Lithium-ion battery waste recycling

Lithium-ion batteries (LIBs) are promising battery technologies widely used in consumer electronics, electric vehicles (EV) and stationary storage applications. LIB recycling is the recycling of batteries that have reached their end of life, to recover intrinsic materials, preferably to bring back into the manufacturing supply chain. Recycling these batteries is a multistage process including steps such as collection, sorting, dismantling, physical separation and refining to recover intrinsic materials. Some of these materials are classified as critical or strategic for the Indian manufacturing industry, and their recovery can help alleviate supply chain risks and reduce import dependency. We estimate that Odisha could generate about 6.6 kilotonnes of cumulative LIB waste by 2030, driven primarily by the uptake of electric vehicles and stationary storage applications such as telecom towers, and consumer electronics. To give more context, as per our analysis, approximately 100 tonnes of lithium can be recovered from this LIB waste. A single car lithium-ion battery pack (of an NMC532) could contain around 8 kg of lithium (Castelvecchi 2021); therefore, 100 tonnes of lithium from this waste can theoretically power 12,500 car battery backs.

Opportunities for 2030

Jobs overview

- A total of **200**[1] cumulative direct FTE jobs can be generated from LIB recycling of **7**[2] **kilo tonnes** of cumulative LIB waste in Odisha between 2024 to 2030 in an ambitious scenario. This scenario assumes a high penetration of EVs across the vehicle segments; specifically, the share of EVs in new sales will reach 80 per cent for 2-wheelers and 3-wheelers, and 50 per cent for 4-wheelers by 2030. Furthermore, it will reach 40 per cent for buses by 2030. It also assumes a complete recycling (100 per cent recycling rate) of all types of LIB waste by 2030. This scenario covers waste generated within Odisha during the evaluation period.

Market opportunity

- **10**[3] **million USD** is the revenue potential from recycling 3[4] kilo tonnes of LIB waste in Odisha in 2030 under the ambitious scenario.

Investment opportunity

- **14**[5] **million USD** is the investment potential (or capital expenditure[6]) to set up LIB waste recycling capacities of approximately 3[7] kilo tonnes per annum in Odisha under the ambitious scenario.

Annexure I contains the detailed methodology.

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[1] Rounded up from 181 jobs
[2] Rounded up from 6.6 kilo tonnes
[3] Rounded up from 10.3 million USD; The market opportunity considers the maximum recovery of materials and their sale.
[4] Rounded up from 3.3 kilo tonnes
[5] Rounded up from 13.5 million USD
[6] Includes cost of land, building and machinery.
[7] Rounded up from 3.4 kilo tonnes

Why should Odisha invest in LIB waste recycling?

- **Domestic supplier of critical materials:** The government of India has set ambitious deployment targets for EV and RE technologies, which will increase the demand for LIBs. Consequently, the LIB waste quantum will increase significantly in India from current levels. By creating a conducive environment, Odisha can potentially be a hub for LIB recycling in India and a supplier of key materials. The supply of these key raw materials to domestic manufacturing industries will reduce import dependence and build local mineral supply chains (Warrior, Tyagi and Jain 2023). This will allow the building of a regional battery ecosystem with the growing LIB component manufacturing industry setting up units in the State (Mercom 2023) wherein recycled raw materials can be supplied.

- **Reduced migration of semi-skilled workforce:** The functions of battery waste handling, testing, and repair can be performed by ITI (Industrial Training Institute) graduates upskilled in the battery sector. Scaling LIB recycling will create employment opportunities for such a semi-skilled workforce within the state in the long run and reduce out-of-state migration.

- **Enhanced environmental safety and reduced contamination:** Battery components such as heavy metals like nickel and cobalt can leak from the casing of LIB if left untreated and contaminate soil and groundwater. Further, discarded batteries with residual charge are a safety threat and can lead to fires. Responsible management of battery waste will help overcome these critical issues. Moreover, circularity in the supply chain of critical minerals will reduce the demand for mining them and save the corresponding carbon footprint (Kumar, Mulukutla and Pai 2023).

Inspiration from a success story

Lohum Cleantech Private Limited is India's first **integrated** used LIB treatment facility, performing repurposing, recycling and refining. Operational since 2018, they have **300 MWh** refurbishing and **10,000 tonnes** per annum recycling facility. The used batteries from electric vehicles are repurposed and reused in stationary storage applications or recycled to recover raw materials. The facility is capable of **recovering all major minerals**, including lithium, cobalt, nickel and manganese, which can be used in the manufacturing of new battery cells and can be recycled endlessly (Lohum n.d.).

Who could support in scaling LIB waste recycling?

1. Role of departments

- **Odisha State Pollution Control Board** (OSPCB) to ensure stricter enforcement of Battery Waste Management Rules, 2022 (BWM Rules). It should work closely with the **Forest, Environment and Climate Change Department of Odisha** to specify guidelines for the safe transportation of waste LIBs till the time the Central Pollution Control Board (CPCB) issues them at a national level. The OSPCB to tackle the potential issue of paper trail recyclers (not undertaking actual operations) in the state as exists for e-waste dismantlers[8] by undertaking audits/checks on registered entities for any malpractices such as incorrect reporting and material balance. In addition, the existing EPR (extended producer responsibility) Portal for Battery Waste Management may be leveraged, and producers may be required to add the quantity of the battery waste generated within the state. OSPCB may recommend to the CPCB to amend the portal in this respect. This data will help build capacities and infrastructure to manage the state's domestic waste and plan to expand its capacity for the LIB waste generated by the neighbouring states.

