ASEAN Journal for Science and Engineering in Materials

Journal homepage: https://ejournal.bumipublikasinusantara.id/index.php/ajsem

Techno-Economic Analysis of the Business Potential of Recycling Lithium-ion Batteries Using Hydrometallurgical Methods

*Dwi Rizky Rachmadhani, Bambang Priyono**

Universitas Indonesia, Indonesia

Correspondence: E-mail: bpriyono@metal.ui.ac.id

ABSTRACT

Indonesia is committed to achieving net zero emissions by 2060 through short-term policies. The focus includes energy efficiency, renewable resources in the electricity sector, and transportation electrification. Transportation electrification leads to increased use of lithium-ion batteries, predicted to grow at a CAGR of 25.45%. The installed capacity of lithium-ion batteries is expected to reach 10.5 TWh, with 8.1 TWh in electric vehicles by 2030. The waste from lithium-ion batteries in Indonesia is estimated to be 250,000 tons by 2020, increasing with electric vehicle policies. By 2040, it is projected to require 0.2 million tons of cobalt and 1.3 million tons of nickel. Recycling support to address domestic lithium unavailability results in a circular economy worth US$ 49,767,416 and reduces emissions by 7,472 tons of CO2 from devices sold in 2022.

ARTICLE INFO

Article History:

Submitted/Received 30 Aug 2023
First Revised 03 Oct 2023
Accepted 17 Dec 2023
First Available online 19 Dec 2023
Publication Date 01 Sep 2024

Keyword:

Electric vehicle,
Hydrometallurgy,
Lithium-ion battery,
Pyrometallurgy,
Recycling technology.

1. INTRODUCTION

Currently, Indonesia is committed to achieving net-zero emissions by 2060 (Rahmanta *et al*., 2023). This requires a shift from fossil fuel usage to the use of new renewable energy sources. Additionally, with the adoption of renewable energy, there is a need for energy storage media to ensure accessibility at all times. The energy sector is a significant contributor to carbon emissions, more than doubling in the last two decades compared to other sectors. In 2021, Indonesia ranked as the ninth-largest emitter of carbon from the energy sector, with emissions reaching 600 million tons of carbon dioxide (Mt CO_2) (Rahmanta *et al*., 2023). The Indonesian government has and will continue to make various efforts to achieve the goal of net-zero emissions by 2060. Policy support is crucial to guide sustainable efforts, with short-term pillars set by the government including energy efficiency, renewable resources in the electricity sector, and electrification of transportation. The Presidential Regulation on Acceleration of Battery Electric Vehicle (BEV) Programs for Road Transportation is a concrete effort to promote battery-based transportation electrification. This will directly increase the demand for batteries in Indonesia, including lithium-ion batteries.

Lithium-ion batteries have become an integral part of daily life due to their widespread use in various industries, including consumer electronics, electric vehicles (EVs), hybrid vehicles, and renewable energy systems. A report from Circular Energy Storage Research & Consulting shows a rapid increase in the lithium-ion battery market in recent years. In 2019, the installed capacity of lithium-ion batteries worldwide reached 700 GWh, with 51% installed in electric vehicles (Rahmanta *et al*., 2023). The increasing demand for these batteries is predicted to continue, primarily driven by the global development of electric vehicles in line with the spirit of net-zero emissions. The lithium-ion battery market is expected to grow at a CAGR of 25.45%, reaching a total installed capacity of 10.5 TWh worldwide, with 8.1 TWh installed in electric vehicles by 2030 (Rahmanta *et al*., 2023). The rising demand for these batteries has also led to the accumulation of electronic waste, including discarded lithium-ion batteries. Improper disposal of these batteries can create serious environmental problems, such as water, soil, and air pollution. **Figure 1** shows the world's need for lithium ion batteries until 2030.

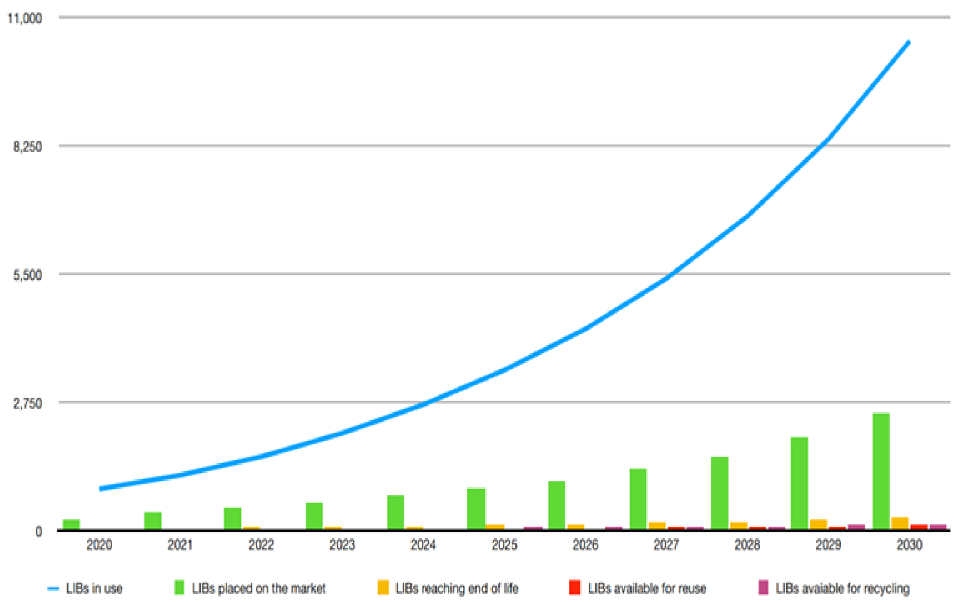

Figure 1. World lithium ion battery needs until 2030 adopted from (Rahmanta *et al*., 2023).

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Recycling or processing lithium-ion batteries is one way to address these environmental concerns and turn waste into wealth. Recycling these batteries can recover valuable metals such as lithium, cobalt, and nickel, reducing the need to mine pure natural resources and minimizing the environmental impact associated with mining activities. Additionally, battery recycling can create job opportunities and contribute to circular economic growth.

Despite the environmental and socio-economic benefits of recycling lithium-ion batteries, the global recycling rate for these batteries remains low (Metzger, 2023). There is a need to raise awareness of the importance of recycling and develop innovative recycling technologies and cost-effective, sustainable business models. Conscious efforts to manage the life cycle of batteries are key to achieving sustainable development goals. Batteries that have reached the end of their life can still be utilized for secondary or tertiary applications in other sectors.

