is their batteries priced relatively expensively. Environmental degradation is a real aspect that requires manufacturing and recycling that safe the environment. The battery chemistry from lithium-ion to lithium metal and those completing for the new technologies such as solid-state form a crucial part in defining these characteristics. It is therefore important to understand and address any issues that lead to degeneration over time in order to ensure that the batteries still have optimum efficiency. The following characteristics work simultaneously to determine the general evolution of EV batteries: These features are still under research given that researchers continue developmental work in a bid to enhance the battery’s efficiency, and at the same time, lower costs while promoting sustainability.

History of Innovation in EV Battery Technology

Technology in electric vehicles, particularly in battery technology, has never stopped developing from the 19th century up to today. Early Developments in Electric Vehicles were first theorized in 1832 when Robert Anderson of Scotland developed the first crude electric carriage, fuelled also by non-rechargeable primary cells [8]. That simple invention was a stepping stone for the future, but, more so and importantly, in 1859, French physicist Gaston Plante created what is now the standard lead-acid battery, then the first rechargeable battery commonly used [9]. But its real breakthrough was its reusability, making it the standard for early EVs. A series of refinements by Camille Alphonse Faure in 1881, such as improving the performance and energy storage of the lead-acid battery, made the technology more practical and viable for use with Evs [10]. Early attempts throughout the 1890s began to raise some attention regarding electric vehicles, such as the Poplar Flocken Elektrowagen in Germany and the Columbia Electric Carriage in the United States, both famous for the ability to run quietly and smoothly [11].

The Mid-20th Century experienced a slowdown in the 1920s and 1930s, which can be attributed to the improvement of ICE vehicles and the better road system, followed shortly by the oil discovery of cheap oil that favored gasoline cars [12], [13]. Interest in EVs was reawakened in the 1960s and 1970s, only to be captured by other concerns about the environment and the oil crises [12]. While prototype cars such as the Henney Kilowatt used lead-acid batteries, the GM Electrovair, with its nickel-cadmium (Ni-Cd) batteries, was the result of experiments with alternatives to the gasoline engine [14].

Modern Developments behan with higher energy densities in the 1980s with nickel-cadmium, followed by nickel-metal hydride (NiMH), first implemented in early electric and hybrid vehicles [9], [14]. The '90s saw the mass production of the first modern-world electric vehicles—General Motors with the EV1, first using lead-acid and later NiMH batteries [9], [14], [15]. It proved that EVs are practical; the main problems were the cost and the range of batteries. In this development, NiMH batteries replaced the EV1's lead-acid batteries, the Toyota RAV4 EV adopted them, and the original Toyota Prius hybrid also embracing them [3]. The breakthrough was marked in 2008 with the introduction of Tesla Roadster, the first highway-legal EV that used Li-ion batteries.

Likely for the first time, it demonstrated to the world the possibility of a 200-mile range per charge and, further, the viability of Li-ion batteries in EV use [2]. Meanwhile, the popularization of hybrid electric vehicles continued. An instance of this is Toyota Prius, famous all over the world. It has applied both NiMH and, later, Li-ion batteries to improve fuel efficiency and cut down on emissions [3].

Between 2010 and 2014, the Li-ion batteries surpassed all the other battery technologies for EVs in market share due to their high energy density and long cycle life, among other benefits [2], [9], [10]. In 2014, Tesla announced its Gigafactory to mass-produce lithium-ion batteries to meet the surging demand for Evs [4]. The critical headline in 2015 was the enormous drop in the price of Li-ion batteries, with constructive results for making EVs affordable and competitive compared to ICE vehicles [4]. New, more advanced batteries have enabled long-distance travel, and models like the Tesla Model S allow trips of over 300 miles with a single charge [4]. The deployment of ultra-fast chargers and the expansion of the charging infrastructure in 2018-2019 made EVs more feasible for long-distance driving [16]. With the increased market access, the cost of Li-ion batteries continued to decrease later on.

Further remarkable improvements in solid-state battery technology-making advancements between 2020 and 2022 has enhance energy density, fast-charging capability, and safety [17]. Other critical contributions will include the discovery of progressive technologies in battery recycling and the development of encouraging policies by the governments [18], [19]. The EV-to-grid (V2G) technologies have enabled vehicles to feed electricity into grids. Meanwhile, the inception and research into the next generation of batteries, namely lithium-sulfur and lithium-air, continued to hold promise for even higher energy densities and lower costs [2], [9], [10], [14]. Further extension of the sustainability of EVs was its linkage with renewable sources and better management of energy systems.

These advances in battery technology for EV applications have developed from the early 19th century until today. From lead-acid batteries to the development of Li-ion and, now, solid-state battery technology, each of these innovations has been a step closer to higher energy density, improved safety, and reduced costs. Fundamentally, these developments have dramatically improved the commercialization and adoption of EVs by realizing a future in transportation that needs to be sustainable and friendly to the environment.

Despite the extensive research on the life cycle of electric vehicles (EVs) and their batteries, the complexity of end-of-life (EoL) processes usually received little emphasis. An electric vehicle battery's possible EoL pathways are multiple, including reuse, repurposing, and refurbishing, before eventual disposal. Either minimal processing is used within the same application, or less demanding applications—such as stationary energy storage—use the first rechargeable batteries other than more demanding applications, or the batteries are put back to charge to recover function, through repair or reconditioning, in what is here defined as the third EoL option. However, the final resting place for all these batteries, including all of these intermediate measures, is recycling, in order to recover the valuable secondary materials. This technique takes into account environmental impacts and saves precious resources, something of use in the way of action towards the development and a circular economy.

Types of EV Batteries

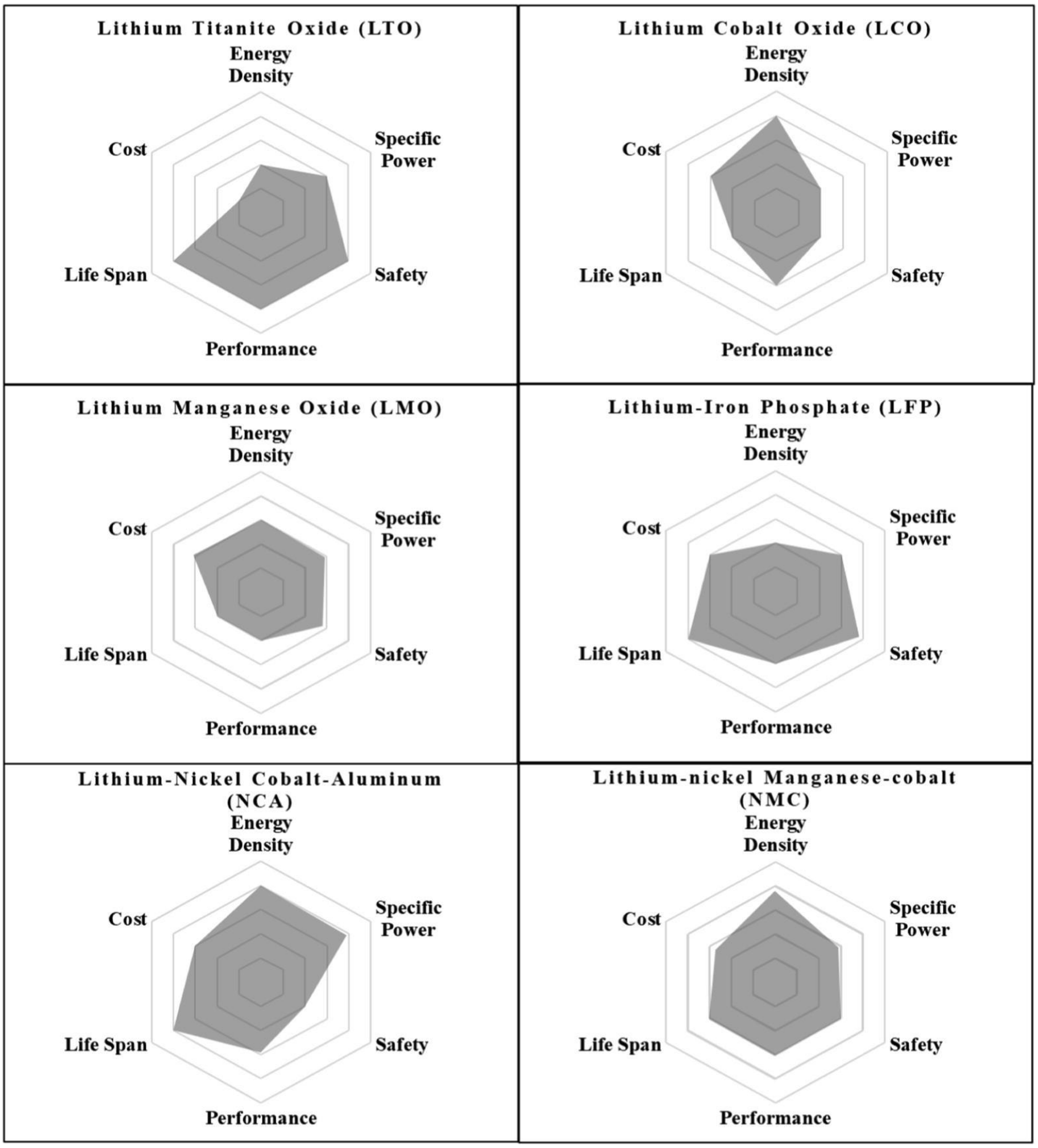

Fig. 1: Comparative Specification of different Lithium based battery technology. [20]

Lead-Acid (Pb-Acid) Batteries

The lead-acid batteries are one of the oldest battery technology used globally. They are still in use despite their ancient existence since they have low manufacturing costs coupled with a high electric power-to-weight ratio [21]. These batteries, however, have significant disadvantages. Their energy density is relatively low. In other words, the unit weight stores less energy than the weights of units of different newer technologies.

Environmental and safety issues are raised by the possible leakage of acid substances, as well as the presence of toxic heavy metals. Moreover, lead-acid batteries exhibit a low energy-to-volume ratio, which means they have to be larger in size for the energy they can store. Because they are highly affordable and durable, lead-acid batteries tend to be used in auxiliary applications of electric vehicles, including starting, lighting, and ignition systems [10], [22].

Nickel-Cadmium (NiCd) Batteries

Nickel-cadmium rechargeable batteries have a remarkable lifespan; they can last for about 1500 charge/discharge cycles [21]. This is one of the longest among rechargeable batteries, and the fact of being so makes them durable for some applications, too. However, this dramatically reduces usage in electric vehicles since it has enormous environmental and health issues linked with cadmium, a heavy metal. Cadmium is toxic to humans and animals, thus raising health and environmental concerns and the very stringent regulation of its use, most notably in the European Union. Although they were considered very robust and performed well under harsh conditions, the environmental footprint of NiCd batteries puts them in a much less relevant position in today's EV applications [9], [10], [22].

Nickel-Metal Hydride (NiMH) Batteries

NiMH batteries possess a few technological attributes similar to NiCd batteries. They are, however, more advanced and consequently ubiquitous in hybrid electric vehicles. One of the significant advantages of NiMH batteries is the lack of memory effect; that is, the battery retains its maximum holding capacity without following the conditioning rule to discharge it fully. NiMH batteries, however, have a lower capacity for energy storage in comparison with lithium-ion batteries. They result in a very high rate of self-discharge when compared to lithium-ion batteries; therefore, they relatively lose charge quite quickly in non-operational situations. This makes them weak and less suitable for applications requiring high-intensity compact forms of energy storage.

Lithium-Ion (Li-Ion) Batteries

Among the most applied batteries for electric vehicles are lithium-ion due to their high capacity and efficiency in providing energy [21]. With high power storage and a good weight-energy density, many considerations of the energy storage application about minimum weight and space can be ideal [22], [23]. Despite all these positive aspects regarding lithium-ion batteries, there are specific challenges: high production costs and possible safety issues during overheating considered to lead to thermal runaway. Despite these downsides, their performance and efficiency benefits far outweigh the flaws in this leading choice of EV battery. It is, however, ongoing research to reduce costs and increase safety to locate them further in the future of electric mobility.

Lithium-Ion Polymer Batteries

The lithium-ion polymer battery is an advanced version of the standard lithium-ion type of battery, with extended lifespan and increased flexibility in design. Among the other examples, instead of a liquid electrolyte, they use polymer electrolytes to allow for shape and size versatility [22], [23]. They are therefore helpful in a range of applications. However, they exhibit functional instability during overloading or discharging below a certain threshold and may be dangerous to safety. These batteries are used in niche EV applications where their unique form factor and long life cycle provide built-in advantages, but they are still held back from broader use due to the need for proper handling to prevent safety risks.

Lithium-sulfur (Li-S)

Lithium-sulfur (Li-S) batteries are one of the next generations of rechargeable batteries that are a major step forward due to the application of sulfur as the cathode material because of the highest theoretical energy density amongst the known chemical elements. Compared to Licious batteries, Li-S batteries demonstrate the prospect to boast much higher capacity of energy storage , which is potentially useful in applications like electric cars, portable electronics, aerospace, and energy storage systems in a grid infrastructure [23]. However, some of the problems associated with sulfur include a low electrical conductivity, dissolution of polysulfide, and a large volume variation during the cycling process that retards their commercial application. Such challenges have been effectively being tackled by researchers across the globe to optimize cathode activity, solidify the surface of the electrode and electrolyte, besides improving on the battery's sturdiness and

durability. However, the fact that Li-S batteries are still at the development stage, it can be asserted that depending on the current efforts, Li-S batteries have a very bright future in next-gen energy storage solutions.

Sodium Nickel Chloride (NaNiCl) Batteries (Zebra Batteries)

Sodium nickel chloride batteries, better known as Zebra batteries, run at high temperatures (270–350°C) and use molten salt electrolyte [23]. They have high energy density to store a large amount of energy [22], [23]. However, the high operating temperature makes it necessary to have thermal solid management, which in many ways complicates their usage. Furthermore, such batteries can be dangerous in terms of safety and unsuitable for long-term storage without maintenance. Zebra batteries are generally used in specialized EV applications as a distinct advantage of high energy density, and their operational challenges can be effectively managed.

Table I. *Battery Chemistry and their Specification in General* [20]

Specifications	**Lead-acid**	**NiCd**	**NiMH**	**LCO**	**LMO**	**LFP**
Specific energy density (Wh/kg)	30–50	45–80	60–120	150–190	100–135	90–120
Internal resistance (mΩ)	<100	100–300	200–300	150–300	25–75	25–50
Cycle life (80% discharge)	200–300	1000	300–500	500–1000	500–1000	1000–2000
Fast charge time	8–16 h	1 h	2–4 h	2–4 h	1 h or less	1 h or less
Overcharge tolerance	High	Moderate	Low	Low		

Self-discharge/ month (room temp.)	5%	20%	30%	<10%		
Nominal cell voltage (V)	2	1.2		3.6	3.8	3.3
Charge cutoff voltage (V/cell)	2.4	Full charge detection		4.2 V		3.6 V
Discharge cutoff voltage (V/cell)	1.75	1		2.5–3.00		
Peak load current	5 C	20 C	5 C	>3 C	>30 C	>30 C
Best result	0.2 C	1 C	0.5 C	>1 C	<10 C	<10 C
Charge temperature (oC)	−20 to 50	0–45		0–45		
Discharge temperature (oC)	−20 to 50	−20 to 65		−20 to 60		
Maintenance requirement	3–6 months	30–60 days	60–90 days	Not required		
Safety requirements	Thermally stable	Thermally stable, fuse protection common		Protection circuit mandatory		
Toxicity	Very High	Very High	Low	Low		
In use since	Late 1800s	1950	1990	1991	1996	1999

Specification of different Battery chemistry is mentioned in Table I.

EV Battery Manufacturers

Battery cell and pack production form the basis of the electrical vehicles through a complex production process. The battery cell manufacturers who are at the forefront in the manufacturing of battery cells using new technologies are CATL, LG Energy

Solution, and Panasonic. These cells go through manufacturing of electrodes and cell fabrication in which cellulose intercalating cathode and anode materials are prepared and incorporated into useful parts. The last step of battery production is the conversion of cells into battery packs with the help of cell manufacturers or automobile manufacturers depends on the delivery of modules, electronics, and thermal systems. The severe amplifying capital cost of this process indicate that it is essential to invest on precision and guarantying the reliability on the road of these EVs.

Table II. *EV Battery Manufacturers Market Share of 2023* [24]

Company	***Country***	***2023 Production (megawatt-hour)***	***Share of Total Production***
CATL	China	242,700	34%
BYD	China	115,917	16%
LG Energy Solution	Korea	108,487	15%
Panasonic	Japan	56,560	8%
SK On	Korea	40,711	6%
Samsung SDI	Korea	35,703	5%
CALB	China	23,493	3%
Farasis Energy	China	16,527	2%
Envision AESC	China	8,342	1%
Sunwoda	China	6,979	1%
Other	-	56,040	8%

Contemporary Amperex Technology Co. Limited (CATL), formerly known as the China Aviation Lithium Battery Technology Co. Limited, only started the research and development of its battery business nine years ago and has emerged as the largest battery manufacturer in the world in less than a decade.

CATL now occupies 34% market share of EV batteries, and its products are used in Chinese-made vehicles such as the Model Y, MG4/Mulan created by SAIC, and Li Auto’s NEVs.

Table III. *Electric Vehicle, Battery Chemistry and Manufacturers 2023* [24], [25]

VEHICLE MANUFACTURER	BATTERY CHEMISTRY	BATTERY MANUFACTURER(S)
BYD	Lithium Iron Phosphate (LFP)	BYD
TESLA INC.	Nickel Cobalt Aluminum (NCA), LFP	Panasonic, CATL, LG Chem
VW GROUP	Nickel Manganese Cobalt (NMC)	LG Chem, CATL, Samsung SDI, SK Innovation
GM	Nickel Manganese Cobalt (NMC)	LG Chem
STELLANTIS	Nickel Manganese Cobalt (NMC)	CATL, LG Chem, Samsung SDI
HYUNDAI MOTOR	Nickel Manganese Cobalt (NMC)	LG Chem, SK Innovation
BMW GROUP	Nickel Manganese Cobalt (NMC)	CATL, Samsung SDI
GEELY AUTO GROUP	Nickel Manganese Cobalt (NMC)	CATL, LG Chem
MERCEDES-BENZ GROUP	Nickel Manganese Cobalt (NMC)	CATL, Farasis Energy, SK Innovation
R-N-M ALLIANCE	Nickel Manganese Cobalt (NMC), LMO	AESC, LG Chem
GAC	Nickel Manganese Cobalt (NMC), LFP	CATL, BYD
SAIC	Nickel Manganese Cobalt (NMC), LFP	CATL, LG Chem, SAIC
GEELY-VOLVO CAR GROUP	Nickel Manganese Cobalt (NMC)	CATL, LG Chem
CHERY AUTOMOBILE	Lithium Iron Phosphate (LFP), NMC	CATL, BYD

CHANGAN AUTOMOBILE GROUP	Nickel Manganese Cobalt (NMC), LFP	CATL
DONGFENG MOTOR	Nickel Manganese Cobalt (NMC), LFP	CATL
FORD	Nickel Manganese Cobalt (NMC)	LG Chem, SK Innovation
HOZON AUTO	Nickel Manganese Cobalt (NMC), LFP	CATL
CHJ AUTOMOTIVE	Nickel Manganese Cobalt (NMC)	CATL
OTHER	VARIOUS (NMC, LFP)	VARIOUS (INCLUDING CATL, BYD, LG CHEM)

Various EVs use different battery chemistries for their use in vehicles, which are mentioned in the above table along with their manufacturers.

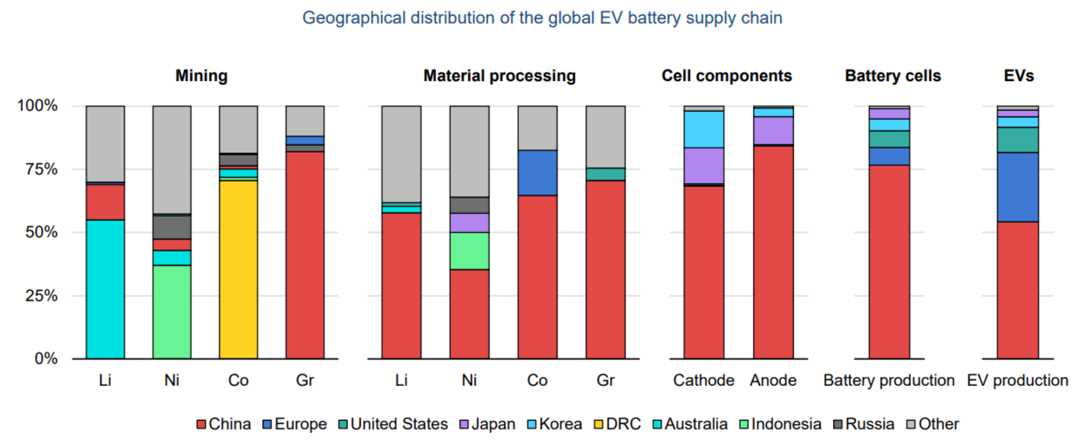

Fig. 2: Major EV battery Supply Chain [19]

The graph represents the dominance of China in the global electric vehicle battery supply chain. China can throw its weight at nearly every stage, from raw material mining to electric vehicle production, in the global battery supply chain. China excels in the mining of graphite, but other countries lead in the mining of lithium and cobalt: Australia and the Democratic Republic of Congo, respectively. In material processing, though, China takes up the critical materials in the most significant share: lithium, nickel, cobalt, and graphite. At the cell component production level, China represents the largest percentage share in both cathode and anode manufacturing. Following this is the headcount of companies producing battery cells and making EVs. In battery cell production and EV manufacturing, China is a leviathan power compared to the others: Korea, Japan, Europe, and the United States. Such dominance holds the country in a pivotal position of power in the overall global transitions toward electromobility.

Market Share by Battery Chemistry

Analysis of the battery chemistry in the market in 2022 revealed that lithium nickel manganese cobalt oxide (NMC) remained the market leader with a generally 60 % market share. Lithium iron phosphate (LFP) batteries were in the second place with slightly under 30%, while nickel cobalt aluminium oxide (NCA) batteries were the third most popular with about 8%.

Table IV. *Battery manufacturers with their corresponding Battery Production.*[24], [25]

Battery Manufacturer	***Battery Chemistry***
CATL	LFP, NMC, NCM
BYD	LFP, NMC
LG Energy Solution	NMC, NCA
Panasonic	NCA, NMC
SK On	NMC, NCA
Samsung SDI	NMC, NCA
CALB	LFP, NMC
Farasis Energy	NMC
Envision AESC	NMC, LMO
Sunwoda	LFP, NMC

LFP = Lithium Irom Phosphate, NMC = Nickel Manganese Cobalt, NCM = Nickel Cobalt Manganese Oxide, NCA = Nickel Cobalt Aluminum, LMO = Lithium Manganese Oxide

The usage rate of lithium iron phosphate (LFP) battery pack reached the peak in the past 10 years, this was studied mainly because of Chinese OEM's inclination [26]. The global LFP batteries were deployed mainly in electric light-duty vehicles, capturing 95% of the total LFP battery demand for vehicles manufactured in China, with BYD's demand being over 50% [24], [27]. Some of the key ones are BYD which increased its

LFP battery purchases by 140% [24], [28], CATL which saw its demand rise to 45% [24], and Tesla which consumed 15% of LFP batteries up from 20% in 2021 to 30% in 2022 [24], [29]. LFP Battery Electric Vehicles constituted 85% of the cars of Tesla, and most of them were manufactured in China, The remaining 15% of Battery Electric Vehicles were made in the United States, but the cells were imported from China [24], [30]. In 2022, the current state of American-made electric cars with LFP batteries remained a meager 3% [24], [31].

LFP batteries differ from others such as NMC and NCA in that they do not use nickel, manganese, or cobalt to form the cathode chemistry ; instead, iron and phosphorus are used [32]. But one of the most significant disadvantages of LFP batteries, which is a widespread problem compared to NMC batteries, is the lower energy density [27]. Moreover, despite some features, such as using phosphorus for battery production, which is an element that is severely needed in the modern world in the production of food, LFP batteries are environmentally friendly and have great potential [33]. Were all batteries produced at present developed LFP, this would require just under 1% of total phosphor used in agricultural industry and thus raise a threat of competition for this compound as battery production skyrockets [34].

EOL of EV batteries

End-of-life (EOL) for electric vehicle (EV) batteries refers to the stage when these batteries can no longer efficiently power vehicles due to diminished capacity or performance. Typically, an EV battery reaches EOL when its capacity drops to around 70-80% of its original value, making it unsuitable for the demanding energy requirements of electric vehicles [35].

Apart from internal combustion engine (ICE) vehicles, EVs consist of large batteries that need replacement after their health gradually decreases. There are several sources for second-hand EV batteries that still possess significant capacity and can be repurposed, remanufactured, or recycled. When an EV is involved in an accident, some battery modules may remain intact and safe to use for other applications. Additionally, scrap vehicles are a valuable source of these batteries.

At this point, EOL management becomes critical to address the environmental and economic impacts. Recycling and repurposing are the primary strategies for EOL battery management. For example, the recycling process involves dismantling the batteries, safely extracting valuable metals like lithium, cobalt, and nickel, and then reintroducing them into the manufacturing supply chain. This reduces the need for new raw materials and minimizes environmental harm. According to the International Energy Agency (IEA), recycling EV batteries can potentially recover up to 95% of these critical metals, making it a highly efficient process [19].

Repurposing, on the other hand, involves giving batteries a second life in less demanding applications, such as energy storage systems for renewable energy. For instance, Nissan repurposes used EV batteries from their Leaf models to provide backup power for streetlights in Japan [36]. Similarly, in California, used EV batteries are being utilized in grid storage systems to stabilize renewable energy supply [37], [38].

Effective EOL management not only mitigates environmental impact but also supports the creation of a circular economy, reducing waste and promoting the sustainable use of resources. As the number of EVs on the road continues to grow, developing robust EOL strategies will be crucial for the automotive and energy sectors.

Second Life Application of EV Batteries

Despite the extensive research on the life cycle of electric vehicles (EVs) and their batteries, the complexity of end-of-life (EoL) processes usually received little emphasis. An electric vehicle battery's possible EoL pathways are multiple, including reuse, repurposing, and refurbishing, before eventual disposal [35]. Either minimal processing is used within the same application, or less demanding applications—such as stationary energy storage [37], [38]—use the first rechargeable batteries other than more demanding applications, or the batteries are put back to charge to recover function, through repair or reconditioning, in what is here defined as the third EoL option [35]. However, the final resting place for all these batteries, including all of these intermediate measures, is recycling, in order to recover the valuable secondary materials. This technique takes into account environmental impacts and saves precious resources, something of use in the way of action towards the development and a circular economy.

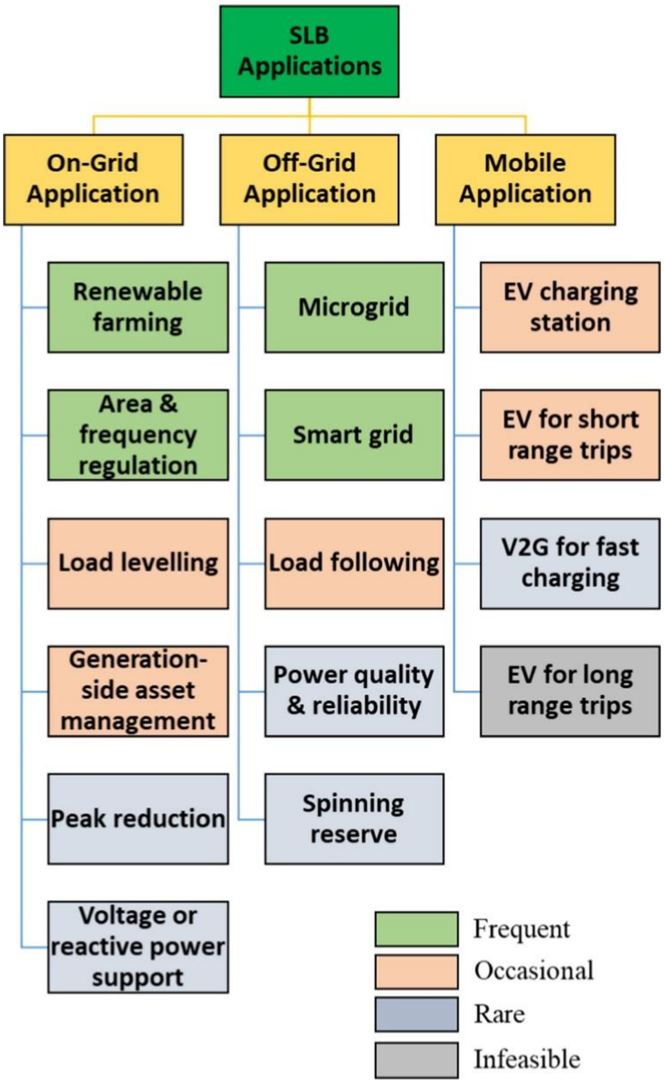

Fig. 3: Possible Second Life Batteries Application for EV Batteries.[20]

The chart categorizes Second Life Battery (SLB) applications into three main areas: On-Grid, Off-Grid, and Mobile Applications. On-grid applications frequently include renewable farming and area/frequency regulation, with occasional uses in load levelling and asset management. Off-grid applications frequently involve microgrids and smart grids, occasionally supporting load following and power quality. Mobile Applications frequently support EV charging stations and short-range trips, with occasional use for vehicle-to-grid (V2G) fast charging. Rare and infeasible applications include peak reduction and voltage support for On-Grid, spinning reserves for Off-Grid, and long-range EV trips for Mobile.