- **The Industries Department,** in consultation with the **Forest, Environment and Climate Change Department and OSPCB**, as per the Odisha EV Policy 2021, to notify a comprehensive policy to encourage recyclers. The policy could focus on creating recycling clusters to bring economies of scale for battery recycling, introduce various fiscal and non-fiscal incentives, promote the uptake of refurbished products, and create markets for reusing recovered materials.

- **Local bodies** to tie up with authorised producers and recyclers and hand over the collected battery waste separately or ensure its channelisation to these authorised entities. Being a relatively new stream, it should facilitate awareness drives and programmes about it. Local bodies should have conditions in their agreements with e-waste recyclers to channelise battery waste, which is a part of e-waste, to authorised recyclers/refurbishers. Further, local bodies could work with OSPCB to build capacities for the waste management staff and the informal sector to ensure the safe handling, transportation, sorting, and storage of battery waste. The OSPCB may facilitate the development of capacity-building modules in consultation with the recyclers.

- **Odisha Skill Development Authority** (OSDA) to create short-term modules to upskill existing ITI graduates and include battery chemistry and battery waste recycling as a part of their courses.

- The **Skill Development and Technical Education Department,** in conjunction with **the State Council for Technical Education and Vocational Training (**collectively **"Skilling bodies")** to facilitate the inclusion of battery chemistries and battery waste management expertise as a part of the ITI curriculum. These courses must be developed in consultation with the recycling industry to meet their requirements and have an internship component to give field exposure to the trainees.

2. **Potential role of the private sector:**

- Battery 'producers', as defined in BWM Rules, must lead the creation of an efficient battery recycling ecosystem. Some immediate priorities include:

  - Reducing waste leakages: producers can explore innovative business models such as 'battery as a service' or introduce incentives such as a deposit refund scheme to ensure the handover of waste batteries for safe treatment. This can also be done by creating a strategic network of collection centres, EV battery replacement, or scrapping centres in cooperation with the recyclers. The private sector involved in the operations and maintenance of stationary storage should tie up with the recyclers for the collection of end-of-life LIBs to close the loop and bring the critical materials back to the LIB production supply chain.

[8] Consultations with OSPCB and e-waste dismantlers

- Channelling waste to authorised recyclers: producers can leverage the EPR portal introduced by CPCB, have direct tie-ups with recyclers, or enter long-term contracts with recyclers. This shall also mitigate recyclers' waste supply issues and secure recycling investments.
- Disclosing battery chemistry and composition: producers can adopt ‘Battery Passport’ to share battery-related information across users in the value chain. This shall ensure efficient sorting and recycling by dismantlers and recyclers.

- In the medium term, battery manufacturers or original equipment manufacturers (OEMs) should adopt strategies such as circular design and standardisation of battery packs for similar applications that can ease and scale the dismantling and recycling process of battery waste. Regular dialogues among OEMs and recyclers would help design effective solutions.
- Waste management entities such as dismantlers and recyclers should collaborate with the OSDA and state Skilling bodies to update the respective courses and curriculum with practical skills on testing and discharging batteries, knowledge of chemistries, operating relevant machineries, etc.
- Recyclers can also collaborate with local bodies or the Housing and Urban Development Department (H&UDD) to communicate any minimum sorting requirement of battery waste that can be potentially undertaken at the level of the local bodies.

Overcoming challenges to scale LIB waste recycling

- **Low levels of LIB waste aggregation:** Most of the collection of LIB waste found in e-waste (such as mobiles and laptops) remains in the unorganised/informal sector. This sector has a better reach for waste generators and offers competitive salvage value to formal channels, leading to supply-related challenges for formal waste management entities. Furthermore, as the informal sector does not process waste efficiently and safely, there is limited resource recovery and significant environmental degradation. Additionally, due to the lesser quantity of LIB waste generation in other applications from EVs and stationary storage, currently, aggregation of LIB waste is a challenge. Hence, efficient reverse logistics of batteries is urgently needed to tap the battery recycling market opportunity.

  Way forward:

  1. Awareness among consumers: Targeted awareness campaigns should be undertaken for registered vehicle scrapping facilities and entities engaged in operations and maintenance of stationary storage batteries to ensure that the batteries are channelised to authorised recycling facilities. They should also be made aware of the regulatory and environmental implications of mismanagement of such batteries to ensure fulfilment of this requirement. The local bodies can facilitate awareness drives and programmes, both for citizens and groups/associations of dealers, the informal sector, etc., to highlight the provisions of the BWM Rules and the roles and responsibilities of the different stakeholders. These can be coupled with the existing awareness drives for waste segregation to guide the deposition of battery waste with either e-waste or domestic hazardous waste or separately.

2. Integration of the informal sector: The BWM Rules can draw parallels from E-waste (Management) Rules, 2022, to recognise informal workers and facilitate the formation of groups to set up facilities for primary activities such as sorting batteries, which can then be channelised to registered processing units. The OSDA can organise skill, health, and safety training for the workforce, both formal and informal, performing such activities.

3. Proactiveness by local bodies and OSPCB: The local bodies can tie up with authorised producers and recyclers to channelise the battery waste, either sorted in existing municipal facilities or dedicated battery waste facilities as set forth above, to create a more formal supply chain. Further, they can create a separate empanelment process for private entities who intend to collect, sort, and channel battery waste to authorised processing units for accountability and compliance with the BWM Rules.

- **Low availability of skilled workforce:** The existing workforce in waste management sectors lacks knowledge of various battery chemistries (to handle and prepare the waste for processing) and operation of the relevant machinery. The limited skillset of the workforce is a huge impediment to the battery recycling industry.

  Way forward: The OSDA to create short-term modules to upskill existing ITI graduates and the curriculum with such topics. It should leverage battery training programmes run by other institutions, such as MEiTY, to customize the curriculum for this sector (MEiTY n.d.).