Based on the above description, this research aims to explore the potential of recycling lithium-ion batteries as a profitable business venture and provide insights into current market trends, demand, and the supply chain for lithium-ion batteries. Research on the life cycle of lithium-ion batteries is crucial to support government efforts to achieve net-zero emissions targets while enhancing domestic economic capacity through the involvement and participation of various stakeholders. Indonesia is currently building an integrated electric vehicle battery industry to enhance energy resilience. The primary focus should be on acceptability standards, particularly environmental aspects. This research will also assess the legal framework and regulations governing the recycling of lithium-ion batteries, highlighting challenges and opportunities for entrepreneurs, investors, and policymakers interested in this industry.

2. METHODS

2.1. Workflow

The life cycle analysis of batteries in this research utilizes secondary data with a descriptive quantitative approach. Data collection involves specific samples and populations for statistical analysis to test predetermined hypotheses. Additionally, a descriptive approach is used to characterize the research object, considering technical frameworks and policies. The secondary data analysis approach aims to utilize quantitative or qualitative data to identify new issues. These issues are then analyzed to become opportunities for developing solutions that bring benefits both socioeconomically and environmentally. This research begins with a literature review to identify various battery life cycle issues and potential improvisations. To explore the opportunities for lithium-ion battery recycling in Indonesia, data on the number of devices utilizing lithium-ion batteries are collected to assess the potential waste generated. Information on the lifespan of devices is also needed to estimate the recycling time. The devices reviewed in this study include electric vehicles, smartphones, digital cameras, laptops, and tablets, which extensively use lithium-ion batteries. The metal composition in battery waste can then be calculated, along with the potential percentage that can be separated and recovered for use in other applications. The economic potential of the circular economy is analyzed by calculating the economic value of each metal.

The carbon footprint of lithium-ion battery production is quantitatively evaluated to understand the environmental impact throughout the recycling process cycle. This information is used to compare greenhouse gas emission reductions from recycling compared to battery production, including mining activities.

Recommendations for lithium-ion battery recycling opportunities are made by comparing the potential metals obtained from recycling with future raw material needs to accommodate the goal of net-zero emissions by 2060. The economic revival potential is assessed based on the unavailability of mineral resources for battery production domestically. This is done to ensure the sustainability of domestic production, accompanied by mitigating challenges outlined in the domestic industry roadmap. **Figure 2** shows the steps in this research.

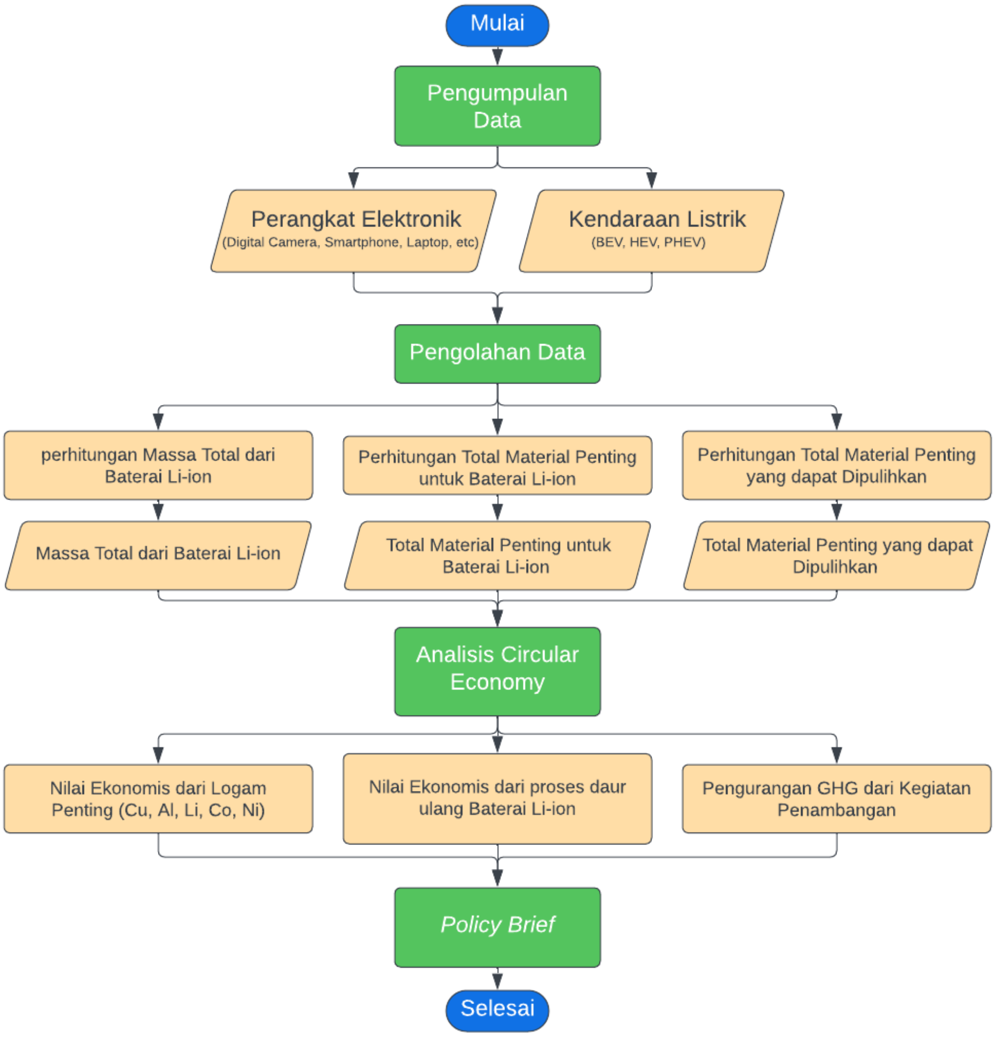

Figure 2. Research workflow.

2.2. Lithium-Ion Battery Recycling Technology

Processing used batteries has become essential, particularly concerning various aspects such as emission factors and environmental safety. Used batteries can be processed in one of two ways: reuse and recycling (Fan *et al*., 2018; Pagliaro, 2019; Vanderbugt, 2023). Reusing batteries involves extending their second life as energy storage media in the electric grid or other applications. On the other hand, recycling is chosen to separate and recover various valuable metals like nickel, lithium, cobalt, manganese, aluminum, and more.

The production process for all types of batteries, including lithium-ion batteries, involves a series of materials and energy, resulting in a carbon footprint and influencing climate change. Lead-acid batteries have been successfully recycled using mature technology because their recycling process is simpler compared to lithium-ion battery recycling (Bolsi, 2023; Jiang, 2022). However, the lead-acid battery recycling technology can serve as motivation to develop recycling methods to separate and recover valuable metals from lithium-ion batteries. Currently, two widely used technologies are pyrometallurgy and hydrometallurgy, or a combination of both.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

The recycling process fundamentally aims to obtain valuable metals from the cathode, starting with disassembly to remove modules from the battery pack and other components. The modules are then cut and shredded into small pieces and particles. These small particles are separated based on physical properties such as magnetic attraction, yielding plastic, metals, anodes, and cathodes. If the cathode structure is to be maintained, the process continues with re-lithiation by adding lithium to restore the composition of the cathode, allowing it to be built into a new battery. If the cathode structure is not to be maintained, extraction of the metal content within the cathode can be done through either hydrometallurgy or pyrometallurgy (Larouche *et al*., 2020).

