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Research Article

Optimizing the Supply Chain for Recycling Electric Vehicle NMC Batteries

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ABSTRACT

The rapid growth of electric vehicle production has led to increased waste batteries that can no longer be used. This increase causes environmental and economic challenges. Lithium-ion battery waste harms the environment as it contains toxic and flammable chemicals. New raw materials need to be procured economically due to the need for more infrastructure and a circular economy. Therefore, the solution to overcome the impact of the accumulation of lithium battery waste is to recycle the battery. Recycling end-of-life batteries is necessary to mitigate material supply risks, reduce demand for new materials, and mitigate harmful environmental and health impacts. This study aims to provide a conceptual model for the supply chain network design of electric vehicles' Nickel Manganese Cobalt (NMC) battery recycling process. We developed a mathematical model to determine the allocation of multi-product recycling products from multi-suppliers and other related entities such as manufacturers and landfills over multiple periods. The analysis method utilizes techno-economic investment feasibility analysis and load distance method. The problem in the recycling process supply chain network is formulated in a Mixed Integer Linear Programming (MILP) model. The MILP optimization results show that the proposed model produces a globally optimal solution for allocating NMC batteries. The application of this study is to provide a solution to the treatment of waste batteries from electric vehicle end-users in Java Island, Indonesia. In addition, it can develop economic opportunities in the waste battery recycling business in the electric vehicle industry. It is building a contribution to a sustainable electric vehicle battery management system by reducing the dependence on demand for new materials from mining and analyzing the sustainability of the NMC electric vehicle battery recycling process.

Keywords: Recycling, optimization, network design, mixed integer linear programming

INTRODUCTION

The development of global electric vehicles has shown a significant trend in recent years. Based on the International Energy Outlook report, global electric vehicle sales reached more than 6.6 million units and are expected to reach 21 - 31.1 million by 2030 [1]. In Indonesia, the adoption of electric vehicles has also increased [2]. To support this transition, the Indonesian government continues to encourage mass production of electric vehicles through Presidential Regulation No. 5 of 2019 and Minister of Energy and Mineral Resources Regulation No. 13 of 2020, with a target of 2 million electric cars and 13 million electric motorcycles by 2030. The rapid growth of electric vehicles has triggered a surge in lithium-ion battery consumption.

Lithium-ion batteries are becoming one of the most popular and widely used energy storage devices, especially as an energy resource for electric vehicles (EVs) [3]. They are characterized by long-term lifetime, high power density, and low maintenance costs, making them a significant component in stationary energy storage [4]. Furthermore, lithium-ion batteries are becoming the technology of choice to prevent significant environmental damage caused by transportation emissions [5]. The dominating battery cathode type in large electric vehicles such as electric cars today is Nickel Manganese Cobalt Oxide (NMC) [6]. According to research by Chau et al. [7], the trend in the next few decades indicates that lithium-ion batteries with high-nickel material will dominate EVs. It is estimated that NMC batteries will make up 75% of the global battery market by 2030 [8].

The lithium-ion battery is a technology designed to provide an ideal solution for energy storage that is compact, cost-effective, portable, pollution-free, has high energy and power density, high energy efficiency, and a long lifecycle [9]. The most common cathode and anode materials for electric cars are the elements Li (Lithium), Co (Cobalt), Mn (Manganese), and Ni (Nickel) [10]. Major electric vehicle manufacturers are increasingly adopting NMC batteries for their commercial fleets, which will continue to drive demand for these batteries in the global market. By 2030, there will be approximately 11 million tons of used lithium-ion batteries worldwide, with batteries from electric vehicles accounting for most of this accumulation [4]. Used batteries with a 50-70% storage capacity pose a significant environmental challenge due to the presence of toxic materials and environmental hazards, necessitating proper recycling [11]. The properties of nickel, manganese, and cobalt make them valuable for recovery. Nickel offers high specific energy but poor stability, while manganese contributes to low internal resistance but offers low specific energy. Combining these metals enhances their strengths, with common cathode combinations including equal parts of nickel, manganese, and cobalt (1-1-1) [12]. Given the increasing demand for materials and the growing accumulation of used batteries, recovering valuable materials like nickel, manganese, and cobalt from NMC batteries is essential. It is predicted that NMC batteries will play a significant role in the future of battery recycling [13].

Currently, recycling end-of-life batteries is a necessary and important approach to mitigate material supply risks by reducing the demand for new materials as well as mitigating harmful environmental and health impacts [14], [15]. Many chemicals in lithium-ion batteries are toxic and flammable, making their proper disposal and recycling essential. This necessity is supported by Presidential Regulation Number 101 of 2014, which addresses hazardous waste management, including lithium-ion battery waste. Recycling not only helps manage waste but also transforms significant amounts of metal in used lithium-ion batteries into secondary metals, reducing the demand for new material production from mining [16]. This process can also reduce dependence on imported materials, emphasizing the need to organize recycling routes and reverse logistics to establish a circular economy [17]. However, despite its importance, battery recycling management has yet to be effectively implemented in Indonesia, especially in Java.

The urgency of recycling lithium-ion batteries in Indonesia is further driven by the environmental hazards posed by lithium-ion battery waste and the challenges in sustaining the supply of critical raw materials such as lithium, cobalt, and nickel. Mining and extracting these raw materials are not sustainable in the long term [18]. Recycling lithium battery waste is thus a key requirement for the sustainability of a future circular economy [5]. Proper recycling of lithium batteries offers both economic and environmental benefits by preventing further raw material consumption and mitigating environmental pollution [19].

Valuable metals in NMC batteries, such as cobalt (Co) and nickel (Ni), can be recovered to ensure a stable supply chain for lithium battery production [16]. The recycling process for NMC batteries specifically aims to recover non-renewable materials like nickel, manganese, and cobalt, reducing costs in new battery production and mitigating risks of explosion and fire hazards caused by contamination with other waste types. In NMC cathode recycling, hydrometallurgical methods are widely used due to their ability to extract heavy metals such as lithium, cobalt, and nickel, along with other components like graphite, copper, aluminum, and electrolytes, with a low energy impact. Hydrometallurgical recycling methods are favored for their low cost, energy efficiency, and minimal environmental footprint compared to direct physical and biological methods [20].