  Further, the state Skilling bodies can facilitate the inclusion of battery chemistries and battery waste management expertise in the ITI curriculum, including practical training and visits to battery recycling facilities. These can be undertaken at different levels depending on the aptitude, experience, and qualifications of the students. Given its hazardous nature, such training will make the workforce aware of the requisite safety measures.

- **Flammability of LIBs:** LIBs are highly flammable, and due to high residual charge, the transportation of battery waste is likely to cause fire hazards. Hence, it is a huge safety challenge.

Way forward: In this regard, it is important for the CPCB (and/or OSPCB) to specify guidelines, standards or other compliance requirements for the safe collection and packaging, labelling, transportation, and storage of battery waste, as have been issued for hazardous waste management (NPC 2019). The SPCBs enforce these guidelines. The guidelines should be supplemented with awareness and skills development (discharging, sorting) for all workers engaged in collection and transportation activities.

Risk-proofing the scale-up of LIB waste recycling

- **Environmental risks:** Battery recycling is a complex process and could potentially lead to severe environmental footprint if the spent chemicals used in recycling or the unprocessable waste is not disposed properly. OSPCB to ensure, through audits or inspections, that all certified waste management entities adhere to all safety and environmental norms to avoid any impact on the local surroundings, including disposing of unprocessable waste in authorised treatment, storage, and disposal facilities (TSDF).

- **Risks in investment and volatility in commodity prices:** With the battery manufacturers being more cognisant of supply chain risks in various battery materials, there are visible trends of technology evolution to reduce the content of these materials. For instance, cobalt-free batteries such as lithium-ferro phosphate (LFP) are gaining traction over lithium nickel manganese cobalt oxide (NMC) (IEA 2023). These technology shifts will reduce the economic benefits of recycling. Hence, an obsolescence risk of current battery technologies can impact investments in today's recycling infrastructure. Additionally, there is a risk that the relatively lower-value batteries, such as LFP, will not be recycled as much due to relatively lower profits (Willing 2023). Hence, these patterns should be identified to ensure that such LIBs are not disposed of without proper management, and recycling is encouraged through mechanisms such as financial incentives or subsidies.

  The battery waste recycling infrastructure requires significant capital investment. The commodity prices of materials recovered from battery waste are volatile as they depend on the demand and supply of materials from the industries it caters to. For instance, slowing demand for EVs for a short period compared to the production targets can cause a drop in LIB prices and potentially risk the return on investments made overall. Recyclers must stack multiple revenue streams to secure returns on their investments.

Annexure I

Scoping of the lithium-ion battery waste recycling value chain

The scope of the LIB waste recycling value chain is limited to jobs generated from recycling operations that include partial secondary transportation to the recycling facilities[9], sorting, testing and discharging, recycling (dismantling and physical separation) and refining[10] undertaken at the recycling facility. These jobs are created at or by a recycling plant.

Activities prior to recycling, which include primary collection and aggregation, are not included in the scope of the current analysis due to data unavailability. The scope excludes corporate functions of the recyclers, such as accounts, human resources, legal, etc., and ancillary activities related to insurance, banking, chartered accountants, etc. These functions are not directly linked to the operational capacity of the recycler. Hence, only direct jobs from recycling operations are estimated in this analysis.

Jobs

- Direct jobs are converted to a full-time equivalent (FTE). The full-time equivalent or job year is defined as simply a ratio of the time spent by an employee on a particular task/project in a given year to the standard total working hours in that particular year. The FTE formula translates short-term or one-time employment into a full-time equivalent or job-year (Tyagi et al. 2022).
- In this analysis, FTE for recycling operations is the number of workers engaged in the recycling operations in a year divided by the quantity of waste recycled in a year.
- Key informant interviews (KIIs) were conducted with identified players in the LIB waste recycling ecosystem in order to arrive at the FTE. The interviews focused on the number of people employed for LIB recycling operations, average capacity utilisation, challenges and risks for the ecosystem, skilling requirements, etc.

Market opportunity

- The market opportunity is estimated as the revenue accrued by selling recovered materials from recycling LIB.

Investment opportunity

- Investment opportunity refers to the capital expenditure to be incurred in setting up the LIB waste recycling facilities. This includes the cost of land, building, and machinery.

[9] The transportation is partial herein since occasionally the LIB waste supplier transports the LIB waste to the recyclers. In this context, we have accounted for employment by the recycler towards partial/limited transportation of waste to the recycling facilities. Any jobs created by other than the recyclers have not been included in this study.

[10] Refining stage employment numbers have been estimated only on a pilot basis. Hence, actual employment numbers may vary when refining operations are scaled.

Detailed methodology for market, employment, and investment opportunity

Two scenarios were developed for estimating the market, investment, and employment opportunity: policy and ambition. These differ in the quantum of waste and recycling targets.

FTE estimation

KIIs were conducted with identified players to calculate the LIB waste recycling FTE and estimate the jobs.

- A mix of purposive and convenience sampling strategies was used to identify the stakeholders for KIIs.
- Six KIIs were conducted with recyclers, of which four recyclers' data have been obtained and considered for analysis. The recyclers’ activities included partial waste transportation to the recycling facilities, storage, testing and discharging, sorting, recycling (dismantling and physical separation), and refining at a *pilot* stage. The annual recycling capacity of these facilities ranges from 350 to 3,600 tonnes.
- Questionnaires were used to gather information and data from the respondents. The broad heads under the questionnaire included specifications of the recycling plants such as capacity, personnel deployed for overall recycling operations, etc., and stages of recycling. There were also qualitative questions on skill requirements at different stages of recycling, risks associated with the recycling ecosystem, prevalent challenges in the ecosystem, and interventions that can potentially solve them.