2.3. Hydrometallurgy

Hydrometallurgy is a process used to extract metals, achieved by dissolving metals as salts through several stages, including leaching, purification, and recovering the target metal through selective precipitation or electrowinning (Kholkin *et al*., 2000). This method plays a crucial role in extracting essential and rare metals. It is now applied to produce more than 70 metallic elements and includes selective separation in battery recycling, leading to salt extraction. For metals at low concentrations, ion exchange leads to various methods of separation and recovery after the desorption of absorbed ions.

Battery recycling initially involves disassembling (and partially dismantling larger batteries), sorting, physical separation, and mechanical treatment, including crushing. Subsequently, it is followed by the hydrometallurgical process to recover metals in ion form from the black mass. This process extracts materials with purification and extraction levels that make them viable both economically and commercially for reuse in the battery supply chain. **Figure 3** shows lithium-ion battery hydrometallurgy process.

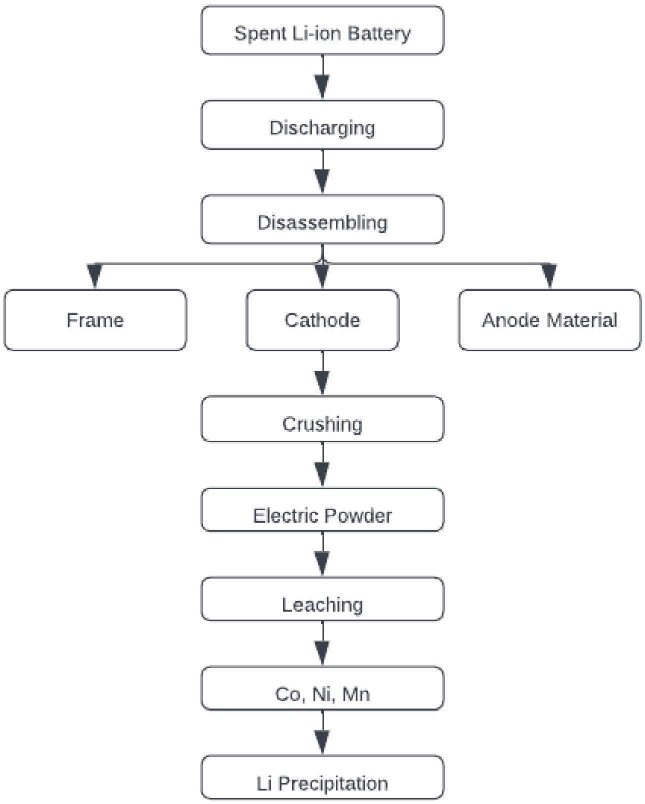

Figure 3. Lithium-ion battery hydrometallurgy process.

DOI:
p-ISSN : 2828-3309X e-ISSN: 2828-3236

2.3.1. Pyrometallurgy

Pyrometallurgy is a heat-based extraction and purification process that involves three steps:

(i) Roasting: heating compounds in the air and transforming sulfide ore into oxides, producing gas.

(ii) Smelting: carried out in a furnace to reduce metals and typically involves the formation of carbon dioxide, for example, reducing iron ore in a blast furnace.

(iii) Refining: sorting metals by exploiting their chemical and metallurgical properties. Metal separation is achieved by melting in a furnace at high temperatures. Refining includes various processes involving different types of furnaces and electrolytic processes.

Pyrometallurgy requires a significant amount of energy, as LiB is heated to high temperatures up to 1,600°C (Bahfie, 2020). Through smelting, some battery raw materials can be separated. However, only a few raw materials like cobalt and nickel can be recycled. Lithium, aluminum, and manganese end up in slag and cannot be recovered because it is not economically viable. One highly efficient recycling technology for recovering valuable metals from lithium-ion batteries is Li-Cycle, a company based in Mississauga, Ontario. The company has received funding from Sustainable Development Technology Canada (SDTC) to establish a pilot plant in Kingston, Ontario, and another facility in Rochester, New York, with a capacity of 5,000 tons per year. Li-Cycle boasts a recycling efficiency between 80-100%, with capabilities for qualitative battery analysis, closed-loop battery recovery, and damaged battery management. The table below illustrates the differences between Li-Cycle technology and traditional lithium-ion battery recycling methods. This process is more cost-effective and is suitable for recycling lithium batteries through a safer and automated dismantling process. The environmental impact is reduced with no solid waste, air emissions, and the reuse of process water within the facility, resulting in lower energy consumption (Flexer *et al*., 2018; Sommerville *et al*., 2021).

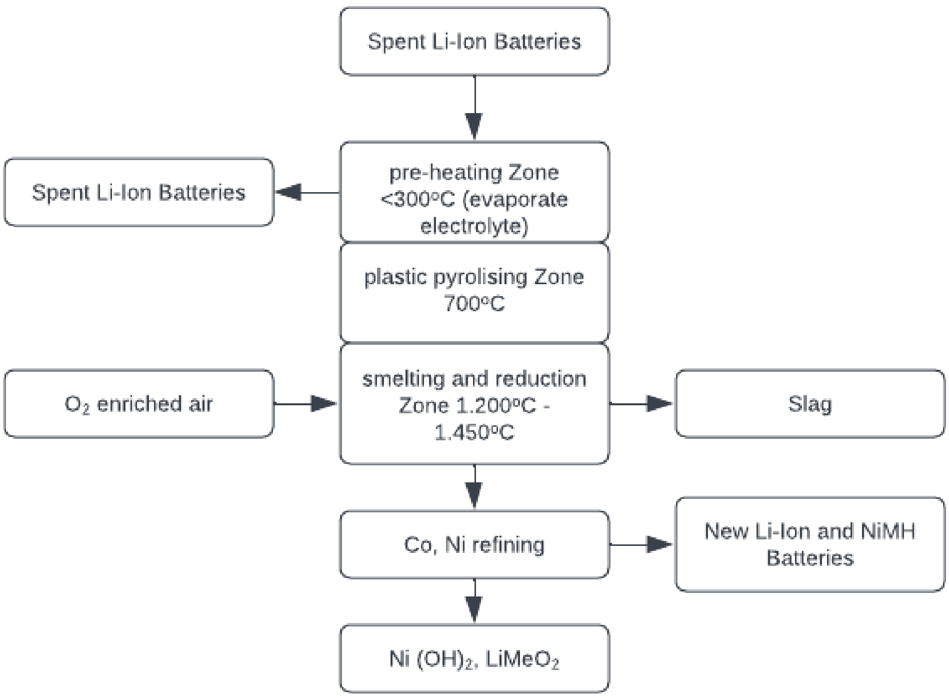

Figure 4. Lithium-ion battery pyrometallurgy process.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