Despite the benefits of recycling, there are still a limited number of environmentally conscious customers motivated to return end-of-life products to collection centers [21]. This highlights the potential opportunity to develop recycling activities that utilize secondary raw materials, reducing dependence on depleting primary raw materials [22]. To address these issues, this paper seeks to answer the following research questions:

- How can a supply chain network design support stakeholders' strategic decisions to optimize electric vehicle battery recycling and strengthen the infrastructure?
- How can the optimal location for recycling facilities and material flow be determined by network integration to enhance the efficiency of recycling?

By exploring these questions, this research aims to contribute to the development of a more efficient and sustainable recycling system for lithium-ion batteries.

This research proposes a supply chain model to optimize the material flow of NMC waste battery management and determine the optimal location for recycling facilities. The model supports critical decision-making in supply chain network design, benchmarking the success of the network from the end-user of EV batteries back to the manufacturer or landfill. Furthermore, it aids stakeholders in making strategic decisions to optimize waste battery management within the EV battery recycling network. To achieve these objectives, Supply Chain Network Design (SCND) is employed, focusing on determining the chain structure or modeling the supply chain to maximize cost efficiency and enhance performance [23]. Effective coordination among parties involved in the supply chain is essential to create a robust and efficient system [24]. Building on this foundation, the study leverages linear programming and mathematical programming to address challenges related to the optimal allocation of battery materials, ensuring optimality in the recycling supply chain network design [25]. Specifically, Mixed Integer Linear Programming (MILP) is applied to select superior suppliers capable of efficiently handling orders for companies with multiple manufacturers, leveraging optimization software programs [26], [27].

In advancing these efforts, this research introduces a comprehensive supply chain network design model that integrates various entities, including collection centers, recycling facilities, manufacturers, and landfills. This holistic approach addresses the limitations of previous studies, such as Budak and Ustundag [28] and Demirel et al. [29], which focused solely on cost minimization. Additionally, it surpasses the works of Lin et al. [8] and Yükseltürk et al. [30], which emphasized cost efficiency but lacked considerations for investment feasibility or sustainability. By covering the entire recycling cycle, from waste collection to end-of-life disposal over multiple periods, the proposed model provides a complete view of the recycling process and enhances the assessment of economic and environmental feasibility.

To contextualize these contributions, it is essential to examine prior research objectives. Previous studies carried distinct goals, ranging from cost minimization to profit maximization and network optimization based on economic and environmental factors. For instance, Budak and Ustundag [28] optimized reverse logistics for healthcare waste in Turkey, while Aydemir et al. [31] prioritized profit-oriented recycling of hazardous waste. In contrast, Wasesa et al. [22] evaluated the economic and environmental impacts of lithium-ion battery recycling using hybrid simulations but lacked a comprehensive supply chain perspective. Table 1 highlights these research gaps, illustrating the need for an integrated approach such as the one proposed in this study.

This research goes further by integrating profit maximization with sustainability considerations. Unlike studies such as Aydemir et al. [31], which focused on profit without addressing sustainability, or Chouksey et al. [32], which minimized costs without considering environmental impacts, our approach balances economic and environmental objectives. Additionally, while studies like Ximena et al. [33] maximized product collection or Tadaros et al. [34] minimized transportation costs, they lacked thorough analyses of the environmental impacts of recycling facilities. By addressing these gaps, the proposed model provides a comprehensive framework incorporating collection centers, recycling facilities, manufacturing, and waste disposal while ensuring investment feasibility and sustainability.

Table 1. Previous Related Studies

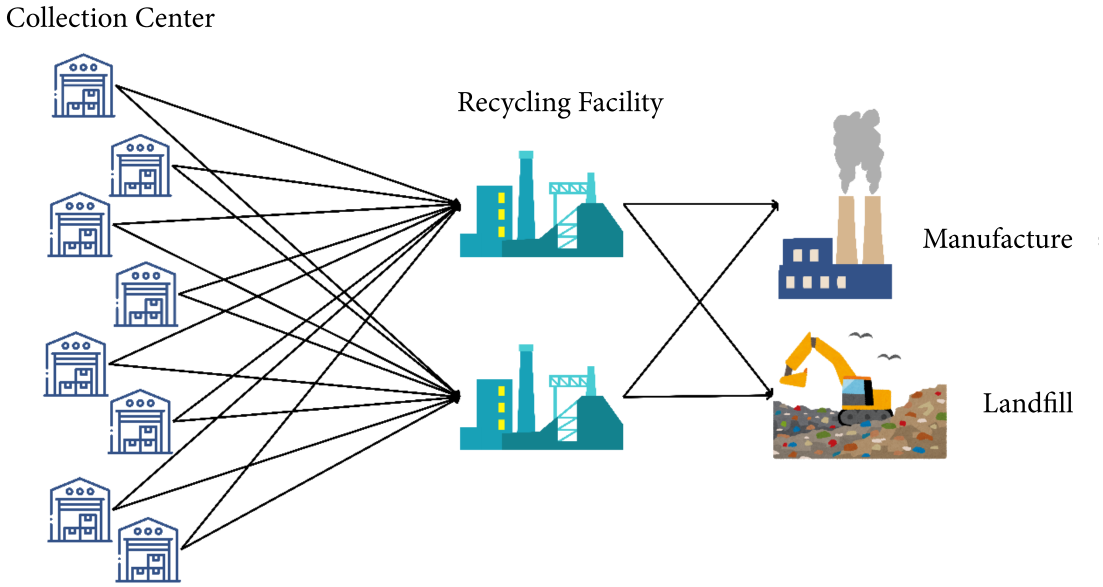
Authors	**Methods**	**Economic Analysis**					**Multi Products**	**Sustainability**
		Revenue	**Recycle Cost**	**Inventory Cost**	**Investment Cost**	**Transport Cost**		
Budak & Ustundag [28]	MILP	-	✓	✓	-	✓	-	-
Demirel et al. [29]	MILP	✓	✓	-	-	✓	✓	-
Aydemir et al. [31]	MILP	✓	✓	-	✓	✓	-	✓
Tadaros et al. [34]	MILP	-	✓	-	-	✓	-	-
Yükseltürk et al. [30]	MILP	-	-	✓	-	✓	-	-
Ximena et al. [33]	MILP	-	✓	-	✓	✓	-	-
Wasesa et al. [22]	Hybrid Simulation	✓	✓	-	✓	✓	✓	✓
Lin et al. [8]	MILP	✓	✓	-	-	-	-	-
Chouksey et al. [32]	MILP	-	-	-	✓	✓	-	-
This Research	MILP	✓	✓	✓	✓	✓	✓	✓