Annual FTE for LIB waste recycling is computed as:

$$Full\ time\ equivalent\ (per\ kilo\ tonnes) = \frac{Total\ number\ of\ workers\ employed\ for\ recycling\ and\ refining\ operations}{Total\ waste\ recycled\ and\ refined\ in\ the\ year\ (in\ kilo\ tonnes)}$$

Table 1: Annual FTE calculated using data received from the KIIs

<table>
<tr><th colspan="9">Recycling FTE (workers per kilo tonne[11])</th></tr>
<tr><th rowspan="2">Recycling facilities</th><th colspan="7">Recycling</th><th>Refining</th></tr>
<tr><th>Transportation</th><th>Unloading and loading</th><th>Storage</th><th>Testing and discharging</th><th>Sorting</th><th>Dismantling</th><th>Physical separation</th><th>Pilot stage refining</th></tr>
<tr><td>Facility 1</td><td>-</td><td colspan="6">30.8</td><td></td></tr>
<tr><td>Facility 2</td><td colspan="5">5</td><td colspan="2">13</td><td>13</td></tr>
<tr><td>Facility 3</td><td>-</td><td>-</td><td colspan="5">29</td><td></td></tr>
<tr><td>Facility 4</td><td colspan="2">2.2</td><td>1.9</td><td>5.4</td><td>1.9</td><td>2.1</td><td>2.4</td><td>48.6</td></tr>
<tr><td>Average (per kilo tonne)</td><td colspan="7">23.44</td><td>30.81</td></tr>
</table>

[11] 1 kilo tonne is 1000 tonnes.

FTE for recycling (per kilo tonne)	**23.44**
FTE for refining at a pilot stage (per kilo tonne)	**30.81**
Combined FTE (per kilo tonne)	**54.25**

Source: Authors' analysis based on stakeholder consultations

- It should be noted that this analysis does not consider any reduction in employment due to increased automation of various recycling operations.

Market opportunity

The market opportunity has been estimated from the sale of materials recovered from LIB waste within or outside Odisha. The following methodology was used to calculate the market opportunity across the two scenarios: policy and ambitious.

- First, the LIB waste generated in Odisha from 2024-2030[12] was projected under three product categories: electric vehicles (EVs), stationary storage (from telecom towers), and consumer electronics (mobiles and laptops/computers). The sections below discuss this in detail. Next, the LIB waste was characterised (battery type and composition) based on the product categories. Thereafter, recycling rates as per the extended producer responsibility (EPR) targets under the Battery Waste Management Rules, 2022, were applied to the waste projected to calculate the LIB waste to be recycled. Recovery rates for hydrometallurgy recycling were used to arrive at the quantum of recovered materials from recycled waste. Lastly, it was multiplied with the market price of the materials to estimate the revenue from recycling. The market opportunity is, therefore, a summation of the quantum of product and price of all recoverable materials from LIB waste:

Market opportunity (USD) = $\sum$*(Recovered material from LIB waste (kg))*$_i$ ** (market price (USD/kg))*$_i$
i indicates the recoverable materials from the LIB waste
USD to INR = 83

- The following sections detail these stages:

i. Composition of different battery types:

The LIB waste is bifurcated into different types of batteries based on the type of vehicle or product. Thereafter, the composition of materials for different batteries by weight is used to calculate the quantum of different materials in the LIB waste.

Table 2: Composition of different battery types

Quantity of material in 1 GWh of battery	NMC (Nickel Manganese Cobalt) (in tonnes)	LFP (Lithium Iron Phosphate) (in tonnes)	NCA (Nickel Cobalt Aluminum) (in tonnes)
Lithium	93	96	102

[12] Note: For stationary storage, the estimation of market opportunity is up to 2031. For EVs and consumer electronics, the estimation of market opportunity is up to 2030.

Manganese	72	0	0
Iron	0	731	0
Nickel	614	0	674
Cobalt	77	0	127
Phosphorus	11	427	11
Aluminium	162	262	171
Fluorine	42	77	41
Copper	284	466	265
Graphite	915	1,055	905

Source: Niti Aayog 2022

Mineral composition for LCO (Lithium Cobalt Oxide) battery	**Composition (in %)**
Lithium	2
Iron	5
Oxygen	8
Cobalt	15
Phosphorous	3
Aluminium	17
Fluorine	11
Copper	11
Graphite	15
Other (plastics and electronics)	14

Source: Niti Aayog 2022

ii. Recovery rates

Thereafter, materials found in the LIB waste and to be recovered are multiplied by the recovery rates to estimate the quantity of recovered materials from LIB waste using **hydrometallurgy recycling**. Below are the recovery rates of minerals from hydrometallurgy recycling of LIB waste:

Table 3: Recovery rates of minerals from hydrometallurgy recycling of LIB waste

Recovery rates of minerals from hydrometallurgy recycling of LIB waste	**NMC (in %)**[13]	**LFP (in %)**[14]	**NCA (in %)**[15]	**LCO (in %)**[16]

[13] Gupta, et al. 2019; Feng, Jin et al 2023.
[14] Gupta, et al. 2019; Feng, Jin et al 2023.
[15] Joulié, M., et al 2014; Muzayanha, Soraya Ulfa et al 2019; Feng, Jin et al 2023.
[16] Tao, Ren et al 2022; Jha, Manis Kumar et al 2013; Feng, Jin et al 2023.

Lithium	94	81	80	88
Manganese	100	-	-	-
Iron	-	99	-	-
Nickel	97	-	100	-
Cobalt	100	-	94	99
Aluminium	100	100	100	100
Copper	100	100	100	100
Graphite	83	83	83	83

iii. Prices of recovered materials

The quantum of recovered materials is then multiplied by the market prices to arrive at the market opportunity for this value chain.[17] There is a huge range in the prices of recycled materials depending on their purity. As a result, we have used the price of virgin counterparts as a proxy for recycled materials in this analysis.