3. RESULTS AND DISCUSSION

3.1. Battery Raw Material Requirements and Availability

The significant growth of the battery industry, driven by the expansion of electric vehicles, requires several metals such as nickel, cobalt, copper, aluminum, iron, manganese, lithium, and others. According to research (Xu, 2020), the material demand for lithium batteries will be dominated by lithium, nickel, and manganese. The factors for increased demand from 2020 to 2050 are 18-20 for lithium, 17-19 for cobalt, and 28-31 for nickel. This indicates the need for a more extensive expansion in the supply chain and the discovery of resources for these metals. While most studies assess that closed-loop recycling plays a minor role, it will become crucial to reduce material needs by 2050. However, technological improvements in recycling will also significantly impact improving the economic feasibility of recovering these metals from used batteries. Meanwhile, the second life of batteries will postpone the recycling needs.

Lithium, nickel, cobalt, manganese, and graphite play a crucial role in battery performance, lifespan, and energy density (Kelly *et al*., 2020). Additionally, rare earth metals are essential for permanent magnets, crucial for electric vehicle motors and wind turbines. The electric grid requires large quantities of copper and aluminum, with copper forming the basis of all electrical engineering. In a scenario to meet the goals of the Paris Agreement, the EIA estimates that the total demand for these metals will significantly increase over the next two decades, reaching nearly 90% for lithium, 60-70% for nickel and cobalt, and over 40% for copper and rare earth elements. Electric vehicles and battery storage have replaced consumer electronics to become the largest consumers of lithium, poised to surpass stainless steel as the largest end-user of nickel by 2040 (Elwert *et al*., 2015).

Demand levels will be heavily influenced by technological innovation and policy uncertainty. EIA analysis results show that cobalt demand could range from 6 to 30 times higher than current levels, depending on climate policies and approaches to battery chemistry evolution. Similarly, rare earth elements may experience demand up to seven times higher in 2040 compared to today, depending on the strength of policy support and choices for wind turbines. The largest source of demand variance comes from the uncertainty surrounding the stringency of climate policies. Policymakers play a crucial role in narrowing this uncertainty and translating targets into actions. This will be vital to reduce investment risks and ensure the bankability of each project.

3.1.1. Nickel-Cobalt

Nickel ore usually contains associated metals such as iron and cobalt, with rarely reported presence of other associated metals. Indonesia dominates 22.1% of nickel reserves and contributes 31% to global nickel mining production, with a total reserve of 21 million tons of Ni. Indonesia's nickel mining production reached 771,000 tons of Ni in 2020, constituting 31% of the global nickel mining production. This positions Indonesia as the leading country in terms of both nickel reserves and mining production in the world. The government's policy to ban nickel ore exports as of January 2020 has proven effective in promoting the downstream processing of nickel commodities. The success of nickel downstream processing is evidenced by the increase in nickel export value from $3 billion in 2017 to $29 billion in 2022. Indonesia has now become the world's largest exporter of stainless steel slabs.

Based on the current industrial input capacity, the lifespan of high-grade nickel reserves (>1.7% Ni) is estimated to last for 13 years until 2035, while low-grade nickel (<1.7% Ni) is projected to be depleted in 47 years until 2069. The projection for downstream industry demand until 2045 shows a significant increase, driven by the rising demand for nickel-based

DOI:
p-ISSN : 2828-3309X e-ISSN: 2828-3236

batteries (2.8%). Indonesia's contribution as a supplier of nickel raw materials for the global battery industry ranges between 60-80%.

The reserves and resources of cobalt in Indonesia amount to 3.6 million tons. According to data from the Geological Agency of the Ministry of Energy and Mineral Resources, estimated reserves of Indonesian cobalt ore and metal are 449.08 million tons and 231.768 million tons, respectively. Meanwhile, the estimated reserves for cobalt metal are around 231,768 tons. Based on MIND.ID, Indonesia's demand for cobalt is 12,000 tons per year, which is not met by the annual production of only 10,000 metric tons.

3.1.2. Lithium

Lithium is one of the rare earth metals required in the battery industry, alongside nickel and cobalt. Lithium can be found in brine, hot springs, seawater, minerals, and clay (Salafudin, 2021). The industrial process depicted in **Figure 5** illustrates the lithium processing process from natural resources (Speir, 2014). Indonesia is not recorded as a lithium-producing country globally due to the lack of in-depth research on this resource.

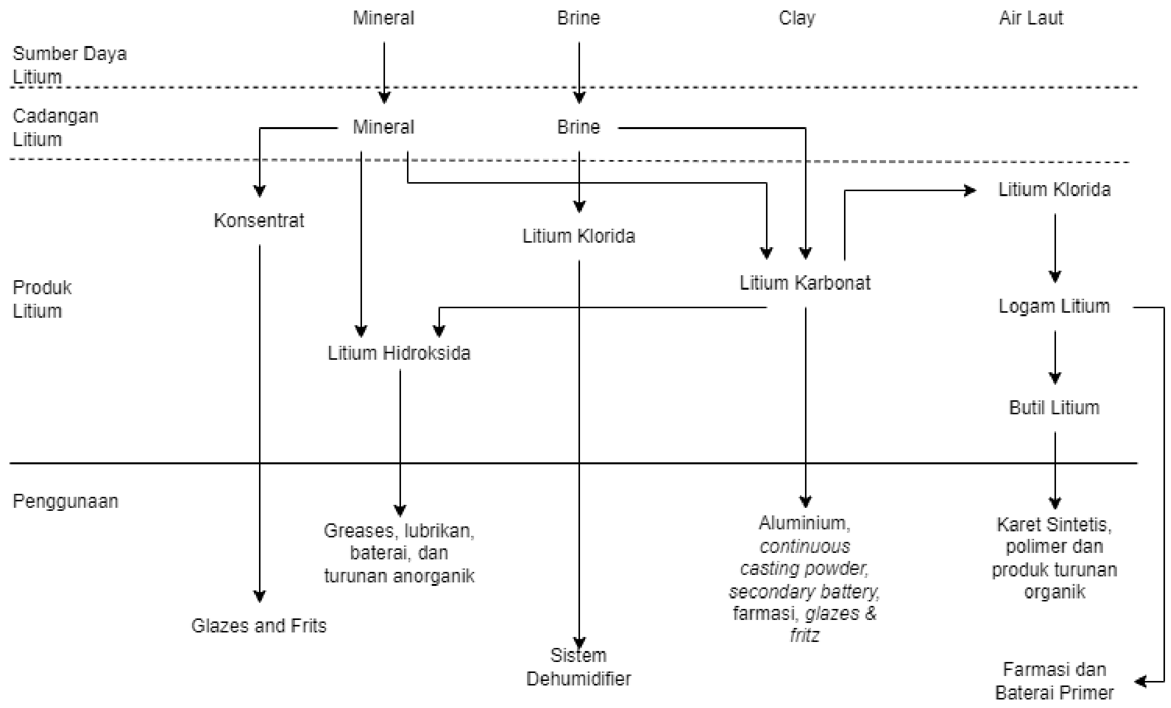

Figure 5. Lithium processing industrial tree.