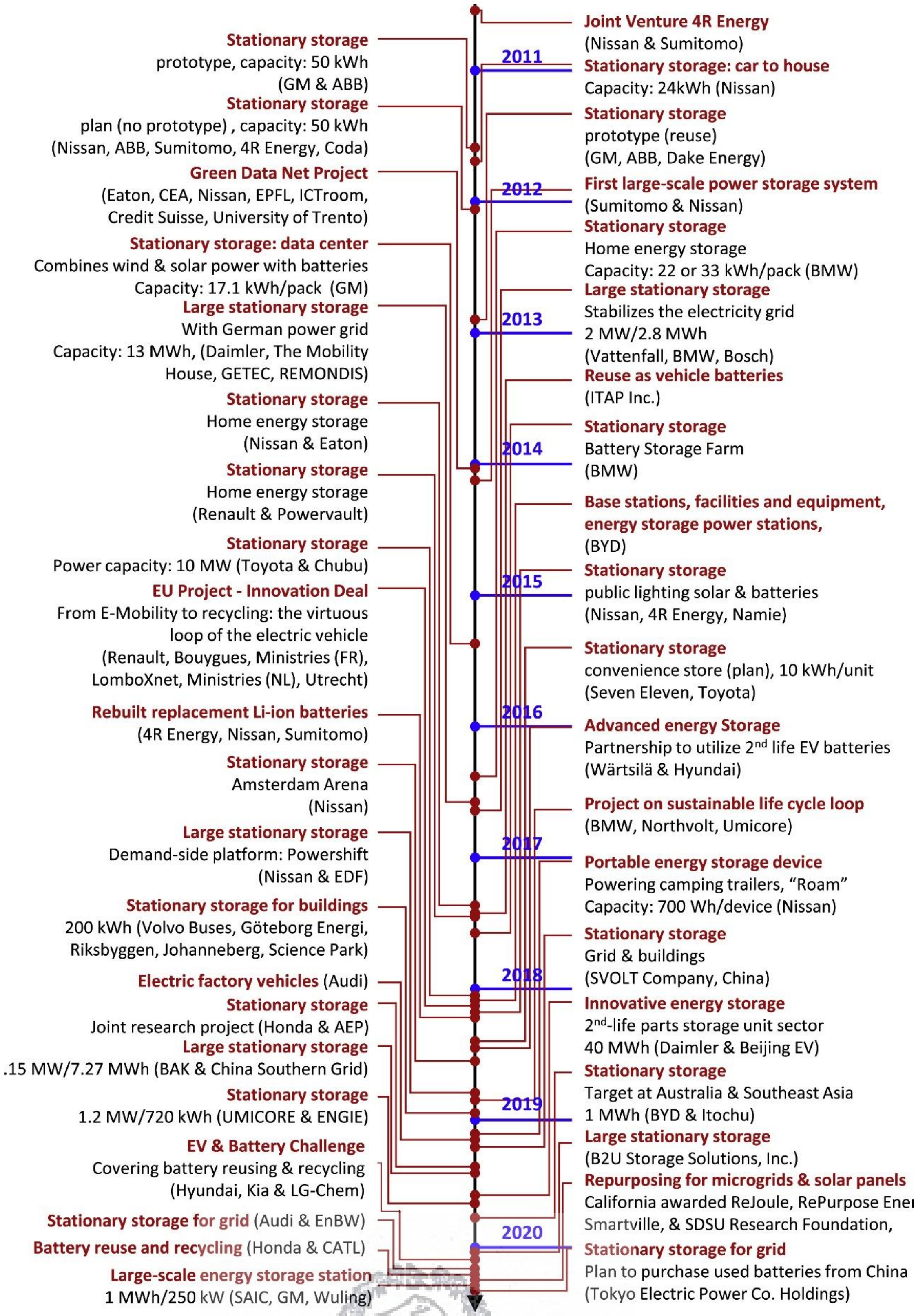

Fig. 4: History of Second-Life EV Battery application performed by different companies. [23]

The figure 4 is a timeline illustrating various projects and initiatives related to second-life batteries and energy storage from 2011 to 2020. It highlights key developments in stationary storage, advanced energy storage, and large-scale storage systems.

- **2011**: Introduction of stationary storage prototypes and plans by GM & ABB, Nissan, ABB, Sumitomo, and 4R Energy.
- **2012**: Projects like the Green Data Net Project and the first large-scale power storage system by Sumitomo & Nissan.
- **2013**: Implementation of home energy storage by BMW and large stationary storage with German power grid integration.
- **2014**: Developments in home energy storage by Nissan & Eaton, and the launch of BMW's Battery Storage Farm.
- **2015**: Projects include Toyota & Chubu's 10 MW power capacity storage and the EU Project - Innovation Deal.
- **2016**: Introduction of rebuilt replacement Li-ion batteries by 4R Energy and Nissan's Amsterdam Arena storage.
- **2017**: Launch of large stationary storage platforms and portable energy storage devices by Nissan.
- **2018**: Audi's electric factory vehicles and joint research projects by Honda & AEP.
- **2019**: Large stationary storage initiatives by Daimler & Beijing EV and repurposing projects by Hyundai, Kia & LG Chem.
- **2020**: Introduction of large-scale energy storage stations by SAIC & WM and plans to purchase used batteries from China by Tokyo Electric Power Co. Holdings.

Each year is marked by significant projects demonstrating the progression and innovation in battery reuse, storage capacities, and collaborations across the globe.

Table V. *Current reallife second life application of EV batteries* [38], [39], [40], [41], [42]

Project/Company	*Second-Life Application*	*Details*
RWE and Audi	Grid frequency maintenance, energy storage	Decommissioned Audi e-tron batteries repurposed for grid storage and other applications
Jaguar	Grid storage	Expanded second-life battery storage unit to 7.5 MWh
Relectrify	Residential, industrial, grid storage	Uses second-life Nissan Leaf batteries with integrated BMS and inverter technology
Nissan and Ecobat	Battery energy storage systems, mobile power	Recover, repair, and repurpose Nissan Leaf batteries for various second-life applications
American Battery Technology	Second-life storage, mobile charging stations	Part of US government-funded initiative for recycling and repurposing EV batteries
Cirba Solutions	Integrated process for processing spent EV batteries	Develops megawatt-scale second-life storage solutions
Element Energy	Various second-life storage applications	Part of US government-funded initiative for recycling and repurposing EV batteries

This table summarizes various projects and companies involved in the repurposing of second-life batteries for different applications, including grid storage, residential and industrial energy storage, and mobile power solutions. Each entry provides details about the specific second-life application and the technology or process utilized in the repurposing of decommissioned electric vehicle batteries. Notable initiatives include efforts by RWE and Audi in grid frequency maintenance using repurposed Audi e-tron batteries, Jaguar's expansion of second-life battery storage capacity, and Relectrify's innovative use of Nissan Leaf batteries with integrated management systems. Additionally, companies like Nissan and Ecobat focus on recovering and repairing batteries for diverse uses, while American Battery Technology and Element Energy participate in US government-funded recycling and repurposing initiatives. Cirba Solutions is noted for developing megawatt-scale second-life storage solutions through an integrated battery processing approach.

Second Life Application of used EV batteries has some advantages and some disadvantages along with challenges that can occur.

Advantages:

Recycling and repurposing EOL EV batteries offer substantial advantages. Sustainable resource management is a key benefit, as recycling recovers valuable materials, reducing the need for new extractions and their associated environmental impacts. Tesla's battery recycling facility Navadia will be able to recycle 100,000 tons of EV batteries, minimizing waste [43]. Proper recycling and repurposing also significantly reduce environmental pollution by preventing hazardous waste and lowering greenhouse gas emissions from battery production. Companies like Redwood Materials highlight these benefits by cutting down on waste and reducing the carbon footprint [43] . Additionally, second-life applications for EOL batteries extend their lifecycle and maximize their value. Nissan's use of Leaf batteries in the xStorage system provides backup power and supports grid stability, demonstrating the potential for extended battery use [38].

Disadvantages:

There are several disadvantages to consider in the recycling and repurposing of EOL EV batteries. The recycling process is complex and energy-intensive, requiring specialized equipment and significant resources, which can be costly and technically challenging. The hydrometallurgical process, for example, involves multiple stages of chemical treatment [32], [44], [45], [46]. Safety risks are also a concern, as handling EOL EV batteries can pose fire hazards and exposure to toxic chemicals, as evidenced by fires in recycling facilities caused by damaged lithium-ion batteries [47], [48], [49]. Logistical challenges further complicate the process, as collecting and transporting these batteries requires specialized logistics solutions due to their weight, size, and hazardous nature. The need for specialized transportation and storage solutions increases logistical costs and complexity, making efficient management of EOL batteries challenging [20], [50], [51], [52].

Table VI. *Pros and Cons of Approaches to 2nd Life Applications Path of EV Batteries* [53], [54], [55], [56], [57], [58], [59], [60]

Aspect	**Refurbishing EV Batteries**	**Repurposing EV Battery Packs**
Process Complexity	Requires dismantling packs, collecting modules, testing, sorting, repacking, and certifying batteries	Ready to use, reducing the time and cost of repurposing batteries
Supply Chain Requirements	Necessitates a specialized supply chain, increasing the cost of battery reuse	Reuse of existing native pack BMS reduces the need for additional supply chain setup
Technical Know-How	Few system integrators currently possess the necessary expertise	Integration activities can be provided by several system integrators
Time Required	Takes more time to realize and certify repackaged modules	Quicker process due to the ready-to-use nature of the approach
BMS Requirements	A new module (tray) BMS must be developed	Requires a specific Master BMS for the entire system
Integration	Similar to common Battery Energy Storage Systems (BESS)	Integration is limited to parallel connections only, needing additional DC/DC converters or oversized PCS for voltage adjustments
Space Requirements	Standard space requirements	Requires more installation space compared to standard stationary BESS
Performance Guarantees	Performance warranties can be guaranteed by the system integrator	The system integrator does not guarantee battery performance (life extension, efficiency, C-rate) but the

		battery manufacturer guarantees the expected residual capacity

This table contrasts refurbishing and repurposing EV batteries. Refurbishing involves a complex, time-consuming process requiring dismantling, testing, and repacking, with higher supply chain and technical demands. It needs a new BMS and standard space, offering performance guarantees by the integrator. Repurposing is quicker and cost-effective, using existing BMS and simplifying supply chain needs. It allows for easier integration but requires more space and additional components for voltage adjustments, with performance guarantees provided by the battery manufacturer.

Challenges:

Several challenges must be addressed to improve the management of EOL EV batteries. There are several manufacturers with unique technology and batteries are not made to be disassembled and unique, so there is no uniform procedure for every battery which makes the job time-consuming and labour-intensive. Developing more efficient and cost-effective recycling technologies is crucial to maximize material recovery and minimize environmental impact. Ongoing research into effective hydrometallurgical and direct recycling methods aims to improve recovery rates and reduce energy consumption. Establishing a robust infrastructure for the collection, transportation, and processing of EOL batteries is essential to support large-scale recycling and repurposing efforts. This requires investment in a network of collection centres, recycling plants, and logistics solutions. Regulatory compliance is another challenge, as companies must navigate complex and evolving regulations to ensure legal compliance and sustainability. For example, companies must adhere to the EU's Battery Directive and similar regulations in other regions, which can be resource-intensive and require constant adaptation. Generally, there are technical and economic challenges acting as barriers to the second-life application of EV batteries mentioned below.

Table VII. *Technical Challenges of Second Life EV Batteries* [54], [55], [59], [60]

Technical Challenge	Description
State of Health (SoH) Assessment	Accurately assessing the remaining capacity and performance due to variable usage patterns.
Battery Management Systems (BMS)	Need for customized BMS for different applications to ensure proper monitoring and safety.
Thermal Management	Transition from active (in EVs) to passive systems (in stationary applications), affecting performance.
Safety Concerns	Hidden defects or damage in used batteries that could lead to safety hazards, requiring rigorous testing.
Economic Viability	High costs of collecting, testing, and repurposing batteries must be justified by economic benefits.
Standardization and Variability	Diverse designs and chemistries of EV batteries complicate creating standardized repurposing procedures.
Regulatory and Environmental Compliance	Ensuring compliance with regulations for the disposal and recycling of non-repurposable batteries.
Technological Innovation	Need for advancements in battery testing, management systems, and recycling technologies.

Table VIII.*Economic Challenges of Second Life EV Batteries* [20], [61], [62]

Economic Challenge	Description
High Initial Costs	High costs associated with collecting, testing, and refurbishing used batteries for secondary use.
Falling Costs of New Batteries	Decreasing costs of new batteries make second-life batteries less economically attractive.
Lack of Standardization	Diverse designs and chemistries complicate standardization, increasing refurbishment complexity.

Uncertain Market Demand	Demand for second-life batteries can be uncertain, making investment riskier.
Regulatory and Policy Challenges	Immature regulatory regimes and lack of clear policies create uncertainties and compliance costs.
Economic Viability of Second-Life Batteries	Economic viability is challenged by performance limitations and the need for significant cost advantages over new batteries.
High Logistics Costs	Costs associated with transporting and storing used batteries can be prohibitive.
Technological and Process Innovations	Need for advancements in refurbishing processes and technologies to reduce costs and improve efficiency.

Reliability:

The reliability of recycling processes is heavily dependent on the advancement and adoption of new technologies. Investments in research and development by companies like Li-Cycle are essential for developing reliable recycling technologies that can handle the increasing volume of EOL batteries. Policy-driven support and incentives also play a crucial role in ensuring the reliability and growth of the recycling industry, providing the necessary framework and financial backing. Government grants and subsidies for recycling infrastructure, for instance, can help establish a reliable and sustainable industry. Collaboration among manufacturers, recyclers, and policymakers is vital to establish reliable and sustainable EOL battery management practices. The Global Battery Alliance, a multi-stakeholder initiative, aims to ensure sustainable battery production and recycling through industry collaboration and policy advocacy.

Treatment:

Treatment of EOL EV batteries involves several steps to manage them effectively. Recycling processes are designed to recover valuable materials from the batteries, which can then be reused in new batteries or other applications, contributing to resource efficiency and sustainability. Companies like Umicore use advanced smelting and refining processes to recover and purify metals from EOL EV batteries. Repurposing

EOL batteries for secondary applications, such as stationary energy storage systems, is another key treatment method. Nissan, for instance, repurposes its Leaf batteries for use in stationary storage systems, providing backup power and supporting renewable energy projects. Batteries that cannot be recycled or repurposed are disposed of in compliance with environmental regulations to minimize harm. In regions with strict environmental regulations, such as the EU, non-recyclable batteries are treated and disposed of in controlled facilities to prevent soil and water contamination.

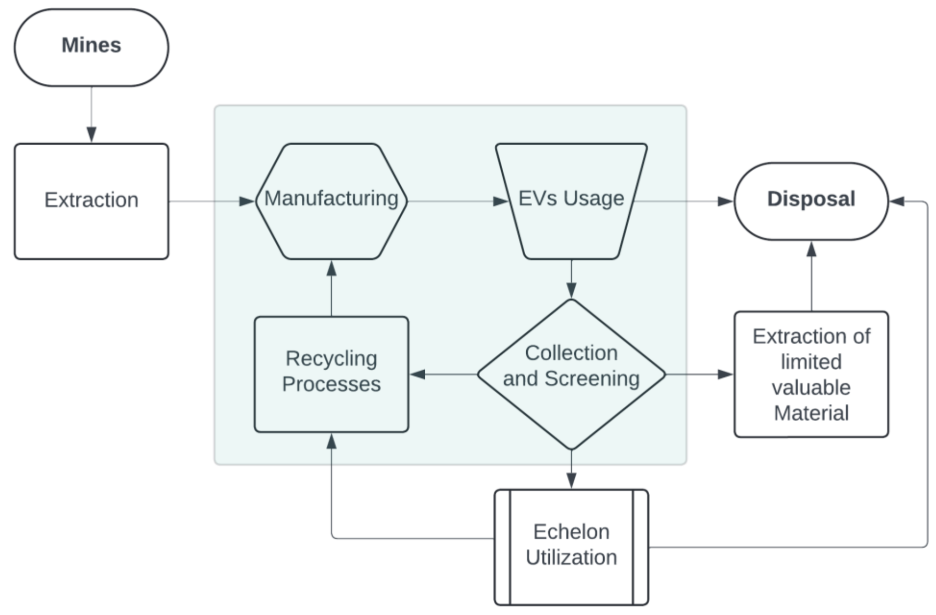

Fig. 5: Life Cycle Assessment of an EV battery

Figures 5 and 6 illustrate the lifecycle of materials used in electric vehicles (EVs). It begins with extraction from mines, followed by manufacturing and usage of EVs. After their initial use, batteries undergo collection and screening. Depending on their condition, they are directed either to echelon utilization for secondary applications or to recycling processes. Valuable materials are extracted during disposal, which re-enters the cycle through recycling. This process highlights the steps from raw material extraction to eventual disposal and recycling, emphasizing material recovery and reuse.

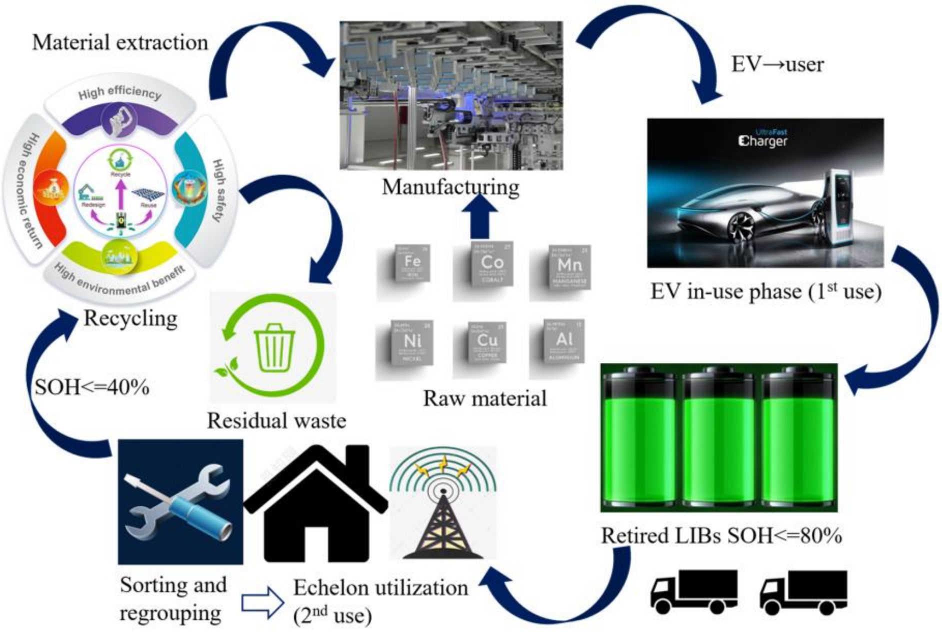

Fig. 6: EV battery Life Cycle [21]

End life of EV batteries may undergo some process

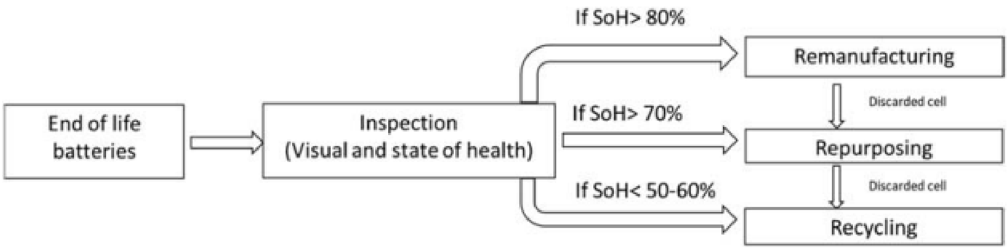

Fig. 7: Processing End-of-Life of Lithium-ion Batteries [35]

The provided diagram illustrates the processing steps for end-of-life lithium-ion batteries (LIBs) to maximize their value proposition. The value chain follows a hierarchical approach: remanufacturing is prioritized first, followed by repurposing, and lastly, recycling. The decision on whether a LIB module, submodule, or component will be remanufactured, repurposed, or recycled is based on specific criteria, primarily the State of Health (SoH). SoH is a widely accepted criterion used to predict the remaining useful life and safety of LIB packs.

Processing Steps:

This systematic approach helps in efficiently managing end-of-life LIBs, reducing waste, and recovering valuable materials, contributing to environmental sustainability and resource efficiency.

Inspection

The provided diagram illustrates the processing steps for end-of-life lithium-ion batteries (LIBs) to maximize their value proposition. The value chain follows a hierarchical approach: remanufacturing is prioritized first, followed by repurposing, and lastly, recycling. The decision on whether a LIB module, submodule, or component will be remanufactured, repurposed, or recycled is based on specific criteria, primarily the State of Health (SoH). SoH is a widely accepted criterion used to predict the remaining useful life and safety of LIB packs [35].

Remaufacturing (Refurbishing)

Remanufacturing refers to the process of isolating and scraping out damaged cells or modules in a battery pack, and replacing them so that the battery pack recovers its optimal performance it as it was when newly purchased, known off the shelf battery pack. This approach saves a great deal of material and energy needed to produce other battery packs, increases the average cycle of battery packs and thus helps to cut costs and environment harm [63].

End-of-life batteries, which have reached the end of their initial lifecycle, undergo an inspection process that involves both visual examination and an assessment of the SoH. The inspection aims to categorize the batteries based on their health status to determine the most suitable next steps for processing. Batteries with a SoH in between 70%-80% are directed towards remanufacturing [35], [64].

Procedure

- Identify the component, module, sub-module, or cell that no longer meets operational demands.
- Determine the specific part of the battery pack that is separable and locate the defective cell.

- Remove the defective cell.
- Insert a new cell.
- Reassemble the battery pack.
- Conduct vigorous testing to confirm the pack's performance meets standard levels.

On average, LIB packs can be considered for remanufacturing when its SoH level is strictly between 70% to 80%. The acceptable SoH has to do with the application of the battery pack including electric vehicles that should use battery packs with SoH higher than 80% and stationary storage applications which require battery pack with SoH of only 50% to 60% [65]. Interestingly, degradation in SoH is commonly attributed to the poor performance of just a few cells which represents only 5-30% of the total rather than the whole pack. In this way, one is able to enhance the total SoH, since poor performing cells are substituted when their capacity drops to certain level.

A study by Mathew et al has revealed that redistributing fresh sub-sets of modules to replace the degraded ones can increase SoH of pack or battery back to 80% even if they have been cycled 2000 times; this means that, through systematic process of replacing bad cells, packs can reach 30,000 cycle age or more [66]. Fig. 2. 3 illustrates the common/basic flowchart for the remanufacturing process and it has been noted that this flowchart is not complicated and in some cases may actually be simple, in relation to the forms of the cells within the LIB pack [67].

For example, cylindrical cells present difficulties because there are so many conditions needed to build a functional battery module, not to mention the fact that it is generally a problem to constantly monitor the SoH of each cylindrical cell [68]. Techniques that can be applied include spot welding, laser welding or bond wire, or even ultrasonic welding that will be used to join cells and modules and these may make it harder to disassemble. Some of the measures that have been taken to try and reduce this include peculiar shapes that would require easy dismantling of the weld connections such as the one that involves welding a single nickel plate across parallel cells than using strips [69].

Prismatic cell designs use Aluminium bus bars and joinings including laser welding joinings; the use of adhesive conductive pastes is also explored to minimize the conductivity reduction [70]. Pouch cells, which are cells that are popular for their sensitivity, present challenges of handling when stored for remanufacturing as well as in the separation process whereby cells glued on aluminium sheets are involved [69].

To date, there have been challenges when it comes to the scale-up of remanufacturing processes of LIBs despite advancements in laboratory settings. Some of the leading automotive producers among which are Toyota, Johnson Controls, and Tesla are defining patents and programs for increase in this sphere due to growing environmental issues and improvement in value creation. These standard enforcement include the use of UL 1642, UL 2054, IEC 62133, IEC62281, SAE J2464, and IEEE 1625 and 1725 for avoiding short-circuit conditions and fire risks during the remanufacturing process [71].

In conclusion, more challenges yet exist for remanufacturing for the vast LIB market but comprehensive research and current development strongly indicate they can make battery lifecycle management more environmentally friendly in the future.

Some of the top remanufacturing startups along with their activities are mentioned in the table below;

Table IX. *Top 10 Remanufacturing Startups of 2023* [72]

No.	*Company Name*	*Activities*
1	Evolve Renewable Materials	Scarce Battery Materials Recovery
2	Battri	Advanced Battery Diagnostics
3	Redivivus Technologies	Battery Shredding
4	Cylib	Additive-Free Battery Recycling
5	No Canary	Plug & Play Battery Recycling Lines
6	BatX Energies	Reverse Battery Logistics

7	NEU Battery	Redox Battery Recycling
8	EXELx	Battery Regeneration Technology
9	Li-Tech	Battery Identification Sensor
10	AraBat	Sustainable Hydrometallurgy

Repurposing

Bringing back used electric vehicle batteries into the electricity grid is a crucial approach to sustainable power handling as it has numerous advantages in terms of environmental conservation and costs. Generally, the batteries are utilized within automotive applications, but as they remain effectively capable in the second life when many other systems and components of the electric vehicle are already worn out, the batteries can experience second-life application [73]. Some of the applications of battery energy storage include; residential & commercial battery storage, grid balancing, and ancillary services, and battery energy storage system with renewable energy systems particularly solar and wind systems [74]. Further, second-use applications of EV batteries include but not limited to off-grid storage, backup power systems, and low-power mobility such as electric bicycles and scooters [75]. A novel technique called ‘echelon utilization’ which involves the application of batteries in a cycle sequentially depending on capacity and efficiency of the battery for the next utilization further enhances the lifetime of the EV batteries [76]. For instance, battery usage may start as grid energy storage with power demands meeting necessities of a high demand and later may be shifted for duties involving household backup power as the battery loses some storage capability [77]. Through echelon utilization and thus making these batteries live longer on powering devices, we lessen the need for the new raw materials for their production, and decrease the amounts of the electronic waste, making a step forward towards a more sustainable energy system [78]. Similarly, when these batteries get to the end of their second life, recycling processes can help in recovery of several materials, which makes this method of battery utilization better for resource conservations and the environment [50].

Batteries that exhibit a SoH greater than 70% but are not suitable for remanufacturing are sent for repurposing. This step is particularly beneficial in finding new applications for batteries that still have significant capacity left, thereby reducing waste and making efficient use of the resources embedded in these batteries [79].

Currently there are various approaches to battery re-use, for example by SK Innovation and Kia for battery recycling, and Renault, Veolia and Solvay concentrate on battery recycling consortia. New recycling approaches: technological advancements and types such as Direct recycling present higher efficiency in terms of MV and environmental impact [80]. Voluntary measures and collaborations such as policies, OEM and recycler partnerships, and partnerships between car manufacturers and battery manufacturers create investments to reuse and recycle batteries sustainably and make use of every material of the battery [81].

Table X. *2nd Life Stationary Application comparison with 1st Life Application*

Aspect	**1st Life in EVs**	**2nd Life in Stationary Application**
Voltage Required	400 V	~ 800 - 1000 V
Operating Hours for 10A	~16,800 h (on)	Max. 87,800 h (on)
Ambient Temperature	-40 to 60 °C	10 to 35 °C
C Rates	- Continuous: 2 to 3 C	- Continuous: < 0.5 C
	- Peak: > 5 C	- Peak: 0.2 to 2 C
Thermal Management	Active (Air/Liquid)	Passive (Only active in specific critical cases)
Vibration	Yes (due to EV movement)	None (Stationary)
State of Health (SOH)	100% (at beginning of 1st life)	70-90% (at beginning of 2nd life)

This table compares the key aspects of electric vehicle (EV) batteries during their 1st life in EVs and their 2nd life in stationary applications. It highlights differences in voltage requirements, with EVs needing 400 V and stationary applications requiring around 800-1000 V. The operating hours at 10A are significantly longer in stationary use (up to 87,800 hours) compared to EVs (around 16,800 hours). Ambient temperature ranges are wider for EVs (-40 to 60 °C) than for stationary applications (10 to 35 °C). Continuous C rates are higher in EVs (2 to 3 C) than in stationary use (< 0.5 C), and peak C rates are also higher in EVs (> 5 C) compared to stationary applications (0.2 *to 2 C). Thermal management in EVs is active (air/liquid) while it is mostly passive for stationary applications, except in critical cases. EV batteries experience vibration due to vehicle movement, whereas stationary applications do not. The state of health (SOH) at the beginning of 1st life is 100%, but it drops to 70-90% at the start of 2nd life in stationary applications.*

Recycling

Recycling is a crucial step in the lifecycle of EV batteries, particularly when the battery health is too low for second-life applications, or when used batteries go through remanufacturing. In this process, damaged parts are separated, and totally destroyed batteries from vehicle accidents or scrap are processed to recover valuable minerals. The recycling process involves dismantling the batteries and extracting critical materials such as lithium, cobalt, and nickel. These recovered materials are then reintroduced into the manufacturing supply chain, reducing the need for new raw materials and minimizing environmental impact.

Comparative Analysis of three afterlife battery management practices.