Building on these foundations, the proposed model enhances supply chain efficiency by integrating network design with location and material allocation strategies using the MILP approach. This integration enables identifying optimal facility locations and efficient material flow, reducing transportation and operational costs. These efficiencies not only enhance the feasibility of investments but also increase profitability. Furthermore, conducting an investment feasibility study for plant construction becomes a priority to bridge the gap between strategy and implementation [35]. An investment feasibility study plays a critical role in providing stakeholders with a detailed understanding of procurement and operational strategies. This allows stakeholders to make informed decisions that facilitate the development of electric vehicle support infrastructure. Once decisions and plans are in place, the establishment of EV battery recycling facilities becomes more accessible, economically viable, and more likely to garner stakeholder support.

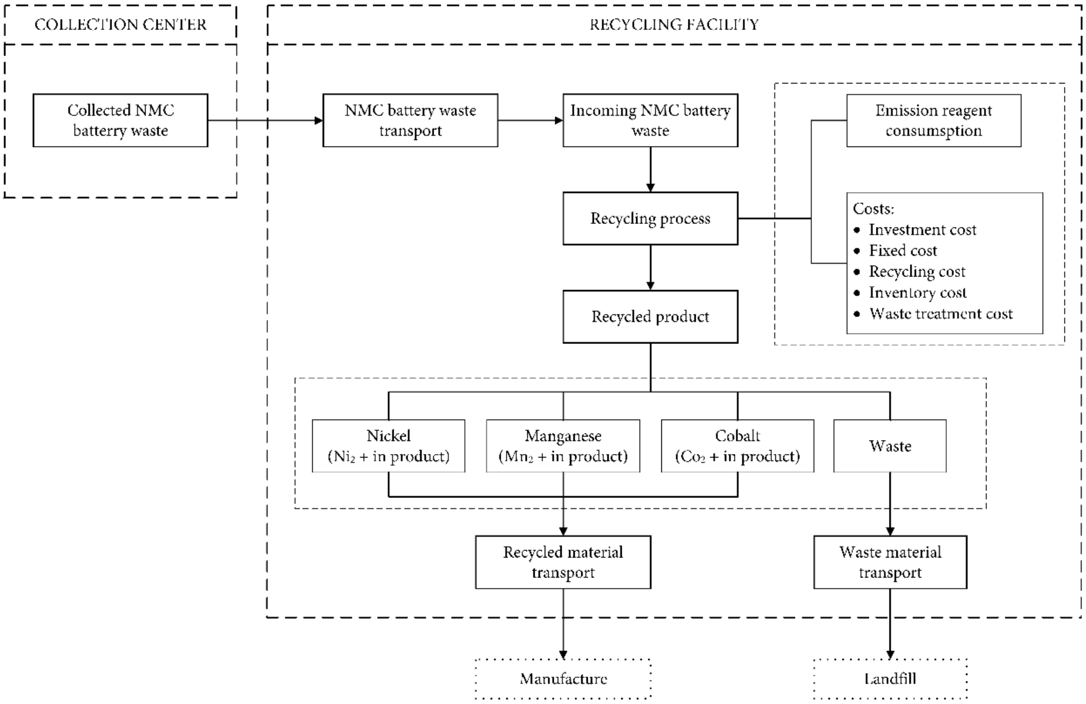
The benefits of the proposed model are multifaceted. Economically, it promotes the creation of a circular supply chain and fosters opportunities in the EV battery materials industry. Environmentally, it mitigates the harmful effects of metal waste, reduces carbon emissions associated with new material production, and decreases dependence on mining activities. By supporting efficient recycling of EV batteries, this study aligns with global efforts to establish a sustainable electric vehicle battery management system. Moreover, it accelerates the development of EV infrastructure and supports Indonesia in achieving its sustainability goals for a clean energy transition. The integrated approach, encompassing economic feasibility, environmental sustainability, and supply chain optimization, ensures effective management of NMC waste batteries and paves the way for a sustainable future.

METHODS

In this section, we develop a mathematical model of the battery recycling supply chain network. We also determine the location of recycling facilities using the Load Distance method. This method will identify the optimal location for establishing recycling facilities based on distance and load on proximity factors [36]. Furthermore, the results of determining the number and location will be used to assess the feasibility of investment in establishing recycling facilities. The feasibility analysis will use several indicators: Net Present Value (NPV), Internal Rate of Return (IRR), and Return On Investment (ROI). NPV compares the present value of cash inflows and cash outflows over the life of a project. IRR is a key metric that represents the expected annual growth rate, making it a crucial factor in investment evaluation. ROI measures the efficiency of an investment by calculating the ratio of net income to the initial investment. In this study, NPV assesses whether the expected returns will exceed the initial and ongoing



(a) Conceptualized SC Network



(b) The proposed Recycling Model

Figure 1. SC System Description for Recycling Electric Vehicle NMC Batteries

investment, reflecting long-term value creation. IRR helps compare a feasibility's profitability to a benchmark interest rate or alternative investment opportunities. ROI provides profit that is generated relative to the size of the investment. The parameters of investment feasibility, including NPV, IRR, and ROI, provide comprehensive insights into a recycling facility's financial feasibility. This research will develop a mathematical model to maximize profits in the recycling facility supply chain network with several entities over multiple periods, including collection centers, recycling facilities, manufacturers, and landfills in Figure 1. A mixed-integer linear programming (MILP) model is developed to identify the optimal recycle facility locations, allocated materials, and waste. The model parameters include the recycling process costs for each entity, the amount of battery waste, the capacity of each entity, and the conversion factor. The decision variables in the model are binary variables for establishing a recycling facility and allocating each material from multiple entities. The constraints used include each entity in the recycling process to optimize the supply chain. The model parameter Therefore, the IBM ILOG CPLEX package was used in Python to solve the model problem in a computer with Intel Core-i3 Processor and 8GB of RAM.