3.2. Battery Demand and Current Industry Conditions

The lithium-ion battery industry is heavily influenced by the development of technology in electronic devices and energy storage for electric vehicles. The development policies for electric vehicles result from efforts to reduce the use of conventional cars with internal combustion engines. The current development of Battery Electric Vehicles (BEV) technology includes Battery Electric Vehicles (BEV), Plug-in Electric Vehicles (PHEV), and Hybrid Electric Vehicles (HEV). As a crucial component in Battery Electric Vehicles, lithium-ion batteries have various cathode types, such as LFP (lithium iron phosphate), NCA (lithium nickel cobalt aluminum oxide), and NMC (lithium nickel manganese cobalt oxides). The future use of lithium batteries is predicted to have a more dominant nickel content in the cathode.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Until 2022, two electric vehicle manufacturing companies, Hyundai and Wuling, have entered Indonesia, each with a total production capacity of 150,000 - 250,000 units per year and 10,000 units per year, centered in West Java.

A study by Wood Mackenzie indicates a shift in market demand towards Nickel derivative products. Until 2021, Nickel was still in demand for stainless steel, with global consumption reaching 69% of total production. Since the increased use of electric vehicles in 2020, the demand for nickel precursor market is projected to increase from around 50 thousand tons in 2020 to more than 2 million tons in 2040, dominated by the demand for NMC-type batteries with an average nickel content of 80%. Meanwhile, the use of lithium-ion batteries in electric vehicles will continue to rise, projecting a need for raw materials of 0.2 million tons of cobalt and 1.3 million tons of nickel (Directorate General of Mineral and Coal, Republic of Indonesia, 2021).

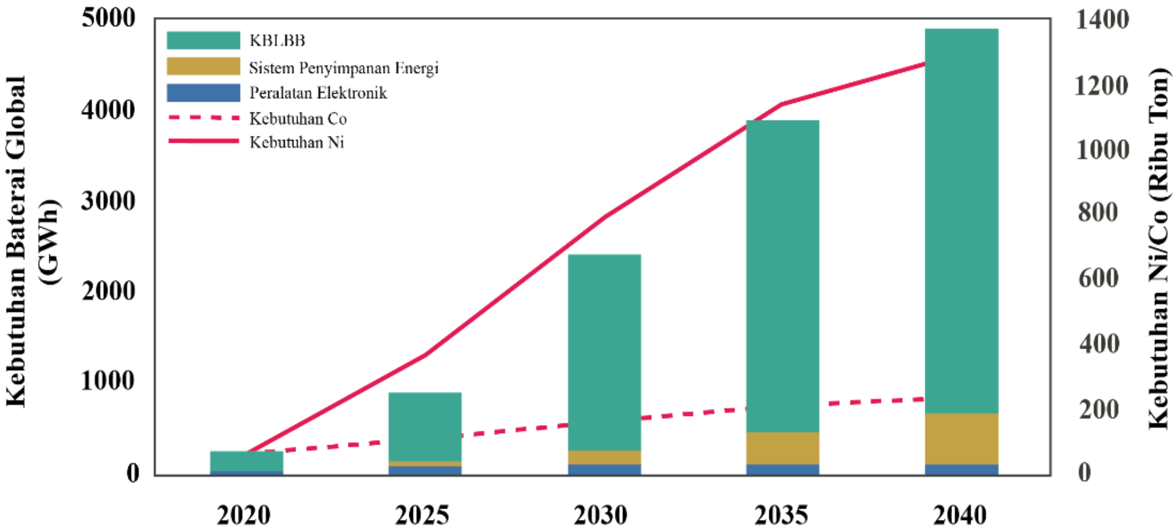

Figure 6. Global battery and raw material requirements.

Based on research conducted by NREL published in 2018, there are 23 companies engaged in the recycling of electric vehicle batteries, consisting of 12 companies in Europe, 5 companies in North America, and 6 companies in Asia. According to the study, the recycling capacity in North America is approximately 14,500 tons/year, Europe around 45,810 tons/year, and Asia between 29,750-46,150 tons/year (Kuhne *et al*., 2018). Recycling facilities in the Asian region are currently mainly focused on Japan and China, creating significant opportunities for Indonesia to develop similar facilities supporting the Asia-Pacific region.

Currently, Indonesia has one electric vehicle recycling company, namely PT Indonesia Puqing Recycling Technology in Morowali, Central Sulawesi. However, the company's operations are still hindered by permits related to hazardous and toxic waste (B3 waste). Additionally, Indonesia does not yet have sufficient used lithium as raw material for production, requiring import permits.

3.3. Collection of Used Batteries

The Indonesian government's policy regarding the development of electric vehicles has led to significant growth in the electric vehicle sector, reaching around 250 thousand tons per year from 2020 to 2040. Additionally, lithium-ion batteries are commonly used in smartphones, digital cameras, tablets, and laptops. Research conducted by the Central Bureau of Statistics (BPS) in 2016 indicated that the usage of lithium-ion batteries in emergency lights was around 900 thousand units per year, power banks were around 14

DOI:
p-ISSN : 2828-3309X e-ISSN: 2828-3236

million units per year, and other household electrical appliances were around 1.2 million units per year (Puspita, 2021).

Indonesia is predicted to become one of the world's largest lithium battery producers in the coming years, supported by its abundant mineral resources. This is further supported by the acceleration of investment realization in downstream industries through the issuance of permits and tax holiday facilities for industry players. Additionally, Indonesia, with its large population, represents a potential market for lithium-ion batteries in future electronic devices and electric vehicles. A case study conducted in this research calculates the number of electronic devices using lithium-ion batteries circulating in Indonesia in 2022. The table below shows that the number of devices sold in 2022 requires serious consideration regarding the electronic waste generated when these devices reach the end of their lifespan. The underlying approach involves calculating the percentage of battery mass in each device category (smartphones, digital cameras, laptops, and tablets) and electric vehicles (BEV, HEV, PEV). These devices have the potential to generate electronic waste of approximately 10,080 tons of lithium-ion batteries for recycling. This value is expected to increase further with the continued growth of the battery and electric vehicle industry domestically. Table shows mass of lithium-ion batteries in sold devices in 2022.