Material Recovery Rates

- Repurposing: No immediate recovery; delayed recovery upon eventual recycling or disposal [82].
- Recycling (Mechanical): High recovery rates for metals like copper, aluminum, and steel; moderate for lithium and cobalt [83].
- Recycling (Hydrometallurgical): High recovery rates for lithium, cobalt, nickel, and manganese [45].
- Recycling (Pyrometallurgical): High recovery rates for cobalt and nickel; lower for lithium [84].
- Disposal: No material recovery.

Energy Consumption

- Repurposing: Lower energy consumption compared to manufacturing new batteries but higher than simple disposal [85].
- Recycling (Mechanical): Moderate energy consumption [83].

- Recycling (Hydrometallurgical): Variable energy consumption; generally lower than pyrometallurgical [45].
- Recycling (Pyrometallurgical): High energy consumption [84].
- Disposal: Minimal immediate energy consumption but high environmental cost [86].

Greenhouse Gas Emissions

- Repurposing: Lower emissions due to extended battery life and reduced need for new batteries [87].
- Recycling (Mechanical): Lower emissions compared to pyrometallurgical processes [83].
- Recycling (Hydrometallurgical): Lower emissions due to chemical processes at lower temperatures [45].
- Recycling (Pyrometallurgical): High emissions due to energy-intensive processes [84].
- Disposal: High emissions related to transportation and potential landfill emissions [86].

Echelon Utilization of Battery.

Growing realization of need and recognition for the usage of lithium-ion batteries (LIBs) in electric vehicle technology have resulted in an increasing trend of environmental pollution and energy crises. Thereby, a substantial number of LIBs on electric vehicles are now approaching their end of life, and derivation of proper management and recycling strategies has now become very essential. End-of-life LIBs may incite severe safety risks like electric shocks, explosion, and corrosion besides harboring environmental issues stemming from poor disposal, such as pollution through toxic substances like nickel, cobalt, and lithium salts.

Used EV batteries are repurposed for grid support and energy storage systems, providing benefits such as peak shaving and infrastructure deferral. For instance, Nissan and Renault repurpose batteries for powering streetlights and elevators respectively.

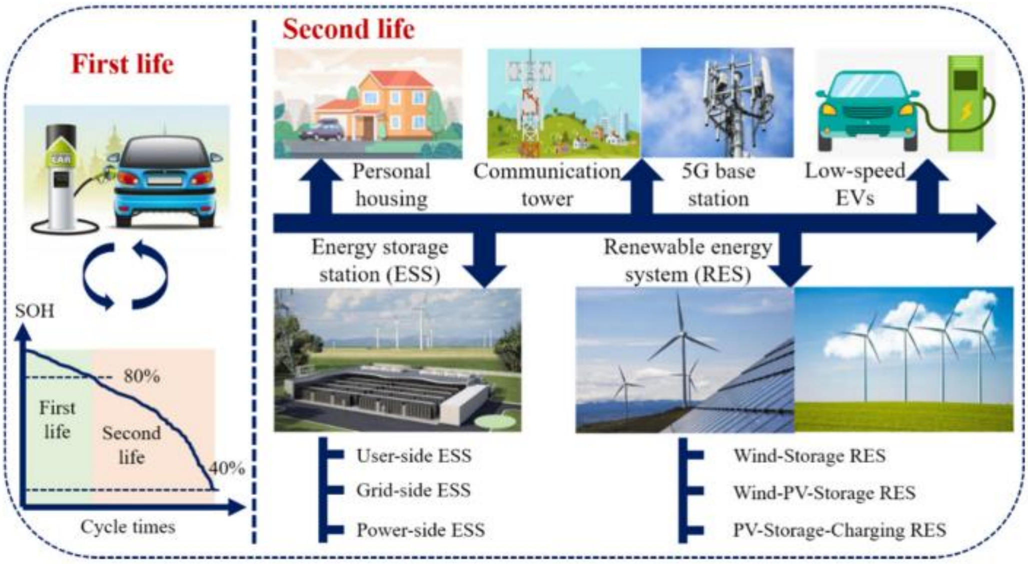

Fig. 8: Echelon utilization of EV battery [88].

This image illustrates the lifecycle of electric vehicle (EV) batteries, which is divided into two main phases: "First life" and "Second life." In the first life, EV batteries are used in electric cars until their state of health (SOH) decreases to around 80%. Once this threshold is reached, the batteries transition to their second life, where they can be repurposed for various applications, including personal housing, communication towers, 5G base stations, and low-speed EVs. Additionally, in their second life, these batteries can serve in energy storage stations (ESS) such as user-side, grid-side, and power-side ESS, as well as in renewable energy systems (RES) like wind-storage, wind-PV-storage, and PV-storage-charging combinations. The graph in the image depicts the decline in SOH over cycle times, highlighting the transition from the first life to the second life as the SOH drops from 80% to 40%.

Echelon utilization means using LIBs whose performance has degraded to between 70% and 80% of their original capacity in applications where the performance requirements are much less severe, for example, stationary Energy Storage System (ESS), communication base stations, home inverters, wind-PV-storage, and low-speed electric vehicles. This will go toward extending the life cycle of the battery, thus reducing the need for newly produced batteries, and will lower the environmental footprint. Retired LIBs should be recycled for the recovery of important metals such as lithium, nickel, cobalt, and manganese, which will save resources and reduce environmental pollution.

Challenges for Echelons Utilization

Although echelons seem to hold great potential in the utilization of retired power LIBs, there remain many technical challenges and the obvious need for knowledge and technology transfer to the global market more than 20 years later [28]. The processes of recycling and reuse are complicated and strongly depend on each specific case. The main challenges include ensuring safety, creating correct ways of performance evaluation, being economical, producing a solid supply chain, and good regulation and certification processes [81].

Table XI. *Key Barriers for Second Life Application of EV Batteries.* [53]

Key Barriers	***Solutions to Overcome Barriers through Melilla Project***
Complex and unknown technical procedures to better select, integrate, and operate 2nd life system in a safe and economical way	• Development of technical standards to select second-life batteries. • Definition of Test Protocol for better sorting • Definition of minimum acceptance KPI values based on classifications and the most promising applications • Definition of guidelines for system integration to guarantee safety operation (BMS VS master BMS interaction) • EVs standardization for interoperability of different systems
Lack of data about battery performance in both first and 2nd life applications	• Make available battery log data during operation Melilla system and definition of a degradation model • Implementation of an open platform to monitor data from first life use to understand the condition of the

	batteries and set the time to move in second use, in cooperation with car and battery manufacturers
Economic uncertainty about 2nd life battery value	• Identify and promote the adoption of technical features/standards suitable for application to 2nd life batteries already in the phase of EV battery production

Safety issues

Strictly speaking, the biggest problem in giving old LIBs at their end of life is safety. Safety is an issue because the LIB, at this stage, has been through very heavy usage. Proper management throughout the life cycle of the battery is needed to preclude potentially hazardous events, like a thermal runaway, which may be further fueled by side reactions during the ageing of the battery.

Performance Evaluation Techniques

An accurate assessment of retired power LIBs is needed to determine the reuse potential of the LIB. Current methods available for performing these kinds of assessments include the estimation of SOH, the prediction of Remaining Useful Life (RUL), and Electrochemical Impedance Spectroscopy (EIS). There are also differences in the performance of batteries as a result of the differences in their usage as well the production process of batteries [89].

Developing a Supply Chain

Large-scale utilization of retired LIBs for power requires a well-organized supply chain among manufacturers, government, and third-party organizations. It is important to enable recycling, dismantling, screening, reorganization, installation, and maintenance of these batteries, while ensuring safety for all such processes.

Standardization and Certification

A proper echeloning has strong but often underutilized technologies as long as there are no professional regulations and certification standards. It must be set up with rules on uniform standards for battery coding, loading, and interaction with data and comprehensive rules for development of the industry and for acquisition.

Echelon Use Cases and Economy of Repurposed Power LIBs

Echelon Utilization Scenarios for Retired Power LIBs

Retired power LIBs have broadly diverse echelon utilization scenarios, which can be divided into two general applications: static and dynamic. Static scenarios typically include energy storage systems, communication base stations, and microgrids. These uses apply the remaining capacity of the retired batteries to store energy and support communication infrastructure. Dynamic scenarios involve using retired LIBs to power low-speed vehicles such as electric bicycles, urban sanitation vehicles, and other low-speed electric vehicles.

According to convention, common applications of phased-out power LIBs are presented in a common echelon utilization mode, and satisfactory market potentials are put forward in areas that include, for example, communication base stations, low-speed EVs, energy storage stations, and renewable energy systems. The current application covers mainly two technical routes: echelon applications at the cell level and the module level.

Cell-Level Echelon Usage

It is a process by which LIB modules that are retired are deconstructed down to the cell level, which is then tested using equipment designed to test performance indicators, including capacity, internal resistance, and state of health. The cells are ranked and regrouped according to their states, and these can be for different applications. This efficiently deals with inhomogeneity at the battery module level but becomes a labor- and time-intensive process; thus, it is not really efficient in terms of economics.

Module-level utilization

This method measures the performance of entire battery modules without disassembly. The basic idea of this method is that modules are divided into classes, reordered according to performance, and applied directly to suitable scenarios. This method can reduce labor, time costs, and improve efficiency with economic benefits. With the continuous advancement of manufacturing processes of LIBs and the improvement of performance accuracy and consistency, this module-level utilization was gradually promoted to the major approach.

Echelon Utilization Economy of Retired Power LIBs

In this regard, echelons cost-benefit analysis has to be detailed to ascertain the economic viability of implementing the same for retired power LIBs [90]. Though the price of LIBs is always falling due to a reduction in raw material cost and enhancements made in process technologies and mass production, still, LIBs form a considerable percentage of the total price of Evs [52]. Business and benefit streams are also necessary to ensure that economic appraisals of projects are not just profitable but also provide confidence for the investor [91].

The economics of the previously described applications have been evaluated by several studies and models; for instance, the United States' National Renewable Energy Laboratory has modeled echelon utilization to cost $44/kWh, with the battery at $20/kWh and cascade utilization at $24/kWh [21].

Economic analysis can also not be restricted to a comparison of only the cost of the new and the retired batteries. In certain research, the results seem to suggest that retiring LIBs for residential use is not that economically feasible, although can be useful in secondary electricity markets [92]. Moreover echelon utilization may, in fact, be more advantageous to nations like Germany due to a better policy and the economic set up [90].

More extensive work is needed to model costs and benefits in a more integrated fashion across multiple application scenarios. For instance, the case of retired LIBs for stationary energy storage systems has shown that the policy landscape of Germany is likely to make such uses very impactful [52]. Governments are strongly urged to introduce policies for the purpose of incentivizing investment in echelon utilization systems [90]. The 3R principles of reduce, reuse, and recycle apply to considerations of the retired power LIB and the echelon utilization that yield environmental and economic benefits in the long term. This further reduces the dual burden of both environmental and economic consequences, which calls for a multidimensional approach to the economic consideration regarding large-scale retired LIB utilization [93].

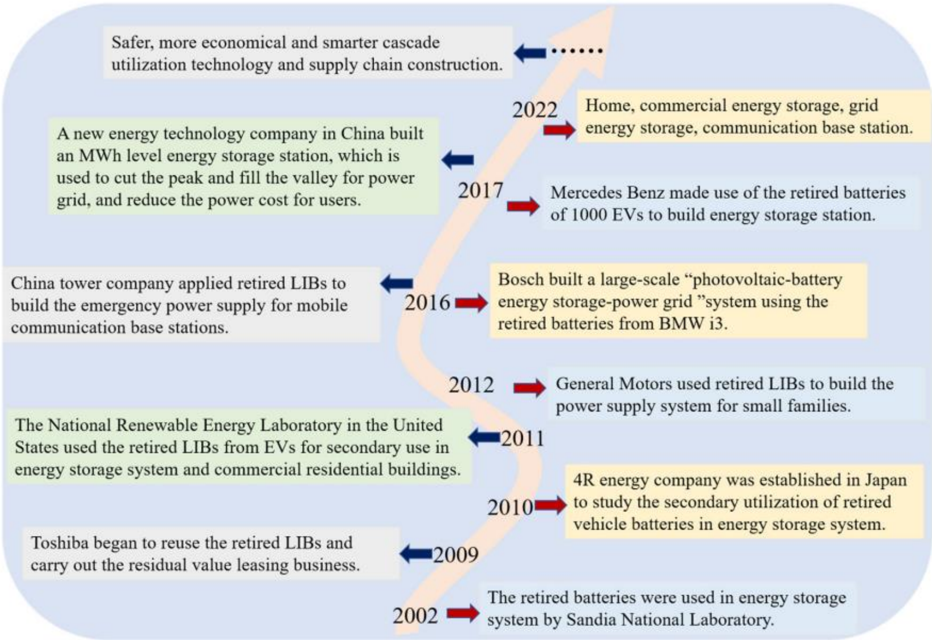

Fig. 9: EV battery Trend

The timeline in the image highlights the evolution of repurposing retired lithium-ion batteries (LIBs) from electric vehicles for secondary uses. Starting in 2002, Sandia National Laboratory utilized these batteries in energy storage systems. By 2009, Toshiba began reusing retired LIBs and exploring residual value leasing. In 2010, Japan's 4R energy company focused on studying secondary utilization. By 2011, the National Renewable Energy Laboratory in the U.S. repurposed LIBs for energy storage and residential buildings. In 2012, General Motors used these batteries for small family power supplies. Bosch, in 2016, built a large photovoltaic-battery storage system using BMW i3 batteries, while China's tower company employed retired LIBs for mobile communication base stations. In 2017, Mercedes Benz built an energy storage station with 1,000 EV batteries. By 2022, a Chinese company constructed an MWh-level energy storage station for grid peak management, leading to advancements in home, commercial, and grid energy storage, and communication base stations. The timeline underscores ongoing advancements in safer, more economical, and smarter cascade utilization technology and supply chain construction.

Market Share on Repurposing

The market for repurposing electric vehicle (EV) batteries is rapidly expanding as the automotive and energy sectors seek sustainable solutions for battery lifecycle management. With the increasing adoption of EVs, the volume of retired lithium-ion batteries is set to rise significantly, creating a substantial opportunity for second-life applications. Repurposing these batteries not only extends their useful life but also provides a cost-effective and environmentally friendly alternative to new energy storage systems.

Several major companies are leading the charge in this market. For instance, automakers like General Motors and Mercedes-Benz have initiated projects to reuse EV batteries for residential and grid energy storage. Technology companies, such as Bosch and Toshiba, are also developing large-scale energy storage solutions using retired batteries. Additionally, research institutions and new energy companies are continuously exploring innovative ways to integrate second-life batteries into renewable energy systems and smart grid applications.

This growing market is characterized by collaborative efforts between automotive manufacturers, energy companies, and technology firms. These partnerships are crucial for advancing repurposing technologies and creating efficient supply chains for the collection, refurbishment, and redistribution of used EV batteries. As the market matures, it is expected to play a significant role in the global transition to sustainable energy solutions.

Table XII. *Activities in Second Life Application by different Companies* [94], [95], [96]

S.N.	*Company*	*Activities in Second Life Application of EV Batteries*
1	BAIC Motor Corporation Limited (China)	Partnering with startups and research institutions to repurpose EV batteries for energy storage systems.
2	China Lithium Battery	Developing second-life battery applications in renewable energy storage and industrial use.

	Technology Co., Ltd. (China)	
3	BYD Co, Ltd. (China)	Repurposing EV batteries for use in large-scale energy storage systems and grid stabilization projects.
4	BAK Power (China)	Focusing on second-life applications in stationary energy storage and small-scale commercial uses.
5	CALT (China)	Engaging in research and pilot projects for reusing EV batteries in residential and commercial energy storage solutions.
6	Samsung SDI Co., Ltd (South Korea)	Utilizing second-life EV batteries in renewable energy projects and commercial energy storage systems.
7	LG Chem Ltd. (South Korea)	Implementing second-life battery solutions in grid energy storage and renewable energy integration projects.
8	4Renergy (Japan)	Joint venture with Nissan, focusing on repurposing used EV batteries for energy storage systems and industrial applications.
9	Toyota Motor Corporation (Japan)	Recycling and reusing EV batteries in energy storage systems for buildings and renewable energy projects.
10	Global Battery Solutions, Ltd. (U.S.)	Specializing in the refurbishment and repurposing of EV batteries for various second-life applications, including energy storage.
11	Daimler AG (Germany)	Converting used EV batteries into stationary energy storage units for renewable energy integration and grid support.

12	Groupe PSA (France)	Exploring second-life battery uses in home energy storage systems and renewable energy projects.
13	Groupe Renault (France)	Using second-life batteries in large-scale energy storage solutions, including grid applications and renewable energy projects.
14	Spiers New Technologies (U.K.)	Providing refurbishment and repurposing services for EV batteries to be used in energy storage and other second-life applications.

Table XIII.*Companies performing Repurposing* [43]

S.N.	*Manufacturer*	*Location*
1	Tesla, Inc.	United States
2	Lithium Recycling Inc.	Canada
3	24M Technologies	United States
4	Accure Battery Intelligence GmbH	Germany
5	Aceleron Ltd.	United Kingdom
6	Sunnova Energy International Inc.	United States
7	A123 Systems LLC	United States
8	Relectrify Pty Ltd.	Australia
9	Battery Resourcers LLC	United States
10	Lithium Werks B.V.	Netherlands
11	ReVolt Technology	Norway
12	Battery Energy Storage Systems (BESS)	United States
13	Fortum Corporation	Finland

14	NexWafe GmbH	Germany
15	Li-Cycle Corp.	Canada

Recycling

Recycling is the process of collecting, processing, and repurposing waste materials into new products to prevent the excessive consumption of fresh raw materials, reduce energy usage, and mitigate environmental pollution. This practice plays a pivotal role in conserving natural resources and minimizing the ecological footprint of industrial activities.

In the context of electric vehicle (EV) batteries, recycling involves the recovery and reuse of valuable components from spent batteries. EV batteries, primarily lithium-ion batteries, contain materials such as lithium, cobalt, nickel, and manganese, which are essential for their performance and longevity. These materials are not only costly but also finite, with their extraction posing significant environmental and social challenges.

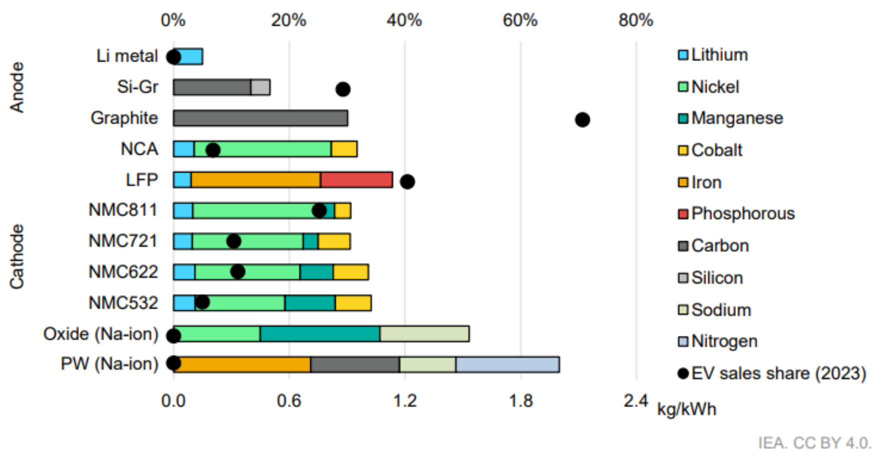

Fig. 10: Material content in Anodes and Cathodes, by chemistry, 2023 [19]

This chart illustrates the composition of various battery chemistries used in electric vehicles (EVs), highlighting the percentages of different materials within the anode and cathode components. The anode materials include lithium metal, silicon-graphite (Si-Gr), and graphite, while the cathode materials comprise NCA (nickel-cobalt-aluminium), LFP (lithium iron phosphate), NMC (nickel-manganese-cobalt) in various ratios (811, 721, 622, 532), as well as sodium-ion variants (oxide and PW). Each material's proportion is represented by coloured bars indicating the presence of elements like lithium, nickel, manganese, cobalt, iron, phosphorous, carbon, silicon, sodium, and nitrogen. The black dots on the chart indicate the EV sales share in 2023, demonstrating the market penetration of each battery type. The chart provides a detailed overview of the material composition and market share of different battery technologies used in EVs.

The most popular batteries used in the present EV market are LFP (Lithium Iron Phosphate) and graphite-based batteries. LFP batteries are composed primarily of lithium, iron, and phosphorous. These materials make LFP batteries safer and more stable, offering longer life cycles and enhanced thermal stability compared to other chemistries. From LFP batteries, key materials such as lithium, iron, and phosphorous can be efficiently extracted and repurposed.

Graphite-based batteries, predominantly used in anodes, are composed mainly of carbon. Graphite is favoured for its excellent electrical conductivity and stability during charge and discharge cycles. The extraction potential from graphite anodes is primarily focused on carbon, which can be reused in various applications, including new battery production. Both LFP and graphite-based batteries play a crucial role in the current EV market due to their advantageous properties and the recyclability of their constituent materials.

By recycling EV batteries, we can achieve several critical objectives:

1. **Resource Conservation**: Recycling enables the recovery of precious metals and minerals from used batteries, reducing the need for new mining activities. This conserves natural resources and helps maintain a sustainable supply of raw materials for future battery production.
2. **Environmental Protection**: Proper recycling processes prevent hazardous materials in batteries from contaminating soil and water, thereby protecting ecosystems and human health. It also reduces the greenhouse gas emissions associated with the extraction and processing of new materials.

3. **Economic Benefits**: The recycled materials from EV batteries can be reintroduced into the manufacturing cycle, reducing the cost of producing new batteries. This can make EVs more affordable and accelerate their adoption.

4. **Waste Reduction**: Recycling helps manage the growing volume of battery waste resulting from the increasing number of EVs reaching the end of their lifecycle. This reduces the burden on landfills and promotes a circular economy where materials are continually reused.

For batteries with a SoH between 50% and 60%, the next step is recycling [35]. Recycling involves the extraction of valuable materials from the batteries for use in new products. The recycling process is essential for recovering valuable metals and materials that can be reused in the production of new batteries or other products, thereby contributing to resource efficiency and environmental sustainability. Batteries that do not meet the criteria for remanufacturing or repurposing are also discarded and sent for recycling, ensuring that no valuable materials are wasted.

The decision-making criterion for the end-of-life processing of LIBs is primarily based on the SoH. Various techniques for estimating SoH and processing methods for remanufacturing, reusing, and recycling are detailed in the subsequent sections of the source material [89]. These techniques ensure that a judicious decision is made regarding the end-of-life processing of LIBs, optimizing their value recovery and sustainability.

The systematic approach to managing end-of-life lithium-ion batteries involves a hierarchical processing method where batteries are first considered for remanufacturing, then for repurposing, and finally for recycling based on their SoH [35]. This approach not only helps in efficiently managing end-of-life LIBs but also significantly reduces waste and recovers valuable materials, thereby contributing to environmental sustainability and resource efficiency. The detailed examination of SoH and the adoption of appropriate processing techniques ensure that the maximum value is extracted from these batteries, aligning with sustainable practices and the circular economy model.

Recycling methods of LIBs employed in EoL include pyrometallurgy, hydrometallurgy, and bioleaching. Pyrometallurgy refers to the extraction of metals at high temperature whereas hydrometallurgy refers to chemical leachings, and bioleaching refers to the use of biological agents for the extraction of metals. Pyrometallurgy has been widely researched and developed in Europe, America as well as Japan. Argonne National Laboratory has recorded studies of the EV battery life cycle value since 1996 [97], Sandia National Laboratory since 2002 has focused on the use of retired batteries in energy storage systems [98], and Toshiba and Japan's 4R Energy Corporation have since 2010 researched reusing retired LIBs as well as secondary battery usage [98], [99].

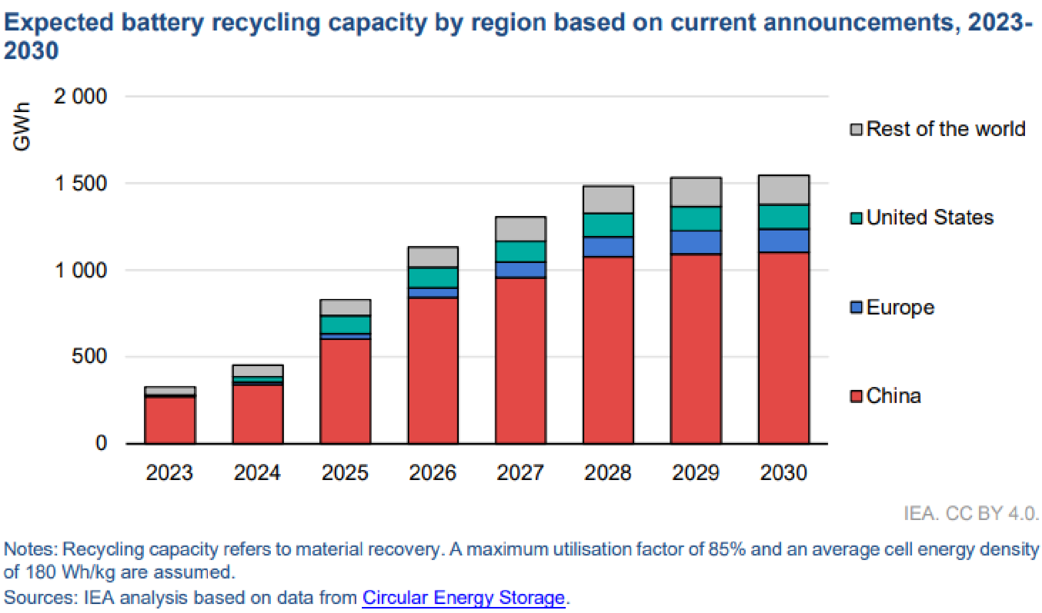

Fig. 11: Forecast on Battery Recycling Capacity till 2030 [19]

The figure 11 represets the forecast by IEA on the recycling capacity installation by country. It is expected that China will be leading the recycling business by huge share by 2030 and recycling capacity will increase significantly by 2030.

Terminology in Recycling

- **Closed-Loop Recycling:** The material attained is utilized for the manufacturing of the same product. However, the deficit lies in the understanding of remanufacturing techniques and the quality of resynthesized cathode materials.

- **Open-Loop Recycling:** Materials that are recovered as inputs in other product systems, in the case of functional recycling; or when recovered metal is not suitable for its original purpose, in the case of nonfunctional recycling.
- **Collection Rate:** Proportion of EoL products that are collected and enter the recycling chain.
- **Recovery Rate/Process Efficiency Rate:** Proportion of collected material recovered in usable form.
- **EoL Recycling Rate:** Proportion of all EoL product material recovered by recycling, dependent on both process efficiency and collection rate.
- **Recycled Content:** Fraction of a product's manufacturing inputs that are recycled as opposed to virgin material.

Steps Involved in Recycling

- **Collection and Transportation**: Used EV batteries are collected from various sources, including end-of-life vehicles, scrap yards, and battery replacement centers. They are then safely transported to recycling facilities, following strict regulations to prevent accidents and leaks.
- **Discharge**: To ensure safety, the batteries are fully discharged to eliminate any residual charge. This step is crucial to prevent any short circuits or potential fires during the recycling process.
- **Dismantling**: The batteries are manually or mechanically dismantled to separate different components such as modules, cells, casings, and wiring. This step allows for the efficient sorting and processing of various materials.
- **Shredding and Crushing**: The dismantled battery components are shredded and crushed into smaller pieces. This mechanical process breaks down the battery into a mixture of materials, facilitating further separation.
- **Separation**: Advanced separation techniques such as magnetic separation, sieving, and flotation are used to separate different materials like metals, plastics, and electrolytes. This step ensures the effective recovery of valuable components.

- **Chemical Processing**: The separated materials undergo chemical processing to extract valuable metals like lithium, cobalt, nickel, and manganese. Techniques such as hydrometallurgical and pyrometallurgical processes are commonly used for this purpose.
- **Purification**: The extracted metals are purified to achieve the required quality and purity levels. This step is essential for reintroducing the recovered materials into the manufacturing supply chain.
- **Reintegration into Supply Chain**: The purified metals and other recovered materials are reintegrated into the supply chain for the production of new batteries or other applications, thus promoting a circular economy and reducing the need for virgin raw materials.

Processes Involved in Recycling

Collection and Dismantling

The battery packs are discharged and dismantled down to the module level. These are then treated through mechanical pre-treatment or pyrometallurgy and usually through hydrometallurgical treatment to recover cobalt, nickel, aluminum, copper, and steel [19]. There is a system of batteries taken back at the end of life by the manufacturing company.

