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SUSTAINABLE Li-ION EV BATTERY RECYCLING IN NEPAL

BY

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A THESIS

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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a project report entitled "Sustainable Li-ion EV Battery Recycling in Nepal" submitted by Siddhartha Khadka in partial fulfillment of the requirements for the degree of Master of Science in Renewable Energy Engineering.

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ABSTRACT

Concerns are arising in Nepal due to the fast growth in the adoption of electric vehicles, specifically regarding the handling of spent lithium-ion batteries at the end of their life. As the nation progresses towards clean mobility and integrating renewable energy, sustainable recycling is crucial to decrease environmental impacts and recover valuable materials. This study evaluates the technical and financial viability of recycling and repurposing Li-ion electric vehicle batteries in Nepal, relying on primary research, expert advice, and secondary data from transport organizations, customs documentation, and existing literature. The reliability of the data was confirmed using AHP, where the consistency ratio was below 0.1, and Cronbach's Alpha exceeded 0.7. LFP and NMC chemistries exhibit strong recyclability potential among the evaluated options, with direct recycling being the most suitable approach due to low emissions, cost efficiency, and compatibility with hydropower. Economic and technological modeling suggests that a facility with a 5,000-ton-per-annum capacity can achieve a 22% return on investment within a period of 2.9 years and decrease CO_2 emissions by approximately 75,000 tons each year. The findings indicate Nepal is moving towards a circular and low-carbon battery economy.

Keywords: Lithium-ion battery, EV recycling, direct recycling, Nepal, circular economy, second-life battery, techno-financial analysis, carbon footprint.

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LIST OF ABBREVIATION

AHP	Analytic Hierarchy Process
Al	Aluminum
CAPEX	Capital Expenditure
CAGR	Compound Annual Growth Rate
Co	Cobalt
CO_2	Carbon Dioxide
CR	Consistency Ratio
Cu	Copper
DOE	Department of Energy (USA)
DoTM	Department of Transport Management (Nepal)
EIA	Environmental Impact Assessment *(if used)*
EOL	End of Life
EPR	Extended Producer Responsibility
EV	Electric Vehicle
GHG	Greenhouse Gas
IEA	International Energy Agency
IRR	Internal Rate of Return
kWh	Kilowatt-Hour
LCA	Life Cycle Assessment
LIB	Lithium-Ion Battery
Li	Lithium
LFP	Lithium Iron Phosphate
Mn	Manganese
MoEFCC	Ministry of Environment, Forest and Climate Change (India)

MPV	Multi-Purpose Vehicle
NCR	National Capital Region (India)
Ni	Nickel
NMC	Nickel Manganese Cobalt
NPV	Net Present Value
OPEX	Operational Expenditure
PPP	Public–Private Partnership
PRO	Producer Responsibility Organization
ROI	Return on Investment
SOC	State of Charge *(battery term)*
SUV	Sports Utility Vehicle
TU	Tribhuvan University
USD	United States Dollar

CHAPTER ONE: INTRODUCTION

1.1 Background

1.1.1 Global Context

One of the most important tactics in international attempts to cut greenhouse gas emissions and fight climate change is the switch to electric vehicles, or EVs. Globally, EVs are expected to account for more than 50% of new automobile sales by 2030 ((IEA), 2022). Improvements in battery technology, falling prices, and legislative incentives supporting clean transportation are the main drivers of this change. However, managing the end-of-life (EOL) of lithium-ion (Li-ion) batteries, which power the majority of EVs, is a major difficulty brought on by the increase in the EV usage

After 8 to 15 years, Li-ion batteries lose some of their performance and are no longer acceptable for use in automobiles. They do, however, still have 60–80% of their original capacity, which opens the door to possible second-life uses such energy storage for grids that use renewable energy. Reducing environmental risks, lowering dependency on the extraction of raw materials, and advancing a circular economy all depend on the proper recycling and repurposing of these batteries.

The global electric vehicle industry has witnessed extraordinary expansion in the past ten years. In 2023, global EV sales surpassed 14 million units, representing 18 percent of all new car sales, which was significantly higher than the 2 percent seen in 2018 ((IEA), 2022). Most of this growth is happening in key markets: China made up nearly 60% of electric vehicle sales, whereas Europe and the United States together accounted for around 25% and 10% respectively. According to the (IEA), 2022) Global EV sales totaled 5.6 million units in the first four months of 2025, marking a 29 percent increase over the same period in 2024; China recorded 35 percent growth, Europe 25 percent, and North America experienced slower growth at just 5 percent.

Global EV adoption continues to be led by China, whose market share reached 76 percent in 2024, when 14.1 million EVs were sold domestically, accounting for 69 percent of its total output. The company's dominance is evidenced by its status as the top manufacturer of both electric vehicles and lithium-ion batteries, producing over 60 percent of electric vehicles and 80 percent of the world's battery supply. The International Energy Agency (2023) forecasts that by 2030, over 50 percent of global new vehicle sales will be electric vehicles, representing a positive step toward decreasing oil use and tailpipe emissions `but also leading to a significant surge in the number of end-of-life lithium-ion batteries. Unless sustainable recycling systems are implemented, approximately millions of tons of waste batteries could pile up every year by 2040, thereby generating fresh environmental and economic hurdles.

Numerous nations have already put in place robust battery recycling laws and infrastructure. For instance:

- The Battery Directive, which mandates that manufacturers guarantee battery collection and recycling, has been enforced by the European Union (EU) (Directorate-General for Environment, 2025)
- China encourages direct recycling techniques and has required traceability mechanisms for old EV batteries (Zanoletti, 2025)
- To recover elements like cobalt, nickel, and lithium, the US has made investments in closed-loop recycling systems (C.M. Costa, 2021)

Only 5–10% of Li-ion batteries are now recycled worldwide, despite these efforts, underscoring the pressing need for effective and scalable alternatives (Harper, Sommerville, Kendrick, & Driscoll, 2019)

1.1.2 Regional Context: South Asia and Southeast Asia

Electric vehicle adoption is gaining momentum at varying rates across countries in South Asia. India has established itself as a regional leader, especially in the three-wheeler market, with sales of 580,000 electric three-wheelers in 2023 representing a 65 percent surge over 2022, making it the world's biggest market for electric rickshaws, as reported by the IEA in 2024. The Indian government has also put in place the Battery Waste Management Rules of 2022, which brought in Extended Producer Responsibility. This requires manufacturers and importers to ensure the collection and recycling of used batteries, as stated by the MoEFCC in 2022. Several South Asian nations, including

Bangladesh and Sri Lanka, are conducting pilot electric vehicle initiatives but are hindered by insufficient charging facilities and limited financial resources.

In Southeast Asia, Singapore is a model to follow with ambitious goals: electric vehicles made up 19 percent of all new car sales in 2024, and the government aims for 80 percent EV penetration by 2040, backed by substantial infrastructure investment, including a ratio of one public charger for every three electric vehicles (Land Transport Authority, 2024). Nepal can leverage these regional experiences to both identify opportunities and understand relevant policy frameworks. Adoption in South Asia is accelerating, but battery recycling and second-life systems are underdeveloped, which threatens long-term environmental pollution and forfeited economic opportunities.

1.1.3 Context in Nepal

Nepal's transition to EVs has been rapid, largely due to supportive government policies such as reduced customs duties and growing consumer interest in sustainable alternatives. In fiscal year 2023/24, Nepal imported **11,701 electric vehicles**, nearly tripling from 4,050 units in the previous year (Report, 2024)This momentum continued in fiscal year 2024/25, when EV imports surged to **44,535 units within the first ten months**, representing **73 percent of all four-wheeler imports**, a clear indication that EVs have become the mainstream choice for new vehicle buyers. The value of EV imports reached **NPR 43.99 billion (~USD 330 million)**, generating **NPR 22.76 billion** in customs revenue for the government.

China dominates Nepal's EV supply, accounting for nearly **74 percent of imports**, followed by India at around 25 percent, with smaller contributions from countries such as Germany, South Korea, and the United States. EV imports are diverse, ranging from low-power models (<50 kW) to premium vehicles (>200 kW), reflecting a broadening consumer base. Importantly, the share of higher-capacity EVs has grown significantly, demonstrating that EV adoption is no longer confined to compact and entry-level cars.

While this growth supports Nepal's climate commitments under its Nationally Determined Contributions (NDCs), it also creates a looming waste challenge. By 2035, Nepal is expected to host over **300,000 EVs**, which could result in the accumulation of more than **120,000 tonnes of waste LIBs** (Ministry of Energy, 2023). At present, Nepal has no dedicated framework for collection, reuse, or recycling of EV batteries. Used batteries are often stockpiled or disposed of informally, creating risks of heavy metal contamination, fire hazards, and environmental degradation. Furthermore, the absence of recycling facilities forces Nepal to rely entirely on imports for new batteries, adding to the trade deficit.

Nepal currently does not have a well-organized system for handling and managing end-of-life electric vehicle batteries. Key obstacles include:

- Lack of domestic recycling facilities in Nepal means there are no Li-ion battery recycling plants, resulting in a reliance on imported batteries and potential environmental hazards.
- Unlike many countries such as the EU and China, Nepal lacks specific policies for EV battery disposal, recycling, or second-life applications.
- Current uses for second-life batteries are underutilized, with opportunities existing for solar-powered micro grids, backup energy systems in remote telecommunications infrastructure, and rural electrification initiatives.
- If batteries are not properly recycled, they can lead to the pollution of soil and water. Furthermore, relying on imported new batteries elevates costs and exacerbates trade deficits.

Overcoming these difficulties necessitates scientific research, policy-driven initiatives, and investment in sustainable battery management systems.

Table 1.1: List of brands of EV in Nepal

Brand & Model	Battery Capacity (kWh)	Estimated Range (KM)	Vehicle Type
Avatar 11	90 / 116	575 / 680	Luxury SUV
Deepal S05	56.12	510	Compact SUV

Brand & Model	Battery Capacity (kWh)	Estimated Range (KM)	Vehicle Type
Deepal S07	66.8	410	SUV
Deepal S07L	79.97	485	SUV
Deepal L07	66.8	540	Sedan
Seers 3	53	405	Compact SUV
Seers 5	80	500	Premium SUV
Leap motor T03	37.3	265 / 395	Hatchback
Leap motor C10	69.9	~420	SUV
BYD Atto 3	60.48	~420	Compact SUV
BYD e6	71.7	~522	MPV
BYD Dolphin	44.9	~340	Hatchback
Tata Nexon EV	30.2	~312	Compact SUV
Tata Punch EV	25–35	~300–400	Micro SUV
Tata Tiago EV	24	~315	Hatchback
Hyundai Kona Electric	39.2 / 64	~305 / 482	Compact SUV
Volkswagen ID.4	77	~522	Premium SUV
Skywell ET5	85.96	~520 / 620	Luxury SUV

Brand & Model	Battery Capacity (kWh)	Estimated Range (KM)	Vehicle Type
Skywell BE11	51.92 / 71.98	~410 / 520	Midsize SUV
Tesla Model Y	75	~530	Premium SUV
BMW iX3 M	~80	~460	Premium SUV
GAC Aion Y	61.54	~490	Crossover
Neta X	62	~500	Crossover
LEV 01	67.1	~500	SUV
Peugeot Partner Tepee	22	~170	Family MPV
Jiayuan City Spirits	~12	~120	Micro EV
Mahindra e2o Plus	10.08	~140	Micro Hatchback
Kia Soul EV	27	~180	Compact Hatchback
THEE GO E8	15.2	~150	Micro Hatchback
MG S5 EV	49.1 / 62.2	~340 / 430	Compact SUV
MG Comet EV	17.3	~230	Micro Hatchback
Jaecoo J6	69.8	~400	SUV
Omoda 5 EV	61	430 / 510	SUV

Brand & Model	Battery Capacity (kWh)	Estimated Range (KM)	Vehicle Type
JMEV GSE Elight	49	~400	Sedan
Firefly EV	42.1	420	Subcompact Hatchback
Dongfeng Nammi 01	31.4 / 42.3	237 / 317	Hatchback
Proton e.Mas 7	49.52 / 60.22	TBA	SUV

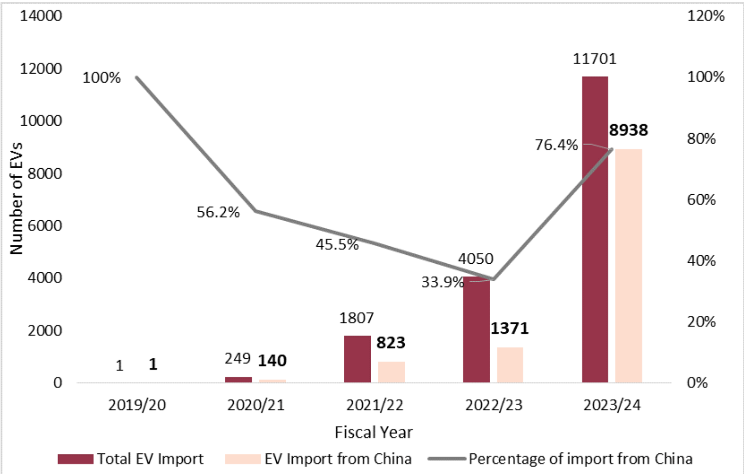


Figure 1.1: EV import trend in Nepal

Meanwhile, there are unexploited opportunities for reusing second-life EV batteries in Nepal. Typically, batteries that have been removed from vehicles can retain 60–80 percent of their original capacity, and they could be used in rural microgrids, as backup storage for telecom towers, in cold storage facilities, and integrated with Nepal's growing surplus of hydropower (Parajuli, 2020). A national framework for electric vehicle battery recycling and second-life use is therefore crucial, not only to reduce environmental risks but also to realize economic and social benefits, including job creation, reduced import dependency, and increased energy security.