Table 1. Mass of lithium-ion batteries in sold devices in 2022.

Type of Devices	Service Life	Device Mass (kg)		Lithium Ion Battery in Device (%)		Estimated Number of Devices sold	Lithium Ion Battery Mass (tons) in Device		
		Min	Max	Min	Max		Min	Max	Avg
Smartphone	4	0.11	0.22	13.3	15	40,900,000	512	1,155	834
Kamera digital	6.5	0.4	0.8	15	20	8,400,000	502	1,338	920
EV (BEV,HEV,PHEV)	9	1200	2500	15	30	15,427	2,777	11,570	7,174
Laptop	5.5	1.35	2.8	13.4	16.7	2,600,000	470	1,216	843
Tablet	5.1	0.4	0.7	7.7	15	4,570,000	141	480	310
Total							4,402	15,759	10,080

One challenge in this industry is the difficulty in determining the amount of battery waste in Indonesia. This is due to the presence of many unused electronic devices stored in households or discarded with domestic waste, posing environmental hazards. Electronic devices such as smartphones, digital cameras, laptops, and tablets that have been circulating in Indonesia since the 1990s to the early 2000s will contribute significantly to electronic waste if accumulated. Furthermore, there are currently no recycling facilities for lithium-ion batteries in Indonesia. According to a report from BPPT, by the year 2020, the cumulative amount of lithium-ion battery waste requiring recycling reached 250,000 tons.

The cumulative amount of lithium-ion battery waste in 2020, equivalent to 25 times the potential LiB waste from devices sold in 2022, seems reasonable given the current normal usage rate. This figure is expected to increase continually with the growing battery and electric vehicle industry domestically, coupled with the scenario of achieving net-zero emissions by 2060. With a limited number of recycling facilities in the Asia-Pacific region and the potential for a significant increase in battery waste in the future, Indonesia has an opportunity to become a hub for an integrated battery recycling industry aligned with electric vehicles and battery production.

3.4. Metal Recycling Value

3.4.1. Socio-economic benefits

The future price of batteries will be significantly influenced by several factors, such as energy density and battery chemistry. For example, the reduction in cobalt mining in developing countries like the Democratic Republic of the Congo can have economic implications and reduce the supply of cobalt metal. Batteries are expected to become more compact and efficient than before, maintaining the same performance but with lighter weight, meaning less need for metal mining. The uncertainty regarding the number of batteries that can be recycled should also be a concern to mitigate difficulties in planning the capacity of the upcoming industry. The volatility of precious metal prices (Co, Ni, and Li) will also impact the industry in the future. **Figure 7** below illustrates the common configuration of lithium-ion batteries regarding the metal content they contain.

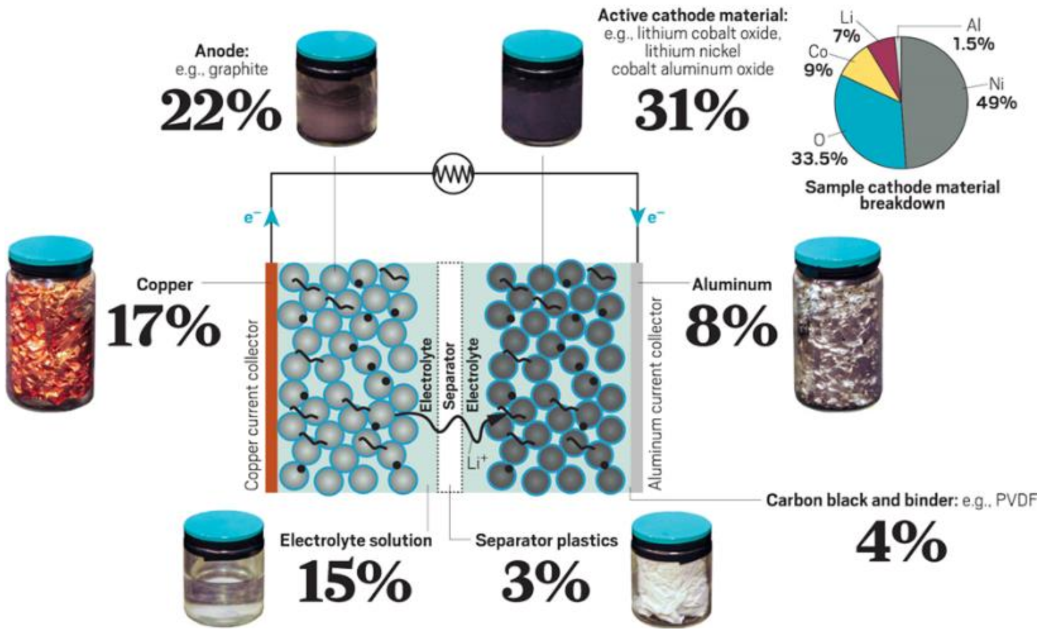

Figure 7. Composition of lithium-ion battery components (Argonne National Laboratory).

Various studies have been conducted to improve the efficiency of recovering metals from batteries. According to literature (Kala, 2021), the efficiency of recycling metals from lithium-ion batteries ranges from 50-68%. The value of these precious metals will be significantly influenced by the efficiency of their recovery, especially for metals not found in Indonesia, such as lithium. The economic benefits of reducing import burdens will be strongly felt by Indonesia. **Table 2** below shows the metal content in batteries and the amounts that can be recovered from the recycling process.

Table 2. Economic value of battery recycling.

Metal	Content in Battery (tons)	Recycling Efficiency (%)	Recoverable Metal Volume (tons)	Metal Value (US$/ton)	Total Economic Value (US$)
Cu	1.714	98	1.679	8.183	13.742.136
Al	853	60	512	2.371	1.213.882
Li	219	55	120	39.011	4.693.277
Co	281	57	160	34.180	5.479.208
Ni	1.531	68	1.041	23.664	24.638.913
Total					49.767.416

Indonesia imports lithium in various forms and applications. According to data from Trade Map, for HS 850650: Lithium cells and batteries (excluding spent), Indonesia's import volume is 383 tons with a value of USD 27,576, and the largest importing country is China (over 80%) (Trademap, 2021). China serves as a central hub for recycling lithium-ion batteries in Asia, along with Japan. Based on this comparison, it is evident that recycling lithium-ion batteries to recover precious metals, such as lithium, not locally available in Indonesia, could significantly alleviate import burdens. For 383 tons of lithium-ion batteries, assuming a lithium content of 7%, approximately 27 tons of lithium are needed. This implies that, for products under HS 850650, the entire raw material requirement for lithium can be met through recycling.