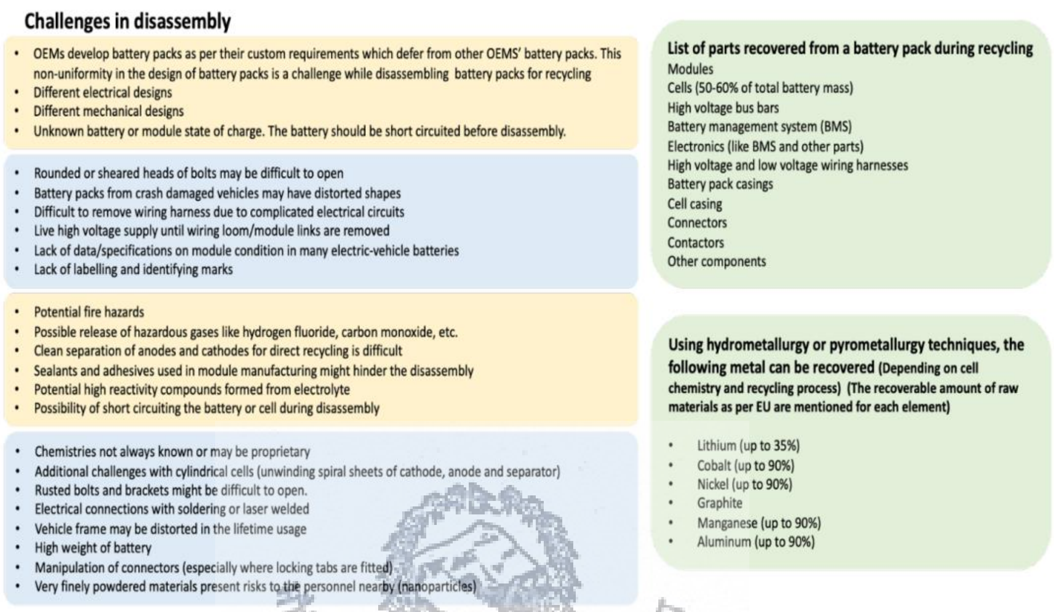

Fig. 12: Battery Disassembly challenges for recycling, by Kapil Baidya, Tata Motors [100].

Mechanical Pre-Treatment

Batteries are put through a shredder, and the contents are segregated by adding a fluff stream, metal enriched liquid, and metals solids thereby, allowing the facility to harvest copper, aluminium, steel casings and a 'black mass' that needs to be further processed by metallurgcal processes.

Material Treatment Processes

Mechanical treatment process involves pyromatallurgy, hydrometallurgy, direct recycling which is explained below.

Table XIV. *Recycling Process for EV batteries*

Recycling Method	***Process Description***
Pyrometallurgy	Smelting of spent batteries
Hydrometallurgy	Complete or selective dissolution of spent batteries
Direct Recycling	Recover and restore cathodic material for direct use in new batteries

Pyrometallurgical Recycling

The high-temperature recovery step typically produces a concentrated alloy of cobalt, nickel, and copper, with lithium and manganese ending in slag that may be useful for construction or further processing to recover lithium [101]. The method is efficient and fast but very energy intense and with the mentioned potential losses of lithium [102].

Advantages:

- Pyrometallurgy is adaptable to any type of battery chemistry and configuration [103].
- It does not require sorting or other mechanical pre-treatment steps [104].
- It achieves high recovery rates for metals such as cobalt, nickel, and copper [105].
- This is a well-established and proven technology that can be implemented in existing facilities [106].

Disadvantages:

- It is unable to recycle lithium, aluminum, or organic materials [107].
- It cannot process lithium iron phosphate (LFP) batteries [108].
- The process requires expensive gas clean-up to prevent toxic air emissions [109].
- Pyrometallurgy is energy-intensive and requires significant capital investment [110].
- Additional refinement is needed to separate elemental metals from the metal alloys produced during smelting [111].

Hydrometallurgical Recycling

In this type of chemical process, leaching is satisfied by acid leaching, alkali leaching, and organic solvent dissolution to eliminate impurities and precipitate the valuable metals [112]. The experimental methods are: the methods of ethanol and sulphuric acid to recover lithium and cobalt; an ammonia leaching system to recover cobalt and copper; and formic acid to recover lithium carbonate (Li2CO3) with recuperation close to 100% [113], [114], [115].

Advantages:

- This method is suitable for any battery chemistry and configuration [116].
- It allows for flexible separation and recovery processes targeting specific metals [46].
- Hydrometallurgy can achieve h
- igh recovery rates, especially for lithium [107], [108].
- It produces high-purity products that are suitable for making new cathode materials [109].
- The process is energy-efficient and produces no air emissions [107], [108].

Disadvantages:

- Battery cells need to be crushed, posing safety concerns [44].
- The use of acid breaks down the cathode structure [117].
- There is a high volume of process effluents that need treatment and disposal [118].
- Hydrometallurgy is not cost-effective for LFP batteries [119], [120].
- It does not recover anode materials such as graphite and conductive additives [121].

Direct Anode Recycling

This is a procedure combing processes in order to recover cathode materials for their direct re-use in battery manufacture. Work in this area is spearheaded by research at the ReCell Center located at Argonne National Laboratory with a focus on creating sustainable and efficient recycling methods [122].

It is the integration of advanced recycling technologies, digital tracking, and approaching them on a systematic basis to the life cycle of LIBs that lay at the core of sustainable management of batteries [123], [124]. This way, among other things, the industry has a chance to improve its methodology of recycling and strategy aimed at the diminishing of negative environmental impacts and at the economic benefits, rendering it relevant on the way to sustainability [125].

Advantages:

- Direct recycling retains the valuable structure of the anode [48].
- Almost all battery materials, including the anode, electrolyte, and foils, can be recovered [49].
- This method is suitab+le for recycling LFP batteries [126], [127].
- It is energy-efficient and convenient for recycling manufacturing scraps [126].

Disadvantages:

- The process requires complex mechanical pre-treatment and separation steps [128].

- The recovered materials may not perform as well as new materials and may become outdated by the time they reach the market [129].
- Mixing different cathode materials could reduce the value of the recycled product [130].
- Regeneration processes for direct recycling are still under development [51].
- The method has not yet been scaled up to an industrial level [131].

EV Batteries Recycling Market Share

Table XV. *Top Li-ion Recycling Companies 2023* [132]

No.	*Company Name*	*Activities*
1	American Battery Technology Company	Focuses on lithium-ion battery recycling, extraction of battery metals, and materials manufacturing.
2	American Manganese Inc. (RecycLiCo Battery Materials Inc.)	Specializes in recycling lithium-ion battery cathode materials.
3	Ecobat	Engages in recycling, refining, and producing lead and lead alloys, including lithium-ion batteries.
4	Ganfeng Lithium Group Co., Ltd.	Integrates lithium resource development, refining, and battery manufacturing.
5	LG Energy Solution Ltd.	Develops and manufactures lithium-ion batteries and focuses on recycling initiatives.
6	Li-Cycle Holdings Corp.	Provides sustainable lithium-ion battery recycling solutions and resource recovery.
7	Lithion Recycling Inc. (Lithion Technologies)	Specializes in advanced battery recycling technologies for lithium-ion batteries.

8	Redwood Materials, Inc.	Recycles end-of-life batteries and manufacturing scrap to recover materials.
9	Retriev Technologies, Inc. (Cirba Solutions)	Offers battery recycling services for various battery chemistries, including lithium-ion.
10	Umicore N.V.	Engages in materials technology and recycling, focusing on battery recycling and recovery of precious metals.

The table provides a comprehensive overview of various companies engaged in the battery recycling and materials manufacturing industry. It lists key players and summarizes their main activities. For example, the American Battery Technology Company focuses on lithium-ion battery recycling, extraction of battery metals, and materials manufacturing. Ecobat is involved in recycling, refining, and producing lead and lead alloys, including lithium-ion batteries. Li-Cycle Holdings Corp. offers sustainable lithium-ion battery recycling solutions and resource recovery. Redwood Materials, Inc. specializes in recycling end-of-life batteries and manufacturing scrap to recover valuable materials. Umicore N.V. is known for its expertise in materials technology and recycling, particularly in battery recycling and the recovery of precious metals. This table serves as a useful resource for understanding the significant players in the battery recycling sector and their specific areas of expertise.

Table XVI. *Some other companies performing Recycling for EV Batteries*

S.N.	*Manufacturer*	*Location*
1	Battery Solutions LLC	United States
2	Gopher Resource LLC	United States
3	Ecobat Logistics	United Kingdom
4	Terrapure BR Ltd.	Canada
5	East Penn Manufacturing Company	United States
6	Retriev Technologies	United States
7	COM2 Recycling Solutions	United States
8	Call2Recycle	United States
9	Exide Technologies	United States
10	Gravita India Ltd.	India

Maufacturers Performing Recycling, Reusing, and Repurposing [132]

Second Life EV Batteries Ltd

Second Life EV Batteries Ltd focuses on extending the life of used electric car batteries by repurposing them for new applications. They handle batteries from various manufacturers, including Tesla, BMW, and Nissan. Their ethos is centered around reuse, recycle, and repurpose, aiming to reduce waste and promote sustainability.

American Battery Technology Company

Based in Reno, Nevada, USA, and established in 2011, American Battery Technology Company is at the forefront of lithium-ion battery recycling. They use innovative methods to extract and remanufacture critical materials from used batteries, thus supporting a closed-loop economy. Their work not only reduces environmental impact but also addresses supply chain issues for battery materials.

American Manganese Inc. (RecycLiCo Battery Materials Inc.)

Established in 1987 and based in Surrey, BC, Canada, American Manganese, now known as RecycLiCo Battery Materials Inc., specializes in the recycling of lithium-ion batteries through its patented RecycLiCo process. This technology allows them to efficiently recover valuable materials such as lithium, cobalt, and nickel from spent batteries, which are then used to produce new batteries. They focus on recycling 99% of cathode metals from lithium-ion battery scrap and upcycling materials to battery-ready materials with high purity.

Ecobat

Founded in 1994 and based in Dallas, Texas, USA, Ecobat is a global leader in battery recycling, offering services for a variety of battery types, including lithium-ion. They focus on creating a sustainable cycle by recovering and reprocessing battery materials, thereby reducing environmental impact and conserving natural resources. Their services include collection and recycling management of lithium batteries, crushing and sorting capabilities, and advanced diagnostics and engineering for EV batteries and modules.

Tesla

Tesla is not only a leading manufacturer of electric vehicles but also actively involved in the recycling and remanufacturing of their EV batteries. They work on recovering critical materials from used batteries to produce new ones, aiming to minimize waste and ensure a sustainable supply of battery materials.

BMW and Volkswagen (VW)

Both BMW and VW are engaged in the repurposing and remanufacturing of used EV batteries. They are exploring ways to reuse these batteries for stationary energy storage solutions and other applications, thus extending the lifecycle of the batteries and reducing environmental impact.

Panasonic (Tesla Battery Supplier)

Panasonic, a major supplier of batteries to Tesla, is involved in the recycling of EV batteries. They extract precious minerals like lithium, nickel, and cobalt from used batteries and remanufacture these materials into new battery components, supporting a sustainable battery supply chain.

Rematec

Rematec provides insights into the latest technologies and trends in battery remanufacturing. They highlight advancements in battery health monitoring and longevity, which are crucial for effective remanufacturing processes.

Ganfeng Lithium Group Co., Ltd.

Based in Xinyu, Jiangxi, China, and founded in 2000, Ganfeng Lithium Group Co., Ltd. specializes in lithium battery manufacturing and recycling, metallic lithium smelting, and resource mining. They focus on compound deep processing and the recycling of lithium batteries.

LG Energy Solution Ltd.

Established in 2020 and based in Seoul, South Korea, LG Energy Solution Ltd. has a closed-loop system for collecting and recycling non-reusable batteries and scraps. They engage in joint ventures for battery recycling plants and have developed a battery reuse process.

Li-Cycle Holdings Corp.

Founded in 2016 and based in Toronto, Ontario, Canada, Li-Cycle Holdings Corp. specializes in closed-loop resource recovery, logistics management, battery identification and consulting, EV packaging for transport, on-site services, and customized customer programs.

Lithion Recycling Inc.

Based in Montreal, Québec, Canada, and founded in 2018, Lithion Recycling Inc. focuses on the recovery of lithium-ion battery components and the regeneration of materials for new chargeable battery manufacturing. They process all types of lithium-ion batteries and are constructing a critical minerals extraction plant.

Redwood Materials, Inc.

Founded in 2017 and based in Carson City, Nevada, USA, Redwood Materials, Inc. specializes in the collection, refurbishment, recycling, refining, and remanufacturing of batteries. They aim to create a circular supply chain for end-of-life batteries and recover key battery elements for reuse in new batteries.

Retriev Technologies, Inc. (Cirba Solutions)

Based in Ohio, USA, and established in 1984, Retriev Technologies, now part of Cirba Solutions, uses a patented hydrometallurgical process for battery management and recycling. They offer comprehensive EV battery recycling services.

Umicore N.V.

Established in 1989 and based in Brussels, Belgium, Umicore N.V. is a circular materials technology company providing advanced battery recycling solutions. They focus on the recovery of cobalt, lithium, and nickel from battery materials and have launched Battery Recycling Solutions.

EoL Forecasting by Koroma

Koroma analysed the EoL of EV batteries in three scenario as mentioned in figure and forecasted the end life on ev batteries in four different stages.

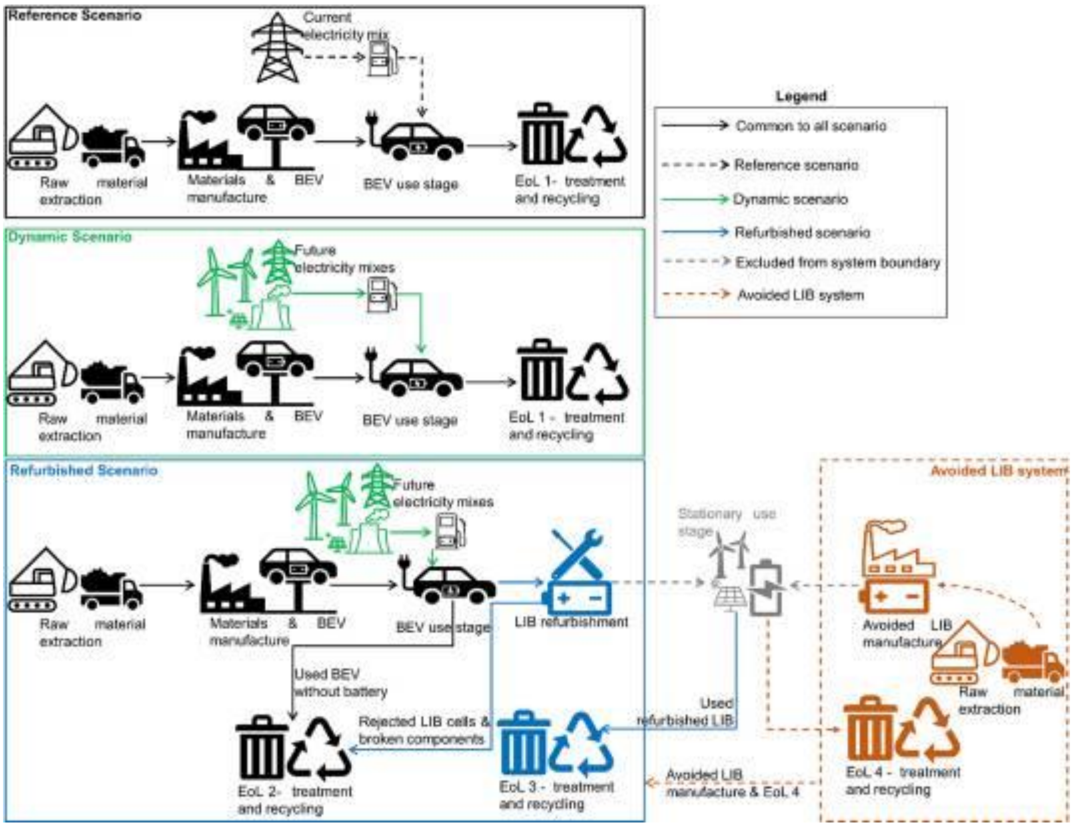

Fig. 13: EoL scenario for after-life of battery by Koroma [133]

For the new batteries in 2023, EoL is assumed that the entire battery electric vehicle (BEV) and its components reach the end of life, including the glider, e-drive, LIB cells, LIB pack, BMS, cooling system, and packaging by 2031. This comprehensive approach ensures all parts are addressed, but it can be costly and environmentally impactful due to the extensive resources required for disposal or recycling.

EoL1

By 2031, EoL1 will focus on refurbishing the vehicle and its battery components, particularly addressing rejected cells and components. It includes the glider, e-drive, LIB cells (50% recycled, 50% refurbished), LIB pack, BMS, cooling system, and packaging (50% recycled, 50% reused). This model reduces waste and environmental impact but involves complex logistics and quality control for refurbished components.

EoL2

By 2036, EoL2 emphasizes the recycled LIB cells from the previous refurbishment stage, including the remaining 50% of LIB cells, LIB pack, BMS, cooling system, and packaging (recycled). This continues the lifecycle extension and further reduces waste, although delayed recycling could lead to storage challenges.

EoL3

Finally, in 2041, EoL3 envisions that 100% of the avoided LIB cells are recycled, including the LIB cells, LIB pack, BMS, cooling system, and packaging. This model aims for maximum recycling and minimal waste, representing an ideal sustainable scenario, but the feasibility of achieving 100% recycling depends on advancements in technology and economic viability.

Disposal of EV Batteries

The disposal process of EV batteries, on the other hand, is not an easy task and brings with it severe consequences both environmentally and economically. Proper methods of disposal are integral as they offer risk mitigation from hazardous materials, help prevent environmental contamination, and also ensure public safety. This section delves deeper into the complexities surrounding safe disposal practices for EV batteries, the processes involved, the challenges faced, and potential solutions.

Hazardous Nature of EV Batteries

The batteries of EV are mainly lithium-ion (Li-ion) and contain various dangerous materials that may be potentially risky if not appropriately handled:

Toxic Metals: Cobalt, Nickel, and Manganese are elemental constituents conventionally and are commonly found in an EV battery; these can also leach into the ground and water sources and introduce serious environmental and health risks [134].

These also are toxic to humans and animals alike and are known to have long-term ecological impacts [47].

Electrolytes: Electrolytes in Li-ion batteries primarily consist of flammable and toxic solvents. In case of damage or misuse, the latter can catch fire, leading to fire and explosion incidents [135].

Residual Voltage: Even after becoming unserviceable, EV batteries can attain a high voltage due to residual voltage. This residual voltage forms the risk of electric shock and short circuits from handling and disposal [47].

Safe Disposal Methods

Safe disposal methods of EV batteries include a series of steps to be taken from the neutralization of harmful materials to the recovery of reusable valuable components [136].

Sectioning and Dismantling

Discharge Processes Electrical Discharge

Battery, before being disassembled, are still demand and left to charge fully to reduce the risk of electric shock and short-circuiting. The battery should be discharged safely at its voltage level, which is safe to handle. Controlled electrical discharge methods ensure that the batteries are de-energized without causing any damage to the cells, hence safer if they are to be dismantled and recycled [48], [125], [126].

Discharge in Salt Water: In this method, the battery can be submerged in saltwater to be discharged safely. The process has proven to be very effective; however, it will cause high corrosion and contamination of other materials and, therefore, is less desirable compared to controlled electrical discharge. Usually, the saltwater route is left as a last and highly undesirable option if no other mechanisms are plausible.

Manual Dismantling

The primary step in this process is manual dismantling to separate batteries into various components, followed by battery cells, casing, and electronic control units. This process involves experienced personnel who safely handle the batteries to avoid increased risks of short-circuiting and exposure to harmful materials. This process needs to be cautiously separated to ensure proper processing of the individual parts.

Robotic Assistance: Automated systems, including robots, assist in the taking apart, mainly in repetitive and dangerous methods such as unscrewing battery modules and their separation. The robots will improve safety and productivity by performing in an environment and on a hazardous or monotonous task for human workers. These systems are necessarily designed to care for batteries softly to avoid damage and possible dangers.

Safe Disposal of Residual Waste

Neutralization

Any residual hazardous reagents, e.g., acids or alkalis from the recycling process, are neutralized so that they can be safely disposed of. This is achieved by chemical reactions to change the harmful substances into non-harmful ones [134].

Landfills and Incineration

Safe landfilling or incineration of non-recyclable pieces and neutralized waste are done strictly under controlled conditions, according to rigorous environmental guidelines. Land disposal facilities for hazardous waste are designed with improved containment systems to prevent the escape of toxicants into the environment. Similarly, incineration units, if properly equipped with advanced pollution control features, ensure that the waste material is burnt safely without releasing harmful emissions into the atmosphere [134].

Safe Disposal Challenges

It is technically complex to safely dispose of electric vehicle batteries because they are designed using multiple materials and tight integration, making both safe disassembly and safe recycling considerably hard. Often, the complexity involved means there is usually a need for special equipment along with techniques to manage them. For example, advanced robotics and automation can make the process safer and more effective, but this demands a high level of investment in technology and training [47].

Procedure for disassembly of retired EV battery packs

The first step in handling retired battery packs as a crucial process known as "disassembly process". While there are rare case where old batteries can reusable as complete unit without disassembly. A common standard procedure for disassembly and reorganizing their components are [137]:

- Disconnecting both electrical and mechanical connection among the batteries
- Disconnecting coolant supply through battery
- Opening the battery pack casing
- Removing auxiliary electronic components
- Afterward proceed inspection process.

The disassembly process timeframe is depend upon the available workforce , the types of work to be done etc and disassembly timeframe reduce by introducing automation into the process and to prevent cathode oxidation, it is vital to carry out the battery pack disassembly in a controlled environment in less contact with atmosphere.

Retired battery packs come in three primary types: cylindrical, prismatic, and pouch-shaped batteries. Among these, cylindrical batteries pose the greatest disassembly challenge due to their structure, which consists of a single unit with a separator between the cathode and anode, This design makes them more complex to disassemble when compared with the other two battery types. Prismatic batteries, on the contrary, have a larger cathode, anode, and separator, rolled and compressed into a flat cubic shape. This particular configuration makes them the easiest to disassemble among the three battery types; Pouch-shaped batteries, typically formed by adhering four batteries together into a module, are also easier to disassemble than cylindrical batteries [47].

Due to the absence of standardized specifications and configurations for retired battery packs and modules, the disassembly of battery equipment is done by skilled technician. Given the high voltage associated with battery packs, the disassembly procedure poses inherent hazards. So that the introduction automation or robot-assisted battery disassembly process may reduce the chance of accident happened [76]. CHOUX has developed a robot disassembly task planner specifically designed for dismantling LIBs of Evs [76]. The goal is to improve the system's versatility and stability, thereby optimizing the efficiency of the disassembly process. The designed task scheme has undergone validation through laboratory tests, with a focus on an Audi A3 Sportback hybrid lithium-ion battery pack. The results demonstrate that the measurement error associated with this method is less than 5 mm [47].

Virtual disassembly enables the simulation of the disassembly process by utilizing data pertaining to device configuration, components, connections, weight, and materials. Another innovative technology for battery disassembly involves cloud networking. This approach collects field data from the internet and orchestrates the disassembly process based on cloud-driven discoveries. Some researchers have introduced a framework for automated Electrochemical Impedance Spectroscopy (EIS) data collection using robotic arms. This framework minimizes health and safety risks associated with LIBs by reducing human intervention during the data collection process [76]. For further progress, collaboration between vehicle and battery manufacturers is needed. Together, they should work towards developing standardized, universally applicable, easy-to-assemble-and-disassemble design solutions that are safely and carefully useful for echelon utilization [76], [134].

Case Studies of Current Practices

Example: KERUI Machine Process [138]

After the battery disposal by consumer safely to the recycler company after that further procedure applied to recycle the disposal battery which is described below:

Many recycler company used automation technology machine to complete further recycle process like KERUI Machinery lithium battery recycling machine which is capable of recycling various type of lithium battery including soft package battery, cell phone battery, cylindrical battery etc. So this machine has its own unique procedure to be followed step by step to recycle LIBs now let's discussed the KERUI machine process:

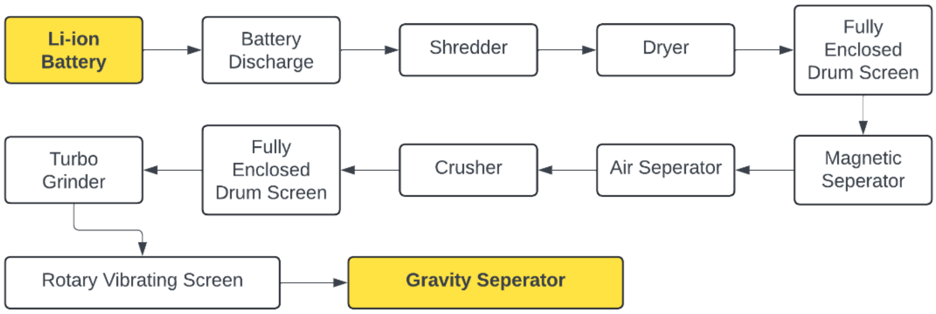

Fig. 14: KERUI machine process [138].

First step all the lithium ion batteries are placed on conveyor belt of machine after that further process proceed step by step shown below:

Fig. 15: All lithium ion batteries placed on conveyor belt. [139]

- **Discharge process**: By immersing lithium battery into saline solution to convert battery from charged state to completely discharge state because further process are crushing , shredding etc so that to prevent from any accident like spark , explosion etc.

Fig. 16: Charged battery immersed in saline solution for discharge process [139].

- **Shredder:** it converts lithium batteries into small pieces.

Fig. 17: Transform batteries into small pieces for further process [139].

- **Dryer:** In this process moisture is remove from lithium battery soaked during discharge.
- **Crusher:** Again crushes the lithium battery small piece into smaller pieces.
- **Turbo Grinder:** In this process convert small piece of lithium battery into tiny particle for further process effortlessly.

- **Air separator:** In this process the plastic are separates from lithium batteries.
- **Fully enclosed drum screen:** From this process most of the black mass screen out which is known as new gold it is most valuable resource to manufacture new battery.
- **Gravity separator:** In this process separates metal such as copper and aluminum present in lithium batteries.
- **Magnetic separator:** In this process the iron separates from lithium batteries.

The final product out after KERUI process is shown in figure below:

Fig. 18: Final product out after Kerui process [138]

After extracting the main resource from the disposal batteries the important resources transport to the Batteries manufacturing plant for manufacture new battery.

Industry Landscape

Current State of LIB Recycling Industry

- **Development Background**: The lithium-ion battery (LIB) recycling industry originally focused on consumer electronics, primarily in China and South Korea. Pilot and commercial facilities are also emerging in Europe, North America, and Canada, although many are not yet operating at full capacity.
- **Global Expansion**: The recycling industry is expanding globally in response to increased EV demand and anticipated EV battery retirements.

- **Feedstock Sources**: Currently, consumer electronics and battery manufacturing scrap are the main sources of feedstock for recycling. However, retired EV batteries are expected to become the primary source in the future.
- **North American Market**:
    - **Operational Facilities**: Companies like Interco and Redwood Materials produce battery-grade materials for new batteries.
    - **Pretreatment Specialists**: Companies such as Li-Cycle and Cirba Solutions specialize in pretreatment, producing 'black mass' for further refining.
    - **Expansion Plans**: There are plans to expand operations to produce battery-grade materials in the U.S., with new plants expected to be operational in 2023.

Policies Affecting End-of-Life (EoL) of EV Batteries

- **Policy Objectives**: EoL policies can drive design and manufacturing changes, promote reuse and remanufacturing, and support recycling. Policies often designate responsible parties for proper disposal and can focus on producers or consumers.
- **Extended Producer Responsibility (EPR)**: Commonly used to hold producers accountable for the costs and logistics of battery collection and disposal, encouraging them to plan for EoL during the design phase.
- **Landfill Bans**: Place responsibility on consumers, with the government creating disposal pathways.
- **Design for Recycling (DfR)**: Policies may encourage producers to implement changes that reduce costs and increase safety in disassembly, remanufacturing, and recycling.
- **Government Grants**: Used to boost recycling and repurposing industries through research and development, aiming to make recycling more economically viable.

Regional Policy

European Union (EU)

There have been several policies that the EU has put forward to regulate sustainability in the battery lifecycle. The Battery Directive (2006/66/EC) mandates that the producer must pay for the collection, transportation, and recycling of the batteries. Initially, it targeted nickel-cadmium and lead-acid batteries and states that 50% of the weight of the battery must be recycled. The new European Battery Regulation (2020) is to create the battery material circular economy in order to reduce dependencies and enhance the manufacturing of batteries. However, for that to be done, the requirements are set for the recycled material content, supply chain impact, digital passport for batteries, and concept in the extended producer responsibility. Furthermore, the European Battery Alliance sets in motion impetus to stimulate sustainable industry practice with respect to the increasing use of lithium-ion batteries and the creation of Battery Passport for end-of-life management.

China

Among others are the Promotion Plan for Extended Producer Responsibility System (2016), which provides for developing a recycling system formulating a policy on extended producer responsibility. A trial recycling operation of electric vehicles in 17 cities/regions to enhance existing facility structures. The establishment of the battery traceability management to achieve monitoring of electric vehicle batteries. The Interim Measures for the Management of Recycling and Utilization of Power Batteries (2018) require manufacturers to collaborate with recycling companies and practice design for recycling.

United States

United States does not have any national policy and the market-based approach is backed by grants for research, development, and demonstration in recycling and repurposing. In the Bipartisan Infrastructure Law 2021, there was an allocation of funds, out of which, currently, ten projects regarding battery EOL processing are being done, getting $73.9 million amount for repurposing batteries for EV charging and technological up-gradation for recycling of battery material. Battery related regulations: Battery Act (1996): The Battery Act prescribes that the states should manage disposal of any and all kind of batteries according to federal Universal Waste regulations. U.S. Department of Transportation Regulations: This prescribes the shipment of live and/or discharged lithium-ion batteries.

State Level EoL Lithium-Ion Requirements in the U.S.