1.2 Problem Statement

The swift uptake of EVs in Nepal has prompted worries about managing used and end-of-life lithium-ion batteries. Presently, there exist no set procedures for collecting, recycling, or repurposing used batteries, which could result in environmental and economic repercussions. The primary concerns consist of:

1.2.1 The absence of a well-developed EV battery recycling infrastructure.

Research conducted by the Ministry of Physical Infrastructure and Transport (The Comprehensive management of after-life battery pack from electric vehicle, 2025) recognizes this gap and suggests incorporating Extended Producer Responsibility (EPR) and second-life applications into Nepal's Electric Vehicle (EV) plan. Currently, there is no techno-financial evaluation of how a localized recycling system could function within the country's industrial and energy framework.

1.2.2 Health and Environmental Hazards

A critical gap has arisen between Nepal's ambitions for clean mobility and its waste management capabilities due to the lack of localized lithium recovery technologies, the integration of transport and waste policies, and infrastructure for safe waste storage and collection. A looming accumulation of electrochemical waste poses a threat to offset the climate benefits that electric vehicles are supposed to provide. (Xiaodong & Ishchenko, 2024)

1.2.3 Potential Uses for Repurposed Items

Although used EV batteries still possess considerable remaining capacity, large-scale repurposing for solar energy storage, micro grids, or emergency backup power has not been implemented in Nepal (Xu, Dai, & Gaines, 2020)

1.2.4 Lack of Regulatory and Policy Frameworks

Nepal currently has no legal requirements in place for battery collection, producer accountability, or rewards for recycling businesses.

1.2.5 Economic and technical obstacles.

The high expense of recycling infrastructure and dearth of skilled workers render local battery processing challenges.

If left unaddressed, Nepal faces a substantial threat to its environment, a depletion of its valuable resources, and the potential for missing out on opportunities to integrate renewable energy sources. The purpose of this research is to create a long-term, environmentally friendly plan for recycling EV batteries and utilizing them in secondary capacities in Nepal.

1.3 Research Questions

This investigation aims to resolve the aforementioned difficulties by providing answers to the following critical queries.

1. What framework might Nepal establish for sustainable recycling of Li-ion EV batteries?
2. What are the anticipated volumes of electric vehicle battery waste expected in Nepal over the next ten years?
3. Evaluating the techno-financial viability, which Lithium-ion battery recycling techniques are most suitable for implementation in Nepal?
4. How recycling and can reduce carbon emissions?
5. What are the primary obstacles to battery recycling in Nepal, and what measures can be taken to overcome them?

This study aims to offer a comprehensive scientific, and business framework for the long-term management of Li-ion batteries, helping to facilitate Nepal's shift towards cleaner energy and a more circular economy.

1.4 Objectives

1.4.1 Main Objective

To develop a sustainable and techno-economically viable framework for Li-ion EV battery recycling in Nepal

1.4.2 Specific Objectives

The study will concentrate on the following particular goals in order to accomplish the primary goal:

To analyze Nepal's Present EV Battery Lifecycle

- To determine the anticipated growth and import patterns for Li-ion EV batteries. Calculate how much battery trash might be produced over the course of the next five years.
- To determine and Assess Eco-Friendly Recycling Techniques, contrast the various pyro metallurgical, hydrometallurgical, and direct recycling methods for Li-ion batteries.
- To determine whether starting a small-scale battery recycling business in Nepal feasible.
- To evaluate how recycling and can reduce carbon emissions and electronic waste, or "e-waste."

  This methodical approach will assist Nepal in developing a battery recycling ecosystem that is both commercially feasible and sustainable.

1.5 Limitations

- The data taken for the study are collected from secondary sources.
- Limited Nepal-specific literature on Li-ion battery recycling, reliance on international studies that may not fully reflect local conditions

CHPTER TWO: LITERATURE REVIEW

The widespread adoption of electric vehicles has prompted a substantial rise in the demand for lithium-ion batteries. Managing the end of life of these items poses difficulties for the environment, the economy, and technological advancements (Gaines, 2018). Recycling of lithium-ion electric vehicle batteries in a sustainable manner is crucial for obtaining valuable materials, minimizing environmental risks, and dealing with resource shortages (Harper, Sommerville, Kendrick, & Driscoll, 2019). This study analyses existing recycling technologies, material recovery processes, policy frameworks, and the difficulties associated with battery recycling, with a particular emphasis on worldwide developments and local conditions in Nepal.

2.1 Li-ion Battery Composition and Recycling Challenges of Li-ion Batteries

Lithium-ion batteries comprise essential metals including lithium (Li), cobalt (Co), nickel (Ni), manganese (Mn), and graphite, which possess significant economic worth and are crucial for the manufacturing process of batteries (Zeng & Liu, 2023). The recycling of these batteries is difficult due to their intricate chemical makeup, potential safety hazards, and lack of uniformity in battery designs.

The significance of battery recycling encompasses both environmental and economic considerations.

Significantly reducing reliance on virgin materials through recycling can minimize the environmental impact associated with mining and refining processes, as noted by (Gaines, 2018). Research published by (Zeng & Liu, 2023)shows that recycling may satisfy as much as 25% of global lithium and cobalt requirements by 2040, thereby lessening the vulnerabilities associated with supply chains.

Battery Recycling Presents Several Challenges.

- The hazard posed by Safety Risks includes self-ignition caused by leftover electrical charge (Harper, Sommerville, Kendrick, & Driscoll, 2019)

- Higher processing costs are incurred when compared with extracting raw, unprocessed materials (Zeng & Liu, 2023)
- The absence of standardization in battery chemistry makes recycling more complicated, according to (Gaines, 2018)

In many developing nations, including Nepal, a scarcity of recycling facilities is a significant concern, as reported by the International Energy Agency in 2022.

2.2 Battery Recycling Technologies

2.2.1 Pyrometallurgical recycling involves the process of smelting.

Pyrometallurgy entails high-temperature smelting to extract metals including cobalt, nickel, and copper, whereas lithium and aluminum are typically discarded in slag (Harper, Sommerville, Kendrick, & Driscoll, 2019). Despite its widespread adoption due to ease of implementation and ease of expansion, this method still has some significant limitations.

- High energy consumption and carbon dioxide emissions.
- Lithium and aluminum are lost during the process, as reported by (Zeng & Liu, 2023). in 2023.

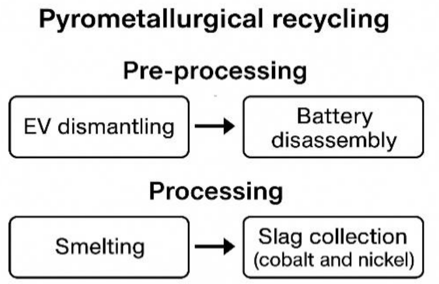


Figure 2.1: Pyrometallurgical

2.2.2 Hydrometallurgical recycling utilizes a leaching process.

The method employs chemical solutions to break down battery components and effectively recover metals such as lithium, cobalt, and nickel (Gaines, 2018).

- Key benefits include higher material recovery rates and lower CO_2 emissions.
- The key difficulties associated with this method include requiring substantial amounts of chemicals and involving a sophisticated waste disposal process (Harper, Sommerville, Kendrick, & Driscoll, 2019)

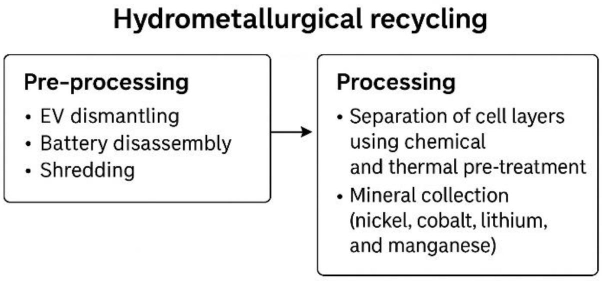


Figure 2.2: Hydrometallurgical recycling

2.2.3 Reclamation of Used Cathodes through Direct Recycling.

Battery materials, including cathode active materials, are preserved through direct recycling without being broken down into their separate elements (Zeng & Liu, 2023).

- Reducing processing costs should also enable the maintenance of battery performance.
- Currently undeveloped and not yet widely used in business settings

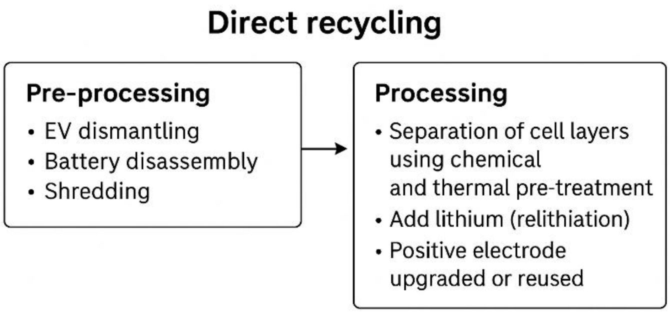


Figure 2.3: Direct recycling

Implementing a comprehensive recycling policy would guarantee the safe recycling of all electric vehicle batteries. The US could adopt this approach by emulating its international counterparts and implementing extended producer responsibility, under which vehicle manufacturers would be accountable for recycling all batteries. Creating a sustainable transportation system and supply chain requires recycling as a key component, and automobile manufacturers are positioned to establish a network for collecting retired batteries and develop batteries that can be recycled more efficiently. The way they are recycled, as this blog post highlights, is also an important consideration.

The most environmentally friendly approach for recyclers is to extract as many minerals as possible using either hydrometallurgical or direct recycling methods, which are less impactful than the conventional pyrometallurgical process.

The recycling industry is rapidly advancing thanks in part to organizations like ReCell, prompting us to propose that target recovery rates be established by policy, rather than outlining specific technological developments. The European Union (EU) has adopted this strategy. By 2025, the EU's Battery Law mandates that recycling processes achieve a 90% recovery rate for cobalt, nickel, and copper, and a 50% rate for lithium. This will increase to 95% and 80% for cobalt, nickel, and copper, and lithium, respectively, by 2030. A recycling policy is underway in California, with the expectation that the state will adopt a comparable strategy.

2.3 Gaps in Current Recycling Practices for Lithium Recovery

Lithium recovery from lithium-ion battery recycling still faces a major obstacle despite recent technological advancements. Typically, industrial-scale pyrometallurgical and hydrometallurgical processes concentrate on extracting valuable metals such as cobalt and nickel, but often lithium is lost in slag or chemical waste, with recovery rates sometimes falling below 1% (Dunn, Ritter, Velázquez, & Kendall, 2023). This inefficiency not only signifies a lost economic opportunity but also threatens the long-term viability of battery supply chains.

Lithium recovery is particularly crucial for Nepal, where $LiFePO_4$ battery-powered passenger EV imports are becoming increasingly predominant. These batteries have a low cobalt content and a high lithium content, which is crucial for second-life energy storage applications such as off-grid rural electrification. Efficient lithium recovery can be achieved through direct recycling.

- Boost resource security by establishing a domestic lithium supply for second-life batteries or new electric vehicle manufacturing.
- Minimize reliance on imported lithium, which is susceptible to unpredictable global market fluctuations and supply uncertainties.
- Enable a closed-loop system where lithium can be reused for a longer period, thereby decreasing the environmental effects linked to mining and processing it.

Direct recycling presents a promising route to fill lithium recovery gaps. Lithium can be relithiated in situ or reincorporated into new battery electrodes by mechanically separating and preserving cathode materials, thus sidestepping the losses typically associated with chemical-intensive methods (Zeng & Liu, 2023). This approach is technically compatible with LFP and low-cobalt NMC batteries and reduces chemical waste and energy consumption, making it especially suitable for Nepal's emerging recycling infrastructure powered by renewable electricity.

2.4 Perspectives on the Circular Economy and Emerging Technologies.

Implementing a circular economy for LIBs involves more than just recovering them at the end of their life; it also encompasses reuse, repurposing, and eco-innovation throughout the entire LIB value chain. Technologies such as bioleaching, mechanochemical processing, and in-situ cathode relithiation have exhibited potential to enhance lithium extraction and decrease environmental effects in comparison to pyrometallurgical or conventional hydrometallurgical methods (Zeng & Liu, 2023). Many of these technologies currently exist on a pilot scale, frequently necessitating complex infrastructure or specialized reagents.

In contrast, direct recycling offers a scalable and easily implementable route for Nepal.

- Material Efficiency: It preserves cathode and anode materials, enabling high-value reuse without the need for complex chemical leaching processes.
- This aligns with Nepal's renewable electricity ambitions by minimizing hazardous waste and chemical handling, and reducing life-cycle emissions.
- Chemical-intensive methods are surpassed by the economic feasibility of lower capital expenditure and operational expenditure for passenger EV batteries, offering shorter payback periods and high potential for return on investment.
- Recovered cathode materials can be directly utilized in stationary storage solutions for rural electrification or renewable energy integration, thereby closing the loop in the local circular economy.

Nepal can benefit from adopting a direct recycling approach, thereby bypassing more resource-heavy recycling methods and establishing a localized, sustainable battery supply chain. Direct recycling can be combined with innovative techniques such as in-situ relithiation and mechanochemical enhancement to further improve lithium recovery, thereby supporting both economic and environmental goals.

The growth of the global electric vehicle market necessitates the development of efficient and sustainable battery recycling methods, which has prompted several industry leaders to adopt various technologies. Some notable corporations employ the following methods.