The prices of the recovered material from recycling LIB have been taken from secondary sources. The average prices for five years, 2019-2023, have been used for the assessment period (2024 to 2030). The prices are kept constant, and any change in the prices will directly impact the market opportunity.

Table 4: Average prices of materials

Market price of minerals	$ per tonne
Lithium	28,733
Manganese	48
Iron	119
Nickel	18,713
Cobalt	42,871
Aluminium	2,206
Copper	7,777
Graphite	870

Source: Indian Bureau of Mines and Daily Metal Prices

[17] The market opportunity considers the maximum recovery of materials and their sale.

Market opportunity for the three product categories across the two scenarios: policy and ambitious.

1. **Market opportunity for electric vehicles (EVs)**

Waste generation:

- 2w, 3w, cars, and bus sales in Odisha were taken from the **Vaahan dashboard** and projected until 2030 using a CAGR (compound annual growth rate). (Refer to **Annexure II** for detailed calculation).

- New EV sales in Odisha were obtained from the Vaahan dashboard from 2014 to 2023. The EV penetration percentage in each vehicle category was calculated using the formula below.

  EV penetration in each category = (total EV sold in the year / total vehicle sold in that year)*100

- Thereafter, the life of the batteries was derived from the extended producer responsibility (EPR) targets under the Battery Waste Management Rules, 2022 (BWM Rules). The life of 2w, 3w, cars, and buses is applied to EV sales to calculate the number of LIB waste from 2024 to 2030. The life of the vehicle has been taken from secondary sources.

Table 5: Life of battery and vehicles

Vehicle category	**Battery life**
2-Wheeler	4
3-Wheeler	5
cars	8
Buses	8
Vehicle category	**Lifespan of the vehicles**
2-wheelers	12
E-rickshaw	5
3-wheelers	10
cars	12
buses	12

Source: Battery Waste Management Rules, 2022 for battery life; For the lifespan of the vehicles: 2-wheelers - AMO Electric Bikes 2022, e-rickshaw - Shandilya et al. 2019, 3-wheelers - expert consultations, cars - Government of NCT of Delhi 2021, buses - Khanna et al. 2024

Table 6: Battery size of different vehicle categories:

Vehicle category	Battery size (In KWh)
2W	2
3W	7
cars	40
Bus	250

Source: Niti Aayog 2022

- Under the **policy scenario**, it is assumed that Odisha will also meet India's EV penetration target of **EV30@30** (Niti Aayog 2023), i.e., 30 per cent of new EV sales by 2030. In this regard, the current EV penetration percentage, i.e., in 2023, is projected to reach 30 per cent across all the vehicle categories by 2030, and the EV sales are calculated year on year from 2024 to 2030 using this trend. In this context, the LIB waste generation from EVs for the period 2024-2030, under the policy scenario, was estimated:

Table 7: Estimated LIB waste generation from EV in Odisha under the Policy scenario for 2024-30

Vehicle categories	LIB waste (in GWh)
2W	0.57
3W	0.07
Cars	0.02
Buses	0.01

Source: Authors' analysis

- Under the **ambitious scenario**, it is assumed that EV sales penetration will be 30 per cent of private cars and 70 per cent of commercial cars; therefore, an average of 50 per cent is taken for cars. Additionally, penetration will be 40 per cent for buses and 80 per cent for two and three-wheelers by 2030. This scenario is conditional on the success of FAME II and other measures India takes (NITI Aayog and Rocky Mountain Institute 2019). In this regard, the current EV penetration percentage, i.e., in 2023, is projected to reach these percentages across all the vehicle categories by 2030 and, the EV sales are calculated year on year from 2024 to 2030 using this trend. Similarly, the LIB waste generation from EVs for the period 2024-2030, under the ambitious scenario was estimated:

Table 8: Estimated LIB waste generation from EV in Odisha under the ambitious scenario for 2024-30

Vehicle categories	LIB waste (in GWh)
2W	0.69
3W	0.08

Cars	0.02
Buses	0.01

Source: Authors' analysis

- The below conversion metrics were used to calculate the LIB from Wh to kgs:

Table 9: Size of different types of LIBs

Type of LIB	in kg	in Wh
NMC	1	170
LFP	1	115
NCA	1	225
LCO	1	170

Source: Niti Aayog 2022

Waste characterisation:

- The LIB technologies for different vehicle categories have been taken from CEEW analysis of the demand for transport technologies. These technologies are kept constant for the assessment period (2024 to 2030).

Table 10: Battery technology for LDVs

Battery technology - 2w, 3w, cars (light-duty vehicle or LDV)	Demand
NMC (Nickel Manganese Cobalt)	72%
LFP (Lithium Iron Phosphate)	10%
NCA (Lithium Nickel-Cobalt-Aluminum Oxide)	10%

Table 11: Battery technology for HDVs

Battery technology - buses (heavy-duty vehicles or HDV)	Demand
NMC	5%
LFP	94%

Source: Warrior, Tyagi, and Jain 2023

- It is important to note that recent reports have shown a declining trend for NMC batteries in LDVs and leaning more toward LFP, as shown in the table below. This trend is mainly driven by Chinese original equipment manufacturers (OEMs).