A few states such as New York, Minnesota, and New Jersey have their own enacted EoL requirements for Li-Ion batteries with the EPR principles, but some enacted state-level laws have problems, like the poor reporting and enforcement system, so the recycling rate maybe low. California is considering comprehensive policies since they are leading in the adaptation to EVs. In March 2022, the California Lithium-ion Battery Advisory Group issued recommendations for potential policies to enhance recycling of EV batteries. Senate Bill 615 by Senator Allen would implement the recommendations. There are innumerable regulations in California related to innumerable activities of regard on disposal of Li-ion batteries on federal and state code and standards from different organizations. Some key regulatory bodies include the CFR, CPUC, CCR, IEEE, NFPA, OSHA, RCRA, and UL.

Environmental Impact Analysis

Lithium-ion batteries, which are predominant in EVs, pose significant environmental challenges at the end of their life. Effective management practices can mitigate negative impacts and recover valuable materials.

Afterlife Battery Management Practices

Repurposing (Second-life Applications)

Repurposing involves using EV batteries in secondary applications once they no longer meet the performance requirements for vehicle propulsion. Common second-life applications include energy storage systems (ESS) for residential, commercial, and grid stabilization purposes.

Environmental Impact:

- Material Recovery Rates: Repurposing does not recover materials immediately but extends the battery's useful life, delaying recycling or disposal.

- Energy Consumption: Lower energy consumption compared to manufacturing new batteries; refurbishment and integration processes consume energy but significantly less than producing new batteries.
- Greenhouse Gas Emissions: Emissions are primarily associated with refurbishment processes and transportation. By extending battery life, repurposing delays the environmental impact related to recycling or disposal.

Benefits:

- Reduces the immediate demand for new batteries, conserving raw materials and energy.
- Provides sustainable solutions for energy storage, enhancing renewable energy utilization.

Challenges:

- Limited by the remaining capacity and health of the used batteries.
- Eventually, second-life batteries will need to be recycled or disposed of, shifting the environmental burden to a later stage.

Recycling

Recycling involves breaking down spent batteries to recover valuable materials for reuse in new batteries. The main recycling methods are mechanical, hydrometallurgical, and pyrometallurgical processes.

Mechanical Recycling:

Environmental Impact:

- Material Recovery Rates: High recovery rates for metals like copper, aluminum, and steel; moderate for lithium and cobalt.
- Energy Consumption: Moderate energy consumption primarily for shredding and mechanical separation processes.

- Greenhouse Gas Emissions: Emissions are relatively low compared to pyrometallurgical processes, as mechanical recycling involves fewer high-temperature processes.

Hydrometallurgical Recycling:

Environmental Impact:

- Material Recovery Rates: High recovery rates for lithium, cobalt, nickel, and manganese through selective leaching processes.
- Energy Consumption: Lower than pyrometallurgical processes, but energy consumption varies depending on the specific leaching process.
- Greenhouse Gas Emissions: Lower emissions due to chemical processes at ambient or low temperatures.

Pyrometallurgical Recycling:

Environmental Impact:

- Material Recovery Rates: Effective for recovering cobalt, nickel, and other metals; lower for lithium.
- Energy Consumption: High energy consumption due to high-temperature smelting processes.
- Greenhouse Gas Emissions: High emissions due to the energy-intensive nature of the process and combustion of organic materials within the batteries.

Benefits:

- Reduces the need for virgin materials, conserving natural resources.
- Can recover a wide range of valuable metals, reducing the environmental impact of mining.

Challenges:

- High energy consumption and associated greenhouse gas emissions, particularly for pyrometallurgical processes.

- Complexity in efficiently separating and recovering all valuable materials.

Disposal

Disposal refers to landfilling or incinerating spent batteries, generally considered the least environmentally friendly option.

Environmental Impact:

- Material Recovery Rates: No material recovery; all valuable materials are lost.
- Energy Consumption: Minimal energy consumption for the disposal process itself, but high environmental costs due to the loss of recoverable materials.
- Greenhouse Gas Emissions: Emissions from transportation to disposal sites and potential emissions from battery degradation in landfills.

Benefits:

- Simplicity and low immediate cost.

Challenges:

- Significant environmental impact due to the loss of valuable materials and potential contamination of soil and water.
- Landfilling and incineration contribute to long-term environmental degradation and health risks.

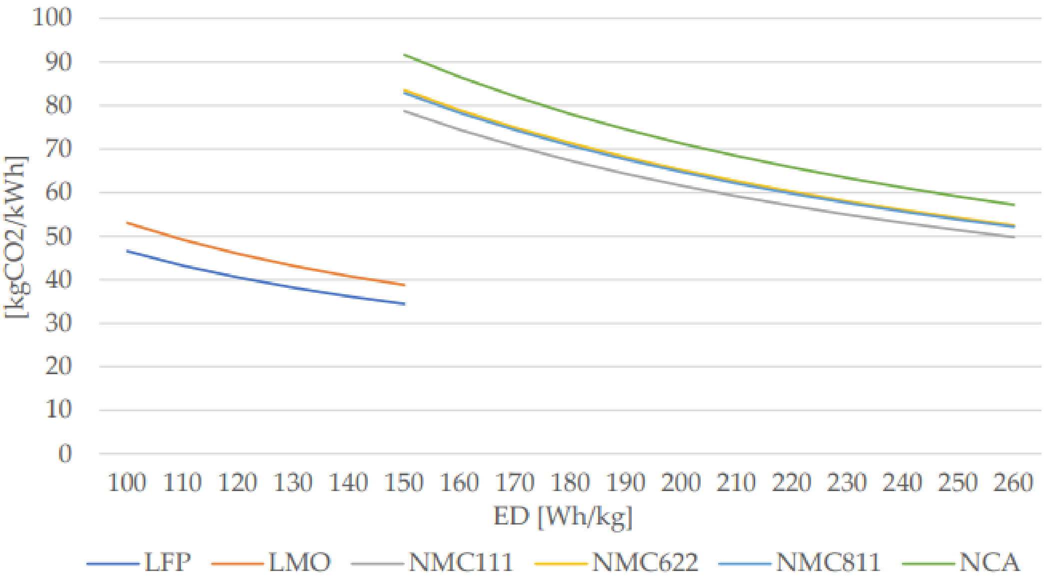

Fig. 19: Battery Production emission at different energy densities [140]

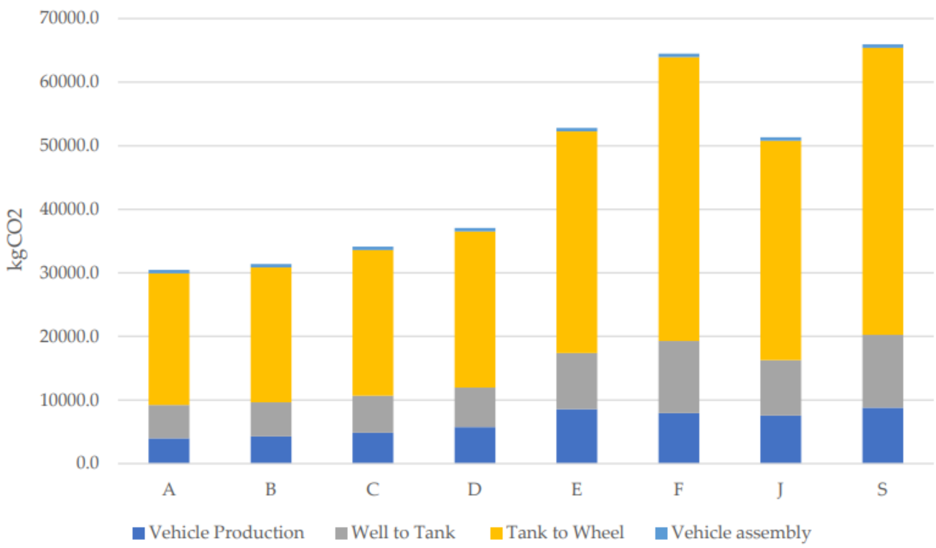

Fig. 20: ICEV Life Cycle Emission calculation for eight different ICEV [140]

Considerations for the Emission Result for ICEV and BEV above.

- All vehicles were assumed to have an NMC811 battery with an energy density of 180 Wh/kg.

- The European electric mix's emission factor (294 gCO2/kWh) is used to evaluate the production emissions of both the vehicle and the battery, as well as to calculate the Well to Tank emissions.
- A vehicle lifetime mileage of 150,000 km is considered.
- The WLTP guide cycle was used to measure WTT (Well to Tank) and TTW (Tank to Wheel) emissions.
- The vehicle is assumed to be used at a room temperature of 20°C.

The figure above compares CO2 emissions from different stages of the vehicle lifecycle. Here's a comparison based on the segments shown:

Vehicle Production: This stage involves emissions from the manufacturing process of the vehicle, including the production of parts and materials.

Well to Tank: This segment accounts for emissions from the extraction, refining, and transportation of fuel before it reaches the vehicle.

Tank to Wheel: Typically the highest, this represents emissions from the combustion of fuel in the vehicle's engine during operation.

Vehicle Assembly: This includes emissions associated with the assembly of the vehicle's parts into a complete product.

The graph clearly indicates that 'Tank to Wheel' emissions are the most significant, emphasizing the impact of fuel combustion on the overall carbon footprint of vehicles.

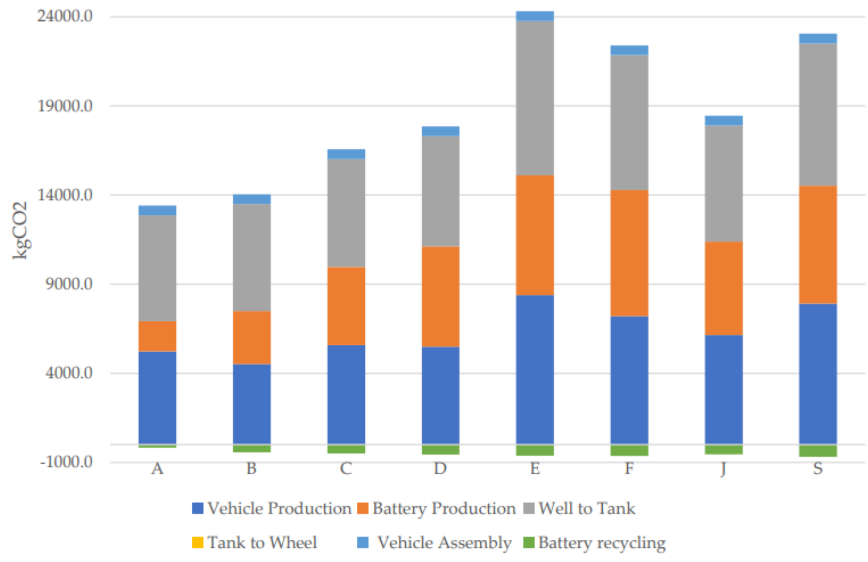

Fig. 21: BEV Life Cycle Emissions for eight different BEV [140]

The figure abouve compares CO2 emissions from different stages of the vehicle lifecycle. Here's a comparison based on the segments shown:

Vehicle Production: This stage involves emissions from the manufacturing process of the vehicle, including the production of parts and materials.

Battery Production: This segment accounts for emission from the extraction, refining, and transportation of fuel.

Well to Tank: This segment accounts for emissions from the production, transportation, and distribution of energy up to the point where it is stored in a vehicle's tank or battery.

Tank to Wheel: This segment refers the emission produced by EV while operation. This is zero because EV is considered zero tailpipe emission.

Vehicle Assembly: This includes emissions associated with the assembly of the vehicle's parts into a complete product.

Battery Recycling: This includes emission reduction due to recycling the EV batteries.

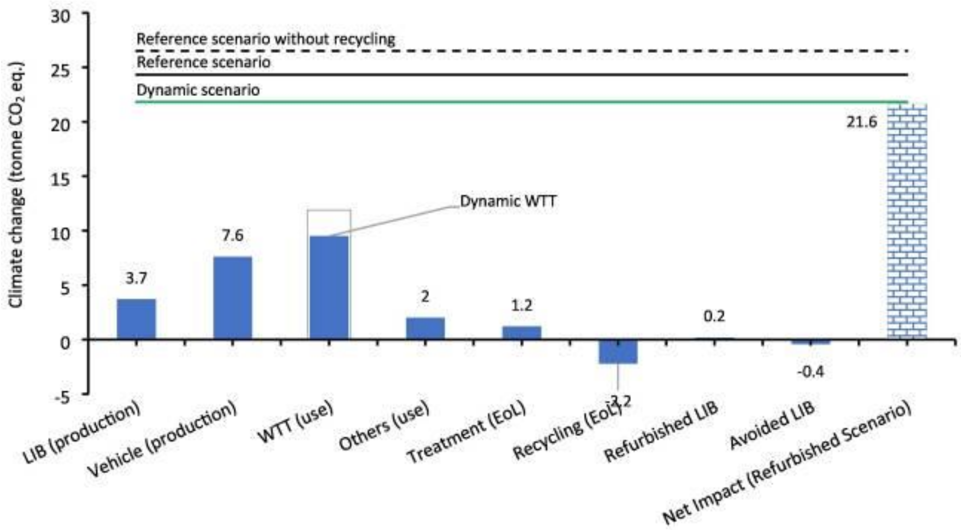

Fig. 22: Emission by EV from LIB prediction to Disposal [133]

The emission produced throughout the life including EoL application is mention in the above figure. The emission production is maximum for Wheel To Tank which may vary due to electricity mix from place to place. However, the EoL treatment is found to produce 1.2 tonne of CO2. Since the used battery is usable to recycling which can reduce a about 2.2 tonne of carbon emission by omitting the necessaties of mining and processing for new batteries. However, refurbising and reusing of the EV batteries seems to have produced emission, they will extent the need for recycling and need for producing newer batteries resulting to reduction in huge amount of emission.

Emission Reduction due to different processes

Indicators	Improvement strategies			Total reductions
	Recycling	LIB repurposing	Electricity mix changes	
Global warming	−8.3%	−0.8%	−9.4%	−18.4%
Fine particulate matter formation	−17.2%	−4.2%	−2.1%	−23.5%
Mineral resource scarcity	−25.2%	−2.9%	0.4%	−27.6%
Human carcinogenic toxicity	−14.3%	−1.0%	−2.3%	−17.6%
Human noncarcinogenic toxicity	−22.3%	−2.3%	−1.6%	−26.2%

Fig. 23: Emission reduction due to Recycling, Repurposing, and Electricity Mix [133]

The figure highlights the effectiveness of different strategies in mitigating various environmental and health impacts associated with battery usage. Recycling stands out as the most effective strategy across all indicators, particularly in reducing mineral resource scarcity (25.2%), fine particulate matter formation (17.2%), and human non-carcinogenic toxicity (22.3%). This underscores the importance of recycling programs in achieving substantial environmental benefits.

LIB repurposing, while contributing less significantly compared to recycling, still offers notable reductions, particularly in fine particulate matter formation (4.2%) and human non-carcinogenic toxicity (2.3%). This strategy leverages the remaining value of batteries before they are fully recycled, extending their useful life and reducing overall impact.

Changes in the electricity mix, primarily through integrating cleaner energy sources, also contribute to reductions in all indicators except mineral resource scarcity, where it shows a slight increase (0.4%). This strategy is particularly effective in reducing global warming potential (9.4%), highlighting the role of energy transition in mitigating climate change.

The combined effect of these strategies results in significant total reductions across all indicators, with the most substantial impacts observed in reducing mineral resource scarcity (27.6%) and fine particulate matter formation (23.5%). These findings emphasize the need for a multi-faceted approach to battery management, incorporating recycling, repurposing, and clean energy integration to maximize environmental and health benefits.

Effectiveness of Second Life Application of EV Batteries on Emission Control.

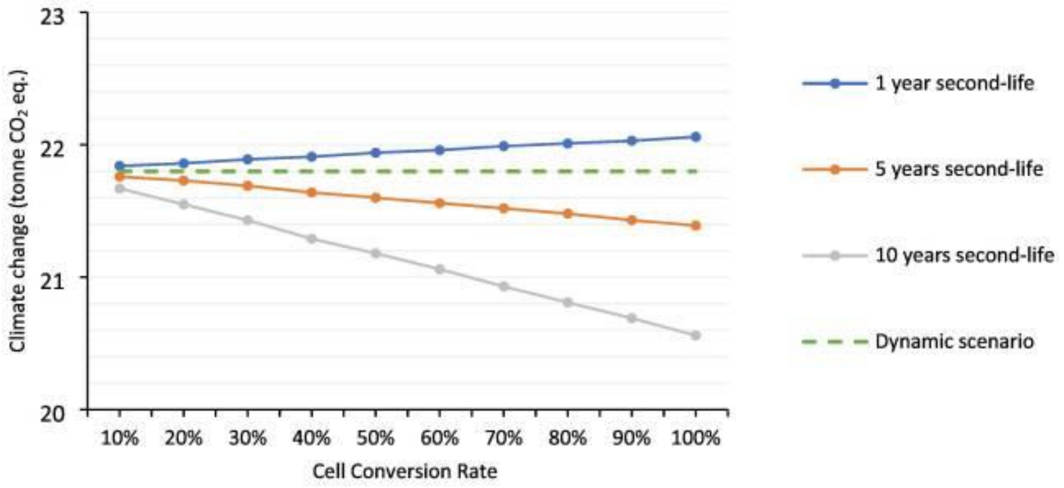

Fig. 24: Second Life Emission Control [133]

The blue line for the 1-year second-life scenario indicates that the climate change impact remains relatively constant across different cell conversion rates, staying around 22 tonnes of CO2 equivalent. This suggests that short-term second-life applications do not significantly reduce the climate impact regardless of the conversion rate.

The orange line for the 5-year second-life scenario shows a gradual decrease in climate change impact as the cell conversion rate increases. Starting slightly below 22 tonnes of CO2 equivalent at a 10% conversion rate, it decreases to approximately 21 tonnes at a 100% conversion rate. This indicates that medium-term second-life use provides moderate climate benefits, with higher conversion rates leading to more significant reductions in CO2 emissions.

The gray line for the 10-year second-life scenario demonstrates the most substantial decrease in climate change impact, starting from about 21.5 tonnes of CO2 equivalent at a 10% conversion rate and dropping to just below 21 tonnes at a 100% conversion rate. This suggests that long-term second-life applications can substantially reduce climate impact, with the benefits increasing as more cells are converted.

The green dashed line for the dynamic scenario remains almost flat across the conversion rates, indicating a constant climate change impact of around 22 tonnes of

CO2 equivalent. This serves as a baseline or reference scenario, showing the impact without significant second-life applications.

The graph highlights the potential climate benefits of extending the life of battery cells through second-life applications. The longer the second-life duration (from 1 year to 10 years), the more significant the reduction in CO2 emissions. The most substantial benefits are observed in the 10-year second-life scenario, where increased cell conversion rates correlate with a notable decrease in climate impact. Conversely, the 1-year second-life scenario shows minimal climate benefits, indicating that short-term use may not be sufficient to achieve meaningful reductions in CO2 emissions. This analysis underscores the importance of promoting longer second-life applications for battery cells to maximize environmental benefits. Increasing the cell conversion rate further enhances these benefits, supporting the case for robust second-life battery programs and technologies to extend the lifespan and reduce the overall climate impact of battery usage.

Well-to-Wheel Greenhouse Gas Emissions

Well-to-wheel emissions for electric vehicles (EVs) refer to the total greenhouse gas emissions produced over the entire lifecycle of the vehicle's energy source, from the extraction and production of fuel (well) to the vehicle's operation on the road (wheel). This comprehensive measure includes all stages: the extraction of raw materials, fuel production, transportation, and the energy used to charge the vehicle, as well as the emissions produced during the vehicle's operation. Well-to-wheel analysis is crucial for understanding the true environmental impact of EVs, as it provides a complete picture of their carbon footprint compared to traditional internal combustion engine vehicles. This analysis helps in identifying areas for improvement in energy efficiency and emission reduction across the entire supply chain and usage cycle of EVs.

Life cycle emissions encompass all greenhouse gases released throughout a product's entire life, from its creation and usage to its eventual disposal.

To effectively compare these emissions, the metric tons of CO2 equivalent (tCO2e) unit is used, as it accounts for the various greenhouse gases and their respective global warming potentials.

The following provides an overview of the life cycle emissions in 2021 for medium-sized electric, hybrid, and internal combustion engine (ICE) vehicles. The emissions are measured in tCO2e considering a usage period of 16 years covering a distance of 240,000 kilometers [141].

Table XVII. *Well to Wheel CO2 Emission (ton CO2 emission)* [141]

		Battery electric vehicle	**Internal combustion engine vehicle**
Production emissions (tCO2e)	Battery manufacturing	5	0
	Vehicle manufacturing	9	10
Use phase emissions (tCO2e)	Fuel/electricity production	26	13
	Tailpipe emissions	0	32
	Maintenance	1	2
Post consumer emissions (tCO2e)	End-of-life	-2	-1
	TOTAL	39	55

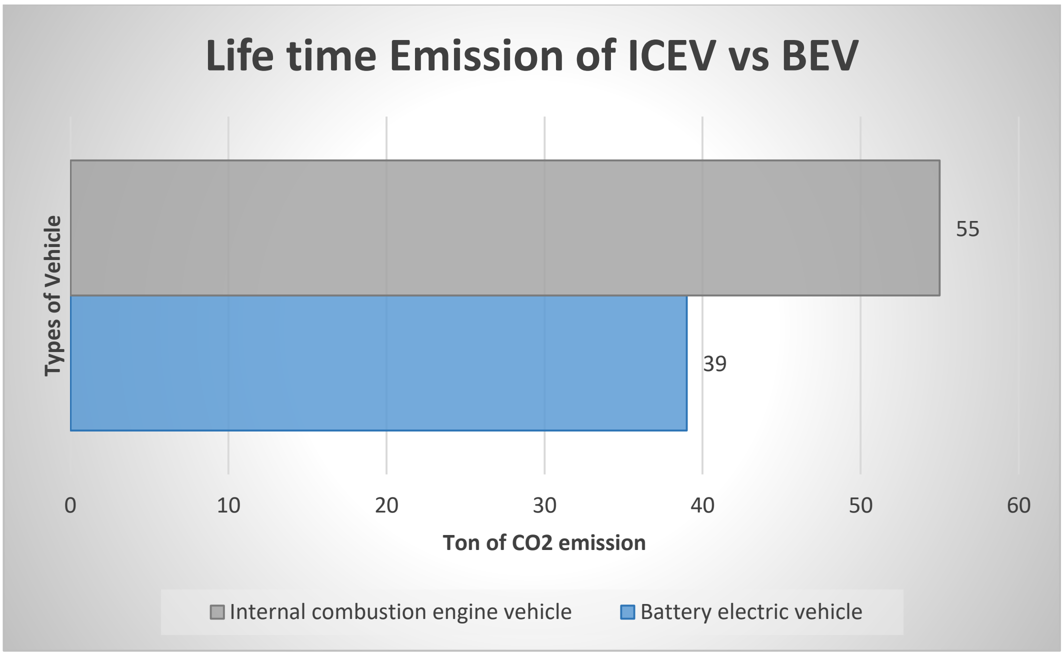

Fig. 25: Comparision of ICEV and BEV Well-To-Wheel Emission.

As shown in figure above, the life time emission of BEV is 30% lower than ICEV which is around 16 tonn of CO_2 emission, that is slightly greater than emission needed to manufacture a new BEV.

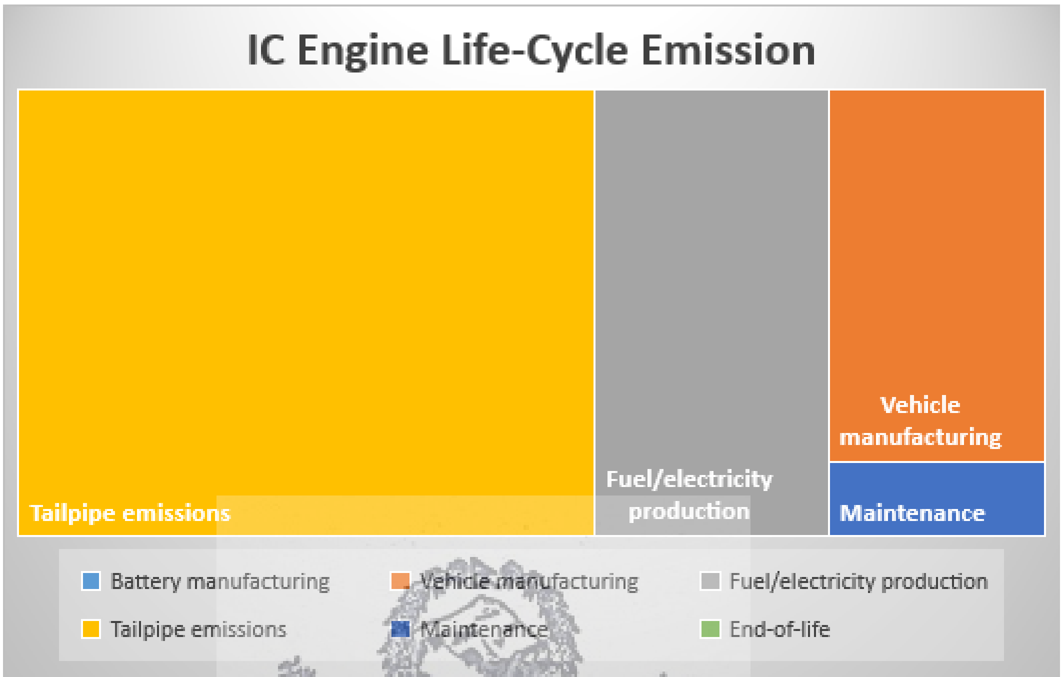

Fig. 26: ICE Vehicle life cycle Emission.

As shown in figure above, the tailpipe emissin of of ICE vehicles accounts for major emission followed by fuel production.

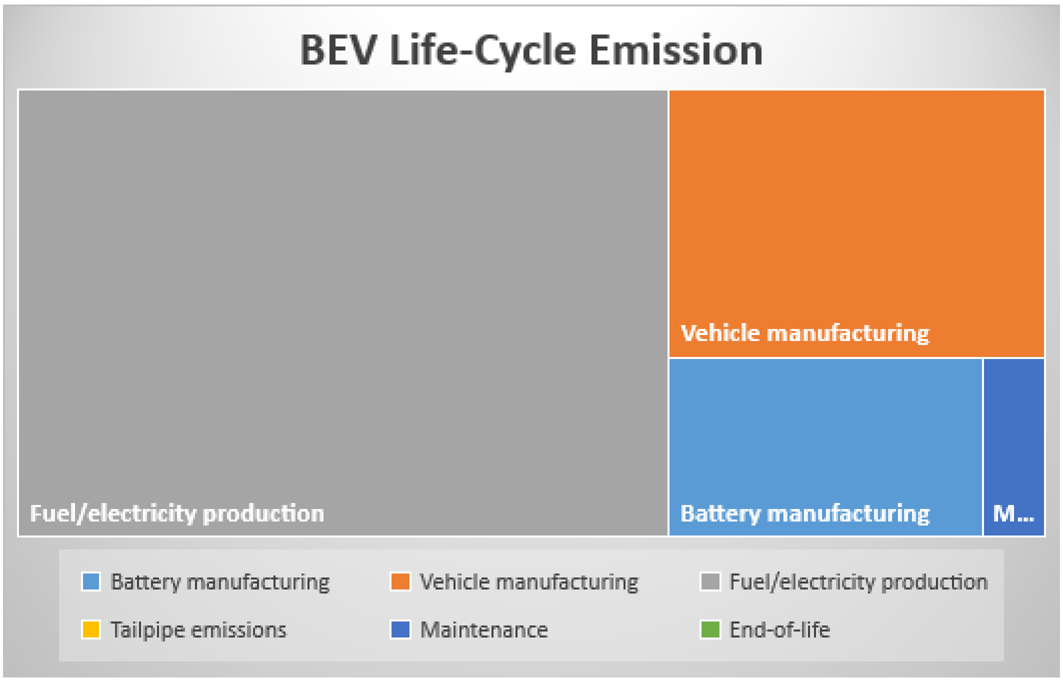

Fig. 27: BEV Life Cycle Emission.

As shown in the figure below, the major emission produced by BEV is from source of electricity production. In BEV, Vehicle manufacturing and Battery Manufacturing looks significant because of overall low emission. On improving the electricity source by sifting to renewable sources, we may achieve relatively very low emission.

Emission Reduction Potential

Government aspirations in the arena of road transport electrification alone save 2 Gt CO2 by 2035 on a well-to-wheel basis. But at the same time, some increase in short-term emissions is expected to result from the electrification of road transport due to electricity generation for the use of electric vehicles. Despite this, not over many decades to come, electrification of road transport will result in significant emission reductions. In the Stated Policies Scenario (STEPS), total emissions avoided by 2035 resulting from using EVs combined with the ICE fuel economy improvement will exceed 2 Gt CO2 equivalent [19].

Electricity-related emissions increase another 210 Mt CO2-eq, measured net of offsets, leading to an estimated net savings of 1.8 Gt CO2-eq in 2035 under the STEPS [19]. In the APS, more avoided net emissions of about 2 Gt CO2-eq may be saved by 2035 as a result of the continuation of decarbonization in electricity generation.

Ambition Gap

The gap between the current policies and those needed to reach a net zero emissions (NZE) pathway by 2050 is considerable. Measured in 2030, emissions in the avoided NZE Scenario are 40% higher than in the APS and merely 5% higher than in the STEPS [19].