Model Assumption

1. NMC battery waste from electric vehicles has the potential to be recycled with a conversion rate in each material element, such as the recovery of heavy metal materials nickel, manganese, and cobalt [37].
2. Collection centers were established in each city on Java Island as suppliers of recycled raw materials for mini plant recycling facilities [22]. The starting point of EOL waste batteries in the network is the collection center. Batteries must go through the collection center before being sent to further processing or recycling facilities [8].
3. The raw material used in NMC battery waste is considered sufficient to ensure the optimal performance of the recycling facility. The collection rate of NMC batteries is 41% [38]. The average mass of a battery pack for an electric car is 0.288 tons/unit [39], and the average mass of a battery pack for an electric motorcycle is 0.0054 tons/unit [40].
4. The recycling facility was built to handle hazardous waste that can damage the environment and reduce the mining of primary mineral raw materials.
5. In this study, the calculation of economic aspects assumed that LIB waste is available for free [22].
6. The location of the recycling facility was chosen based on the potential weight of used NMC battery waste and the distance between cities on the island of Java.

Model Indices, Parameters, Decision Variables, and Model Formulation

The following are model indices, parameters, and decision variables for mathematical formulation.

Model Indices

c	Index for collection center location NMC battery waste; $c = 1, 2, \ldots, C$
r	Index for recycling facility; $r = 1, 2, \ldots, R$
m	Index battery manufacture Nickel, Manganese and Cobalt; $m = 1, 2, \ldots, M$
w	Index for waste landfill; $w = 1, 2, \ldots, W$
t	Index period; $t = 1, 2, \ldots, T$

Parameters

LB_{ct}	The number of battery waste from collection center c during period t (kg)
K_{rt}	Capacity of recycling facility r during period t (kg/year)
K_{mt}	Capacity of battery manufacture m during period t (kg/year)
NI	Selling price of Nickel (IDR/kg)
MG	Selling price of Manganese (IDR /kg)
CO	Selling price of Cobalt (IDR/kg)
IC_{rt}	Investment cost of recycling facility r (IDR/facility)
FC_{rt}	Fixed cost of recycling facility r (IDR/facility)
W_{rt}	Treatment cost of waste disposal r (IDR/kg)
IVC_r	Inventory cost at recycling facility r (IDR/kg)
RN_r	Recycle cost of Nickel at recycling facility r (IDR/kg)
RM_r	Recycle cost of Manganese at recycling facility r (IDR/kg)

RC_r	Recycle cost of Cobalt at recycling facility *r* (IDR/kg)
TC_{crt}	Transportation cost of battery waste from collection center *c* to recycling facility *r* during period *t* (IDR/kg)
TC_{rmt}	Transportation cost of recycled material Nickel, Manganese, Cobalt from recycling facility *r* to battery manufacture *m* during period *t* (IDR/kg)
TC_{rwt}	Transportation cost of waste disposal from recycling facility *r* to landfill *w* during period *t* (IDR/kg)
DN_{mt}	Demand from battery manufacture *m* for nickel material during period *t* (kg/year)
DM_{mt}	Demand from battery manufacture *m* for manganese material during period *t* (kg/year)
DC_{mt}	Demand from battery manufacture *m* for cobalt material during period *t* (kg/year)
$\mathrm{Conv}N_r$	Conversion factor for recycled material Nickel at recycling facility *r*
$\mathrm{Conv}M_r$	Conversion factor for recycled material Manganese at recycling facility *r*
$\mathrm{Conv}C_r$	Conversion factor for recycled material Cobalt at recycling facility *r*
$\mathrm{Conv}W_r$	Conversion factor for waste disposal at recycling facility *r*

Decision Variables

U_r	Binary Variable for established recycling facility *r* (If the recycling facility *r* is established, then it is equal to 1; otherwise, it is equal to 0)
LB_{crt}	Amount of battery waste sent from collection center *c* to recycling facility *r* during period *t*
SN_{rmt}	Amount of recycled Nickel sent from recycling facility *r* to battery manufacture *m* during period *t*
SM_{rmt}	Amount of recycled Manganese sent from recycling facility *r* to battery manufacture *m* during period *t*
SC_{rmt}	Amount of recycled Cobalt sent from recycling facility *r* to battery manufacture *m* during period *t*
IN_{rt}	Amount of inventory for Nickel at recycling facility *r* during period *t*
IC_{rt}	Amount of inventory for Cobalt at recycling facility *r* during period *t*
IM_{rt}	Amount of inventory for Manganese at recycling facility *r* during period *t*
PN_{rt}	Amount of recycled Nickel produced at recycling facility *r* during period *t*
PC_{rt}	Amount of recycled Cobalt produced at recycling facility *r* during period *t*
PM_{rt}	Amount of recycled Manganese produced at recycling facility *r* during period *t*
PW_{rwt}	Amount of recycled waste produced at recycling facility *r* and sent to landfill *w* during period *t*

Model Formulation

The mathematical model for establishing an NMC battery recycling facility is based on describing the business process of recycling NMC battery waste from electric vehicles in Java. The process description is formulated mathematically. The purpose of the mathematical model in this study is to maximize the profit (*Z* Maximization) obtained by NMC battery recycling.

$$\text{Maks Z} = (\text{Total Revenue of Recycling facility} - \text{Total Cost of Recycling facility}) \tag{1}$$

$$\text{Maks Z} = \text{Z1} - \text{Z2} \tag{2}$$

$$\text{Z1} = (\text{NI} * \textstyle\sum_r \sum_m SN_{rmt}) + (\text{MG} * \sum_r \sum_m SM_{rmt}) + (\text{CO} * \sum_r \sum_m SC_{rmt}) \tag{3}$$

$$\begin{aligned}\text{Z2} = {} & (\textstyle\sum_r FC_{rt}) + (\sum_r IC_{rt}) + ((\sum_r RN_{rt} * \sum_r PN_{rt}) + (\sum_r RC_{rt} * \sum_r PC_{rt}) + (\sum_r RM_{rt} * \\ & \textstyle\sum_r PM_{rt})) + (W_{rt} * \sum_r \sum_w PW_{rwt}) + (\sum_r IVC_{rt} * (\sum_r IN_{rt} + \sum_r IM_{rt} + \sum_r IC_{rt})) \\ & \textstyle + (\sum_r \sum_m TC_{rmt} * (\sum_m SN_{rmt} + \sum_m SM_{rmt} + \sum_m SC_{rmt})) + (\sum_c \sum_r TC_{crt} * \\ & \textstyle\sum_c \sum_r LB_{crt}) + (\sum_r \sum_w TC_{rwt} * \sum_r PW_{rwt})\end{aligned} \tag{4}$$