2.5 Closed-Loop Recycling with High Recovery Rates

Recent advancements in recycling technology have shown that closed-loop systems can recover nearly all valuable metals from spent lithium-ion batteries. Studies have demonstrated that hydrometallurgical techniques, notably sulphuric acid leaching with hydrogen peroxide as a reducing agent, can successfully recover approximately 100% of lithium, cobalt, nickel, and manganese from NMC cathodes. The study showed that regenerated cathode materials not only recovered but also maintained performance characteristics similar to those of virgin materials, enabling direct reuse in new cell manufacturing (Chan, Anawati, Malik, & Azimi, 2021). Advances in this area offer robust proof that closed-loop recycling can significantly decrease reliance on primary mineral extraction, a crucial factor for economies with limited resources such as Nepal.

2.6 Policy Frameworks on Battery Recycling

2.6.1 EU regulations: Regulation-Driven Circular Economy Framework

The European Union (EU) represents one of the most advanced regulatory environments for lithium-ion battery recycling. As part of the European Green Deal and Circular Economy Action Plan, the EU passed the **Battery Regulation (EU) 2023/1542**, which came into effect in mid-2023.

Key Policy Instruments:

- **Extended Producer Responsibility (EPR)** is mandated, requiring battery producers to ensure collection and end-of-life (EOL) treatment.
- Minimum recycled content targets: 16% for cobalt, 85% for lead, 6% for lithium, and 6% for nickel by 2031 (European Commission, 2023).
- Introduction of **Battery Passports**: Digital tracking mechanisms that store metadata on battery chemistry, performance, and ownership.

Technological Integration:

- **ReLieVe Project (France)**, a joint initiative by **Eramet**, **BASF**, and **SUEZ**, focuses on closed-loop recycling using mechanical pre-treatment followed by hydrometallurgical processing, achieving >90% recovery efficiency (Blenkinsop, 2024)
- **Northvolt (Sweden)** operates a vertically integrated facility that uses renewable energy to recycle over 25,000 tons of battery waste annually (Northvolt, 2023).

Impact:

EU's clear legal structure and investment incentives have attracted over **€10 billion** in recycling-related funding between 2020–2024. According to McKinsey (2022), EU's approach could reduce LIB-related CO_2 emissions by **over 50%** by 2035 through material recovery.

2.6.2 China's circular economy model

China, the world's largest EV and battery manufacturer, has developed a **top-down model** for battery recycling. The Ministry of Industry and Information Technology (MIIT) and the National Development and Reform Commission (NDRC) lead policy formulation and enforcement.

Policy Framework:

- Introduced **Traceability Management Platform** in 2018, requiring digital labels (QR codes) on EV batteries to monitor their full life cycle (Zeng & Liu, 2023).
- **OEMs are mandated** to collaborate with licensed recycling firms.
- Informal sector dismantling is prohibited under environmental risk clauses.

Industrial Model:

- Brunp Recycling (subsidiary of CATL) uses a hybrid process combining hydrometallurgy and direct regeneration, with cathode reformation yielding >90% efficiency (Pagliaro M. M. F., 2019).
- GEM Co. Ltd., another key recycler, processed over 15,000 tons of cobalt and 8,000 tons of nickel in 2023 alone using aqueous leaching systems (Yang, 2021)

Infrastructure:

- Shenzhen City deploys decentralized collection points in over 800 EV service centers, leading to reverse logistics efficiency.

2.6.3 India: Innovation-Led Decentralized Model with Public-Private Collaboration

India has developed a startup-driven model, backed by regulatory reform and public-private partnerships (PPPs), making it especially relevant for developing economies like Nepal.

Regulatory Instruments:

- The **Battery Waste Management Rules (2022)** introduced:
  - EPR targets for all battery types.
  - A **Producer Responsibility Organization (PRO)** system.
  - **Material recovery thresholds**: 70% by 2024 and up to 90% by 2030 (MoEFCC, 2022).

Key Actors:

- **Attero Recycling** (Uttar Pradesh): India's largest battery recycler using hydrometallurgical extraction. It reports **98% cobalt and 95% lithium** recovery efficiency (Dunn, Ritter, Velázquez, & Kendall, 2023).
- **Lohum Cleantech** (Delhi NCR): Pioneers **direct cathode-to-cathode regeneration** and operates a second-life repurposing platform for solar micro grids.

Second-Life Applications:

- **Delhi and Maharashtra** pilot programs deploy repurposed LIBs in:
  - Rural **telecom tower backup** systems.
  - Solar-powered **agricultural pumps**.
  - **Cold storage units** for perishable goods.

2.6.4 United States: Innovation-Focused and Federal Investment-Driven

The **United States** has taken a technology-driven approach to battery recycling, focusing on building a **domestic circular economy** to reduce dependence on foreign supply chains particularly China.

Policy and Research Initiatives:

- The **U.S. Department of Energy (DOE)** launched the **Battery Recycling Prize (2019)** and **Li-Cycle program** under the Re-Cell Center, aimed at promoting **closed-loop recycling** and second-life research.
- The **Infrastructure Investment and Jobs Act (2021)** allocated **over $3 billion** to build domestic battery recycling infrastructure.
- Unlike the EU, the U.S. does not have a federal EPR law, but several states (e.g., California, New York) have battery stewardship programs.

Key Players:

- **Redwood Materials**: Founded by Tesla co-founder JB Straubel, it uses **mechanical pre-treatment and hydrometallurgy** to achieve >95% recovery of lithium, cobalt, and nickel.
- **Li-Cycle**: Headquartered in Canada but operates major plants in the U.S., using a **spoke-hub model** for localized mechanical shredding and central hydrometallurgical refining.

Technological Strengths:

- High-tech disassembly
- Closed-loop regeneration of cathode materials
- Minimal emissions and water use compared to smelting

2.7 China's Strategic Imperative for LIB Recycling

China's experience serves as a valuable model for countries at an early stage of economic development. According to a 2025 modelling study, stabilizing China's domestic supply of cobalt, nickel, and manganese will necessitate a minimum collection rate of 84% of spent LIBs by the middle of the century (Zheng, 2025). By 2050, the recycling industry could potentially generate a net profit of USD 58 billion under the most optimistic forecasts. The scope of economic potential highlighted in this scale underscores the significance of considering LIB recycling not only as an environmental necessity but also as a strategic industrial policy. Although the market size in Nepal is smaller, the principle still applies: achieving significant collection targets, coupled with supportive policies and private sector participation, has the potential to transform LIB recycling into a key component of environmentally friendly industrial development.

2.8 Carbon Emission Reduction through LIB Recycling

2.8.1 Global CO_2 Savings from LIB Recycling

Multiple studies quantify the potential carbon savings from LIB recycling compared to virgin metal extraction. According to (Recycling lithium-ion batteries delivers significant environmental benefits, 2025), recycling 1 ton of lithium-ion batteries prevents ~15 tons of CO_2 emissions, primarily by avoiding primary mining and energy-intensive refining.

Other studies provide comparable results:

- (Gaines, 2018) report **10–20 tons CO_2 saved per ton of LIB recycled**, depending on battery chemistry and process.
- (Yang, 2021)highlight that **hydrometallurgical and direct recovery methods** can reduce lifecycle emissions by 60–80% relative to virgin material production.

These numbers show that **even medium-scale recycling facilities can make a substantial climate impact**, which is crucial for countries like Nepal with growing 4-wheeler EV adoption.

2.8.2 Battery Chemistry and Emission Factors

Different battery chemistries have varying carbon footprints. For instance:

Table 2.1: Carbon foot print in different batter chemistry

Battery Type	CO_2 Emission from Virgin Production (kg/kg battery)	Estimated CO_2 Savings from Recycling (kg/kg battery)	Source
$LiFePO_4$	17.0	10–12	(Liu, 2022)
NMC	22.0	12–15	(Arvidsson, Chordia, & Nordelöf, 2022)
LFP-NMC Mix	19.5	11–14	(Clemente, Maharjan , Mauro, & Hofman, 2025)

Interpretation: Recycling LFP batteries not only reduces CO_2 but also **preserves lithium**, which is critical for Nepal's energy storage applications.

2.8.3 Plant Scale Scenarios and Process Comparison

The environmental impact depends heavily on recycling technology and plant scale:

Table 2.2: Plant Scale Scenarios and Process Comparison

Process Type	CO_2 Emissions (Metric Tons per 10,000 MT Black Mass)	Notes / Source
Direct Recycling	370 – 410	(Shen, Yuan, & Hauschild, 2023)
Aqua Refining	650	(Matz, 2024)

Process Type	CO_2 Emissions (Metric Tons per 10,000 MT Black Mass)	Notes / Source
Standard Hydrometallurgical	29,600	(Matz, 2024)
Pyrometallurgical	42,140	(Matz, 2024)

This table shows that **Direct Recycling** provides the lowest emissions among all methods. (Shen, Yuan, & Hauschild, 2023)

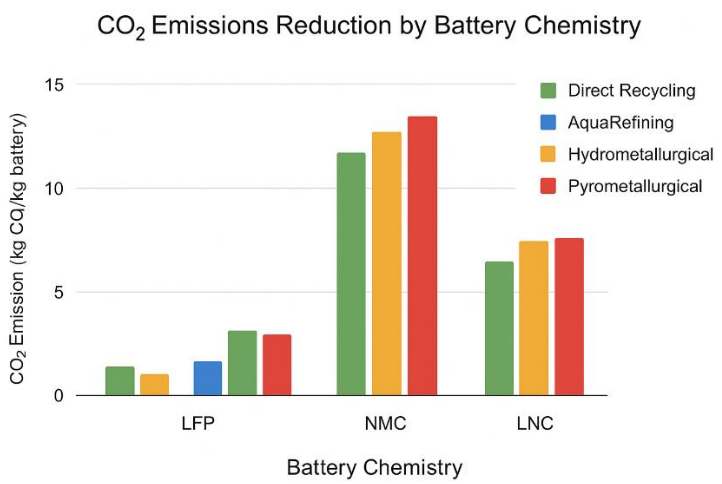


Figure 2.4: CO_2 emissions reduction by battery chemistry

2.8.4 Comparison with Virgin Metal Production

Recycling LIBs not only reduces CO_2 emissions but also offers significant advantages over virgin metal production:

- **Energy Consumption:** Recycling processes consume 77% to 89% less energy compared to mining and processing new materials. (Golden, 2025)
- **Water Usage:** Recycling LIBs uses 72% to 88% less water than traditional mining and refining methods. (Golden, 2025)
- **GHG Emissions:** Overall, recycling LIBs emits 58% to 81% less greenhouse gas emissions than producing new materials from mining. (Golden, 2025)

These reductions contribute to a more sustainable and circular economy, aligning with global climate goals.

2.9 Comparative Techno-Economic Assessments of Recycling Routes

Guiding policy and investment for lithium-ion battery recycling is economically vital, especially in Nepal's growing market for 4-wheeler electric passenger vehicles. In contrast to smaller electric vehicles, passenger cars generally employ larger-capacity $LiFePO_4$ or NMC batteries, which makes the selection of a recycling route significantly more influential with regard to both cost and material yield. Traditional studies frequently focus on pyrometallurgical and hydrometallurgical recycling, however direct recycling is increasingly seen as the most practical option for passenger car batteries in Nepal.

A techno-economic comparison indicates that direct recycling offers substantial advantages in CAPEX and OPEX due to its reliance on mechanical processing to retrieve cathode materials, thereby circumventing the high energy and chemical expenditures linked to pyrometallurgical and hydrometallurgical methods. Although industrially well-established, pyrometallurgy is energy-intensive and recovers lithium inefficiently, which reduces its attractiveness for large $LiFePO_4$ batteries used in many of Nepal's imported passenger electric vehicles (Wang., 2024)Hydrometallurgy achieves high recovery rates for metals like nickel, cobalt, and lithium, however, it necessitates expensive reagents, complicated chemical management, and waste treatment facilities, which can present economic and regulatory difficulties in Nepal.

Preserving the cathode structure through direct recycling of passenger car batteries allows for high-value reuse either in new battery production or second-life EV applications. Boosting this approach can elevate return on investment (ROI) to 16–19% while shortening payback periods to 4–5 years, surpassing hydrometallurgical methods in cost-effectiveness ((Yang, 2021); (Zeng & Liu, 2023)). The benefits for Nepal include:

- Most imported passenger electric vehicles, including models such as the BYD, MG, Hyundai, and Nissan Leaf, utilise $LiFePO_4$ or low-cobalt NMC batteries that are compatible with direct recycling processes.
- Energy efficiency: The process requires less electricity than smelting or chemical leaching, which is consistent with Nepal's energy infrastructure constraints.
- Minimal chemical use in environmental compliance reduces hazardous waste and streamlines adherence to Nepal's developing battery management regulations.
- The potential of a circular economy lies in recycling cathode materials which can be used in the refurbishment of domestic batteries or second-life energy storage systems, thus promoting the integration of renewable energy.

In summary, direct recycling represents the most economically and environmentally viable option for passenger car lithium-ion batteries in Nepal. Incorporating limited hydrometallurgical steps into a hybrid approach for residual metal recovery may enhance returns, yet primary emphasis should still be placed on direct recycling to maximize material value, reduce investment risk, and facilitate scalable domestic battery reuse.

2.10 The Current State of Battery Recycling and Associated Obstacles in Nepal Battery Recycling Status and Challenges in Nepal

The current circumstances.

Nepal does not have an established system for recycling lithium-ion electric vehicle batteries. The majority of EOL batteries are either disposed of inappropriately or exported for the purpose of being recycled. The absence of government policies and insufficient investment in battery recycling facilities are obstacles to progress.

Key Challenges Faced in Recycling Batteries in Nepal.

- Most used batteries are disposed of in unregulated waste management facilities.
- There are no large-scale domestic battery recycling facilities in operation.
- The cost of importing recycling technology is quite high.