Table 12: Battery technology trends in LDVs

Battery chemistry in LDVs	2018	2019	2020	2021	2022
LFP	7%	3%	6%	17%	27%

Nickel based	89%	95%	92%	80%	70%
Others	4%	2%	3%	3%	3%

Source: Compiled from IEA 2023

On the contrary, only approximately 3 per cent of EV cars with LFP batteries were manufactured in the United States in 2022. Additionally, new technologies such as sodium-ion are emerging, which are cost-effective and do not rely on critical minerals (IEA 2023). However, there is limited granular data on battery chemistries and the distribution of various subtypes across vehicle categories. As a result, the earlier available data, which indicated the dominance of NMC chemistry in LDVs, is used in the analysis. This trend may change and will directly impact the market opportunity estimated herein.

Recycling and recovery rates

- **Market opportunity for policy scenario**: The recycling targets under EPR under the BWM Rules have been considered as the recycling rate for EVs from 2024 to 2030, i.e., **70 per cent**. Therefore, the quantity of LIB waste to be recycled cumulatively from 2024 to 2030 for the **policy** scenario is **2.6 kilo tonnes**. Applying the recovery rates and the prices set out above, the market potential comes to be **8.2 million USD**.

- **Market opportunity for ambitious scenario**: Recycling targets are considered to reach **100 per cent**, by 2030 given that considerable increase in recycling capacities are projected in India. Therefore, the quantity of LIB waste to be recycled cumulatively from 2024 to 2030 and for the **ambitious** scenario it is **4.3 kilo tonnes**. Applying the recovery rates and the prices set out above, the market potential comes to be **13.5 million USD**.

2. Market opportunity for LIB waste from stationary storage

Waste generation:

- For stationary storage, only LIBs for telecom towers in Odisha are considered. The contribution of other applications, such as power backup systems, is not considered as these systems largely use lead-acid batteries, and the current penetration of LIB is low. The absence of any Odisha-specific study projecting the future trajectory of LIB penetration in these applications further limits the waste generation modelling.

- As per the Department of Telecom, there are **25,115 telecom towers** in Odisha (Business Standard 2023). Furthermore, as per India Energy Storage Alliance, LIB penetration is up to 20 per cent in the telecom sector (IESA 2022). Therefore, it is assumed that 20 per cent of the stationary storage battery waste from telecom towers will be **LIB waste, i.e., 5,023 units**.

- The calculation of the average battery energy capacity for telecom tower batteries involves utilising the average voltage (V) and ampere-hours (Ah) of the battery. The resulting battery capacity in watt-hours (Wh) is obtained by multiplying V with Ah. On average, the battery capacity for a telecom tower is 600 Ahr and 48 V, having a capacity of 28,800 Wh.

Waste characterisation:

- The primary technology for stationary storage batteries leans towards LFP, with a minor contribution from NMC (Warrior, Tyagi, and Jain 2023). The average weight of batteries, as mentioned in previous sections, is also used for LIB in stationary applications.

- Therefore, the end-of-life LIB waste is calculated using the below formula:

$$LIB\ waste\ (in\ tonnes)\ = \sum_{i} \frac{LIB\ waste\ in\ units * LIB\ capacity\ per\ telecom\ tower * LIB\ technologyy\ percentage_{i}}{Average\ energy\ densityy_{i} * 1000}$$

Where:
i= 1,2 where 1 is LFP battery, and 2 is NMC battery
LIB waste: 5,023 units.
LIB capacity per telecom tower: 28,800 Wh
LIB technology percentage: 17 per cent for NMC and 80 per cent for LFP
Average energy density: 115 Wh per kg for LFP batteries and 170 Wh per kg for NMC batteries.

- As per the above calculation, the LIB waste from stationary storage will be **1,151 tonnes**.

- The life of these batteries is assumed to be eight years, given that they are primarily LFP (Lithium iron phosphate). Since buses are also primarily LFP and have the EPR targets applicable after eight years of placing the battery in the market under the BWM Rules, the same target has been applied to stationary storage batteries.

- In this context, LIB waste from telecom tower stationary storage LIBs existing in 2023 will reach 1,151 tonnes in 2030 in Odisha. Please note that any discontinuity, replacement, etc., has not been considered for this calculation.

Recycling and recovery rates:

- **Market opportunity in policy scenario:** The recycling target for industrial battery under EPR under the BWM Rules has been considered as the recycling rate for stationary storage from 2024 to 2030, i.e., **70 per cent**. Applying the recovery rates and the prices set out above, the market potential is **1.88 million USD** from recycling **800 tonnes**.

- **Market opportunity in ambitious scenario:** Recycling targets are considered to reach **100 per cent**, by 2030, given that a considerable increase in recycling capacities is projected in India. Applying the recovery rates and the prices set out above, the market potential is **2.68 million USD** from recycling **1,151 tonnes**.

2. LIB waste from consumer electronics

Waste generation:

- Two categories of consumer electronics: mobiles and laptops/computers, were selected to estimate LIB waste from consumer electronics generated in Odisha.

Mobiles

- As per Odisha Economic Survey, 2023 (Planning and Convergence Department 2023), 80.7 per cent of households had mobile access in 2015-16 and 88.3 per cent in 2019-21. In this context, the penetration of mobiles in households is projected to reach 100 per cent by 2030.

- Using Odisha's population projections till 2030 (Ministry of Health and Family Welfare 2020) and assuming that the average number of members in a household is 4.3, the number of households was estimated until 2030.

- Thereafter, penetration per cent of mobile access was used to calculate the number of households that had mobile access. It is assumed under this analysis that each household will have one mobile. The average life of mobiles is considered to be three years, even though, as per the E-waste (Management) Rules, 2022, the lifespan is given as five years. This is because of the reduced mobile lifespan (Statista 2023). Applying the life of mobiles to the number of mobiles and the average weight of mobile battery, LIB waste from mobiles was calculated. However, any change in the penetration of mobiles in households will directly impact the market opportunity.