Constraints

$$\sum_{c\in C}\sum_{r\in R} LB_{crt} \leq LB_{ct}, \tag{5}$$

$$\sum_{c\in C}\sum_{r\in R} LB_{crt} \leq K_{rt} \tag{6}$$

$$\sum_{r\in R} PN_{rt} = \sum_{c\in C}\sum_{r\in R} LB_{crt} * \mathrm{Conv}N_r \tag{7}$$

$$\sum_{r\in R} PC_{rt} = \sum_{c\in C}\sum_{r\in R} LB_{crt} * \mathrm{Conv}C_r \tag{8}$$

$$\sum_{r\in R} PM_{rt} = \sum_{c\in C}\sum_{r\in R} LB_{crt} * \mathrm{Conv}M_r \tag{9}$$

$$\sum_{r\in R}\sum_{w\in W} PW_{rwt} = \sum_{c\in C}\sum_{r\in R} LB_{crt} * \mathrm{Conv}W_r \tag{10}$$

$$\sum_{r\in R}\sum_{m\in M} SN_{rmt} + IN_{rt} = \sum_{r\in R} PN_{rt} + IN_{r(t-1)} \tag{11}$$

$$\sum_{r\in R}\sum_{m\in M} SC_{rmt} + IC_{rt} = \sum_{r\in R} PC_{rt} + IC_{r(t-1)} \tag{12}$$

$$\sum_{r\in R}\sum_{m\in M} SM_{rmt} + IM_{rt} = \sum_{r\in R} PM_{rt} + IM_{r(t-1)} \tag{13}$$

$$\sum_{r\in R}\sum_{m\in M} SN_{rmt} = DN_{mt} \tag{14}$$

$$\sum_{r\in R}\sum_{m\in M} SC_{rmt} = DC_{mt} \tag{15}$$

$$\sum_{r\in R}\sum_{m\in M} SM_{rmt} = DM_{mt} \tag{16}$$

$$\sum_{r\in R}\sum_{m\in M}(SM_{rmt} + SC_{rmt} + SM_{rmt}) \leq K_{mt} \tag{17}$$

$$LB_{crt}, SN_{rmt}, SM_{rmt}, SC_{rmt}, PW_{rwt}, PN_{rt}, PC_{rt}, PM_{rt}, IN_{rt}, IM_{rt}, IC_{rt} \geq 0 \tag{18}$$

The objective function is to maximize a recycling facility's profit (1, 2). The revenue of the recycling facility is from selling recycled materials such as nickel, manganese, and cobalt (3). The cost of a recycling facility includes fixed costs, investment costs, recycling costs for each material, waste treatment cost, inventory costs, and transportation costs between the collection center, recycling facility, manufacturer, and landfill (4). In this proposed model, there are several constraints. The amount of waste transported from the collection center to all recycling facilities does not exceed the amount of waste supply or the amount available at the collection center in period *t* (5). The amount of waste processed for recycling does not exceed each recycling facility's capacity in period *t* (6). The amount of nickel, manganese, and cobalt produced by the recycling facility in period *t* according to the conversion of each material (7, 8, 9). The amount of waste the recycling facility produces in period *t* according to the waste conversion (10). The amount of nickel, manganese, and cobalt material sent to manufacturing in period *t* and the amount of inventory material in period *t* is equal to the amount of material produced at the recycling facility in period *t* and the amount of inventory material in the previous period *t*-1 (11, 12, 13). The amount of nickel, manganese, and cobalt recycled material equals the manufacturing demand in period t (14, 15, 16). The amount of recycled nickel, manganese, and cobalt materials sent to manufacturing does not exceed the manufacturing capacity (17). The amount of NMC battery waste and nickel, manganese, and cobalt recycled is non-negative (18).

RESULTS AND DISCUSSION

Case Application

This research focuses on a case study of electric vehicle battery waste management on Java Island, Indonesia. According to 2023 data from State Electricity Company (abbreviated in Indonesian as PLN), several cities on Java Island have the highest number of electric vehicle users in the country. This is largely supported by the concentration of Public Electric Vehicle Charging Station (abbreviated in Indonesian as SPKLU) infrastructure in Java, particularly in Jakarta, which accounts for 88% of the national total [41]. In comparison, other islands such as Sumatra, Sulawesi,

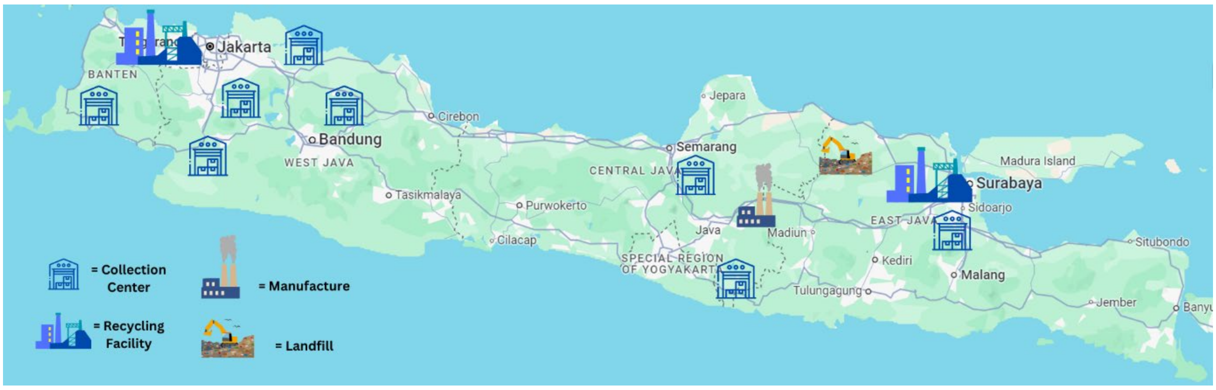


Figure 2. The visualization of battery waste transportation recycling process

and Kalimantan have significantly fewer charging facilities. Given the high adoption of electric vehicles and the limited battery lifespan, the potential for accumulating electric vehicle battery waste on Java Island is expected to increase. Research by Mairizal et al. [42] analyzed the distribution of e-waste generation across Indonesia, including battery waste, and identified Java Island as having the highest percentage of e-waste generation. Despite this, battery recycling management has yet to be implemented effectively in Indonesia, including on Java Island. Moreover, studies providing a comprehensive perspective on the impact of electric vehicle battery recycling processes and their supporting supply chains on business and environmental performance remain limited. Addressing these challenges requires the design and implementation of an optimized supply chain network to manage battery waste efficiently and sustainably.