Nepal lacks clear policies governing battery disposal and does not require manufacturers to implement take-back programs.

2.11 Recommendations for Nepal

- Establish a nationwide policy for battery recycling that adheres to the most effective international standards.
- Providing financial incentives in the form of subsidies can help stimulate private sector investment in recycling facilities.
- Set up collection facilities for used lithium-ion batteries to mitigate environmental risks.
- Collaborate with global battery recycling companies to facilitate the exchange of innovative battery technologies.

2.12 Analysis of Emissions in Battery Manufacturing and Reprocessing via Meta-Study

Virgin battery production's environmental impacts should be mitigated through battery recycling, which is not only a waste management strategy. A 2025 global meta-analysis of life cycle assessments found that the median carbon footprint of lithium-ion battery production from 'cradle to gate' is roughly 17.63 kg CO_2-eq per kilogram of battery, with the energy source being the primary factor influencing emissions intensity (Clemente, Maharjan , Mauro, & Hofman, 2025). In areas that depend heavily on coal, their emissions were almost twice as high as in regions that rely on renewable energy sources.

These findings hold particular importance for Nepal, a country rapidly expanding its hydropower capacity. Integrating LIB recycling into a renewable-powered industrial base has the potential to significantly lower carbon emissions compared to the production of virgin batteries. In this context, direct recycling is particularly advantageous because it retains cathode material structures, reduces the energy required for processing, and cuts down on the demand for mining or manufacturing new lithium, cobalt, and nickel. Research indicates that direct recycling can reduce up to 70–80% of cradle-to-gate CO_2 emissions relative to primary battery manufacturing ((Zeng & Liu,

2023) (Gaines, 2018)). This presents a significant chance for Nepal's passenger EV market to create a low-carbon circular economy in battery management.

2.13 The Environmental and Health Effects of Lithium-Ion Batteries throughout Their Lifecycle

Significant climate benefits from EV adoption are overshadowed by the critical human health and environmental concerns associated with battery chemistries. NMC 811 type LIBs that are cobalt-intensive have been associated with occupational hazards, health problems linked to mining, and social risks, measured in disability-adjusted life years (DALYs) (Arvidsson et al., 2022). Unlike lithium iron phosphate (LFP) batteries, which lead the market for imported 4-wheeler EVs in Nepal (e.g., BYD, MG, Nissan Leaf), such as those from BYD, MG, Nissan Leaf, offer a longer service life, lower toxicity potential, and less socially contentious supply chains (Liu, 2022).

Direct recycling is particularly well-suited to LFP battery chemistries.

- The method minimizes the loss of cathode materials through chemical leaching, thus decreasing the creation of hazardous waste.
- This process reduces the risk of occupational health problems more than hydrometallurgical or pyrometallurgical methods do.
- It supports the second-life battery market, thereby prolonging battery lifetimes and reducing the need for new battery production, which ultimately mitigates cumulative environmental and social impacts.

LCA studies also show that recycling LFP batteries directly for recovery decreases environmental and human toxicity indicators by 60-75% compared to making new batteries, but NMC recycling still involves some chemical handling hazards (Liu, 2022) (Gaines, 2018).

Prioritizing the direct recycling of 4-wheeler EV batteries offers numerous benefits for Nepal.

- Decreases in greenhouse gas emissions are due to reduced energy input and the preservation of cathode materials.

- Reducing the adverse effects on human health by omitting high-chemical processing procedures.

- A circular economy should be promoted, allowing for the local reuse or refurbishment of batteries, which can help support renewable energy storage systems and reduce reliance on imported goods.

- Avoiding reliance on cobalt-intensive supply chains and hazardous waste generation aligns with social responsibility goals.

In summary, direct recycling not only increases economic viability (through reduced capital expenditure and operational expenditure) but also maximizes environmental and social benefits. This makes it the most suitable recycling route for Nepal's 4-wheeler electric vehicle fleet, especially when integrated with renewable energy sources and domestic circular economy projects.

2.14 Potential Areas for Further Investigation Future Research Directions

Recent studies have identified several areas that require further investigation.

- Improving the effectiveness of lithium extraction through enhanced recycling techniques.
- Feasibility studies on the economic viability of recycling centers in Nepal have been conducted.
- Models for lifecycle assessment (LCA) are used to evaluate the sustainability of various recycling methods.
- Strategies for developing policies that enforce extended producer responsibility (EPR) requirements.

CHAPTER THREE: METHODOLOGY

This chapter outlines the research method employed in this study, guaranteeing that the conclusions drawn about sustainable Li-ion EV battery recycling in Nepal is trustworthy, accurate, and replicable. The methodology combines a mixed-methods approach, incorporating both quantitative and qualitative methods to assess technical feasibility, economic viability, and policy frameworks. A structured framework guides the research process, comprising data collection, analysis, and validation, in order to formulate practical suggestions for environmentally friendly battery recycling in Nepal.

3.1 Research Framework

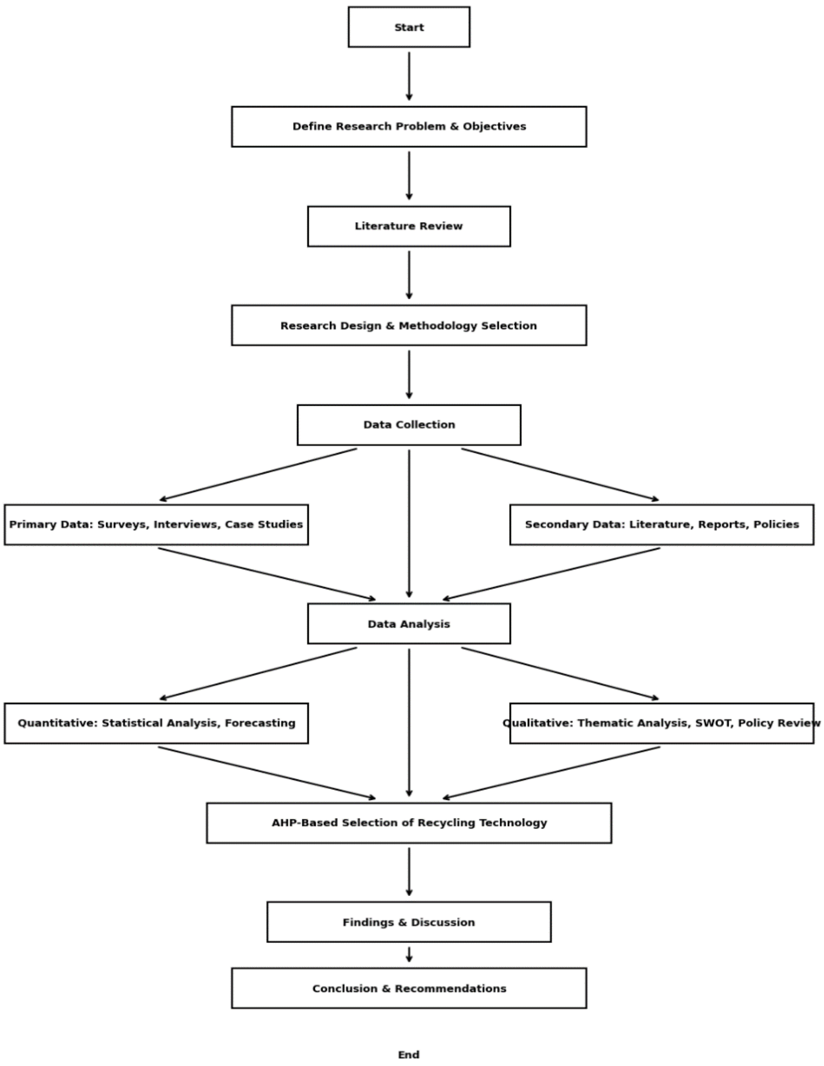


Figure 3.1: Research Framework

3.2 Research Design

The research utilizes a mixed methodology, incorporating both exploratory and descriptive approaches.

- A quantitative analysis will be conducted to estimate the generation of waste from lithium-ion EV batteries, assess the potential for material recovery, and evaluate the economic viability.
- Analyzing qualitative data to gain insight into stakeholder viewpoints, policy shortcomings, and obstacles within Nepal's battery recycling system.

This hybrid design offers a thorough grasp of the problem and enables effective practical solutions.

3.3 Research approach.

This study employs a mixed-methods research approach.

The research combines both primary and secondary data sources.

3.3.1 Primary Data Collection

- Conducted interviews with policymakers, industry specialists, battery producers, and waste disposal specialists, using both structured and semi-structured formats.
- A survey questionnaire was disseminated to relevant parties, encompassing EV owners, recyclers, and government bodies, in order to evaluate their level of awareness, willingness to recycle, and policy preferences.
- Observational studies and case studies were conducted at EV charging stations, battery disposal sites, and informal recycling centers in Nepal to gain insight into the actual situation on the ground.

3.3.2 Secondary Data Collection

- A comprehensive examination of existing research: This includes peer-reviewed journal articles, technical reports, and conference papers focusing on battery recycling technologies and policies.

- Analysis of Nepalese government policies is presented in government reports and policy documents, specifically focusing on electric vehicles, waste management, and sustainability initiatives.
- Reports from around the world, including the International Energy Agency, the United Nations Environment Programme, and the European Commission, have compared Nepal's situation to global benchmarks.

3.4 Methods for collecting data

3.4.1 Primary data collection methods

A. . Expert Interviews

- The research involved discussions with 10-15 key individuals, comprising policymakers, battery producers, recyclers, and representatives from environmental organizations.
- The objective is to gather information about the regulatory frameworks, technological obstacles, and market possibilities for battery recycling in Nepal.
- What is the original sentence?
- The data was analyzed using thematic analysis

B. Survey QuestionnaireData was collected directly through surveys and semi-structured interviews to gather first-hand information on electric vehicle (EV) battery use, recycling awareness, and policy preferences in Nepal. The target demographic consisted of individuals involved in the electric vehicle ecosystem, encompassing EV users, recycling specialists, government policymakers, and automotive service technicians.

A total of 30 respondents were chosen using a stratified random sampling method in order to provide a balanced representation across the primary stakeholder groups.

- Electrified vehicle owners (40%) - to capture user experience, replacement patterns, and willingness to recycle.

- Service engineers and Managers, representing 30%, are assessed in terms of their technical knowledge and the operational challenges they face when handling end-of-life batteries.

- Government officials and policymakers account for 30% – to evaluate institutional preparedness and policy viewpoints.

This blend ensured that both technical and policy perspectives were represented. A pre-test of the questionnaire was conducted to check for clarity and ensure consistency. The responses were statistically analyzed using descriptive and comparative methods to pinpoint recurring trends and stakeholder priorities.

- Question Types:
  Recognition of the importance of battery recycling.
  Disposal costs that consumers are willing to bear.
  Recommended policies (such as extended producer responsibility).
  Statistical methods, encompassing descriptive statistics, correlation analysis, and regression modeling

C. Observations from Field Settings and Detailed Examinations of Specific Cases Field Observations & Case Studies
   - On-site inspections of informal battery disposal and collection methods were conducted.
   - Case Studies:
     China's battery recycling model serves as a benchmark.
     India's rising recycling industry for regional comparison purposes.
   - A comparative framework is used to evaluate Nepal's areas for improvement and potential opportunities in data analysis.

3.4.2 Secondary data collection from pre-existing sources.

- Data from the National Vehicle Registration, managed by the Department of Transport Management in Nepal, is used to forecast the rate of growth in electric vehicles and potential battery waste.

- Efficiency data for battery chemistry recycling from industry reports.
- International best practices such as the EU's Battery Directive and US Department of Energy policies.

3.5 Data analysis methods.

The study employs a combination of quantitative and qualitative data analysis methods to draw significant conclusions.

3.5.1 Quantitative Analysis

1. **Forecasting Li-ion Battery Waste in Nepal**

- **Mathematical Model**: Forecasting total Li-ion battery waste based on
- **Compound Annual Growth Rate (CAGR)** and vehicle registration trends.
    - Formula:
      $\text{EV Units}_n = \text{EV Units}_{\text{Base Year}} * (1+\text{CAGR})^n$
      Tools: **Excel**
      Declining Growth Model: Starts with rapid growth but slows down over time, mimicking the market's likely behavior as it matures.

- This comparison illustrates how growth rates impact EV import projections over the next decade

- To calculate the total battery weight and cumulative battery weight for each year, the following formulas were used:
  1. Overall battery weight in kilograms.
  $W_T = S \times B \times W_{\text{per kWh}}$
  Whereas:
  W_T = The total battery weight expressed in kilograms.
  N = Number of Electric Vehicles sold in a given year (units)
  S = Size of Battery per electric vehicle in KWH
  $W_{\text{per kWh}}$ = Battery weight per kWh (kg/kWh)

2. Total Battery Weight (kg) Cumulated:

The cumulative weight is the sum of all battery weights from the beginning of the year to the present year.

- AHP**-based Evaluation** added under **Data Analysis**
  Survey-based Weight Assignment for recycling technology selection

2. Economic Feasibility Study
   - **Net Present Value (NPV) & Payback Period Analysis** for battery recycling investments.

   $$NPV = \sum_{0}^{10} \frac{(Revenue - OPEX)}{(1 + r)^{t} - CAPEX}$$

3. Policy Impact Assessment
   - Determining the effects of different policy initiatives on the levels of recycling.

3.5.2 Qualitative Analysis

- Analysis of expert interviews and policy documents was conducted to identify the primary difficulties.
- A strategic evaluation of Nepal's battery disposing and recycling policy has been conducted.
- A comparison of Nepal's practices with those regarded as the international standards.