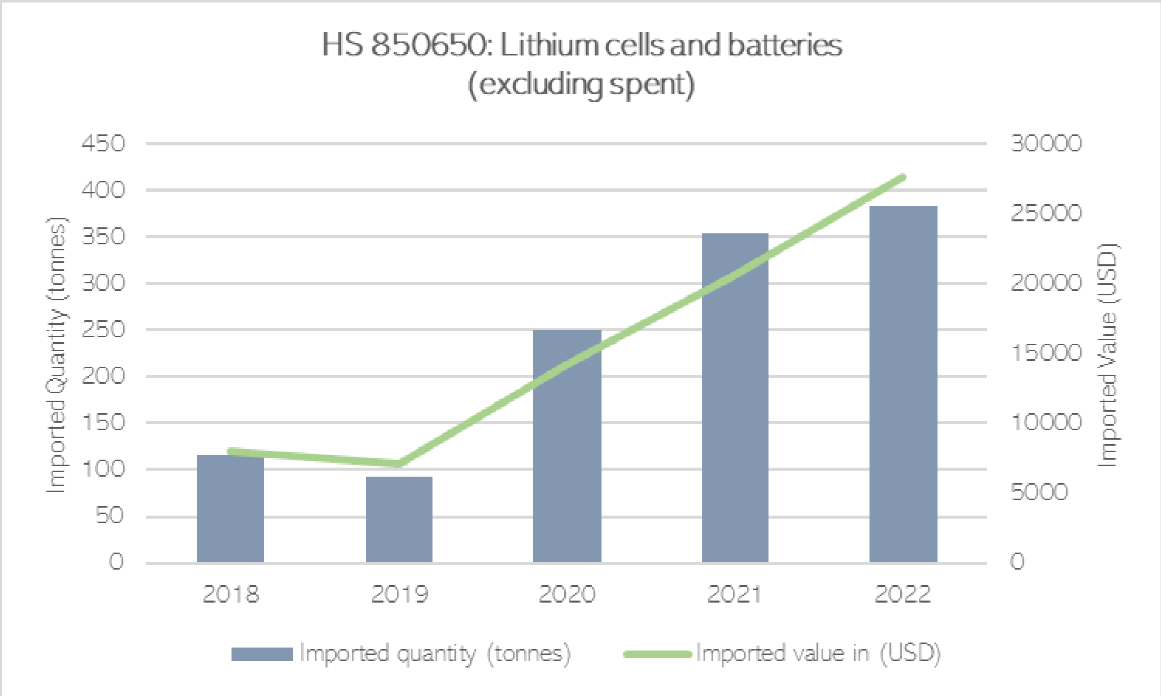

Figure 8. Import value and quantity of lithium-ion batteries.

A lithium-ion battery recycling facility has numerous direct and indirect impacts on the national economy. The new industrial hub will generate employment opportunities for the local workforce, leading to an increase in per capita income and both regional and national GDP. The workforce demand will span across construction and operational phases, encompassing roles from labor-intensive to professional positions. The production of domestic industrial raw materials will boost the Domestic Component Level (TKDN), strengthening the domestic spending capacity on a macroeconomic scale, reducing dependence on imports, and even creating opportunities for export markets.

3.4.2. Greenhouse gas emission reduction

Environmental issues have become a critical consideration in the development of lithium-ion batteries. The production of metals used as components in lithium-ion batteries is often associated with mining activities that result in significant emissions. Cobalt mining is associated with emissions of 1 ton of CO2 for every 1 ton of cobalt mined (Crawford, 2022). Nickel, a key component in the battery cathode, releases emissions of 13 tons for every 1 ton of nickel metal mined (Nickel Institute, 2020). Based on a case study in Indonesia in 2022, the potential carbon credits that could be attributed to the construction of a battery recycling facility amount to 7472.3 tons of CO2 based on cobalt, nickel, and lithium metals.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Table 3. Carbon emission reduction.

Metal Recovery (tons)			GHG reduction (tons CO2)		
Li	**Co**	**Ni**	**Li**	**Co**	**Ni**
120.3065	160.3045	1041.198	3.609195	128.2436	7340.447
Total					**7472.3**

3.5. Roadmap for lithium-ion battery recycling industry
3.5.1. Investment in new industrial facilities

The development of downstream industries in the country must be driven to reduce the trade balance deficit through the optimization and utilization of domestic products. One effort that can be made is to develop recycling facilities to decrease dependence on and the burden of non-renewable natural resource mining activities. The efficiency of the recycling process is greatly influenced by the overall potential of recoverable metals and the economic value that can be created. The recycling process involves collection, initial treatment, and final physical or chemical processing. Based on the availability of domestic raw material resources, several scenarios need to be implemented:

(i) Facilities for collecting used batteries containing valuable metals such as nickel, lithium, and cobalt are expected to be available starting in 2026. Subsequently, sorting and processing facilities are targeted to be in place by 2031 with a capacity of 15,000 tons of nickel (assuming a 50% collection rate) and will be gradually increased (Grand Strategy for Minerals and Coal, Ministry of Energy and Mineral Resources).

(ii) Developing recycling industries and regulating exports. High-grade nickel reserves are predicted to be depleted in 13 years, while low-grade nickel reserves are estimated to be exhausted in four decades. To enhance reserve resilience, it is necessary to develop the recycling industry, restrict the export of downstream waste products, and facilitate the import of downstream waste products.

(iii) Financing support for domestic entrepreneurs through the Sovereign Wealth Fund (SWF) and Bank Himbara. Investments in the downstream sector are still considered highly risky, limiting access to conventional financing. Government support is needed to address this financing constraint, especially for domestic businesses. The SWF has traditionally focused on financing infrastructure and some other sectors such as the digital economy. Given that downstream is a national priority, the SWF needs to prioritize this sector as well.

3.5.2. Managing Policies and Regulations

Government support in the form of policies and regulations is one of the fundamental aspects necessary to bolster the battery industry. Policies related to ease of doing business that favor stakeholders include:

(i) Strengthening the implementation of Presidential Regulation Number 28 of 2021 on the Implementation of the Industrial Sector. In this regulation, it is stipulated that the central government will encourage ease and certainty in doing business and will plan, develop, nurture, and supervise industrial standardization through the application of technical specifications, Indonesian National Standards (SNI), and guidelines for the procedures of domestically produced and imported goods

(ii) Investment promotion. Investment promotion is essential to attract investor interest in investing domestically. Innovative and creative methods, utilizing digital technology that accurately depict investment potential based on the latest and most current data, need

DOI:
p-ISSN : 2828-3309X e-ISSN: 2828-3236

to be continuously developed. This will provide a business model that aligns with existing potential and opportunities.