This gap reduces to nearly half of the margin to less than 35% by 2035 between the NZE Scenario and APS emissions savings; however, net emissions reductions in the APS are over 10% compared with STEPS [19].

Regional and Segment Contributions:

Chinese passenger LDVs accounted for about 35% of global road transport avoided emissions by 2023. This represents the early benefit of electric vehicle deployment for contributions to CO2 savings accumulated over the years [19].

By 2035, the share of avoided emissions from Chinese LDVs will decline to 25% in STEPS as other regions catch up. Trucks and buses then account for almost 15% and 5% of avoided emissions, respectively [19]. Electrified 2/3Ws had over a 10% share of avoided emissions in 2023 and have a share that falls to 5% by 2035 but still means considerable cumulated savings [19].

Price Parity and Policy Support

Retail price parity between electric and ICE cars is projected by 2030 in some regions and segments, driven by a stronger policy support toward electrification of cars relative to other vehicle segments.

LDV has a very aligned sector to the NZE Scenario, attaining over 80% of the net avoided emissions by 2035 in both STEPS and APS [19]. Buses are the least aligned with the NZE Scenario, with STEPS achieving 20% and APS 30% of emissions cuts seen in the NZE Scenario [19]. For trucks, meanwhile, STEPS achieves just shy of half of the net avoided by 2035 and APS almost 70%, reflecting strong US and EU policies and various pledges internationally [19].

Impact of the Electric Car through the Lifecycle

Comparison of Emissions

BEVs exhibit much greater environmental friendliness over their lifetime when compared to conventional internal combustion engine vehicles. A medium-sized BEV emits approximately 50% less CO2 than a comparable ICEV, 40% less than a HEV, and 30% less than a PHEV over a mid-lifetime of 15 years or about 200,000 km [19]. As grids decarbonize, more and more, emissions savings from BEVs are expected to increase. By 2035, emissions from ICEVs are projected to be almost two and a half times lower under the Stated Policies Scenario (STEPS) and more than three times lower in the Accelerated Policies Scenario (APS), compared with BEVs [19]. For example, a medium-sized ICEV is estimated to have a lifetime emissions intensity of 38 tonnes of CO2-equivalent, while a BEV in the same class would only have 15 tonnes [19].

Grid Decarbonization

However, the full realization of these environmental benefits from BEVs demands a fully decarbonized power grid. Emissions related to electricity production (well-to-tank emissions) to be used by new 2023-sold vehicles are projected in this analysis to fall by about 25-35% under both STEPS and APS due to better electricity emissions intensity. The same emissions are further expected to be 55% under STEPS and much greatly fall to 75% under APS in 2035, resulting from a 50-65% cut in the emission intensity of electricity [19].

Impact of Vehicle Size

As a general rule, bigger vehicles especially emit more, however for electric powertrains, this is debilitated. For example, a large ICE Sport Utility Vehicle produces around 50% more lifetime emissions in CO2 terms than a medium passenger car. In contrast, large Battery Electric SUVs increase medium-sized BEV emissions by 20%. Battery electric SUVs have up to 60% less lifecycle emissions over an ICE SUV [19].

Regional Emissions Benefits of Electric Vehicles

United States

Due to the high annual mileages, BEVs have important saving potentials in emissions. One would expect grid emissions intensity to drop by 70% compared to the Stated Policies Scenario by 2035. A medium BEV will emit, when purchased today, 45% less than a PHEV over life, 60% less than an HEV, and 65% less than an ICEV, so over life, it saves around 50 tCO_2e in net over an ICEV.

United Kingdom

With fewer miles traveled annually compared to the U.S., the lifetime emissions savings for BEVs are lower, at under 20 tons of CO_2-equivalent per vehicle.

India

Both the UK and India have similar annual mileage, but the intensity of the higher emissions from power generation due to coal results in reducing the BEVs' emissions benefits. The BEV lifestyles are, however, similar to that of PHEVs and HEVs, with only about 10% difference among them and 20% less than ICEVs. The medium-sized BEV in India saves less than 10 tons of CO_2-equivalent over its lifetime compared to an ICEV. However, the efforts at decarbonization of electricity produce in the country could reduce grid emission intensity by 60% through 2035, making the environmentally friendly virtues of BEVs more vivid. In the same regard, this will also pardon its major cities, such as Mumbai, in terms of air quality.

China

China saves 20% less CO_2 compared to PHEVs, 30% less than HEVs, and 40% less than ICEVs in China save 5–10 tons of CO_2-equivalent, 30% less than HEVs and 40% less than ICEVs. Since the country were using a lot of BEVs, China saves a lot in greenhouse gas emission levels and enjoys much lower per-vehicle emissions than Europe and the U.S., making China top of the pack in terms of road electrification benefits.

In Europe, there are slightly over 6.5 million battery electric vehicles (BEVs) on the roads, while in the United States, the number stands at slightly over 3.5 million BEVs.

Decarbonization Efforts in Battery Manufacturing and Mineral Processing

Efforts to decarbonize mineral processing and battery manufacturing are vitally important if EV batteries are to have a reduced environmental footprint. Besides that, the lifecycle emissions of these batteries are now defined by battery chemistry. Policies that will drive a decarbonizing agenda within the manufacturing process will drive the supply chain to set ambitious targets through collaborative means at an accelerated period. It will be an important step in this direction when common LCA methodologies are defined with a boost on transparency through such initiatives as the battery passport.

Role of Battery Chemistry

The two most common battery chemistries today are so-called high-nickel Nickel Manganese Cobalt (NMC) batteries and Lithium Iron Phosphate (LFP) batteries. An LFP battery is relatively less emissions-intensive compared to an NMC one at the pack level, with about a third less per kilowatt-hour (kWh) [19]. It might be an incentive for driving technology to get widespread use of LFP batteries, particularly in a context in which carbon tariffs or subsidies are linked to lifecycle emissions, should China emerge as a major LFP battery producer.

Chemistry Comparison

Looking at emissions from cradle to grave, processing critical minerals emits 55% of the total emissions for NMC batteries and 35% for the LFPs. Battery production through and through contributes almost 50% of LFP emissions, and 15% goes for NMC [19]. Production of active materials for the cathode and anode also records high emissions.

Emission Sources Across Lifecycle

The strategies will have to be focused on strengthening the process efficiency of the critical minerals, energy, interface efficiency, and decarbonization of the supply chain for enabling decarbonization of high-nickel chemistries. This is further going to be strengthened by using recycled materials. An increased focus should be placed on low-carbon electricity sourcing because electricity-related emissions are about 20-25% of total lifecycle emissions for both NMC and LFP batteries [19]. Efforts are also to be provided toward an increase in energy density to reduce battery material intensity, boost recycling rates.

Future Projections

Going forward, under the Announced Pledges Scenario, lifecycle emissions are projected to drop by around 35% for both NMC and LFP batteries through 2035 [19]. Key drivers are expected to be increased energy density, decarbonization of the electricity sector, and increased recycling rates for cathode active materials [19].

End-of-Life Strategies for Electric Vehicle Batteries

End-of-life Strategies for EV Batteries Effective end-of-life strategies, including recycling and reuse, are essential for creating circular EV supply chains and reducing the demand for critical minerals. Although the recycling sector of these batteries remained very nascent in 2023, it is extremely likely it will be central to the future of EV supply chains, further solidifying the benefits these batteries bring to the environment [19].

Global Recycling Capacity and Expansion

As of 2023, global recycling capacity was already well above 300 GWh per annum, with more than 80% residing in China, followed by Europe and the United States. Many technology developers and industry actors are upscaling to seize the future market opportunity for handling EVs at the end of their life. Global recycling capacity by 2030 is projected to exceed 1,500 GWh [19].

Sources of Supply and Overcapacity Concerns

The recycling plants will source the main portion of their feedstock from EV battery production scrap and retired EV batteries in 2030 [19]. However, this poses an enormous risk in terms of large overcapacity, with supply possibly representing only one-third of the recycling capacity announced under scenarios such as the Stated Policies Scenario (STEPS) and the Announced Policies Scenario (APS) [19]. In case the recycling capacities go above the overcapacity level, it can give rise to financial exposure to the recycling companies and force some market consolidations, which will be highly true for Europe and the United States, where battery recycling businesses have been born in recent years.

Policy and Regulation

There are two enablers—policy and regulation—that lie at the front to ensure traceability, quality, safety, and sustainability in recycling practices. New regulations in China now shift the responsibility for traceability and recycling of EV batteries to the manufacturer [19], [134]. More advanced or comprehensive regulations like this are needed in other regions, such as Europe, to also cover issues regarding transportation and the implementation of tracking systems on issues related to the transportation of end-of-life batteries [19], [134].

Impact of Battery Chemistry and Technology

Technological innovations and changes in battery chemistries are expected to dramatically influence the recycling landscape by 2030 [19]. Since NMC batteries often contain valuable metals, including nickel, manganese, and cobalt, while LFP batteries offer poor residual values after recycling, it is expected that the second type of batteries will be more affected. At the same time, there could be the need for regulations fostering or mandating recycling of EOL batteries - similar to lead-acid batteries in ICEVs - with or without residual value [19]. LFP battery recycling is already economically viable in China if the market price of lithium is high. Consequently, the Chinese recycling industry is preparing to install enough LFP recycling capacity to meet future demand—with the result that there could be excess capacity should all of the currently planned plants be built [19].

Future Outlook and Challenges

LFP battery recycling is already economically viable in China, though its feasibility is influenced by the market price of lithium. The Chinese recycling industry is preparing to build enough LFP recycling capacity to meet future demand, which could lead to excess capacity if all planned plants are constructed [19].

Mapping electric vehicles units and the status of their battery pack in Nepal.

Electric two wheelers:

Nepal has good history of an electric two wheelers in Nepal ranging from electric bicycle to scooter and electric bikes. Electric two-wheelers are becoming increasingly popular in Nepal from past few years due to their decent designs, environmental benefits, operational cost savings, and suitability for the country's urban and semi-urban areas. The total units an electric scooters till date are 15460.

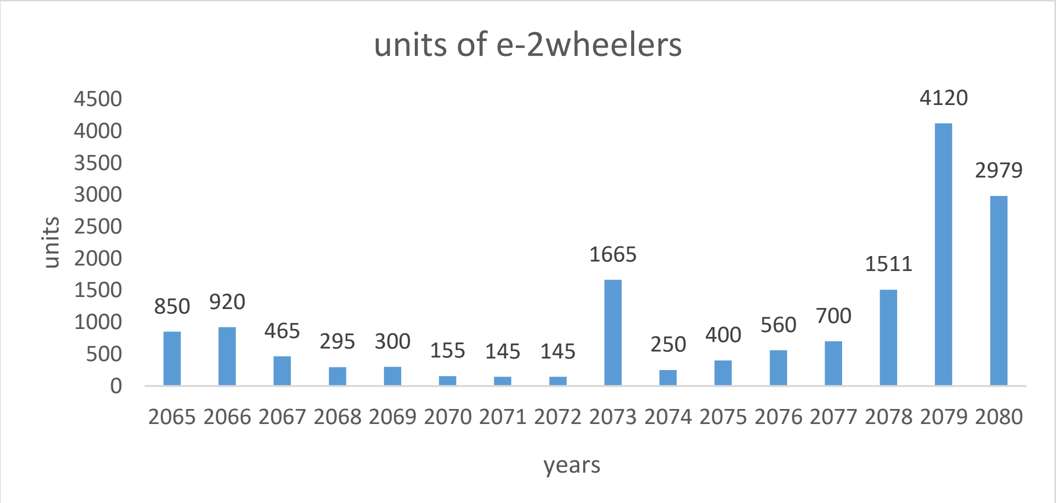

Fig. 28: Number of electric two wheelers in Nepal since 2065 B.S

Major cities like Kathmandu, Pokhara, Bhaktapur and Lalitpur are leading in terms of electric two-wheeler usage. All the electric two wheelers used to be powered by lead acid batteries until an electric scooter by NIU was penetrated in Nepal.

Several importers and authorized dealers are actively promoting and selling electric two-wheelers. Local and international manufacturers are present in the market, including brands like Yatri, Segway, Horwin, ecooter, Luyan, TailG, and NIU are the key players in Nepalese Market.

Electric two-wheelers hold great potential for transforming the personal transportation landscape in Nepal. Despite the different challenges being faced, the market is poised for growth, driven by favorable government policies, technological advancements, and increasing consumer awareness. Strategic and dynamic efforts in infrastructure development, ecosystem, policy formulation, and public education will be key to realizing the full potential of electric two-wheelers in Nepal.

Mapping the battery packs of an electric two-wheelers in Nepal

As most of the electric 2-wheelrs are powered by lead acid batteries, they undergo frequent change of overall battery packs while li-ion powered scooters are still being operated without being changed except few replacements.

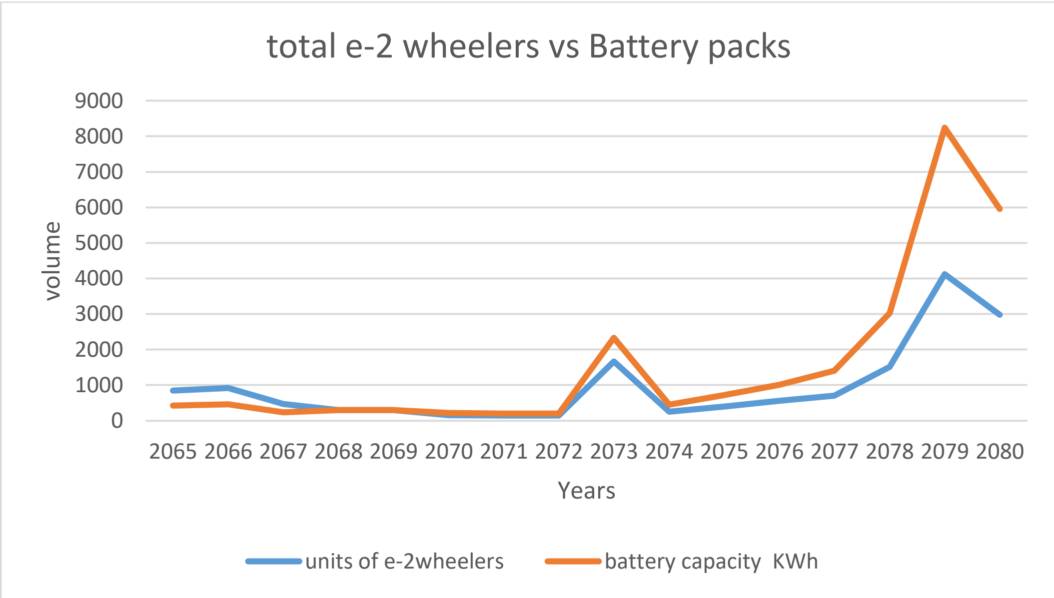

Fig. 29: Mapping of e-2 wheelers vs battery capacity

2079 BS was the best year for Nepal regarding the sales of an electric two wheelers. On that year 4120 units of an electric 2-wheelers were sold win the market.

The total battery pack used for electric 2-wheelers in Nepal are 30998.5 KWh as sold out electric scooter and 61,997 KWh a total battery capacity including the replaced battery packs.

Electric 3-wheelers:

Electric Safa Tempo is one of popular mode of public transportation in Nepal, particularly in the Kathmandu Valley. Safa Tempos were introduced as public transportation at the time when there were very rare use of electric vehicles as a public transportation. They were introduced in early 90’s. These three-wheeled electric vehicles have become an integral part of the urban transport system due to their environmental benefits and cost-effectiveness. Till date 700 units of safa tempos were operating at the fifferent routes of Kathmandu Valley but post covid only 550 units are operating. Out of which 400 units are operating being powered by li-ion battery packs while 150 units are still operating being powered by traditional lead acid battery packs.

While in southern region of Nepal, e-rickshaws/tuktuk, are gaining traction in Nepal due to their eco-friendliness, cost-effectiveness, and suitability for short-distance transportation.

Mapping total battery capacity utilized and being utilized by their types in three-wheelers

Safa tempos have been powered by lead acid batteries for last 19-20 years while from last 6 years, li-ion based battery packs are replacing traditional lead acid batteries.

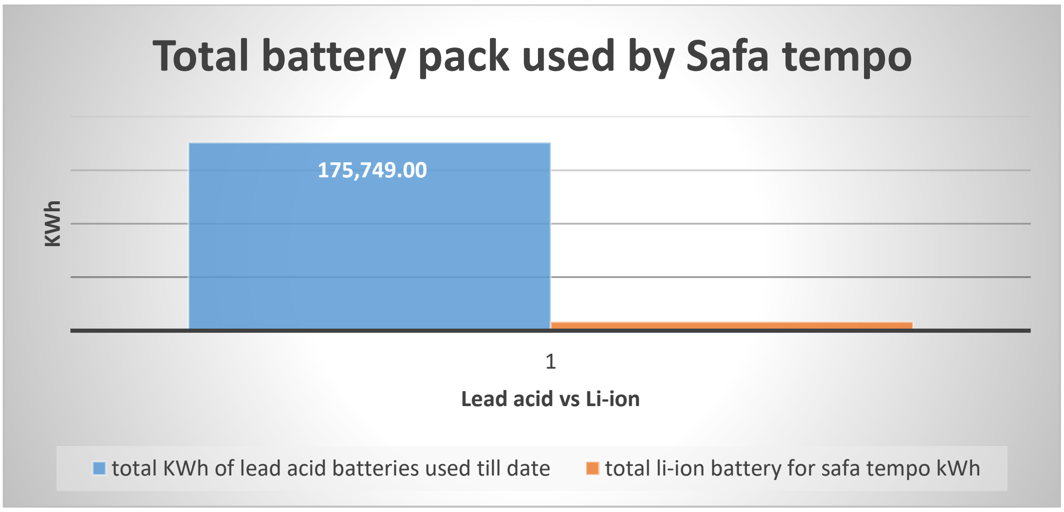

Fig. 30: Mapping of lead acids and li-ion battery packs in Safa tempos

While the three-wheelers like electric ricksaws and tuk tuk shares huge numbers in public transportation in the southern part of Nepal.

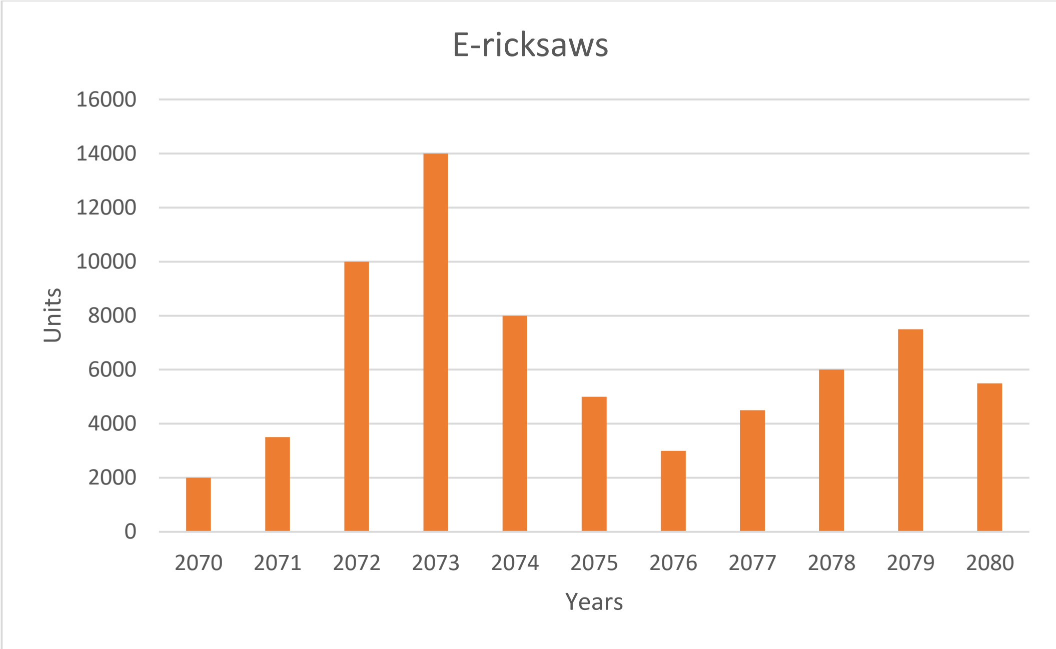

Fig. 31: Volume of e-ricksaws and tuk tuk by years

Till date there are around 69000 units of e-ricksaws and tuk tuk operated in Nepal. Since the lead acids batteries doesn't last long, they are being changed as per the requirements. Since the li-ion has not yet been practiced yet, though few attempts have been performed, traditional lead acid battery pack leads the energy storage system for the three-wheelers.

Following graph plotted briefly details the unit of three wheelers (e-ricksaws) being operated every year and the units of total battery packs including the replaced battery packs in consecutive years.

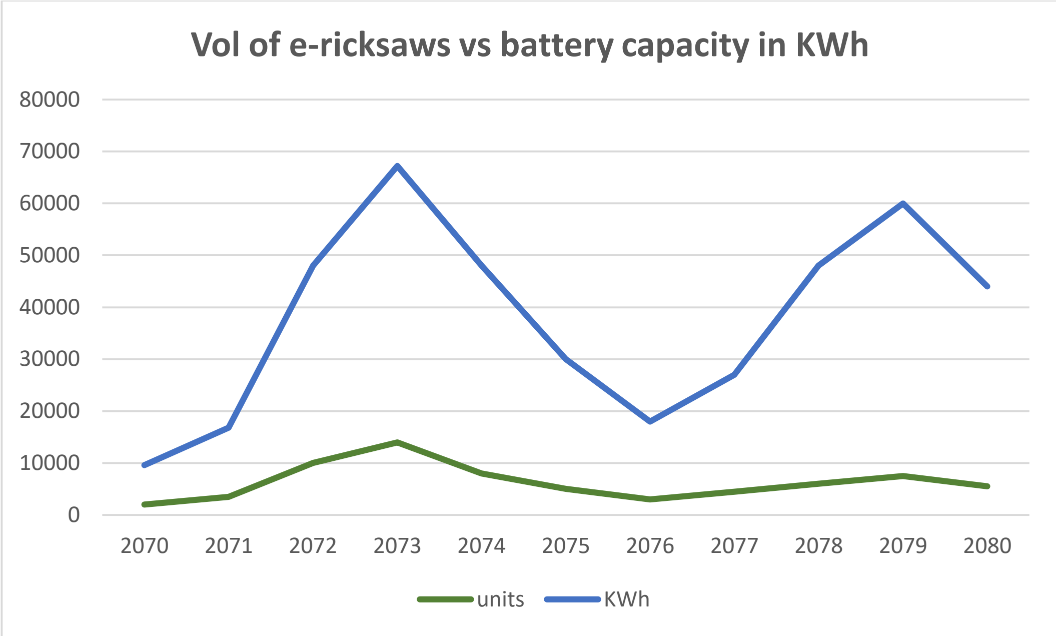

Fig. 32: E-ricksaws sold in the different years including the battery packs replaced in consecutive years

While the figure below shows the battery packs capacities till date while they were in the new electric ricksaw compared to the total battery pack capacity utilized for the sae e-ricksaws including the replaced battery packs. The graph shows that till date there are around 41660 kwh of battery packs used by an electric ricksaws while 1,249,800 Kwh of battery packs have been utilized as an energy storage including the number of battery packs that replaced the unusable battery packs.

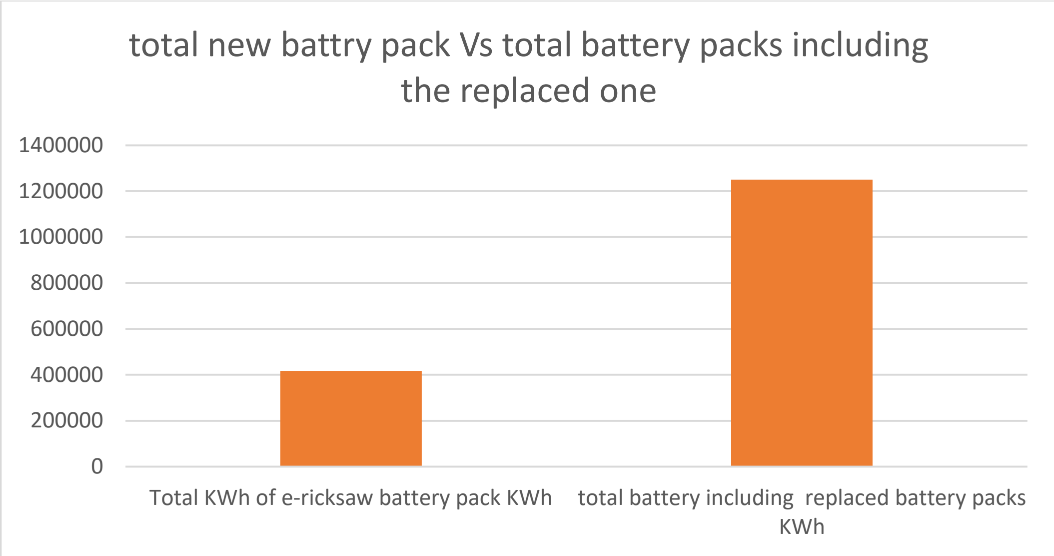

Fig. 33: Total battery pack capacity in new e-ricksaw vs total batteyr pack capacity including the replaced one

Electric 4-wheelers in Nepal

Electric four-wheelers are emerging as a promising solution for sustainable transportation in Nepal. As the country seeks to reduce its reliance on fossil fuels and address environmental concerns, electric vehicles (EVs) are gaining popularity. Electric four-wheelers hold significant potential for transforming the transportation landscape in Nepal. There are different categories of electric 4-wheelers in Nepal ranging from private cars (compact city cars to larger family sedans and SUVs), pickups, commercial passenger and cargo vehicles and buses. Several international brands have entered the Nepali market, offering models like the BYD atto3, Dolphin, E6, Hyundai Kona Electric, Nissan Leaf, and MG ZS EV and many more.

Electric commercial vehicles (ECVs) represent a vital component in Nepal's efforts to modernize its transportation sector, reduce dependence on fossil fuels, and mitigate environmental pollution. The operational cost savings of electric commercial vehicles, including lower fuel and maintenance costs, are significant advantages for businesses. Fleet operators are increasingly considering ECVs for their sustainability goals and corporate social responsibility (CSR) initiatives. Brands such as DFSK, KYC, Kinglong, CRM, Skywell, FOTON, Golden Dragon and Higers are offering electric microbuses and cargo vehicles in the Nepali market while CHTC and BAK have provided electric buses in Nepal.

Table XVIII. *Mapping overall electric vehicles and their battery capacities in Nepal*

E-vehicles type	*Volume*	*Battery capacity KWh*
2-wheelers	18227	**61997**
3-wheelers	69000	**1249800**
4-wheelers	5493	**273315**
4- wheel commercial vehicles	984	**42900**
4-wheel cargo vehicles	65	**1785**
e-buses	46	**7574**

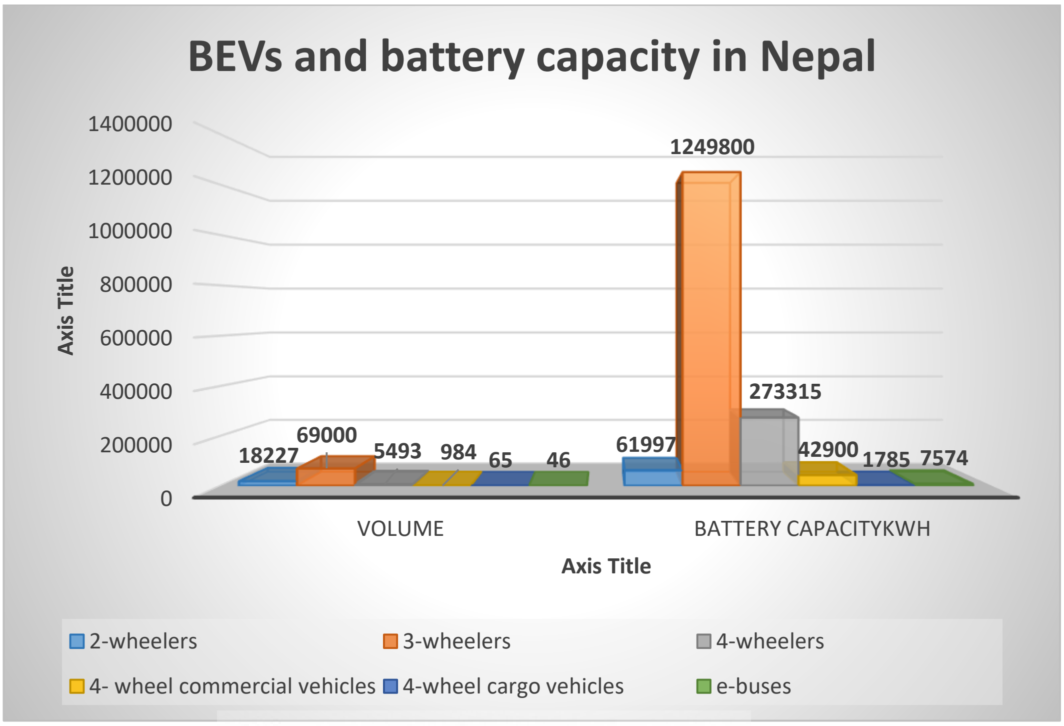

Fig. 34: Volume and Battery Capacity of BEV available in Nepal.