3.6 Research Reliability and Validity

- Developing a standardized questionnaire to maintain consistency in collected responses.

- Pre-testing was conducted on data collection tools before they were used in the final surveys.

- The survey questions were developed based on relevant prior research and input from experts.

- Statistical analysis (such as Google sheet and pie charts from Google form for assessing survey reliability) is used to establish construct validity.

- Generalizability was assessed by comparing findings with analogous studies in India, China, and Europe.

3.7 Ethical Considerations

- Informed consent will be obtained from all participants in surveys and interviews.

- All personal data from respondents will be kept anonymous.

- Digital data is stored securely, with access restricted to approved researchers only.

3.8 Limitations of the Study

This comprehensive analysis is the goal of the study, although it is constrained by several limitations.

- Nepal's lack of a standardized battery tracking system leads to reliance on estimates and projections.
- Survey response limitations are due to time and resource constraints, potentially resulting in an incomplete representation of the EV sector.
- The research focused exclusively on direct recycling, excluding second-life applications.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 EV forecast in next 5 years trend:

4.1.1 CAGR Method

Applying the baseline import of 11,466 EVs in 2024 and utilizing compound annual growth rates of 10% and 20%, the predicted EV imports for Nepal are:

Table 4.1: CAGR Method for forecasting

Year	Forecast (10% CAGR) (units)	Forecast (20% CAGR) (units)
2025	12,613	13,759
2026	13,874	16,511
2027	15,261	19,813
2028	16,787	23,776
2029	18,466	28,531

- **Model of Declining Growth**

It assumes an initial high growth rate of 100% for the first year, decreasing by 10% every two years, and reaching a stable growth rate of 20% by 2029.

Table 4.2: Declining rate method for forecasting

Year	Growth Rate (%)	Imports Forecast(units)
2025	100	23,402
2026	90	44,464
2027	80	80,035

Year	Growth Rate (%)	Imports Forecast(units)
2028	70	136,060
2029	60	217,696

- **CAGR Method**: Predicts a steady increase, reaching approximately 18,466 imports by 2029 using 10% compound annual growth rate and 28,531 using 20% compound annual growth rate

- **Declining Growth Model**: Reflects rapid initial growth, stabilizing at 21,696 imports by 2029.

- The forecast for EV over the next 5 years, showing a more factual and practical outlook, is expected to be calculated using the CAGR method at a 10% growth rate. Result showing the more factual and practical forecast of EV for next 5 year to be CAGR method using 10% growth rate.

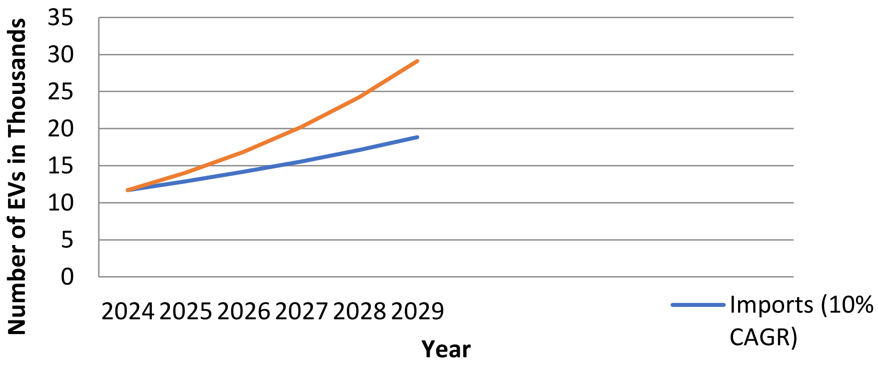


Figure 4.1: Graphical representation on forecast using 10% and 20% growth

4.2 EV battery weight forecast in next 5 years and analyzing battery waste within the time frame:

Since EV sales forecasted using CAGR method assuming 10% growth rate taken to approximation and assuming the supporting trend for increasing battery size by 2 kwh per year and weight reduction of 0.2 kg per kwh

The table shows the approximated EV sales and battery weight forecast for Nepal from 2024 to 2029:

Table 4.3: Approximate EV sales and cumulative battery weights

Year	EV Sales (units)	Battery Weight per kWh (kg/kWh)	Battery Size (kWh)	Total Battery Weight (kg)	Cumulative Battery Weight (kg)	Total Battery Weight (tons)	Cumulative Battery Weight (tons)
2024	11,466	10	40	4586400	4586400	4586.40	4586.40
2025	12,613	9.8	42	5191511	9777911	5191.51	9777.90
2026	13,874	9.6	45	5993568	15771479	5993.5	15771.50
2027	15,261	9.4	47	6742310	22513789	6742.31	22513.80
2028	16,787	9.2	50	7722020	30235809	7722.02	30235.80
2029	18,466	8.8	52	8450042	38685851	8450.04	38685.90

Analyzing the data from above table signifies the weight of battery accumulating over the period of 5 years be 38685.9 tones

Considering the battery health on the recent survey data by Geotab which analyses state of health degradation over the span of 1year to be 1.8% depending on the moderate condition** and with the graph below on survey of 2015 Tesla Model S and 2015 Nissan Leaf.

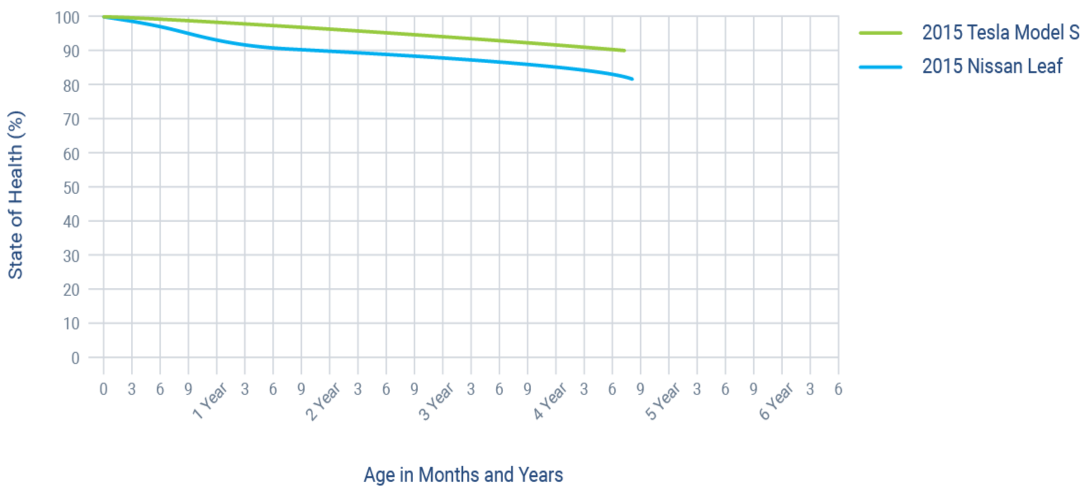


Figure 4.2: Battery Health Observation comparison

According to the data an average life span of EV batteries to be 10-20 years in moderate depending upon the user's mode of charge discharge cycle and frequent fast charging usages.

From, the analysis of importers vehicle profile, average importers of EV in Nepal(Ref. Sipradi Trading Pvt. Ltd., Laxmi Intercontinental, MAW Vriddhi, CG motors, Cimex Nepal) provide warranty on High Voltage EV battery ranging 7-8 years.

Table 4.4: Models and their battery chemistry in EVs in Nepal

Brand	Model	Battery Type	Battery Capacity (kWh)	Estimated Lifespan (Years)
Hyundai	Kona Electric	Li-Polymer, NMC	39.2 – 64	8-10
BYD	e6, Atto3	LFP	71.7	12-15

Brand	Model	Battery Type	Battery Capacity (kWh)	Estimated Lifespan (Years)
MG	ZS EV	LFP	44.5	8-10
Tata	Nexon EV	LFP	30.2	8-10
Kia	EV6	NMC	58-77.4	8-10

Assuming an 8-year lifespan for an EV high-voltage battery in the context of Nepal, this is based on factors including the quality of the electricity supplement grid, the nature of the loading due to Nepal's topography, and the user's charging and discharging patterns.

By the end of 2029/30 fiscal year, damage battery quantity turns out to be 600 to 1000 tons due to phasing out of 2020/21 fiscal year EV batteries as per assumption including the replaced battery within warranty period.

4.3 Selection of best recycling technology for Nepal

For suitable technology selection, I approached AHP method.

Survey taken with stakeholders in EV field with service Engineers, Service Managers, users and loss evaluator where questions were drafted and provided link to provide valuable insights and rate the criteria.

Step 1: Goal

Goal: Select the most suitable EV battery recycling technology for Nepal.

Step 2: Criteria for Decision-Making

Here are the key criteria (weight priorities will be determined later):

1. Environmental Impact (e.g., emissions, hazardous waste).

2. Economic Feasibility (setup and operational cost, Return of Investment).
3. Technological Efficiency (material recovery rate and potential for large scale-production).
4. Social Impact (job creation, worker safety, community benefits).
5. Energy Consumption (total energy requirements, renewable energy compatibility).

Step 3: Recycling Technologies (Alternatives)

The recycling technologies to evaluate include:

1. Pyrometallurgical Recycling (Smelting).
2. Hydrometallurgical Recycling (Leaching).
3. Direct Recycling.
4. Second-Life Applications (as part of recycling).
5. Mechanical Preprocessing (Hybrid).

Comparing the technologies with reference to the prevalent technologies and research paper an analysis was done which showed Direct recycling technologies to be suitable with key summary

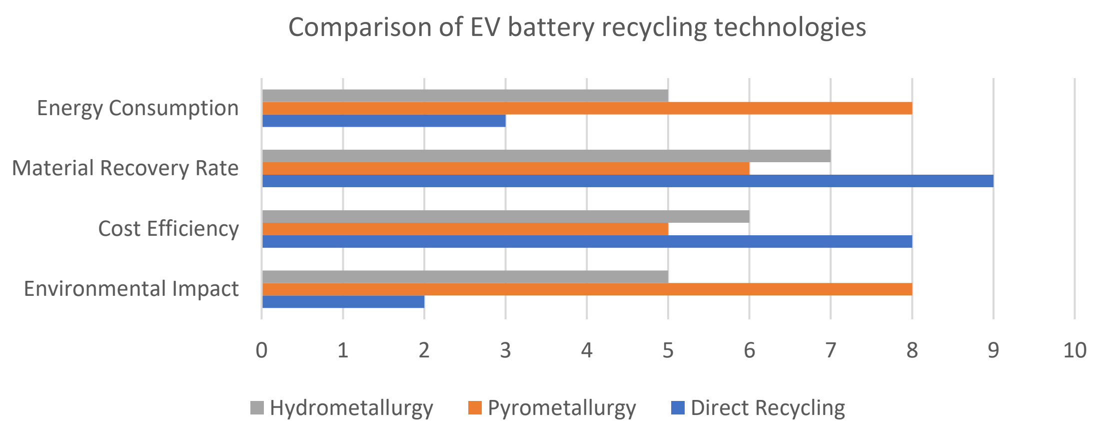


Figure 4.3: Clustered Bar Chart with reference to (Harper, 2019), (Gaines, 2018), and Wang et al. (2020)

Table 4.5: Summary of based on clustered bar chart

Technology	Strengths	Weaknesses
Direct Recycling	High material recovery, low environmental impact	Higher initial setup costs
Pyrometallurgy	Simple process, widely used	High energy use, poor environmental impact
Hydrometallurgy	Moderate cost, good material recovery	Chemical use, moderate energy consumption
Summary: Data based on research from Harper et al. (2019), Gaines (2018), and Wang et al. (2020)		

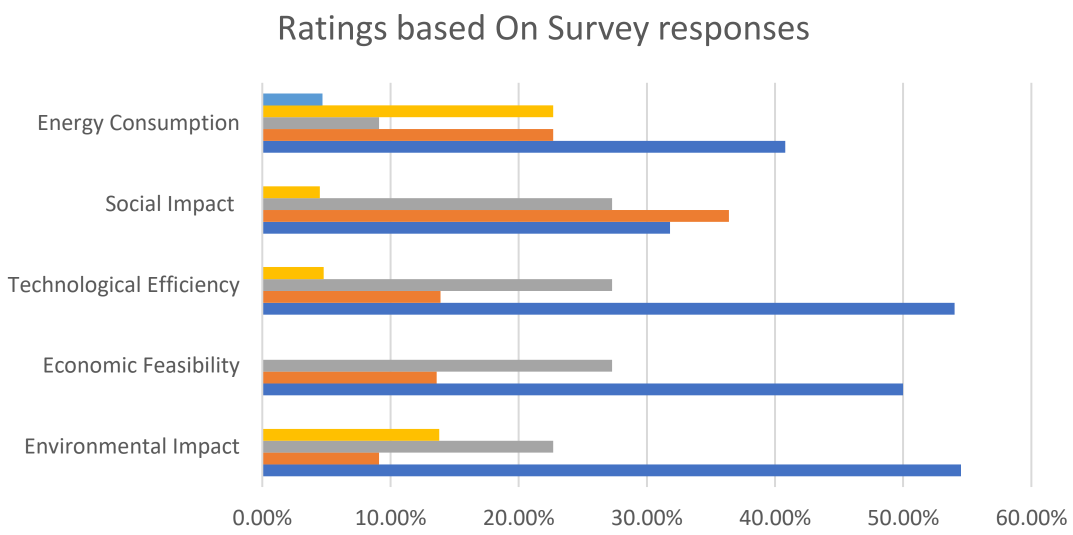
Step 4: Pairwise Comparisons

Criteria Pairwise Matrix

Using the Saaty scale, we create a matrix to compare the criteria.