Computers

- Odisha's computer facility penetration was 4.3 per cent of households in 2019 (Indian Express 2019). It is assumed that each such household will have only one computer/laptop. Assuming this penetration constant till 2030 for the current analysis, the number of computers/laptops sold was calculated. Any change in the penetration of computers/laptops in households will directly impact the market opportunity.

- The average life of computers/laptops is considered to be **5 years** as per the E-waste (Management) Rules, 2022. Applying this life to the number of computers/laptops along with the average weight of their battery, LIB waste from computers/laptops was calculated.

Waste characterisation

- The average battery weight for mobiles is considered to be 56 gms, and for laptops, it is 235 gms. This has been estimated from secondary sources of companies selling these products. However, this weight may vary depending on the battery size, mobile type, and price; therefore, any change in the weight of the battery will change the market opportunity. The average battery weight of Lithium Cobalt Oxide (LCO) is 170 Wh per kg. Consumer electronics will predominantly use LCO battery technology till 2030 (Niti Aayog 2022). Therefore, using the below formula, the quantum of LIB waste from consumer electronics in the period of 2024-2030 can be estimated.

$$LIB\ waste\ (in\ tonnes)\ =\ Number\ of\ LIB\ waste\ units\ in\ the\ year\ *\ average\ battery\ weight\ (in\ tonnes)$$

- On the basis of the above methodology, the LIB waste generated from **consumer electronics for the assessment period 2024-2030 in Odisha is 1.4 kilo tonnes or 1,440 tonnes**.

Recycling and recovery rates

- **Market opportunity in policy scenario**: The recycling target for portable batteries used in consumer electronics that is chargeable under EPR under the BWM Rules has been considered as the recycling rate from 2024 to 2030, i.e., **70 per cent**. Applying the recovery rates and the prices set out above, the market potential is **7.4 million USD** by recycling 1 kilo tonnes.

- **Market opportunity in an ambitious scenario:** Recycling targets are considered to reach **100 per cent** *by the year 2030*, given that considerable increase in recycling capacities is projected in India. Applying the recovery rates and the prices set out above, the market potential appears to be **8.9 million USD by** recycling 1.2 kilo tonnes.

The **total estimated market opportunity** (across all product categories) under the **policy** scenario for recycling (including pilot stage refining) LIB waste generated (from all three categories) in Odisha from 2024-2030 is **17.4 million USD**.

The **total estimated market opportunity** (across all product categories) under the **ambitious** scenario for recycling (including pilot stage refining) LIB waste generated (from all three categories) in Odisha for the period of 2024-2030 is **25 million USD**.

Jobs

The FTEs calculated for recycling and refining (at a pilot stage) are used on LIB waste generated. The results are as follows:

- Under the policy scenario, the total cumulative jobs for the assessment period 2024-2030 is **108** for recycling and refining (at a pilot stage), a cumulative LIB waste of **4.4 kilo tonnes**. The LIB waste generation in the last year 2030 is approximately **2,000 tonnes**.

- Under the ambitious scenario, the total cumulative jobs for the assessment period 2024-2030 is **181** for recycling and refining (at a pilot stage), a cumulative LIB waste of **6.6 kilo tonnes**. The LIB waste generation in the last year 2030 is approximately **3,344 tonnes**.

Investment opportunity

Investment opportunity is the capital expenditure (capex) to be incurred in setting up the LIB waste recycling facilities under different scenarios.

- An average estimate of a secondary source (Moerenhout et al. 2022) and a primary consultation was used as the capital expenditure. **Annexure III** contains the details**.**

- The recycling capacity was sized to the maximum LIB waste generated in Odisha, that is for the year 2030. The number of recycling plants and capacities are indicative to show the investment potential.

Table 13: Capex requirements

Scenario	Annual waste to be recycled in 2030 (in tonnes)	Number of facilities required	Per annum capacity (in tonnes)
Policy	2,000	1	2,000
Ambitious	3,400	1	1,400
		1	2,000

Source: Authors' analysis

- In this context, the investment opportunity under the policy scenario is **8 million USD,** and under the ambitious scenario, it is **13.5 million USD**.

Annexure II: Calculation for estimating end-of-life LIB waste from EVs in Odisha

Table 14: Reported data on vehicle and EV sales

	Reported data[18]											CAGR (in %)
Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**Increase in sales**
Total Vehicle sales (all types of fuels)												
2 Wheelers	*3,83,847*	*4,36,758*	*4,87,491*	*5,36,191*	*6,43,625*	*7,19,115*	*6,85,663*	*4,94,461*	*4,25,614*	*5,05,392*	*5,74,191*	
CAGR from 2013-2023												**4.11%**
3 Wheelers (E-Rickshaws)	0	0	3	1	*103*	*336*	*308*	*248*	*584*	*1,767*	*2,973*	
CAGR from 2018-2023												**75.14%**
3-Wheelers (Excluding E-rickshaws)	0	17,208	18,337	18,942	18,057	20,356	23,007	*11,293*	*6,780*	*9,116*	*15,622*	
CAGR from 2020-2023												**11.42%**
Cars		*34,793*	*38,480*	*40,604*	*49,204*	*54,561*	*50,995*	*44,620*	*54,534*	*65,334*	*68,685*	
CAGR from 2014-2023												**7.85%**
Buses (bus + educational institution bus)		*792*	*906*	*1,130*	*1,254*	*1,293*	*1,141*	*537*	*361*	*929*	*1,417*	
CAGR from 2014-2023												**7%**
Total Electric vehicle sales	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**Increase in EV sales based on scenario targets**

[18] Data till 2023 has been taken from Vahaan portal, post that the data has been projected from CAGR and EV penetration scenarios for the EV sales.