Since the private cars having bigger battery capacity and average daily driven distance to be around 35-40kms per day, the End of Life (EOL) battery from private cars are long way to go, they will lasts at least 8 years to 10 years. While commercial vehicles on the other hand having a daily driven distance to be around 250 kms and EOL to be by the end of 200,000 kms, there’s an expectation of frequent replacement of the battery packs. Accounting 330 working days in a year these commercial microbuses will be going through battery replacements in 2.5 years of operation. The buses on the other hand will too have nearer EOL dropping the efficiency of the vehicles range.

Mapping BEVs and their battery capacity in operation over their 20 years of lifetime operations

Mapping BEVs assuming the current number of electric vehicles in the market. It is found that the battery capacity of about 2,966,846 KWh of battery packs will go for their EOl replacement and shall go for their secondary applications.

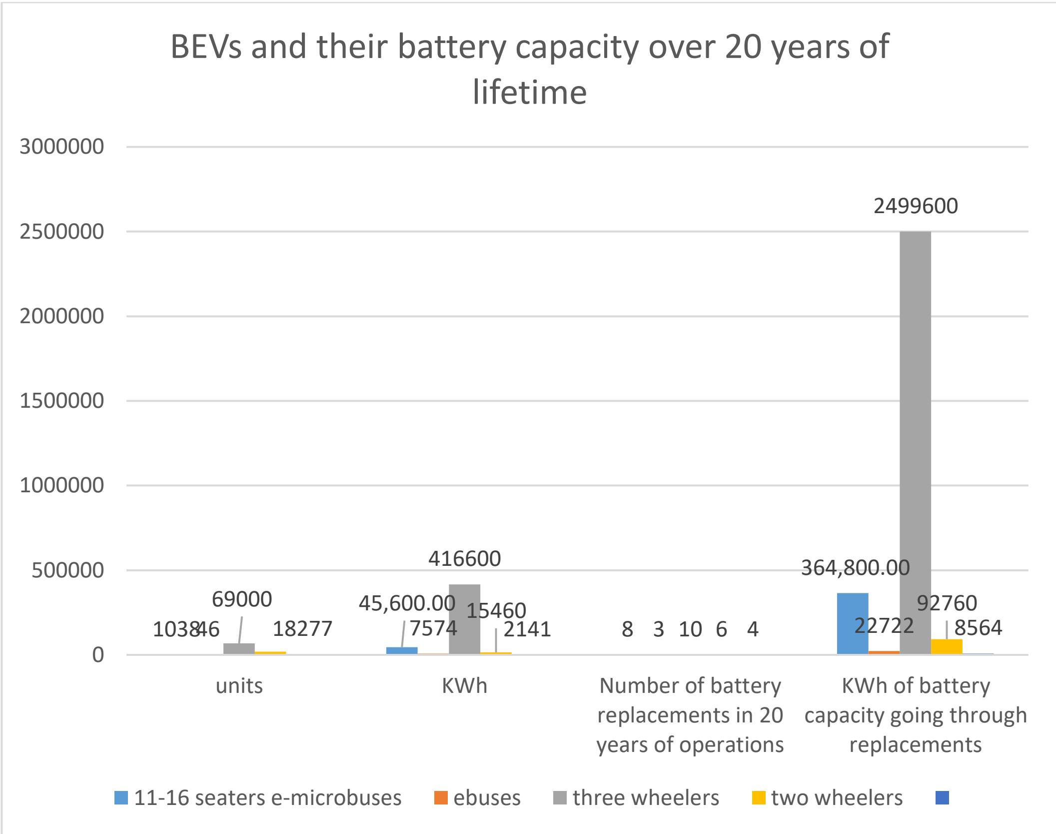

Fig. 35: Forecasting the EOL battery from present electric vehicles in the Nepalese market

Forecasting the number of electric 2-wheeler and their battery capacity in next 20 years

Taking the number of electric 2-wheelers from past few years and forecasting using linear regression with the equation y = 137.6x – 284204, the units of e-2wheelers can be forecasted.

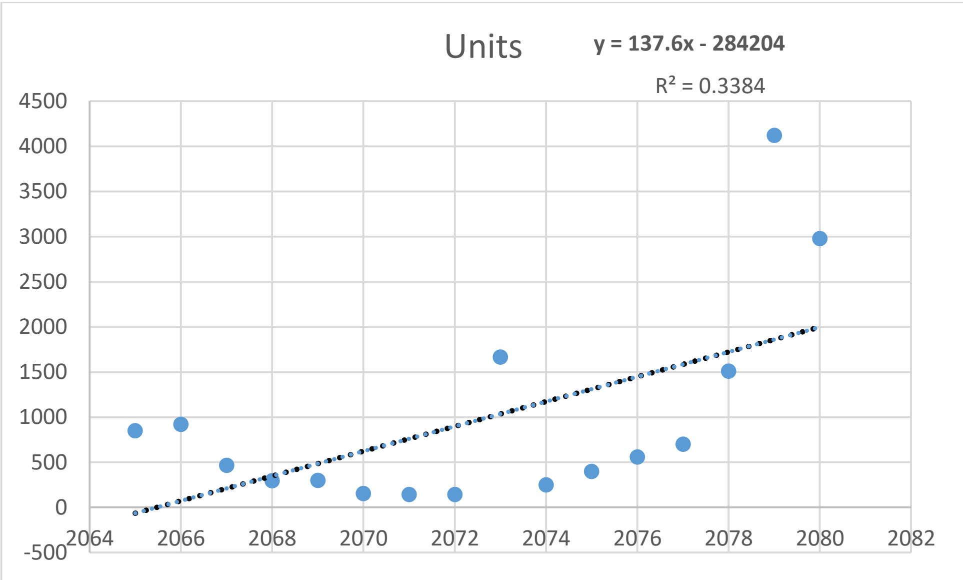

Fig. 36: Mapping the unit of e-2wheelers using the linear regression method

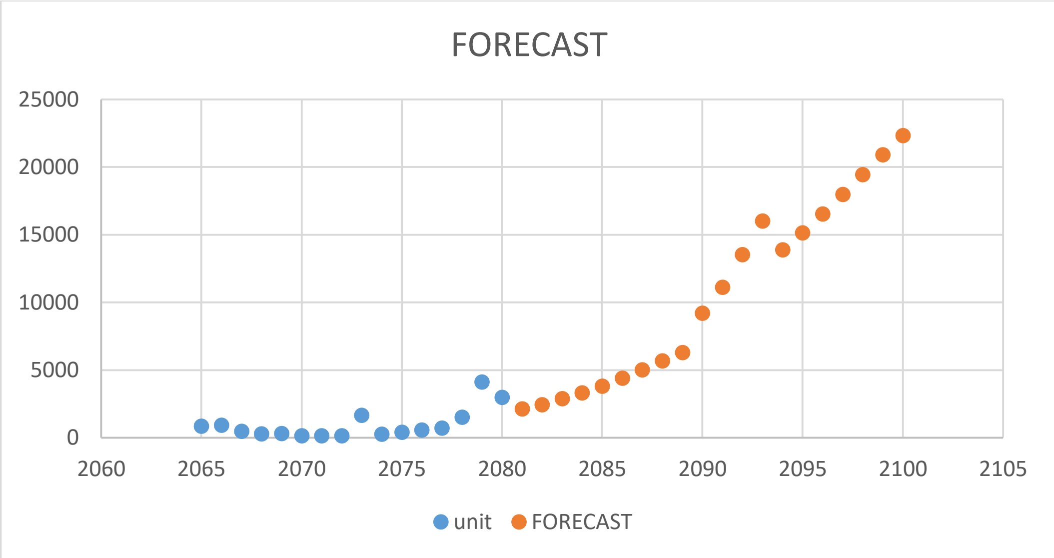

Fig. 37: Forecasted volume of e-2weelers in next 20 years

In the figure 33 above, the unit represents blue scattered data that shows the number of e 2-wheelers in last few years while the yellow scattered data forecasts the data of e 2-wheelers for next 20 years. The figure below forecasts the battery capacity of forecasted e 2-weelers in KWh.

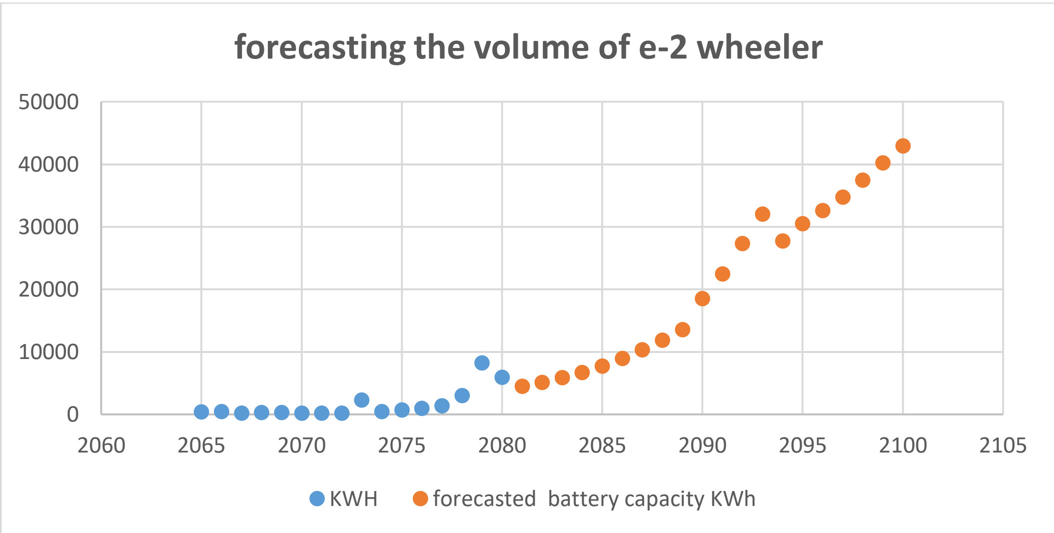

Fig. 38: Forecasted battery capacity of e 2-weelers for next 20 years

The blue scattered data shows the KWh of battery packs from last 15 years while the yellow scattered data shows the forecasted battery capacity from 2-wheelers. Using the linear regression methodology, it has been found that there will be 843,212 KWh of battery packs including the capacity from replaced battery packs. So now we can say that there will be altogether 905,209 KWh of battery packs that will go through EOL time and may undergo repurposing, refurbishing or recycling process for their secondary uses.

Forecasted EOL battery pack for three-wheelers for next 20 years

Since the operation of safa tempos from next 4-5 years are uncertain as they will reach 30 years of operation and will be ending their permitted operation period. So only light electric three-wheelers are being forecasted for next 20 years. Its forecasted that the volume of electric tuk tuk will be around 192,016 in next 20 years.

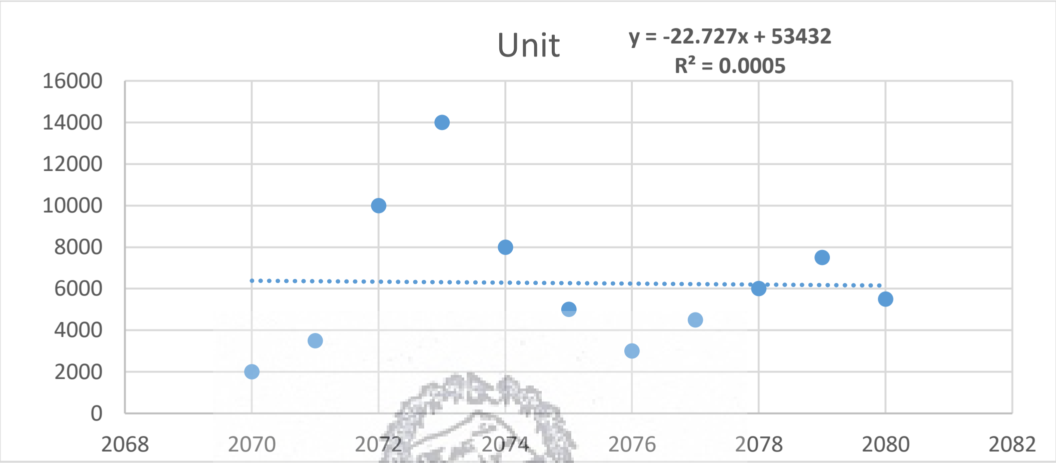

Fig. 39: Mapping the unit of e-2wheelers using the linear regression method

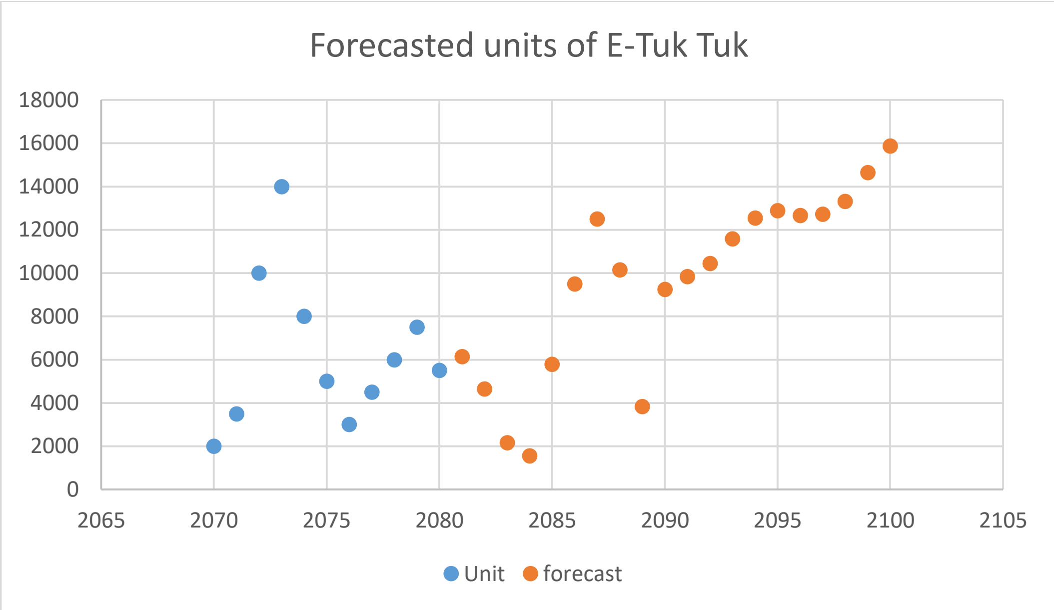

Fig. 40: Forecasted units of electric ricksaws/tuktuk

Calculating the new electric ricksaw/tuk tuk and their respective battery pack, it has been forecasted that 192,016 units of an electric ricksaw/tuk tuk will be using **1793772** KWh of battery pack. Since almost 99 % of an electric tuk tuk have a lead acid battery as an energy source till date, we assume they will continue to use lead acid battery packs till 2083 and due to globalization of li-ion battery packs, li-ion battery packs will replace lead acid battery packs from 2084. Through this assumptions, it has been forecasted that **6,249,356** KWh of battery pack will undergo EOL cycle and may enter any secondary applications.

Forecasted EOL battery pack for private EV cars for next 10 years

Since the electric cars technology is changing with skyrocket momentum, its difficult to forecast the types of an electric with their battery capacity and volumes for 20 years. Also in the past 6-7 years of electric car market, none of the electric cars penetrated between these years have undergone through battery changing process, we consider that an electric car battery will last for 8 years approximately due to an average driving per day limited to not more than 45 kms.

Forecasting the volume of an electric cars for next 10 years, it has been found that there will be at least 294,569 units of e-car penetration.

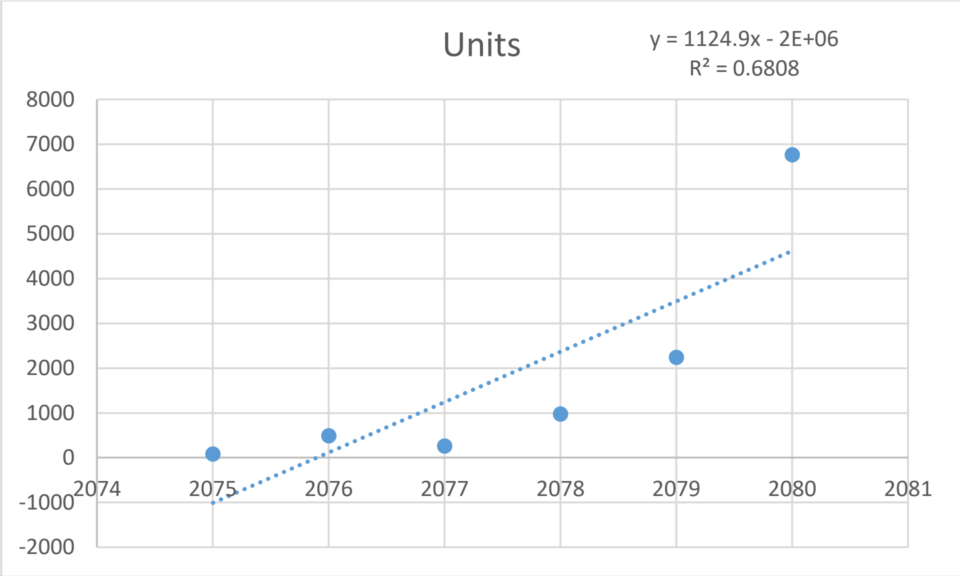

Fig. 41: Private EVs quantity trend in Nepal.

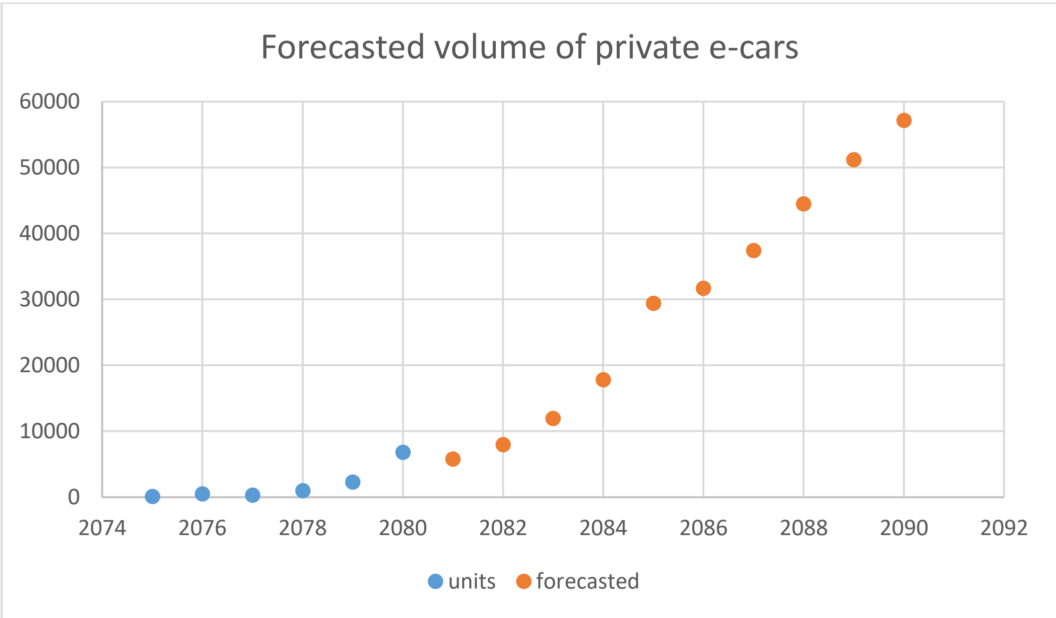

Fig. 42: Forecasted data of electric cars in the next 10 years using linear regression

Since its assumed that e-car battery packs will lasts for 8 years of an operation, the battery pack will be replaced once in next ten years and with simple calculation, its forecasted that there will be 546,630 KWh of battery packs going through EOL cycle and from where **382,641** KWh usable capacity will be available.

.

Forecasted EOL battery pack for commercial electric vehicles for next 20 years.

The most travelled vehicles per day in Nepal are covered by commercial electric vehicles that might go for an average of 250 kms per day**.** In the last 3 years the market of an electric commercial vehicles are increasing very high. Forecasting the volumes of e-commercial vehicles for next 10 years its been forecasted that there will be 38124 units of an electric commercial vehicles of the identical type that are currently available. The reason for forecasting for only 10 years is that an automotive technology is changing very frequently and these commercial vehicles will saturate within 10 years to penetrate newer kinds of vehicles.

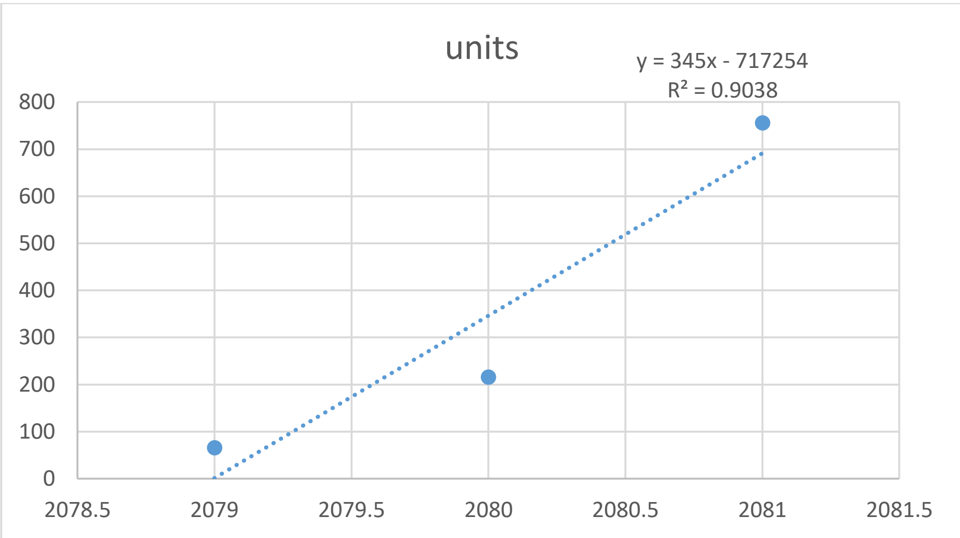

Fig. 43: Commercial EV quantity trend in Nepal

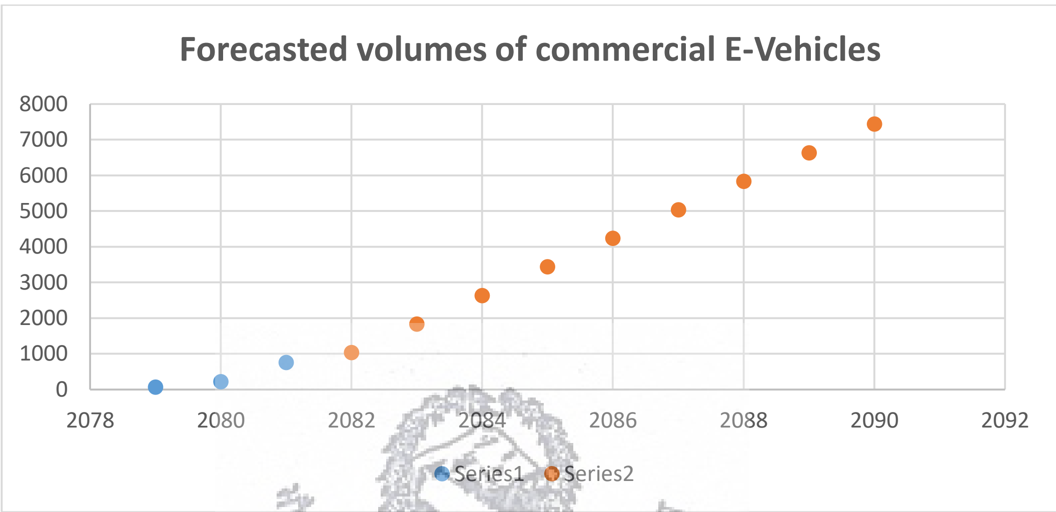

Fig. 44: Forecasted volumes of electric commercial vehicles

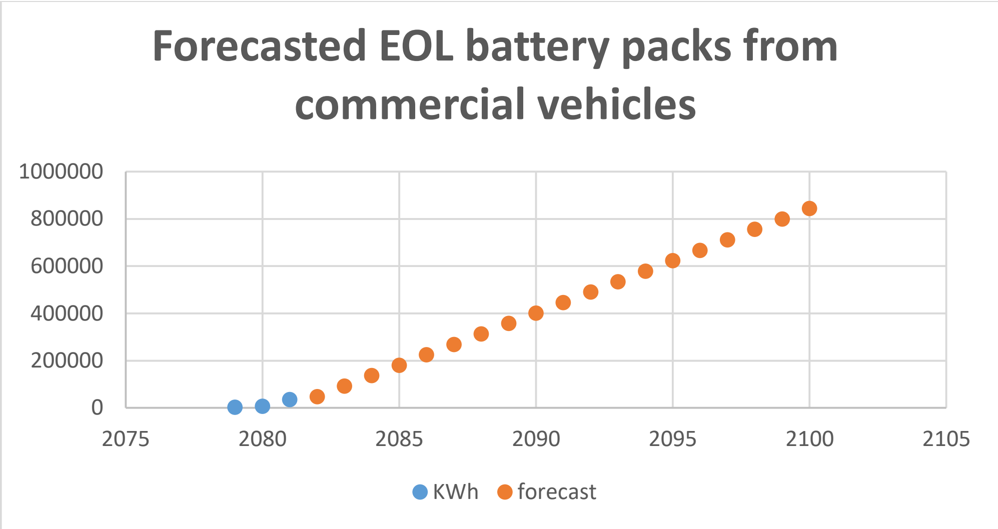

Fig. 45: Forecasted EOL battery packs for next 20 years

But at the other end the vehicles will be operated for next 20 years (atleast) and the battery packs going through EOL by every 200000kms as per present data from battery manufacturers, and being changed by every next 3 years it has been forecasted that by the end of next 15 years there will be around **11,952,047** KWh of battery packs going through their EOL cycle from where around **8,366,433 KWh** will be usable capacity as after EOL, the capacity is around 70%.

Recommendations for optimizing afterlife battery management practices in Nepal.

The managing part of the afterlife battery packs involves crucial optimization activities so as to make sure that the optimized process enhances sustainability and minimize environmental impact. The following recommendations presented below focuses on the entire lifecycle of the battery, from collection and testing to repurposing and recycling.

1. Implement advance collection system:

   The best way to collect afterlife battery pack is to ensure their efficient and safe collection. Developing an infrastructure for the convenient and accessible battery drop-off locations at dealerships, service centers and used battery collectors offering the financial incentives like deposit refund schemes so as to encourage consumers to return used batteries. Different public awareness program can be conducted to educate consumers on the importance of proper battery collection, disposal and the environmental benefits of reusing and recycling.

2. Standardize Testing and Grading Protocols:

   Develop consistent methods for assessing the condition and potential of used batteries so that the collection and grading the battery maintain consistency. The proper segregation of the battery cells will be easier. Implementing the globally recognized industry-wide standardized testing protocols to assess battery health, capacity, and performance by developing a clear grading system of the used battery packs (e.g., Grade A, B, C) based on battery condition, guiding their next use—repurposing or recycling.

3. Promote Battery Repurposing and Second-Life Applications:

   Since there will be at least 70% efficiency of battery packs during their end of life cycle, the life of used batteries can be extended through repurposing for secondary applications.

   The used battery packs can be used for storing energy in power sub staions, solar power plants, academic conversion or study related projects, power bank as secondary mobile ev battery charger and many more. But before the battery packs goes for their secondary applications, it is well recommended to establish the standardized testing protocols to ensure the safety and reliability of repurposed batteries. Investment from national and institutions in Research & Development to explore new and innovative applications for second-life batteries.

4. Develop Comprehensive Recycling Infrastructure: Once the battery packs are no longer suitable for secondary applications, it can be introduced to recycling facilities. The efficiency and capacity of recycling facilities could be enhanced to recover valuable materials. Recycling processes of the used battery packs can be promoted to keep the recovered materials within the battery manufacturing supply chain. But at first investment in Research & Development facilities is must to identify the capacity at national level and required steps to build capacity for recycling process. Collaboration with global recycling plants that have matured and advance recycling practices could speed up the adaptation of recycling plant at efficient way. Comprehensive recycling facilities and efficient infrastructure ensures high recovery rates of valuable materials such as lithium, cobalt, and nickel, which are critical for the production of new batteries and have financial values too.
5. Enhance Collaboration and Knowledge Sharing:

   Cultivate the cooperation practices among different relevant stakeholders to improve battery management practices. Encourage the partnerships between the global battery manufacturers and their local suppliers, authorized electric vehicle dealers/ companies, recyclers, and researchers to share best practices and innovations. Developing a common platforms for sharing data on battery performance, recycling efficiency, and their relevant environmental impact as well as to discuss challenges, opportunities, and advancements in battery management on the parallel side. Investing on Research & Development facilities to conduct comprehensive studies to understand the full environmental impact of different battery management practices and identify areas for improvement. Different awareness program could be conducted to engage the consumers in sustainable battery management practices by educating the importance of proper battery disposal and the benefits of recycling and repurposing. Encouraging the launching of an initiatives to inform the consumer about the importance of proper battery disposal and the benefits of recycling and repurposing. Developing an AI based online platforms and mobile apps to guide consumers on proper, reliable and safe collection/ disposal of their used batteries.

6. Implement Regulatory Frameworks and Incentives:

   Supportive policies and financial incentives to encourage sustainable practices of managing afterlife battery pack will play an impactful role. Enforcement of strict regulations for the safe disposal, recycling, and transportation of used batteries by defining the responsibilities of authorized stakeholder. Mandating that the local suppliers and assemblers/manufacturers takes the responsibility for the entire lifecycle of their batteries, including end-of-life management will filter genuine suppliers and manufacturer as well as will establish a proper system of managing afterlife battery packs. Encourage the local startups working on managing afterlife battery packs by providing financial support to companies investing in recycling and repurposing technologies.