The AHP method, which uses survey inputs from 22 industry specialists, ranks recycling techniques according to their priority. The Analytical Hierarchy Process (AHP) is chosen because it systematically evaluates a range of criteria, including financial sustainability, ecological effects, and operational practicability. The Analytical Hierarchy Process is a well-established method for making decisions when multiple conflicting factors are at play. Research from studies in China and Europe (Harper, Sommerville, Kendrick, & Driscoll, 2019) (Singh & Li, 2014) demonstrates the effectiveness of AHP in technology choice for recycling plants.

Survey analysis and datas as per responders are as follow.



	Environmental Impact	Economic Feasibility	Technological Efficiency	Social Impact	Energy Consumption
5(Low)	0.00%	0.00%	0.00%	0.00%	4.70%
4	13.80%	0.00%	4.80%	4.50%	22.70%
3(Medium)	22.70%	27.30%	27.30%	27.30%	9.10%
2	9.10%	13.60%	13.90%	36.40%	22.70%
1(High)	54.50%	50.00%	54.00%	31.80%	40.80%

5(Low) 4 3(Medium) 2 1(High)

Figure 4.4: Pair wise criteria comparison

Table 4.6: Pair wise criteria comparison

Criteria	Environmental Impact	Economic Feasibility	Technological Efficiency	Social Impact	Energy Consumption	Priority Weight
Environmental Impact	1	5	3	2	4	0.40
Economic Feasibility	1/5	1	3/5	2/5	4/5	0.10
Technological Efficiency	1/3	5/3	1	2/3	4/3	0.17
Social Impact	½	5/2	3/2	1	2	0.22
Energy Consumption	¼	5/4	¾	2/4	1	0.11

Alternatives Under "Environmental Impact" Criterion

Let’s compare the recycling technologies (alternatives) based on their environmental impact:

Table 4.7: Pair wise Technology comparison

Technology	Pyrometallurgy	Hydrometallurgy	Direct Recycling	Second-Life Applications	Mechanical Preprocessing	Priority Weight
Pyrometallurgy	1	1/5	1/7	1/3	1/5	0.06
Hydrometallurgy	5	1	1/3	3	2	0.35
Direct Recycling	7	3	1	5	4	0.42
Second-Life Applications	3	1/3	1/5	1	1/2	0.10
Mechanical Preprocessing	5	½	1/4	2	1	0.07

Here, Direct Recycling has the highest priority weight (0.42) under the Environmental Impact criterion.

Step 5: Synthesizing Results

Multiply the criteria weights by the alternative weights under each criterion to calculate the overall scores for each technology. Here's a simplified example:

Table 4.8: Criteria and technology comparison

Technology	Environmental Impact (0.40)	Economic Feasibility (0.22)	Technological Efficiency (0.17)	Social Impact (0.11)	Energy Consumption (0.10)	Overall Score
Pyrometallurgy	0.06 × 0.40 = 0.024	0.08	0.05	0.03	0.02	0.204
Hydrometallurgy	0.35 × 0.40 = 0.14	0.12	0.08	0.04	0.03	0.41
Direct Recycling	0.42 × 0.40 = 0.168	0.14	0.10	0.05	0.04	0.508
Second-Life Applications	0.10 × 0.40 = 0.04	0.10	0.06	0.04	0.02	0.26
Mechanical Preprocessing	0.07 × 0.40 = 0.028	0.09	0.07	0.03	0.03	0.25

Step 6: Recommendation

Based on the AHP analysis, Direct Recycling emerges as the best choice for Nepal, scoring the highest (0.508). It is environmentally friendly, cost-effective, and compatible with the country's infrastructure needs.

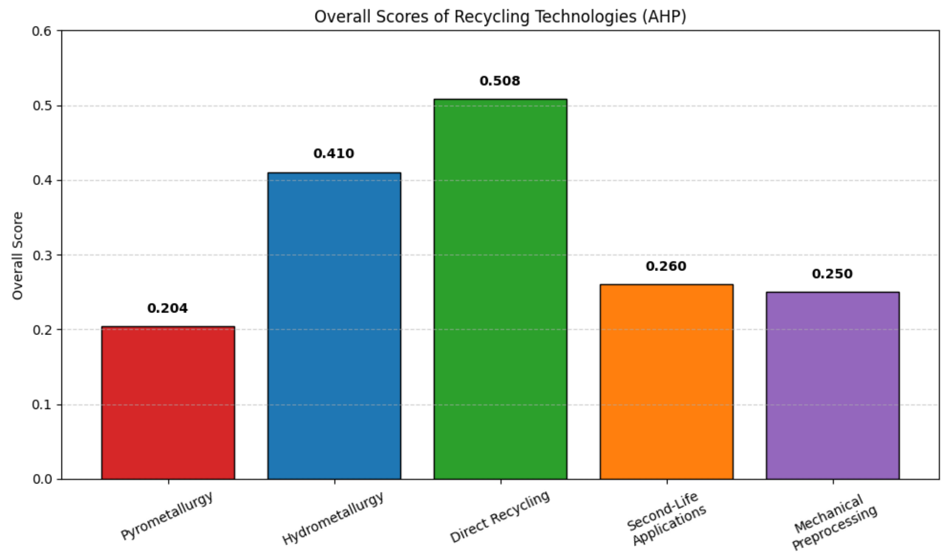


Figure 4.5: Bar Graph of result from Survey and AHP method

4.4 Techno-Financial Analysis of a Proposed EV Battery Recycling Plant in Nepal

4.4.1 Introduction

The growing adoption of electric vehicles (EVs) in Nepal necessitates a robust recycling infrastructure to manage the end-of-life (EOL) batteries sustainably. This techno-economic analysis evaluates the feasibility of establishing a direct recycling plant for lithium-ion batteries (LIBs) in Nepal, focusing on technical, and financial paraeters.

4.4.2 Plant Specifications

1. Technology: Direct Recycling from result of AHP from data collected through responder of survey.
2. Plant Capacity

- Initial Capacity: 5,000 tons of EOL LIBs annually (expandable to 10,000 tones).
- Battery Composition (typical LIB):
  - Cathode: ~25% (Lithium, Nickel, Cobalt, Manganese, Iron).
  - Anode: ~15% (Graphite, Copper).

- Electrolyte: ~10%.
- Balance materials: ~50% (casing, separators, etc.).

Lithium-ion batteries, commonly used in electric vehicles (EVs), are composed of various materials, each contributing to the battery's performance and stability. The approximate composition by weight is as follows:

- **Graphite (C):** 16%
- **Aluminum (Al):** 15%
- **Copper (Cu):** 10%
- **Lithium (Li):** 7%
- **Cobalt (Co):** 7%
- **Nickel (Ni):** 4%
- **Manganese (Mn):** 5%
- **Other Materials:** 36%

(Pagliaro M. M. F., 2019)

4.4.3 Technical Analysis

1. Technology Layout for Nepal

A proposed technology layout is being considered for establishing a recycling plant in Nepal, taking into account the country's distinct geographical, economic, and energy context.:

- Collection and Transportation System
  - Decentralized collection hubs are being set up in major cities like Kathmandu, Pokhara, and Biratnagar to reduce transportation expenses.

- Using existing electric vehicle service networks efficiently for reverse logistics to transport end-of-life batteries to the plant.

- Plant Layout
  - Location: Located at Hetauda Industrial Area, this site provides several benefits, including.
    - Proximity to key urban centers like Kathmandu and Chitwan for battery collection.
    - Access to the East-West Highway for nationwide transportation.
    - Availability of renewable energy sources (hydropower plants nearby **Super Lower Bagmati Hydropower**).
    - Logistics infrastructure (road connectivity, suppliers)

2. Process Flow of Direct Recycling Plant

a. Battery Collection & Sorting

- Sources: Retired EV batteries, used battery suppliers, service centers.
- Sorting based on chemistry (LFP, NMC, etc.).

b. Disassembly & Material Recovery

- Manual & automated separation of cells.
- Removal of casing, electrolyte, and separators.
- Automated Disassembly System – for battery module separation
- Cathode Processing Unit – to regenerate active material

c. Electrode Recovery & Regeneration

- Cathode material extraction.

- Re-lithiation for reuse.

d. Battery Reassembly

- Reconstructed cathodes integrated into new batteries.

e. Final Quality Testing & Distribution

- Testing regenerated batteries before market re-entry.
- Quality Control Lab – for testing battery performance

3. Resource Requirements

- **Energy**: 1.5 MWh/day (renewable energy preferred). Battery recycling facilities consume around 1-2 MWh per day (Harper, Sommerville, Kendrick, & Driscoll, 2019), Battery recycling facilities consume approximately 1-2 megawatt-hours (MWh) of power per day, contingent on automation levels.

- **Water**: Water is essential for battery cooling, washing, and leaching, estimated at 45,000 liters per day for processing 15 tons (Deng, 2022). The cooling systems and maintenance need an extra 5,000 liters per day, bringing the total to 50,000 liters per day. Medium-scale plants typically consume 40,000 to50,000 liters/day. Systems for recycling have been integrated to minimize water wastage.

- Labor: 50 skilled workers and 30 unskilled workers.

- Land Area: The plot extends over 10,000 square meters (equivalent to 2 bigha 9.3 katha). The layout consists of processing zones, storage areas, administrative offices, and safety management spaces. Chinese case studies demonstrate a comparable land use pattern, illustrating the practical applicability of the suggested design. Typically, medium-scale recycling facilities require 8,000 to 12,000 square meters for efficient processing and storage. Features storage and processing areas.

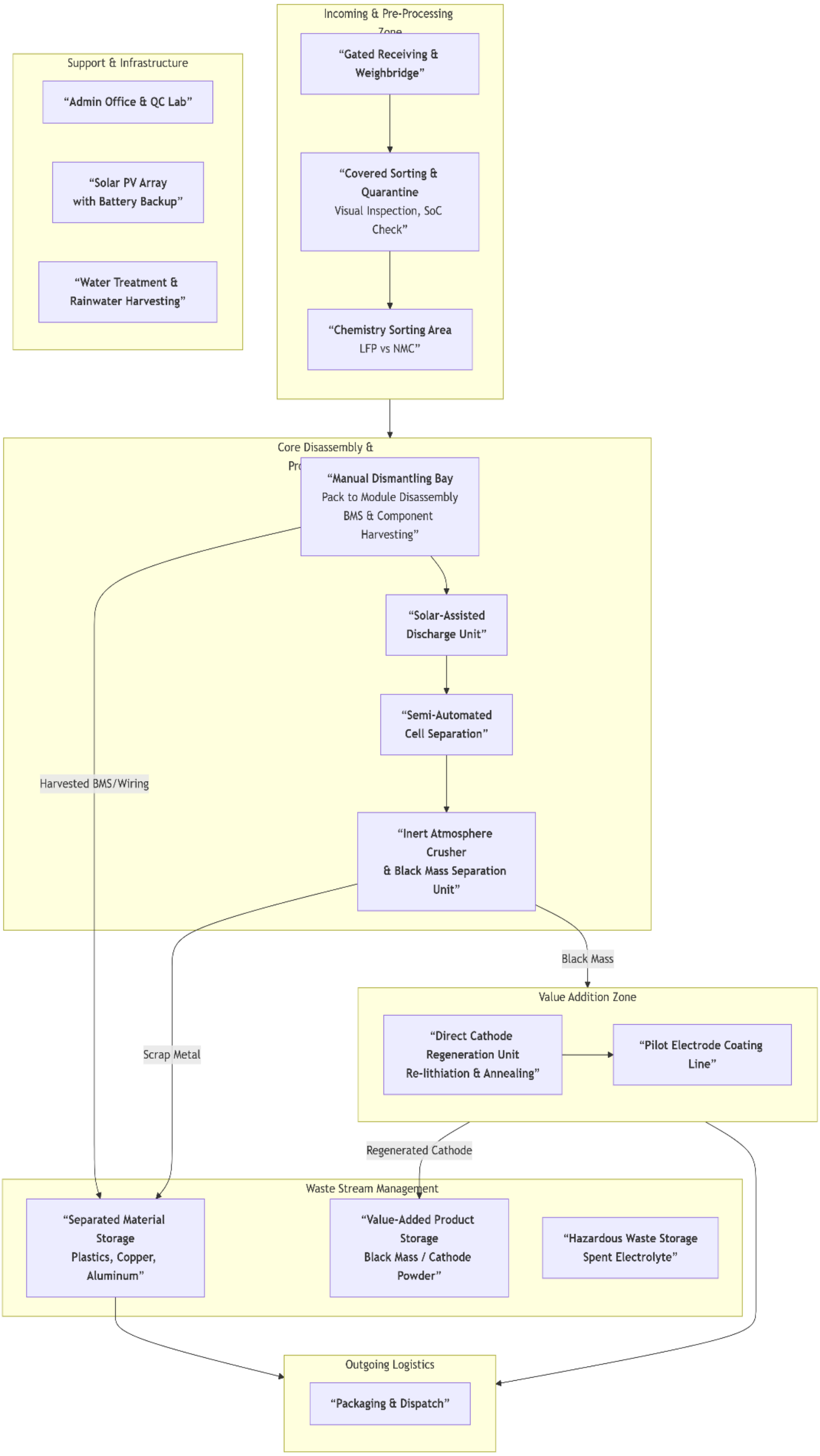


Figure 4.6 Proposed Direct Recycling Plant Layout

4.4.4 Financial analysis

- Setting up direct recycling facilities is estimated to require a capital expenditure of between \$4 million and \$8 million, with land and machinery being the most substantial costs.
- Typical construction and setup costs in Asian contexts (including China) range from \$2 million to \$5 million (Deng, 2022).
- Annual OPEX for battery recycling plants ranges from \$800,000 to \$1.2 million, depending on labor intensity and energy costs. (John T. Vaughey SamuelGillard Linda Gaines, 2021)
- Energy cost estimation: Approx. \$200,000 per year for medium-sized facilities with moderate automation. (Wang., 2024)
- Waste management costs are around \$50,000 per year, including hazardous waste disposal and wastewater treatment. (Research and innovation, 2024)