(iii) Granting special incentives.
The Presidential Regulation on the Acceleration of Battery-Based Electric Vehicle (BEV) Programs for Road Transportation, aimed at promoting battery recycling, provides incentives to industrial companies in the form of fiscal or non-fiscal incentives, including those for companies involved in battery waste processing.

(iv) Collaboration with partner countries to secure access to battery raw materials. Collaboration with partners to secure access to raw materials needs to be maintained to attract investors. For instance, to attract investments in battery cell production, Indonesia needs to build competitiveness for raw materials other than nickel. Access to raw materials will be a key factor in reducing production costs. In the production of battery cells, components of raw materials not possessed by Indonesia are required. Components not owned by Indonesia include lithium, where the main suppliers are Australia (44%), Chile (34%), and Argentina (13%), and graphite, where the main suppliers are China, Brazil, and Mozambique. To carry out this collaboration, synergy with state-owned enterprises (SOEs) (such as IBC or MIND.ID) is needed to encourage the availability of raw materials through investments to acquire mining ownership or enter into purchase agreements for raw materials in other countries.

(v) Export prohibition and imposition of export duties for used batteries. The elimination of import duties and VAT on imported used batteries will accelerate the formation of the lithium battery ecosystem in Indonesia and enhance the economy of lithium battery manufacturing plants, as most of the raw materials are still imported. This fiscal facility will help suppress electric vehicle prices in the community because a significant portion of electric vehicle prices comes from battery components.

4. CONCLUSION

Recycling lithium-ion batteries is an urgent necessity in developing the battery industry to support the electric vehicle (EV) industry. Extracting metals required as raw materials for the battery industry will increase the burden of mining activities, in addition to the environmental effects of the production chain. Mitigating this activity encourages the extraction process from secondary sources through recycling waste batteries to recover valuable metal content. Socio-economically, this will yield benefits through a circular economy and job creation. Various recycling technologies must continue to be developed to enhance process efficiency through research activities in research institutions and industries. Constructive policy frameworks and regulations should also be promoted to be more favorable for domestic investment growth.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

6. REFERENCES

Bahfie, F., Manaf, A., Astuti, W., Nurjaman, F., and Herlina, U. (2021). Tinjauan teknologi proses ekstraksi bijih nikel laterit. *Jurnal Teknologi Mineral dan Batubara*, *17*(3), 135-152.

Bolsi, P. C., Prado, E. O., Lima, A. C. C., Sartori, H. C., and Pinheiro, J. R. (2023). Battery autonomy estimation method applied to lead–acid batteries in uninterruptible power supplies. *Journal of Energy Storage*, *58*, 106421.

Elwert, T., Goldmann, D., Römer, F., Buchert, M., Merz, C., Schueler, D., and Sutter, J. (2015). Current developments and challenges in the recycling of key components of (hybrid) electric vehicles. *Recycling*, *1*(1), 25-60.

Fan, E., Li, L., Wang, Z., Lin, J., Huang, Y., Yao, Y., and Wu, F. (2020). Sustainable recycling technology for Li-ion batteries and beyond: Challenges and future prospects. *Chemical reviews*, *120*(14), 7020-7063.

Flexer, V., Baspineiro, C. F., and Galli, C. I. (2018). Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. *Science of the Total Environment*, *639*, 1188-1204.

Jiang, S., and Song, Z. (2022). A review on the state of health estimation methods of lead-acid batteries. *Journal of Power Sources*, *517*, 230710.

Kala, S., and Mishra, A. (2021). Battery recycling opportunity and challenges in India. *Materials Today: Proceedings*, *46*, 1543-1556.

Kelly, J. C., Dai, Q., and Wang, M. (2020). Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. *Mitigation and Adaptation Strategies for Global Change*, *25*, 371-396.

Kholkin, A. I., Pashkov, G. L., and Belova, V. V. (2000). Binary extraction in hydrometallurgy. *Mineral Processing and Extractive Metullargy Review*, *21*(1-5), 217-248.

Kühne, P., Pöschke, F., and Schulte, H. (2018). Fault estimation and fault-tolerant control of the FAST NREL 5-MW reference wind turbine using a proportional multi-integral observer. *International Journal of Adaptive Control and Signal Processing*, *32*(4), 568-585.

Larouche, F., Tedjar, F., Amouzegar, K., Houlachi, G., Bouchard, P., Demopoulos, G. P., and Zaghib, K. (2020). Progress and status of hydrometallurgical and direct recycling of Li-ion batteries and beyond. *Materials*, *13*(3), 801.

Metzger, P., Mendonça, S., Silva, J. A., and Damásio, B. (2023). Battery innovation and the circular economy: What are patents revealing?. *Renewable Energy*, *209*, 516-532.

Pagliaro, M., and Meneguzzo, F. (2019). Lithium battery reusing and recycling: A circular economy insight. *Heliyon*, *5*(6), e01866.

Puspita, A. N. G., Haryanto, I., and Salsabila, A. M. (2021). Peluang pertumbuhan dan prospek pasar daur ulang baterai di Asia Pasifik. *Jurnal Rekayasa Pertambangan*, *1*(1), 25-33.

Rahmanta, M. A., Adhi, A. C., Tambunan, H. B., Digwijaya, W., Damanik, N., and Hasibi, R. A. A. (2023). An analysis of national position, opportunity, and challenge of indonesia's nuclear program to support net-zero emissions by 2060. *Energies*, *16*(24), 8089.

Salafudin, S. (2021). Sumberdaya alam lithium Indonesia. *Rekayasa Hijau: Jurnal Teknologi Ramah Lingkungan*, *5*(2), 178-187.

DOI:
p-ISSN : 2828-3309X e-ISSN: 2828-3236

Sommerville, R., Zhu, P., Rajaeifar, M. A., Heidrich, O., Goodship, V., and Kendrick, E. (2021). A qualitative assessment of lithium ion battery recycling processes. *Resources, Conservation and Recycling*, *165*, 105219.

Speirs, J., Contestabile, M., Houari, Y., and Gross, R. (2014). The future of lithium availability for electric vehicle batteries. *Renewable and Sustainable Energy Reviews*, *35*, 183-193.

Vanderburgt, S., Santos, R. M., and Chiang, Y. W. (2023). Is it worthwhile to recover lithium-ion battery electrolyte during lithium-ion battery recycling?. *Resources, Conservation and Recycling*, *189*, 106733.

Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., and Steubing, B. (2020). Future material demand for automotive lithium-based batteries. *Communications Materials*, *1*(1), 99.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236