The amount of NMC battery waste is calculated based on the number of electric vehicles in cities on Java Island, as outlined in the PLN Roadmap data [43]. This calculation incorporates the collection rate of NMC batteries and the average battery mass of electric vehicles. Additionally, the availability of Public Electric Vehicle Charging Station (SPKLU) infrastructure, according to PLN data, supports the selection of cities as collection centers. To ensure comprehensive representation across the island, cities such as Jakarta, Bekasi, Bandung, Surabaya, Tangerang, Bogor, Semarang, and Yogyakarta were selected to serve as collection centers, as shown in Figure 2. This study considers multiple entities—collection centers, recycling facilities, manufacturers, and landfills—to establish an efficient and sustainable material flow within the recycling process. Collection centers, strategically located in the selected cities, serve as points for aggregating waste batteries and preparing them for transportation to recycling facilities. At the recycling facilities, the used batteries are processed into secondary raw materials, such as nickel, manganese, and cobalt. These facilities employ a hydrometallurgical recycling process, which is both cost-efficient and effective for recovering valuable materials [44]. Once processed, the recovered secondary raw materials are sent to manufacturers for reuse in producing lithium batteries. The manufacturing site is located in Surakarta, Central Java, where a lithium battery manufacturer specializes in producing batteries for electric vehicles. Meanwhile, waste generated from the recycling process, including non-recyclable materials such as black carbon and PVDF, is transported to a landfill for proper management. The selected landfill, located in Lamongan, East Java, is a hazardous and toxic waste treatment facility equipped to handle such materials.

The material conversion factor used in this study is derived from the conversion calculations shown in Table 2, which detail the materials produced through hydrometallurgical recycling—nickel (Ni), cobalt (Co), manganese (Mn), and waste solids. These calculations are based on material input data adopted from the research of Narang et al. [37]. The distances between recycling facilities and collection centers were estimated using actual road distances calculated via Google Maps. These distances are a critical factor in determining the optimal location for recycling

Table 2. Model Parameter Value

Parameters	Values	Parameters	Values
Conversion Factor of Nickel Product	22%	Recycle cost of nickel product	IDR 24,00/kg
Conversion Factor of Manganese Product	20%	Recycle cost of manganese product	IDR 8,000/kg
Conversion Factor of Cobalt Product	22%	Recycle cost of cobalt product	IDR 96,000/kg
Conversion Factor of Waste	36%	Price of nickel product	IDR 208,000/kg
Transport Cost	IDR 0.2 /kg-km	Price of manganese product	IDR 48,000/kg
Fixed Cost	IDR 15,298,763,112 /unit	Price of cobalt product	IDR 832,000/kg
Investment Cost	IDR 24,758,020,980 /unit	Price of waste treatment	IDR 1,000/kg

facilities, as minimizing transportation distances can significantly reduce fuel consumption and enhance cost efficiency. Additionally, an even distribution of materials between recycling facilities is prioritized to optimize operational costs and ensure that the capacity of each facility is fully utilized. This approach not only improves transportation efficiency but also reduces the accumulation of battery materials at collection centers. By mitigating the risk of material buildup, this strategy minimizes the potential for harmful environmental impacts.

Feasibility Study for Selection of Recycling Facilities

The location of the recycling facility is determined by evaluating the potential amount of NMC battery waste using the Load Distance Method before applying the MILP model. The recycling facility is planned to operate with a capacity of 365 tons/year, distributed across two units. Two establishment options for the recycling facilities are considered to optimize waste management and operational efficiency. The first option places both recycling facilities at a single location on the island of Java, consolidating operations in one city. The second option distributes the two facilities across two different cities, strategically dividing them between Western and Eastern Java. These options aim to maximize the coverage of potential NMC battery waste while optimizing transportation costs and operational logistics.

To select the most suitable locations, the Load Distance Method is used to assess the coverage of potential NMC battery waste. This approach analyzes the amount of waste and the distances between related entities, such as collection centers and recycling facilities, as shown in Table 3 and Table 4. Each potential location is evaluated based on the load of battery waste collected and the distance to other entities. The location with the lowest load-distance value is considered the most optimal for establishing the recycling facility. By selecting optimal locations, this

Table 3. Load Distance Results of the First Option

No.	Collection Center	Latitude, Longitude	Load Distance Value
1	Jakarta	-6.18070, 106.81098	15,359,550,274.01
2	Bekasi	-6.26375, 107.14760	18,489,764,964.69
3	Bandung	-6.91761, 107.63322	33,857,405,438.08
4	Surabaya	-7.34303, 112.72859	34780,842,856.81
5	Tangerang	-6.16084, 106.63371	18,785,459,325.45
6	Bogor	-6.62947, 106.82563	20,070,028,617.25
7	Semarang	-6.98622, 110.37160	82632,202,642.26
8	Yogyakarta	-7.77937, 110.36257	92,043,445,420.94

Table 4. Load Distance Results of the Second Option

No.	**Area 1**		**No.**	**Area 2**	
	Collection Center	**Load Distance Value**		**Collection Center**	**Load Distance Value**
1	Jakarta	**7,078,178,477.85**	1	Surabaya	**3,978,593,351.36**
2	Bekasi	10,696,528,515.84	2	Semarang	8,182,176,181.92
3	Bandung	25,048,240,500.06	3	Yogyakarta	9,095,079,819.85
4	Tangerang	10,695,851,766.62			
5	Bogor	14,402,619,183.36			

approach minimizes the cost of transporting battery waste to the recycling facilities and enhances operational efficiency. Additionally, shorter distances between collection centers and recycling facilities reduce fuel consumption and ensure streamlined operations, contributing to a more sustainable and cost-effective battery recycling process.