Policy scenario												
2-wheelers	97	45	33	23	88	918	834	610	4,944	25,721	34,708	**25.72%**
3-wheelers (E-rickshaw)	0	0	3	1	103	336	308	248	584	1,767	2,973	-
3-Wheelers (Excluding e-rickshaws)	4	2	4	1	4	17	18	25	39	486	1,712	**15.48%**
Cars		2	4		7	5	1	21	60	437	1,291	**48.55%**
Buses (bus + educational institution bus)										30	20	**54.75%**
Ambitious scenario												
2-wheelers	97	45	33	23	88	918	834	610	4,944	25,721	34,708	**44.63%**
3-wheelers (E-rickshaw)	0	0	3	1	103	336	308	248	584	1,767	2,973	-
3-Wheelers (Excluding e-rickshaws)	4	2	4	1	4	17	18	25	39	486	1,712	**32.84%**
Cars		2	4		7	5	1	21	60	437	1,291	**59.79%**
Buses (bus + educational institution bus)										30	20	**61.24%**

Source: Vahan Dashboard

Table 15: Data projected for vehicle and EV sales based on CAGR

	Projected data (*based on the above CAGR*)						
Year	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Total vehicle sales (all types of fuels)							
2 Wheelers	5,97,787	6,22,352	6,47,927	6,74,552	7,02,272	7,31,131	7,61,176
3 Wheelers (E-Rickshaws)	5,207	9,120	15,973	27,975	48,996	85,813	1,50,295

3-Wheelers (Excluding E-rickshaws)	17,407	19,395	21,610	24,079	26,830	29,894	33,309
Cars	74,077	79,891	86,163	92,926	1,00,220	1,08,087	1,16,572
Buses (bus + educational institution bus)	1,512	1,613	1,720	1,835	1,958	2,088	2,228
Total Electric vehicle sales	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Policy scenario							
2-wheelers	45,427	59,456	77,817	1,01,850	1,33,304	1,74,471	2,28,353
3-wheelers (E-rickshaw)	5,207	9,120	15,973	27,975	48,996	85,813	1,50,295
3-Wheelers (Excluding e-rickshaws)	2,202	2,834	3,646	4,691	6,036	7,766	9,993
Cars	2,068	3,314	5,309	8,505	13,625	21,829	34,972
Buses (bus + educational institution bus)	33	55	90	149	245	405	668
Ambitious scenario							
2-wheelers	52,259	78,686	1,18,477	1,78,390	2,68,599	4,04,427	6,08,941
3-wheelers (E-rickshaw)	5,207	9,120	15,973	27,975	48,996	85,813	1,50,295
3-Wheelers (Excluding e-rickshaws)	2,534	3,750	5,551	8,217	12,162	18,003	26,648
Cars	2,225	3,834	6,608	11,388	19,625	33,821	58,286
Buses (bus + educational institution bus)	34	59	102	175	301	518	891

Source: Authors' analysis

Table 16: LIB penetration among other batteries used in EVs

LIB penetration among other batteries used in the EVs	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	CAGR growth between 2022-30
2-wheelers	-	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	
3-wheelers (E-rickshaw)	-	0%	1%	3%	4%	5%	6%	8%	9%	10%	12%	14%	17%	20%	24%	28%	34%	40%	19%

3-wheelers (excluding E-rickshaws)	-	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	
4-wheelers	-	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	
Buses	-	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	

Source: Authors' analysis based on key market players; e-rickshaws: Niti Aayog 2022

Table 17: Sales years considered to calculate the CAGR for projecting overall vehicle sales in different categories

Vehicle category	Years considered to calculate the CAGR	CAGR (in %)	Reason for considering the given years
2w	2013-2023	4.11	Last 10 years considered
3w - e-rickshaws	2017-2023	75.14	Negligible volume before 2017
3w - excluding e-rickshaws	2020-2023	11.42	There was a declining trend before 2020
cars	2014-2023	7.85	Last 9 years considered
buses	2014-2023	7	Last 9 years considered

Source: Authors' analysis

Table 18: Estimated number of EV LIBs attaining end-of-life (EOL) under policy and ambitious scenarios

Policy scenario	2024	2025	2026	2027	2028	2029	2030
2-Wheeler	633	5,032	26,684	35,575	46,060	64,488	1,04,456
E-rikshaws	19	19	51	177	354	736	1,534
3 wheeler	20	29	40	490	1,729	2,220	2,859
4-Wheelers	0	7	7	5	21	67	442
Buses	0	0	0	0	0	0	30

Ambitious scenario	2024	2025	2026	2027	2028	2029	2030
2-Wheeler	633	5,032	26,684	35,575	52,892	83,718	1,45,116
E-rickshaws	19	19	51	177	354	736	1,534
3 wheeler	20	29	40	490	1,729	2,552	3,775
4-Wheelers	0	7	7	5	21	67	442
Buses	0	0	0	0	0	0	30

Source: Authors' analysis

Annexure III:

Data used to estimate investment opportunity

Table 19: Capital expenditure for a LIB recycling facility with a capacity of 5000 to 7000 tonnes per annum

Heads	USD million
Capital Equipment	5
Machinery	
Mechanical shredders	
Conveyors	
Reactors	
Installation and construction cost	1
Technology Acquisition Cost	2
R&D and testing laboratory set-up cost	0.5
Land	0.4
Buildings	1.25
Total	**10.15**
Per tonne	**0.00145**

Source: Moerenhout et al. 2022

The primary consultation suggested that for each tonne of LIB recycling facility, approximately 6,500 USD of capital expenditure is required.

Therefore, an average, 0.0040 million USD per tonne is considered to estimate investment opportunity.

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