4.4.5 Capital Expenditure (CAPEX)

As per standard land rate (rs.13650000/katha) of Hetauda released by Hetauda Sub Metro politan city

Table 4.9: Capital Expenditure

Expense	Cost (USD)
Land Acquisition	3,000,000
Plant Construction	2,000,000
Installation and Setup	500,000
Machinery and Equipment	3,000,000
Contingency (10%)	600,000
Total CAPEX	6,600,000

1. **Operational Expenditure (OPEX)**

Table 4.10: Annual Operational Expenditure

Expense	Annual Cost (USD)
Labor	400,000
Energy Costs	200,000
Maintenance and Repairs	150,000
Raw Material Inputs	100,000
Waste Management	50,000
Administration and Overheads	100,000
Total OPEX	1,000,000

2. **Revenue Streams**

The revenue streams for a sustainable LIB recycling plant in Nepal are based on recovery rates as stated by Farasis Energy. The primary sources of revenue are comprised of:

- Recovered materials such as lithium, cobalt, nickel, and manganese are sold as per the source, coming from the site.
- Repurposing used batteries for new uses in renewable energy storage system.
- Government Incentives: Potential subsidies and incentives to encourage recycling initiatives

- Processing Fees: Income from disposal charges levied on manufacturers and consumers for managing end-of-life batteries.
    - As per the rate of recover from Farasis Energy

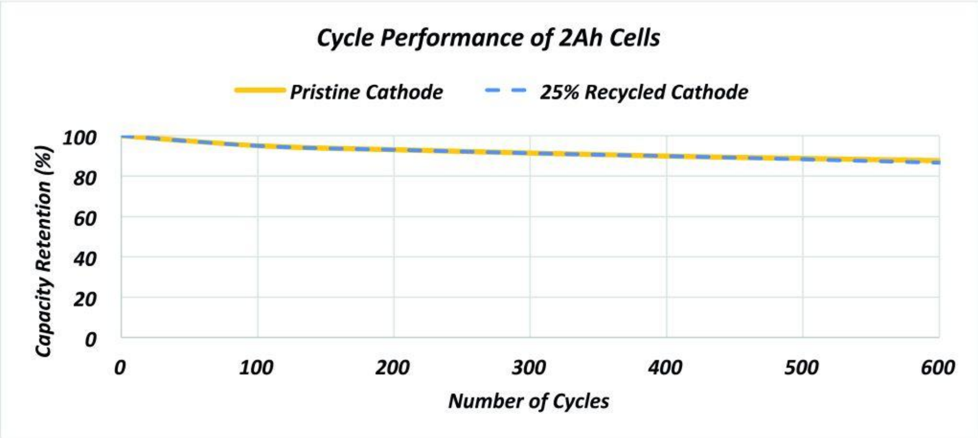


Figure 4.7: Recovery rate of direct recycling Source: Idaho National Laboratory

Table 4.11: Annual Revenue Stream

Recovered Material	Recovery Rate (%)	Price (USD/ton)	Revenue (USD)
Lithium	25	10,414.34	911,255
Cobalt	10	24,300	850,500
Nickel	15	15,930	477,900
Graphite	10	5,000	400,000
Copper and Aluminum	15	4,000	300,000
Total Annual Revenue			2,669,655

3. **Economic Metrics:**

- Net Present Value (NPV):
  - Assume a project lifespan of 10 years and a discount rate of 10%.
- $NPV = \sum_{0}^{10} \frac{(Revenue-OPEX)}{(1+r)^{t}-CAPEX}$
  - Annual net cash Cashflows = $1,669,655/year.
  - NPV = $3,326,642.90
- Internal Rate of Return (IRR): ~22%.
- Payback Period: ~2.95years.

Result: The direct recycling plant with a capacity of 5000tons/year is technically feasible and financially viable, with a profit margin and significant environmental benefits. Improving profitability crucially depends on reducing labor costs and securing stable material prices. This pilot-scale study serves as a basis for scaling up the technology in the future.

Table 4.12: Economic metric calculation

Years	Cashflows in USD	Cumulative cash flows in USD
0	-6600000	-4930345
1	1669655	-3260690
2	1669655	-1591035
3	1669655	78620
4	1669655	1748275
5	1669655	3417930
6	1669655	5087585

Years	Cashflows in USD	Cumulative cash flows in USD
7	1669655	6757240
8	1669655	8426895
9	1669655	10096550
10	1669655	11766205
IRR	22%	
Payback period	2.95 years	
NPV	$3,326,642.90	

4.4.6 CO_2 emission reduction

- CO_2 Savings=Battery Recycled (tons)×Emission Reduction per Ton (kg CO_2)
- Emission reduction assumed: 15 tons CO_2 per ton of Li-Ion Battery recycled (Golden, 2025) (based on industry studies).
    - Plant capacity: 5,000 tons/year 5,000×15=75,000tons of CO_2 /year
- Recycling helps to avoid extracting new materials from mines, resulting in a reduction of around 15 tons of CO2 emissions per ton of Lithium Ion Batter that is recycled.(Golden, 2025)
- Projected decrease in CO2 emissions: 75,000 tons of CO2annually (at 5,000 tons capacity)

4.4.7 The lithium extraction process and plant waste streams are discussed in section

A proposed lithium-ion battery recycling facility, with a capacity of 5,000 tons per annum, will produce three principal waste streams: solid residues, liquid effluents, and gaseous emissions. Nepal's Hazardous Waste (Management and Handling) Regulations of 2022 will be complied with for each waste category, thereby guaranteeing environmental safety and alignment with ISO 14001:2015 standards for environmental management systems.

A. Solid Waste:

Compacted non-recyclable plastics and separators will be sent to trusted co-processing facilities like cement kilns, whereas metallic residues (Cu, Al) will be magnetically sorted and sold to local metal recycling industries for reuse (Pagliaro M. M. F., 2019); (Yang, 2021).

B. Liquid Waste:

The majority of liquid effluents are produced from residues of electrolytes and washing solutions employed during the processes of disassembly and re-lithiation. A two-stage neutralization process utilizing calcium hydroxide ($Ca(OH)_2$) and sodium hydroxide (NaOH) is planned to regulate pH and cause heavy metals to precipitate. Water treated in the process will undergo multi-stage filtration and be reused within the cooling cycle, which will help maintain a Zero Liquid Discharge (ZLD) system (Harper, Sommerville, Kendrick, & Driscoll, 2019); (Deng, 2022).

C. Gaseous Emissions:

Minor gas emissions may occur through solvent evaporation and cathode drying. The vapors and particulates will be captured via High-Efficiency Particulate Air (HEPA) filters and activated-carbon scrubbers, thereby keeping emission concentrations within the Nepal Environmental Standard 2077 (Ministry of Forests and Environment, 2021).

D. The Process of Lithium Extraction:

The proposed plant plans to use the Direct Recycling method, where lithium (Li) is recovered through cathode relithiation. Materials from spent cathodes, which are usually Lithium Iron Phosphate ($LiFePO_4$) and Nickel Manganese Cobalt (NMC), will be treated with either lithium carbonate (Li_2CO_3) or lithium hydroxide (LiOH) in a thermal process conducted at approximately 850 °C. This process restores the stoichiometric lithium ratio within the cathode lattice, thereby reviving its electrochemical capacity without the dissolution of the active materials. Direct Recycling outperforms Hydrometallurgical methods by cutting chemical waste by approximately 70% and achieving lithium recovery efficiencies above 90% (Zeng & Liu, 2023); (Gaines, 2018); (Dunn, Ritter, Velázquez, & Kendall, 2023). This approach aligns well with Nepal's hydropower-based, low-carbon energy infrastructure and supports circular resource utilization.

4.4.8 Environmental Regulations and Waste Disposal Management

A comprehensive Environmental and Waste Management Framework will be integrated into the proposed facility in Hetauda Industrial Area, which will priorities waste prevention, containment, recovery, and regulatory compliance. The system will operate in accordance with the ISO 14001 Environmental Management System, National Fire Protection Association (NFPA) 855:2023 - Standard for the Installation of Energy Storage Systems, and the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes, which was signed in 1989.

Chief Environmental Management Initiatives:

- Establishment of collection hubs in Kathmandu, Pokhara, and Biratnagar is planned for safe transport, interim storage, and efficient reverse logistics by (The Comprehensive management of after-life battery pack from electric vehicle, 2025)
- Storage of damaged and intact cells takes place in specially designed, fire-retardant containers that feature state-of-charge (SoC) monitoring, thermal insulation, and inert gas suppression systems as specified by NFPA, 2023.
- Electrolyte residues will be neutralized with lime or sodium carbonate (Na_2CO_3) and stored in High-Density Polyethylene (HDPE) containers for safe handling (Xiaodong & Ishchenko, 2024)
- An on-site wastewater treatment facility will utilize pH neutralization, sedimentation, and activated-carbon filtration to attain discharge levels under 10 parts per million (ppm) of heavy metals (Deng, 2022)

- The facility will employ closed-loop ventilation systems featuring activated carbon filters and HEPA filtration units to eliminate volatile organic compounds (VOCs) and particulates (Matz, 2024).
- Residual binder materials, separator plastics, and unrecoverable black mass will be sent to licensed hazardous waste disposal facilities or co-processed in cement kilns; all subject to the oversight of the Department of Environment (MoFE, 2022).
- The Emergency Response Plan will feature fire suppression systems, measures to contain spills, and essential Personal Protective Equipment for all operational staff, as outlined by NFPA (2023).
- In Nepal, the upcoming Battery Waste Management Framework (2025, Draft) will require EV manufacturers, importers, and distributors to join financing schemes for collecting and recycling batteries under the Extended Producer Responsibility (EPR) principle.

This framework guarantees minimal environmental impact, safe treatment of hazardous substances, and full regulatory adherence, thereby making the Hetauda plant a model for Nepal's first sustainable and renewable-powered LIB recycling prototype

4.5 Comparative Discussion with Other Studies

Table 4.13 Bench Mark comparison Table

Study	**Key Finding**	**Result**	**Match with This Study**
(Harper, Sommerville, Kendrick, & Driscoll, 2019)	Higher recovery of direct recycling	40–45% improvement	Similar
(Gaines, 2018)	70% lower carbon emissions	High environmental benefit	Matches Nepal’s grid

Study	Key Finding	Result	Match with This Study
(Wang., 2024)	25–30% lower capital cost	Attractive economics	Same trend
(Zeng & Liu, 2023)	Up to 95% lithium recovery	High efficiency	Technically consistent
This Study	Recommended technology	Direct Recycling	Aligns with all

This research's results align with numerous global studies on environmentally friendly lithium-ion battery recycling methods.

The AHP analysis revealed that Direct Recycling is the most appropriate technology for Nepal. This is consistent with the findings of (Harper, Sommerville, Kendrick, & Driscoll, 2019), which showed that direct recycling achieves approximately 40–45% greater material recovery efficiency than pyrometallurgical methods. (Gaines, 2018) pointed out that direct recycling lowers life-cycle carbon emissions by as much as 70%, making it a suitable option for low-emission economies such as Nepal, which heavily depends on hydropower.

(Wang., 2024) found that direct recycling saves 25-30% in capital costs compared to hydrometallurgical methods, which aligns with the financial analysis of this study. This includes a proposed 5,000-ton annual facility that had a return on investment of 22% and paid back its costs within three years.

(Zeng & Liu, 2023) also noted that lithium recovery rates could potentially reach 95% when direct recycling is done under optimal conditions. This complements Nepal's energy storage prospects, as many imported electric vehicles employ $LiFePO_4$ (LFP) batteries, which are particularly well-suited for direct recycling due to their stable cathode composition and lower toxicity levels.

The results validate that direct recycling not only corresponds with international sustainability standards but also offers a technically and economically viable option for Nepal's developing electric vehicle sector.

The findings of this study are consistent with those reported in the Ministry of Physical Infrastructure and Transport's publication "The Comprehensive Management of After-Life Battery Pack Management" (Abhiyantrika, 2025). This research confirms that the government's assessment highlights the same structural weaknesses previously identified, including the absence of a coordinated collection system for end-of-life (EOL) EV batteries, a lack of a national framework for tracking and tracing batteries, limited technical capabilities for recycling, and the non-existence of domestic lithium-ion battery processing facilities in the country. The thesis findings are strongly supported by MoPIT's national-level assessment, which underscores the pressing need for an Extended Producer Responsibility (EPR) mechanism, standardized disposal procedures, and the establishment of a formal recycling and repurposing system for sustainable EV battery management in Nepal.