From Table 3, the first option identifies Jakarta as RF1, hosting two recycling facilities with the smallest load-distance value of 15,359,550,274.01. Similarly, Table 4 indicates Jakarta as the selected location for RF2 in the western region (Area 1) of Java Island, with one recycling facility and a load-distance value of 7,078,178,477.85. For the eastern region (Area 2) of Java Island, Surabaya is chosen as RF3, with one recycling facility and the smallest load-distance value of 3,978,593,351.36. These strategically selected locations aim to minimize transportation costs and enhance efficiency in managing battery waste across the island.

To assess the financial feasibility of these facilities, a comprehensive techno-economic analysis was conducted using Break-Even Point (BEP), Net Present Value (NPV), Internal Rate of Return (IRR), and Return on Investment (ROI). The BEP analysis determined the minimum quantities of recycled materials required to cover costs, with thresholds of 15,996.81 kg for nickel, 14,542.55 kg for manganese, and 15,996.81 kg for cobalt. These thresholds provide a baseline for ensuring financial viability at the recycling facilities. The financial robustness of the proposed investment is further highlighted by the NPV calculation, which yielded a significant positive value of 299,452,293,013.51 IDR. This result confirms that the investment is expected to generate substantial profits, with returns exceeding initial and ongoing costs. Additionally, the IRR analysis reinforces the project's viability, showing rates of 35.63% at a 15% discount rate and 39.28% at a 20% discount rate. These values, which exceed the Minimum Attractive Rate of Return (MARR), demonstrate that the investment will yield returns well above the benchmark rates. Furthermore, the ROI calculation of 77.7% underscores the efficiency of the investment in generating profits relative to the capital invested.

Building on these financial insights, the strategic placement of recycling facilities in Jakarta and Surabaya ensures an optimized distribution process. This logistical strategy not only enhances operational efficiency but also aligns with the broader goal of sustainable waste management. By integrating techno-economic methods and strategic location planning, this study offers a comprehensive framework for evaluating and implementing recycling facilities. Unlike previous research, which often focused on isolated aspects of the recycling process, this study adopts a holistic approach that spans collection, reprocessing, and the reintegration of materials into manufacturing or landfilling. This full-system integration supports improved operational efficiency and delivers sustainable, economically viable solutions for electric vehicle battery recycling in the long term.

Optimal Number of Recycling Facilities, Material and Waste Allocation of The Battery Recycling SC

Using the formulated mixed-integer linear programming (MILP) model based on the parameters in Table 2, the decision was made to establish two recycling facilities under the second option. The first facility, RF2, is located in Jakarta, while the second facility, RF3, is in Surabaya, with one recycling facility allocated to each location. As shown

Table 5. Optimal Batteries Waste Allocation from Collection Center to Recycling Facilities

Collection Center	**Period 1**			**Period 2**			**Period 3**			**Period 4**		
	RF 1	**RF 2**	**RF 3**	**RF 1**	**RF 2**	**RF 3**	**RF 1**	**RF 2**	**RF 3**	**RF 1**	**RF 2**	**RF 3**
Jakarta	0	18,449	0	0	80,514	0	0	182,870	0	0	258,480	0
Bekasi	0	5,230	0	0	22,856	0	0	51,950	0	0	59,165	0
Bandung	0	0	0	0	0	0	0	0	0	0	0	17,908
Surabaya	0	0	4,115	0	0	17,998	0	0	40,854	0	0	57,737
Tangerang	0	3,371	0	0	14,759	0	0	33,501	0	0	47,358	0
Bogor	0	264	0	0	1,174	0	0	2,381	0	0	0	0
Semarang	0	0	1,699	0	0	7,380	0	0	16,750	0	0	23,652
Yogyakarta	0	0	372	0	0	1,619	0	0	3,690	0	0	5,203

Table 6. Manufacture Demand (in -kg)

Material Demand	**Period**			
	1	**2**	**3**	**4**
Nickel	7,300	32,100	73,100	103,300
Cobalt	7,300	32,100	73,100	103,300
Manganese	6,700	29,260	66,400	93,900

Table 7. Optimization Result of Allocation Recycled Material from Recycling Facilities to Manufacture (in -kg)

Amount of Material	**RF**	**Nickel**				**Cobalt**				**Manganese**			
		Period				**Period**				**Period**			
		1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Produced	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	6,009	26,247	59,555	80,300	6,009	26,247	59,555	80,300	5,463	23,861	54,141	73,000
	3	1,361	5,939	13,485	22,990	1,361	5,939	13,485	22,990	1,237	5,399	12,259	20,900
Sent	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	5,939	26,161	59,615	80,310	6,009	26,247	59,555	80,214	5,463	23,861	54,141	73,000
	3	1,361	5,939	13,485	22,990	1,291	5,853	13,545	23,086	1,237	5,399	12,259	20,900
Inventory	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	70	156	96	86	0	0	0	86	0	0	0	0
	3	0	0	0	0	70	156	96	0	0	0	0	0

in Table 5, the facility in Jakarta (RF2) will collect NMC waste batteries from collection centers in Jakarta, Bekasi, Tangerang, and Bogor over four periods. Similarly, the facility in Surabaya (RF3) will gather waste batteries from collection centers in Bandung, Surabaya, Semarang, and Yogyakarta. The model also ensures that the materials produced by recycling facilities meet the demand for manufacturing, as detailed in Table 6. Over time, the demand for recycled materials increases. Table 7 provides a breakdown of the materials produced by each recycling facility, the amount sent to manufacturing, and inventory levels. For example, the demand for nickel and cobalt rises from 7,300 kg in period 1 to 103,300 kg in period 4, while manganese demand grows from 6,700 kg to 93,900 kg during the same period.