The above recommended steps could help to establish following environmental impacts.

a) Magnifies the overall sustainability of the battery lifecycle.
b) Establish a better society by reducing an improper disposal and potential environmental contamination.
c) Maximizes the reuse potential and prolongs battery life by ensuring that used batteries are directed to the most appropriate and sustainable afterlife use.
d) High recovery rate of critical materials like lithium, cobalt, and nickel will minimize the necessity for mining new raw materials, lowering the environmental footprint.
e) Promotes transparency and accountability in the afterlife battery management process accelerating the adoption of best practices and innovative solutions reducing unnecessary disposal.

Protocols for the safe and efficient disassembly, storage and transportation of battery packs to recycling and repurposing facilities.

To ensure safety, efficiency, and environmental sustainability. For the disassembly, storage, and transportation of afterlife battery packs from electric vehicles (EVs), robust protocols must be established. Following protocols shall help to mitigate the overall risks associated with hazardous materials and optimize the process for recycling and repurposing of used battery packs.

1. Disassembly Protocols

   To make sure that the every components of used battery packs are handled correctly and hazardous materials are managed responsibly, battery packs must be disassembled safely and efficiently. The following steps shall be approached to disable the used battery packs.

   I. Preparation of disassembly by:

      - Make sure that only technically trained man powers with an appropriate personal protective equipment (PPE) including gloves, safety goggles, and fire-resistant clothing are engaged in battery disassembly procedures and safety protocols.
      - Verify that all tools and equipment are in good working condition and appropriate for handling high-voltage components.

   II. Apply safety precautions by:

      - Make sure that the battery pack is disconnected from the vehicle and is isolated in a safe zone.
      - Technicians must use insulated gloves and insulated tools to prevent electrical shocks and short circuits.
      - Availability of fire extinguishing equipment in disassembly zone is mandatory.

   III. Disassembly Process:

- External casing must be removed carefully to avoid damaging internal cells.
- Individual cells or modules shall be extracted systematically, labeling and documenting each and every component.
- Hazardous materials (such as electrolyte) shall be isolated or managed following designated environmental regulations and safety guidelines.

IV. Inspection and Sorting:

- Inspect cells for damage or leakage.
- Cells and modules shall be segregated or sorted based on their condition for either recycling or repurposing.

2. Protocols for storing used battery packs

To prevent accidents, degradation, and environmental contamination, the used battery packs and their components shall be stored suing the following steps.

i. Requirements for used battery packs storage facility:

- storage area must be well-ventilated and temperature-controlled
- Make sure that the storage area is secured, fireproof, and equipped with fire suppression systems.

ii. Safety Measures:

- Non-conductive surfaces should be used to store battery packs to prevent short circuits.
- A safe designated distance should be maintained between stored battery packs to minimize the risk of thermal runaway.

iii. Inventory Management:

- All the stored used battery packs and components shall be labelled and well documented noting their condition and intended use (recycling or repurposing).
- A tracking system shall be implemented to monitor the storage duration and condition of each battery pack.

iv. Regular Inspection:

- Regular inspections shall be conducted for signs of damage, leakage, or degradation.
- Ensure immediate removal and proper handling of any compromised battery packs.

3. Protocols for safe Transportation of the used battery packs

To make sure that the used battery packs are safely and efficiently transported to recycling and repurposing facilities, minimizing the risk of accidents and environmental harm, following steps shall be approached.

I. Preparation for Transportation:

- Enhance UN (UN 3840, UN 3481 and IATA) -certified packaging designed for transporting lithium-ion batteries.
- Ensure labeled packaging according to hazardous material transportation regulations.
- Obtain all necessary permits and documentation for the transportation process.

II. Safety Measures:

- Secure battery packs to prevent movement during the entire transportation period.
- if necessary use temperature-controlled container/platform during the transportation to maintain battery stability.

III. Transportation Process:

- Select reputable and certified transporters experienced in handling hazardous materials.
- Ensure transport vehicles are equipped with emergency response kits and trained personnel.

IV. Transportation Process:

- ➢ Certified transporters experienced in handling hazardous materials shall be employed to transport the used battery packs to destination.
- ➢ Emergency response kits and trained personnel are mandatory in the entire transportation of used battery packs

V. Facility at receiver:

- ➢ Verify that the receiving organization is well facilitated to handle and process the incoming battery packs.
- ➢ A handover inspection must be conducted to document the condition of battery packs upon arrival.

Guidelines

For the Development of Standardized Methods for Testing and Grading of used battery packs:

The following guidelines shall be approached for testing and grading of used battery packs so that the overall second life applications and recycling shall go systematically.

1. Initial Inspection: Check for physical damage, leaks, or signs of corrosion via visual inspection process. Verify battery history, including usage patterns and maintenance records as far as possible.
2. Electrical Testing: using standardized discharge/capacity tester devices measure the battery's remaining capacity, assess voltage levels and current delivery capability under load.
3. Thermal Analysis: Used battery temperature shall be monitored during charging and discharging cycles to identify thermal stability issues. Thermal imaging cameras or temperature sensors shall be used during charging and discharging cycles to identify hotspots and unusual thermal patterns.
4. Life Cycle Testing: Conduct accelerated aging tests to estimate the remaining cycle life of the battery.
5. Grading Criteria: As per the practices adopted globally, set up the criteria for grading as explained below:
   - **Grade A:** Batteries with >80% of original capacity, suitable for reuse/repurpose in EVs or energy storage.
   - **Grade B:** Batteries with 50-80% capacity, suitable for stationary energy storage applications.
   - **Grade C:** Batteries with <50% capacity, recommended for material recovery and recycling.
6. Certification: Issue a standardized certificate indicating the test results and grade of the battery.as per the above mentioned testing protocols.

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नेपाल सरकार
सिंहदरबार, काठमाडौं

For safe and efficient recycling of used battery packs

The following guidelines shall be approached for safe and efficient recycling of used battery.

1. Collection and Transportation: Ensure safe and compliant transport of used batteries to recycling facilities as mentioned in above protocols by using designated UN-certified containers for hazardous materials, labelling and documenting the contents and condition of each shipment.
2. Pre-Treatment: Safely discharge batteries using controlled discharge stations to bring batteries to a zero-energy state so as to prevent electrical hazards during recycling.
3. Dismantling: Use advanced manual or robotic systems to separate the casing, modules, and cells to dismantle battery packs safely and efficiently into their constituent components. Handle carefully and store hazardous materials separately.
4. Material Separation: Shred or crush the batteries using industrial shredders to break down battery cells into smaller components.
    - Sieves and classifiers shall be used to separate materials based on size and density.
    - Magnets can be used to extract ferrous metals.
    - Air classification can be applied to separate materials by weight.
5. Chemical Processing: Apply hydrometallurgical and pyrometallurgical process to extract and recover valuable metals.
6. Refinement: Make sure the materials meet industry standards for new battery production post purification of the recovered materials to battery-grade quality.
7. Waste Management: Comply with environmental regulations for safely treatment and dispose of hazardous by-products.

Business Model for Effective Management of Afterlife EV Batteries in Nepal

The efficient and reliable management of afterlife electric vehicle (EV) batteries is very important for environmental sustainability and resource optimization in Nepal. This business model presented in this report outlines a comprehensive approach to collect, test, grade, recycle, and repurpose used EV batteries. It involves collaboration among key stakeholders, leveraging advanced technologies, and ensuring regulatory compliance to maximize economic, social, and environmental benefits for sustainable future of Nepal.

The following fig details the different stages of EOL battery packs going through different stages of re-use and recycling process from where an effective business model can be derived at different time frame of battery life cycles.

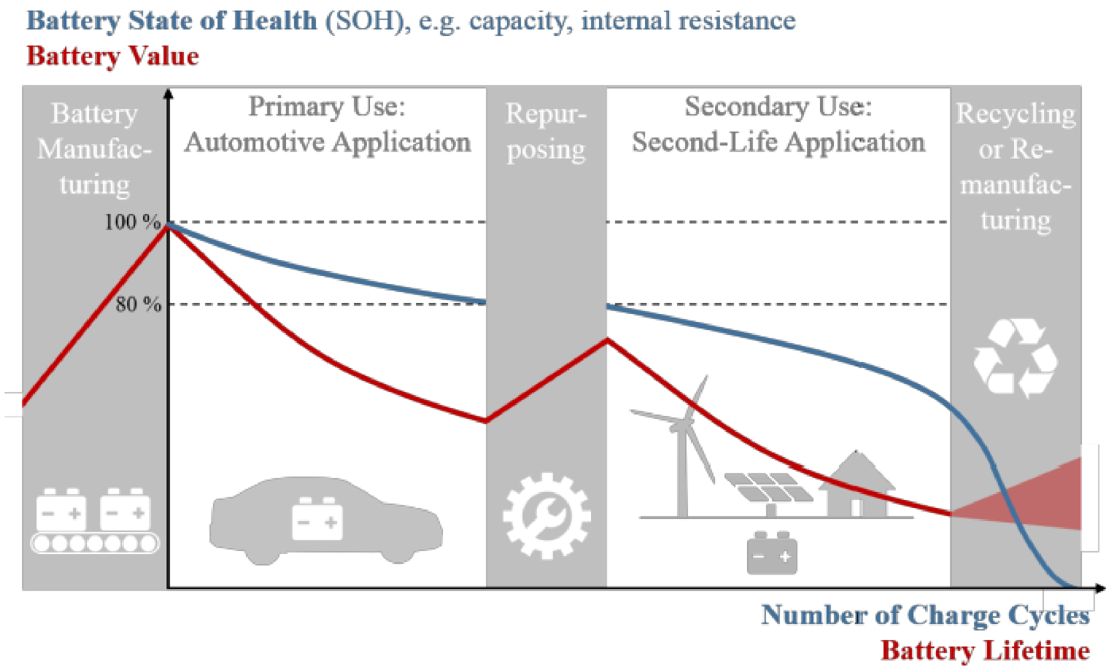

Fig. 46: Battery pack through different life cycle. [142]

"Afterlife EV Battery packs" majorly focuses on repurposing and recycling electric vehicle (EV) batteries that have reached the end of their useful life for vehicles at their different timeline. These batteries still retain significant capacity and can be used in various applications, including energy storage systems for homes, businesses, grid stabilization and raw materials for new Evs.

The following model details different aspect of business model.

Value Proposition:

Cost-effective Energy Storage: Offer affordable energy storage solutions by leveraging repurposed EV batteries.

Environmental Sustainability: Promote eco-friendly practices by extending battery life and reducing electronic waste and carbon footprint.

Target Market:

Hydropower power substations: Energy storage system for substations for more reliable battery packs chemistry compared to traditional lead acid battery packs.

Residential: Homeowners interested in renewable energy and reducing electricity bills.

Commercial: Businesses seeking energy efficiency and sustainable practices.

Utilities: Companies looking for grid stabilization solutions and peak shaving capabilities.

Revenue Streams:

Battery Sales: Sell refurbished EV batteries and recycled raw materials at competitive prices.

Installation Services: streaming revenue by installation and maintenance services for energy storage systems.

Subscription Models: Provide subscription-based plans for battery monitoring, maintenance, and upgrades.

Key Activities:

Battery Collection and Testing: Procure used EV batteries, assess their performance, and refurbish them through in-depth research and development activities.

System Integration: Design and integrate energy storage systems tailored as per national and commercial requirements

Customer Support: Provide ongoing support, maintenance, and upgrades for installed repurposed battery pack systems.

Key Resources:

Supply Chain: Establish partnerships with local EV manufacturers, recyclers, and suppliers of battery management systems. Doko recycler has initiated li-ion battery cell recycling from cell phones and electronic gadgets who could be major stakeholder in years to come

Technology: Utilize advanced testing and refurbishment technologies to maximize battery performance in collaboration with global leaders.

Partnerships:

Local and global EV Manufacturers: Source used batteries directly from manufacturers.

Recyclers: Collaborate with recycling companies for battery disposal and material recovery.

Installers and Contractors: Partner with professionals for system installation and maintenance.

Cost Structure:

Battery Acquisition: Cost of acquiring used EV batteries from manufacturers or recyclers.

Refurbishment: Expenses related to testing, refurbishing, and upgrading batteries.

Operations: Costs associated with logistics, installation, customer support, and administration.

Channels:

Direct Sales: Online platform for direct sales to consumers and businesses.

Partnership Networks: Collaborate with installers, contractors, and distributors for wider market reach.

Marketing and Promotion: Use digital marketing, industry conferences, and partnerships with environmental organizations to raise awareness.

Customer Relationships:

Consultative Sales: Provide personalized advice and solutions based on customer energy needs.

Support Services: Offer ongoing support, monitoring, and maintenance to ensure customer satisfaction.

Present cost structure of repurposing ev batteries.

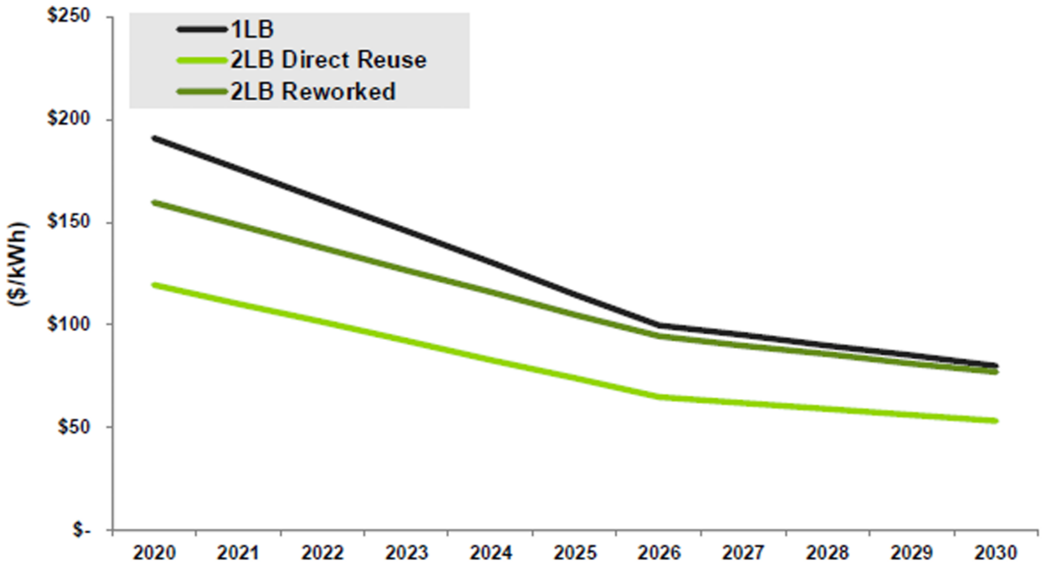

Fig. 47: Forecasting of cost of EV batteries. [53]

The above figure is the forecast of the cost of EV Batteries till 2030. The cost of battery per kWh is predicted to drop in the coming future. The price of reworked EV batteries is almost equal to new EV batteries, whereas the cost for direct reuse is found to be lower even in 2030 [53]. This concludes the effectiveness and importance of direct repurposing over refurbishment.

However, as estimated by Haram M., the price for direct reuse batteries which have passed the technical test for EoL depends upon the state of health, new battery cost, factor of lifespan, factor of discount, and factor of incentive [143].

This model has limitations as other factors like labour, administration, facilities, and additional equipment costs are not considered. The cost estimated in [143] is mentioned in the table below along with its usage.

Table XIX. *Usage and estimated cost for used EV batteries according to SOH.* [143]

SOH Level	Usages	Expected Costs
High SOH (80%-100%)	- These batteries retain most of their original capacity, making them highly valuable.	$80 to $140 per kWh
	- They are ideal for energy storage, backup power, or repurposing for lighter electric vehicles such as bicycles or scooters.	
Medium SOH (60%-79%)	- These batteries have significant remaining capacity but may not be suitable for high-demand applications.	$55 to $100 per kWh
	- They are suitable for stationary energy storage applications like solar energy storage or grid stabilization.	
Low SOH (40%-59%)	- These batteries have limited capacity, making them suitable for low-demand applications or as a supplementary energy source.	$20 to $60 per kWh
	- They can be used in smaller off-grid projects or in applications where weight or size is not a critical factor.	
Very Low SOH (<40%)	- These batteries may not have a useful second life for energy storage and are likely nearing the end of their lifecycle.	$10 to $30 per kWh
	- Their use may be limited to very basic or short-term energy storage needs.	
	- Batteries with less than 20% SOH are considered end-of-life and should be recycled.	

However, in most cases, the battery below 50% is considered best for recycling because of poor energy density and other technical parameters.

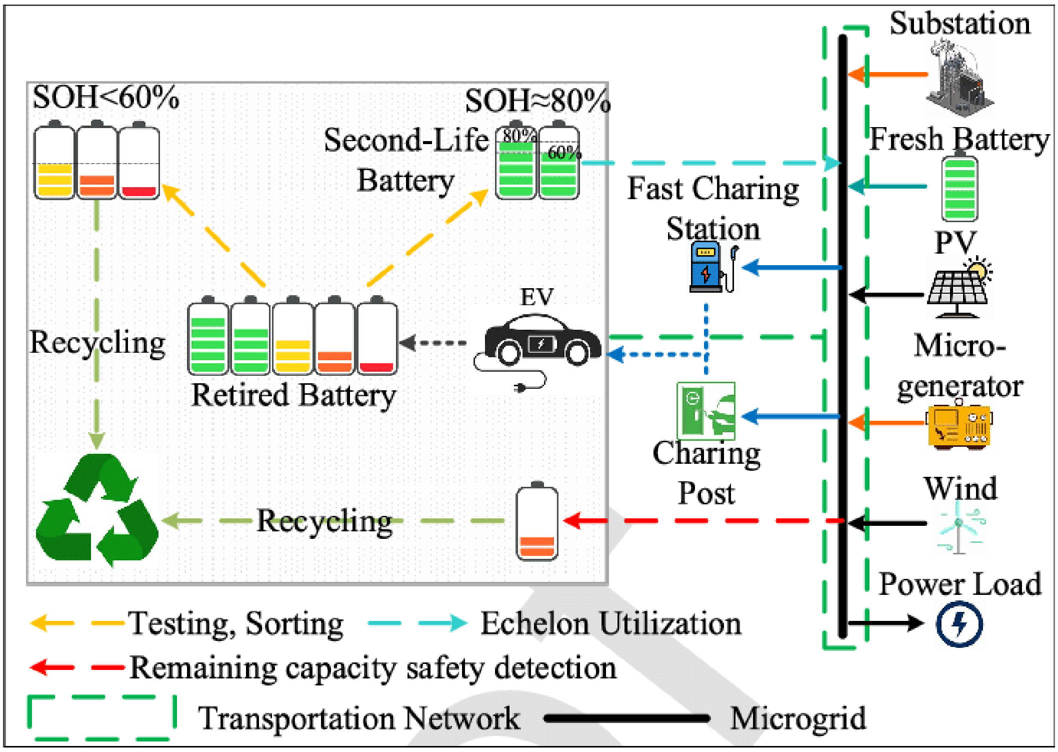

Fig. 48: Retired-battery-processing-and-system-operation-architecture. [144]

If the State of Health (SOH) of a used battery is 80% during the remanufacturing process, it is reconditioned and used again in small electric vehicles after repurposing. However, if the SOH is between 70% and 80% during the repurposing process, the afterlife battery is repacked and utilized in energy storage systems that are connected to alternate energy sources. Batteries with State of Health (SOH) levels below 40% shall go for recycling in order to reclaim valuable materials. The main recycling techniques for LiBs are pyrometallurgical and hydrometallurgical processes. Nepal in the current phase is deficient in recycling technologies and lacks the necessary infrastructure. In order to efficiently manage battery waste in Nepal at the moment, it is crucial to prioritize the implementation of reuse technologies, as the current processes for collection, separation, and sorting are insufficient. But with the proper investment on R&D, Capacity development and required infrastructure Nepal too shall proceed for recycling.

The time frame of battery life cycle at different SOH from one of the research is presented in the figure below.

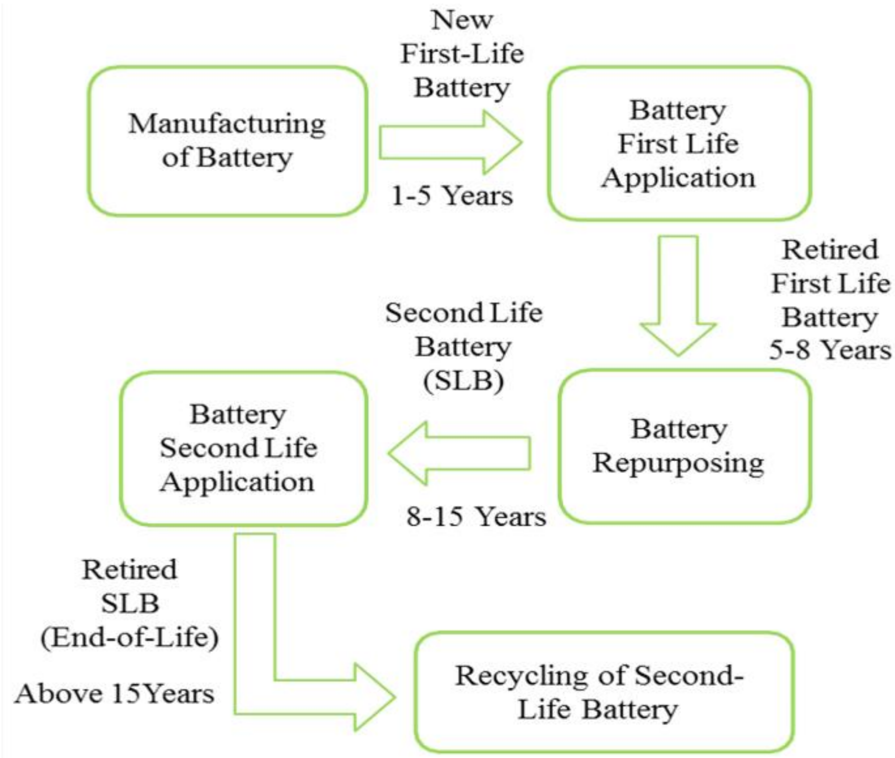

Fig. 49: Flowchart of electric vehicle (EV) battery life cycle. [145]

Conclusion:

With the increasing uptake of e-mobility, the treatment of used EV batteries will become a challenge not only in Nepal but globally. While research on recycling technologies for LiBs is ongoing and showing promising results, the technology is not yet ready for large-scale applications. Additionally, the current lack of availability of EV batteries hinders the development of profitable recycling business models. Second-life applications can act as a buffer to prolong the life of EV batteries until profitable recycling solutions are available. They are, however, not to be considered as interim solutions, but rather actions that offer relevant ecological and economic benefits and should therefore always be sought before recycling.

Ultimately, second-life applications should be integrated into a larger circular economy around end of life EV batteries.

As e-mobility is currently starting to develop in Nepal, the country is at an optimal position to develop a second-life and recycling system in parallel to the increased uptake of EVs. This will help limit negative impacts related to the end of life problem of EVs and can instead provide environmental and economic benefits.

"Afterlife EV Batterypacks" through this report aims to capitalize on the growing demand for sustainable energy solutions by repurposing used EV batteries. By focusing on affordability, reliability, and environmental benefits, an efficient business can establish itself in the burgeoning market of energy storage systems, catering to residential, commercial, and utility customers alike.

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Annex

Annex. 1

Policies and regulations of various countries for ensuring reuse and recycling safety

S. N	COUNTRY	PHASE	POLICY/REGULATION	ACTION
1	Europe	Labeling	New EU battery policy	Labeling complying with ADR norms or any other labeling indicating the presence of hazardous material
		End of first life		SoH data and battery passport
		Other		Prohibits disposal to the environment
2	United Kingdom	Dismantling	Waste battery and accumulator regulations	Details procedure for dismantling battery
		Storage and transportation		Safe and environment-friendly transport
3	United States	Labeling	AB 2832	Information regarding type of material and electrode
4	China	Labeling	GB/T34014-2017	Unique labeling of battery
		Reuse	NEA	Mandatory compliance with safety evaluations Regular evaluation of battery and emergency plan
		Storage	GB 18599-2016	Safe storage of waste power battery
			GB/T33598-2017	Storage management standard
		Dismantling		Dismantling standard

		Packaging and transport	WB/T 1061-2016	Safe transportation and packing
5	Korea	Reuse	KBIA	Second-life battery grading evaluation
6	India	Storage and transportation	Battery Waste Management Rule 2022	CPCB is developing guidelines for storage and transportation
		Post-processing		Disposal according to Hazardous Waste Management Rule 2016

Annex 2.

Stakeholder engaged.

S. N	Name	Organization	Engaged to Vehicle type
1	Bharat Poudel	Clean Energy International Pvt Ltd	Electric two – wheeler and 3-wheeler
2	Rabi Neupane	Green Energy	Electric three-wheeler
3	Baliram Kushuwa		Electric three-wheeler
4	Shrawan Ghimire	Aarsshibad Interprises	Safa Tempo li-ion battery supplier
5	Lopchan Lama	NEVI	Safa Tempo li-ion battery supplier
6	Suhshil Shrestha	BYD	4-wheel private car
7	Jitendra Shrestha	BYD	4-wheel private car
8	Gaurav Raj Pandey	Theego (DFSK)	Commercial vehicle

9	Mukunda	Theego	Commercial vehicle
10	Janak Risal	Saajha Yatayat	Electric bus
11	Dinesh Dahal	SRM	Commercial vehicle
12	Sagar Khadka	KYC/Kinglong	Commercial vehicle
13	Nishan Tamang	Foton	Commercial vehicle
14	Prashant Bajracharya	Ryan Energy	Electric three-wheeler/electric cargo vehicle
15	Dipan Shrestha	Ryan Energy	Electric three-wheeler/electric cargo vehicle
16	Indra Jha	Mahindra Aghni	4-wheel private car
17	Sam Sapkota	Henry	4-wheel private car
18	Dipesh poudel	TATA Sipradi	4-wheel private car
19	Sujan Tamrakar	Yatri	2-wheeler
20	Sachin Aryal	MG Paramount motor	4-wheel private car
21	Surendra Shreshta	Asta Motor	2-wheeler
22	Rohit Shrestha	Battery supplier	2-wheeler
23	Santosh Neupane	Leveneng	2-wheeler
24	Umesh Raj Shrestha	GEMS	Commercial vehicle
25	Gautam Kashapati	Victory	Commercial vehicle
26	Prakash Tuladhar	Go Now	Commercial vehicle

27	Raju Kandel	Higher	Commercial vehicle
28	Pankaj Panjiyar	DOKO recycler	Recycling company
29	Shiva Bohara	Biz News	Media
30	Prof Daniel Tuladhar	Kathmandu University	Institution

Annex 3.

Sample Questionnaire used for collecting the data.

Section 1: Dealer/workshop/media/Recycling/Institution Information

Dealer /workshop/media/Recycling/Institution Name:

Dealer/workshop/media/Recycling/Institution Address:

Name: [Text Field]

Phone Number: [Text Field]

Email: [Text Field]

Years in Operation: [Text Field]

Section 2: Vehicle Sales Data

Total Number of EVs Sold:

[Numeric Field]

Types of EVs Sold:

Passenger Cars: [Numeric Field]

Motorcycles/Scooters: [Numeric Field]

Commercial Vehicles: [Numeric Field]

Other (please specify): [Text Field]

Sales Trend Over the Past 5 Years:

Year 1: [Numeric Field]

Year 2: [Numeric Field]

Year 3: [Numeric Field]

Year 4: [Numeric Field]

Year 5: [Numeric Field]

Market Share (Percentage) in Local EV Market: [Text Field]

Section 3: Technical Capacity and Specifications

Types of Batteries Used in EVs Sold:

Lithium-Ion/LFP

Nickel-Metal Hydride

Lead-Acid

Other (please specify): [Text Field]

Average Battery Capacity (kWh) by Vehicle Type:

Passenger Cars: [Text Field]

Motorcycles/Scooters: [Text Field]

Commercial Vehicles: [Text Field]

Other (please specify): [Text Field]

Typical Range (km) on a Full Charge by Vehicle Type:

Passenger Cars: [Text Field]

Motorcycles/Scooters: [Text Field]

Commercial Vehicles: [Text Field]

Other (please specify): [Text Field]

Charging Time (Hours) by Vehicle Type:

Passenger Cars: [Text Field]

Motorcycles/Scooters: [Text Field]

Commercial Vehicles: [Text Field]

Other (please specify): [Text Field]

Section 4: End-of-Life (EOL) Battery Management

Does your dealership offer EOL battery management services?

Yes

No

If yes, please specify the services provided:

Collection and Storage

Testing and Grading

Recycling

Repurposing/Second-life Applications

Disposal

Other (please specify): [Text Field]

Number of EOL Batteries Managed Annually:

[Numeric Field]

Procedures Followed for EOL Battery Management:

[Text Field]

Partnerships with Recycling or Repurposing Companies:

Yes

No

If yes, please specify the companies and type of partnership: [Text Field]

Percentage of Batteries Collected that are:

Recycled: [Text Field]

Repurposed: [Text Field]

Disposed: [Text Field]

Challenges Faced in EOL Battery Management: [Text Field]

Suggestions for Improving EOL Battery Management Practices: [Text Field]