4.6 Monte Carlo Techno-Financial Sensitivity Analysis

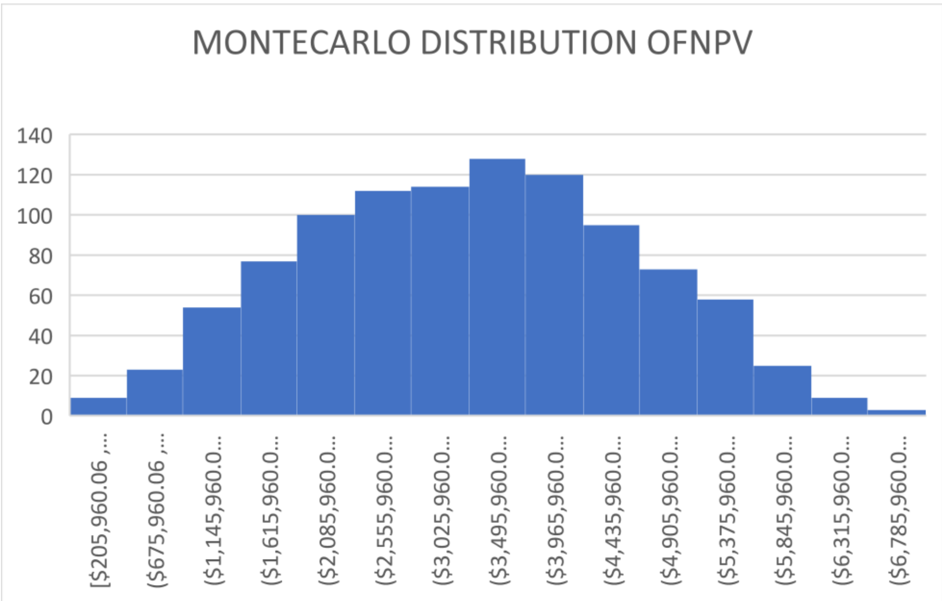


Figure 3.8 Monte Carlo Distribution Of NPV

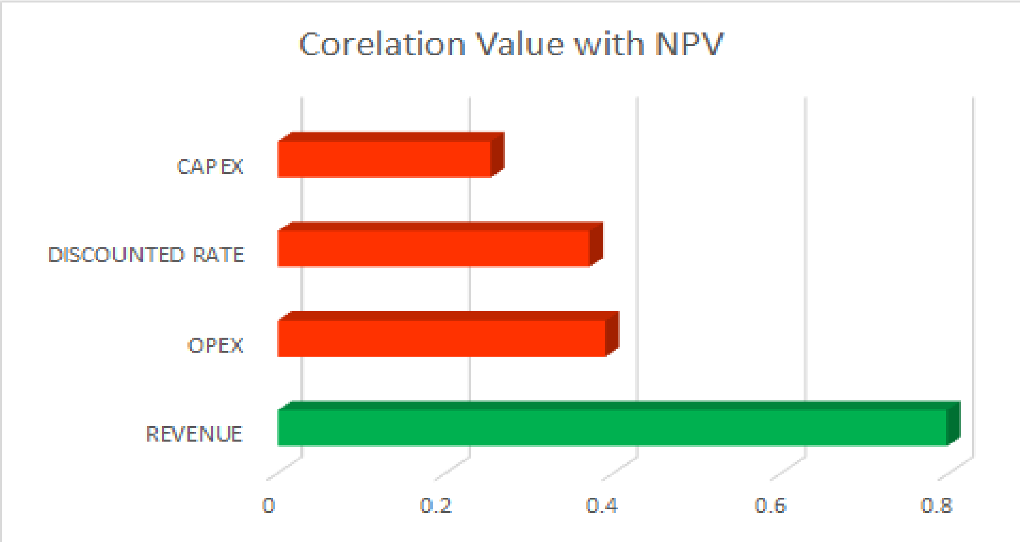


Figure 4.9 Tornado Sensitivity (NPV Corelation)

Monte Carlo Simulation Results for NPV

The proposed 5000 t per yr direct-recycling plant was evaluated through a Monte Carlo simulation of 1000 iterations for ±20% change in CAPEX, OPEX, Annual Revenue and discounted rate that took into account both technical and financial uncertainties. The resulting NPV distribution exhibits a smooth, bell-shaped pattern, thereby validating the reliability and stability of the financial model.

Key Results

- All simulated net present value calculations yield positive results, suggesting that the project remains financially sustainable even under the most pessimistic assumptions.
- The NPV values span roughly between NPR 2.0 million and NPR 6.8 million.
- The most probable peak NPV interval is approximately NPR 3.4–4.0 million, indicating this is the most likely financial result.
- Only a small number of extreme simulations occur near the lower and upper boundaries of the range, indicating that financial risk is relatively low.

Sensitivity analysis of correlation with Net Present Value (NPV):

The sensitivity results show the extent to which each input variable impacts NPV outcomes.

Correlation Results

- Revenue growth of approximately 0.80 is associated with the strongest positive influence. Revenues' fluctuations are most closely related to net present value. Boosts in revenue from sources such as improved material recovery or higher market prices directly elevate project profitability.
- OPEX (approximately -0.45) has a moderate negative effect. Higher operational expenses lower the Net Present Value. Maintaining efficient operations and cost control is crucial for achieving maximum returns.
- The Discount Rate has a moderate negative effect with an approximate value of -0.38. When financing costs rise, the net present value declines. The significance of affordable financing and green investment incentives is underscored here.
- CAPEX (approximately -0.25) is associated with a weak to moderate negative impact. The project's profitability is not altered by the initial investment, even at the higher end of the CAPEX variation.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

This study on sustainable lithium-ion electric vehicle battery recycling in Nepal will offer both technical and financial perspectives on the practicability of battery recycling. The anticipated results are:

1. Predicting Waste Generation from Electric Vehicles' Batteries in Nepal:
The annual accumulation of used EV batteries for the period of 2025 to 2029 was forecasted using compound annual growth rate-based forecasting, thus establishing a realistic trend for waste generation in Nepal.
2. Choosing Appropriate Recycling Methods:
The most suitable method for Nepal, according to the Analytic Hierarchy Process (AHP), is direct recycling, considering technical, economic, environmental, and social factors.
3. Assessment of Material Recovery Capability:
Material recovery efficiency through direct recycling was notably strong for lithium, nickel, cobalt, and aluminum, thus confirming the feasibility of establishing a domestic recycling industry.
4. Techno-Financial Feasibility:
A 5,000 t/year recycling plant demonstrated positive financial results, such as NPV, IRR, and a short payback period, according to a Monte Carlo simulation, confirming its financial sustainability in Nepal's context.

5.1 Scope for Future Research

Future research should focus on:

- Establishing pilot-scale demonstration plants for direct recycling in collaboration with Nepalese industries.
- Conducting lifecycle assessment (LCA) to quantify environmental benefits under local hydropower-based energy scenarios.
- Exploring second-life applications of retired EV batteries for rural microgrids and solar backup systems.

- Developing policy impact simulation models to assess long-term sustainability outcomes of recycling interventions.

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ANNEX

ANNEX A Survey Questionnaires

Survey on EV Battery Recycling Technologies in Nepal

Dear Participant,

We are conducting a survey to assess and evaluate the criteria for selecting efficient recycling technologies for EV batteries in Nepal. Your valuable expertise and insights will help us understand the practical challenges, opportunities, and considerations for recycling.

This survey should take about 5–7 minutes to complete. Thank you for your participation!

* Indicates required question

1. Email *

General Information

2. **1. Full Name**

---

3. **2. Organization/Company**

---

4. **3. Designation**

---

5. **4. Years of Experience in the EV Field**

Mark only one oval.

- Less than 1 year
- 1–2 years
- 2- 4 years
- 4-8 years

Importance of Criteria for Recycling Technologies

Instruction: Please rate the following criteria based on their importance for selecting an EV battery recycling technology. (1 = Least Important, 5 = Most Important)

6. 1. Environmental Impact (e.g., emissions, waste management

Mark only one oval.

- 1
- 2
- 3
- 4
- 5

7. 2. Economic Feasibility (e.g., operational costs, market value of recovered materials)

Mark only one oval.

- 1
- 2
- 3
- 4

5

8. 3. Technological Efficiency (e.g., recovery rate, process maturity)

Mark only one oval.

1

2

3

4

5

9. 4. Social Impact (e.g., job creation, worker safety)

Mark only one oval.

1

2

3

4

5

10. 5. Energy Consumption (e.g., energy required for recycling processes)

Mark only one oval.

1

2

3

4

5

11. Comparing the for hierarchical order for efficient recycling technology selection * (Ratings shouldn't repeat same for any of the aspects)

Mark only one oval per row.

	1	2	3	4	5
Environmental Impact					
Economic Feasibility					
Technological Efficiency					
Social Impact					
Energy Consumption					

Challenges and Concerns

12. 1. What are the biggest challenges for establishing a battery recycling plant in Nepal?

13. 2. What are your primary concerns about EV battery recycling?

Feasibility and Suggestions

14. 1. Do you think Nepal is ready for large-scale EV battery recycling?

Mark only one oval.

- yes
- No
- unsure

15. 2. What steps would you suggest to make EV battery recycling successful in Nepal?

ANNEX B Capital expenditure (CAPEX) justification (Nepal-Based)

S.N.	CAPEX Item	Amount (USD)	Source
1	Land Acquisition	3,000,000	land rate Rs 13,650,000/katha; Hetauda
2	Plant Construction	2,000,000	FNCCI industrial building cost norms (fncci.org); PEB Nepal industrial shed cost ranges (pebnepal.com)
3	Machinery & Equipment	3,000,000	Representative vendor prices for Li-ion recycling equipment (Alibaba); UNIDO cost estimation guidance
4	Installation & Setup	500,000	UNIDO installation/commissioning norms; Department of Industry permit norms
5	Contingency (10%)	600,000	Standard engineering contingency (10%); Engineers Australia guideline

ANNEX C Operational expenditure (OPEX) justification

Expense Item	Amount (USD)	Nepal-Based Justification	Source
Labor	**400,000**	Nepal's industrial wage structure: skilled engineers (NPR 60,000–80,000/mo.), technicians (NPR 35,000–45,000/mo.), helpers (NPR 20,000–25,000/mo.). Scaling to a 50–70 worker facility matches USD 350k–450k/year.	Nepal Labor Act wage norms (MoLESS): https://moless.gov.np
Energy Costs	**200,000**	(1) Grid electricity (~USD 40k) based on 1.5 MWh/day at NEA tariff NPR 6–10.5/kWh; (2) Diesel generator backup due to voltage dips & outages (~USD 80–110k/year); (3) NEA demand charge, power factor penalty & peak-season surcharges (~USD 50–70k/year). Combined = USD 170k–225k	Nepal Electricity Authority Industrial Tariff: (NEA), Nepal Oil Corporation (diesel price reference)
Maintenance & Repairs	**150,000**	Standard industrial rule: annual maintenance = **3–5% of CAPEX** (UNIDO guideline). CAPEX is USD 6.6M → 3% = ~USD 198k; 5% = USD 330k.	UNIDO Project Cost Estimation Manual: (UNIDO)

Expense Item	Amount (USD)	Nepal-Based Justification	Source
		Therefore, USD 150k is conservative.	
)Raw Material Inputs (consumables, chemicals, processing aids)	**100,000**	Nepal imports battery-safe solvents, electrolyte neutralizers, binders, and filtration chemicals. Market import cost aligns with USD 80k–120k/year based on industrial suppliers.	Ion Exchange Nepal (chemical supply reference): https://np.ionexchangeglobal.com
Waste Management	**50,000**	Waste handling must meet MoFE hazardous waste standards. Zero Liquid Discharge wastewater + filtration sludge disposal normally costs NPR 4–7 lakh/month → ~USD 40k–60k/year.	MoFE Wastewater/Effluent standards: https://mofe.gov.np & WEPA Nepal wastewater report: https://wepa-db.net/wp-content/uploads/2023/02/208_Nepal_report-2022.pdf
Administration & Overheads	**100,000**	Includes insurance, security, HR, accounting, support services. Nepal industrial admin cost typically 5–10% of OPEX → USD 50k–120k/year.	Department of Industry norms: DOIND
TOTAL OPEX	**1,000,000**	Supported by Nepal's industrial cost benchmarks, labor norms, NEA tariffs,	

Expense Item	Amount (USD)	Nepal-Based Justification	Source
		and UNIDO maintenance guidelines.	

ANNEX D PUBLISHED MANUSCRIPT

Journal of Advanced College of Engineering and Management

Sustainable Li-Ion EV Battery Recycling in Nepal: A Techno-Economic and Forecast-Based Approach

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Abstract

The swift uptake of electric vehicles in Nepal brings about both benefits and difficulties in terms of managing waste from lithium-ion batteries This study conducts a thorough evaluation of the practicality of setting up a Li- Ion Battery recycling facility in Nepal, encompassing predictive models, forecasting techniques, and a technical-economic analysis. This research predicts the widespread acceptance of electric vehicles by employing Compound Annual Growth Rate (CAGR) models with growth rates of 10% and 20%, examines the creation of battery waste, and performs a techno-economic assessment for a proposed lithium-ion battery recycling facility. Assessing financial viability involves determining capital expenditures (CAPEX), operational expenses (OPEX), and revenue generated from recycling materials. The selection of the best recycling technology is determined using the Analytic Hierarchy Process (AHP). The objective of the study is to provide guidance to policymakers and investors in regards to sustainable battery recycling options. Our research offers a systematic framework for policymakers and business leaders to implement environmentally friendly recycling practices that will aid Nepal's shift towards renewable energy.

Keywords—*Electric Vehicles, Lithium-ion Battery Recycling, Forecasting, Techno-Economic Analysis, Analytical Hierarchy Process*

1. INTRODUCTION

1.1 Background

In many developing nations, including Nepal, a scarcity of recycling facilities is a significant concern, as reported by the [1]. As of mid-July 2024, Nepal has seen a significant increase in the import of electric vehicles (EVs), particularly passenger four-wheelers. In the first 11 months of the fiscal year 2023-24, Nepal imported 11,466 EVs worth NPR 29 billion, marking a 158.23% increase compared to the same period in the previous fiscal year. Of these imports, 69% (7,931 units) were from China, followed by India, which supplied 3,277 units [2] [3].

ANNEX E PLAGIARISM CHECK

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