In period 1, the recycling facilities produced 7,370 kg of nickel, 6,700 kg of manganese, and 7,370 kg of cobalt, with an inventory surplus of 70 kg each for nickel and cobalt. These figures are based on conversion factors of 22% for nickel, 20% for manganese, and 22% for cobalt. In the early stages of operation, the recycling facilities achieved distribution efficiency by minimizing inventory. From periods 2 to 4, production increased significantly, with nickel production rising to 103,290 kg by period 4. This growth aligns with the increasing supply of waste batteries,

Table 8. Optimal Allocation of Waste of Recycled Material from Recycling Facilities to Landfill (in -kg)

	From Recycling Facility	**Period**			
		1	**2**	**3**	**4**
Amount of waste of recycled material sent to Landfill	RF 1	0	0	0	0
	RF 2	9,833	42,949	97,454	131,400
	RF 3	2,227	9,719	22,066	37,620

Table 9. Revenue and Cost Components

Components	**Value**
Revenue Nickel Material	IDR 44,886,000,000
Revenue Cobalt Material	IDR 179,550,000,000
Revenue Manganese Material	IDR 9,420,500,000
Total Revenue Recycling facility	IDR 233,850,000,000
Total Cost Fasilitas Recycle	IDR 138,670,000,000
Total Profit	IDR 95,177,991,703

reflecting the ability of the recycling facilities to scale production in response to rising demand. This balance between increased production and distribution ensures minimal inventory and optimal demand fulfillment. In addition to material production, waste generated during the recycling process is sent to a landfill, as detailed in Table 8. Strategic optimization of facility locations minimizes shipping distances and logistics costs, contributing to the operational efficiency of the NMC battery recycling supply chain network. These optimizations strengthen the overall efficiency and cost-effectiveness of the system.

Revenue from recycling facilities is derived from selling nickel, manganese, and cobalt to manufacturers, as illustrated in Table 9. The total profit generated by the recycling facilities amounts to 95,177,991,703 IDR. Among these, cobalt contributes 76% of the total revenue due to its higher market price, while nickel and manganese contribute 19% and 5%, respectively, as shown in Figure 3. Cobalt's economic significance in recycling aligns with findings from Dunn et al. [44], which emphasize the impact of cobalt prices on the profitability of recycling NMC batteries using hydrometallurgical methods. Sensitivity analysis from the Dunn et al. [44] study further highlights cobalt as the most significant driver of recycling profits.

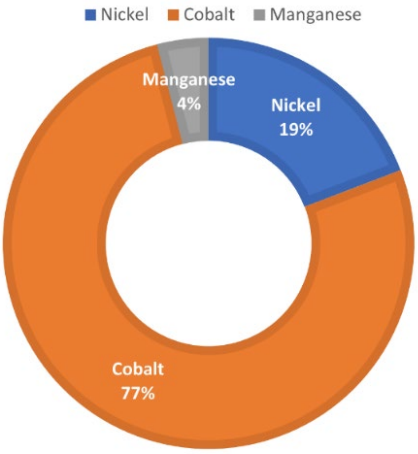


Figure 3. Revenue breakdown of NMC recycling

The total costs incurred by the recycling facility, including fixed costs, investment costs, recycling costs for each material, waste treatment costs, inventory costs, and transportation costs, amount to 138,670,000,000 IDR. Unlike prior models, which often overlook detailed financial analysis, this study emphasizes the integration of revenue streams and cost considerations. It provides a comprehensive evaluation of economic feasibility by incorporating location selection and multi-product material allocation. This approach strengthens the NMC battery recycling supply chain, ensuring long-term profitability and sustainability, from waste collection to the reintegration of recycled materials into manufacturing.

Sustainability Consideration

From an economic perspective, establishing recycling facilities for NMC battery waste offers significant advantages in waste management and financial returns. By recovering valuable metal materials through the conversion factors adopted from Narang et al. [37], manufacturers can reuse these as secondary raw materials, reducing reliance on newly mined resources. The use of a mixed-integer linear programming (MILP) approach enables recycling facilities to generate substantial profits, with an estimated financial contribution of IDR 95,177,991,703. Moreover, recycling waste batteries not only meets the growing global demand for raw materials but also reduces the extraction of new resources from mining processes. Effective recycling ensures that not all waste batteries are sent to hazardous landfills, helping governments minimize the need for constructing additional hazardous waste disposal sites.

Socially, the establishment of recycling facilities creates a range of opportunities for local communities. These facilities generate direct employment and open up roles in supporting sectors such as transportation and material processing. Consequently, they contribute to reducing unemployment rates, improving community welfare, and enhancing local workforce skills through training and development. In addition to economic and employment benefits, these facilities promote public awareness of waste management, particularly for electric vehicle battery waste. This increased awareness fosters community education and active participation in waste management programs, reducing the potential accumulation of hazardous waste and encouraging sustainable practices.

From an environmental standpoint, the recycling process for NMC batteries significantly mitigates risks associated with hazardous waste. Battery waste, classified as hazardous and toxic (B3) waste, requires specialized handling to prevent soil and water contamination caused by chemicals leaching from cathode materials. Recycling these batteries not only addresses these risks but also reduces the need for mining raw materials, which poses significant environmental challenges. Additionally, recycling alleviates the pressure on landfills, lowering the risk of cross-contamination from other waste chemicals. This approach aligns with the principles of a circular economy by keeping products and materials within the economic cycle, thereby reducing waste and conserving natural resources. The hydrometallurgical process used in NMC battery recycling also offers insights into its environmental impact. Over four periods, greenhouse gas emissions from the recycling process are calculated to be 4,397.35 kg/year, 19,199.85 kg/year, 43,606.58 kg/year, and 61,626.94 kg/year, respectively, as derived from the research of Samarukha [45]. These figures highlight the environmental footprint of the recycling process, providing valuable data for understanding and managing its sustainability. By integrating economic, social, and environmental considerations, this recycling initiative supports a comprehensive and sustainable approach to managing NMC battery waste.

Sensitivity Analysis

Sensitivity analysis is conducted to evaluate the impact of changes in demand for nickel, manganese, and cobalt materials on the profit maximization of recycling facilities, as shown in Figure 4. The results highlight that variations in demand parameters significantly influence both profit maximization and the optimal decisions regarding the establishment of recycling facilities. In the range of a -10% to 0% change in demand, profits decrease while the

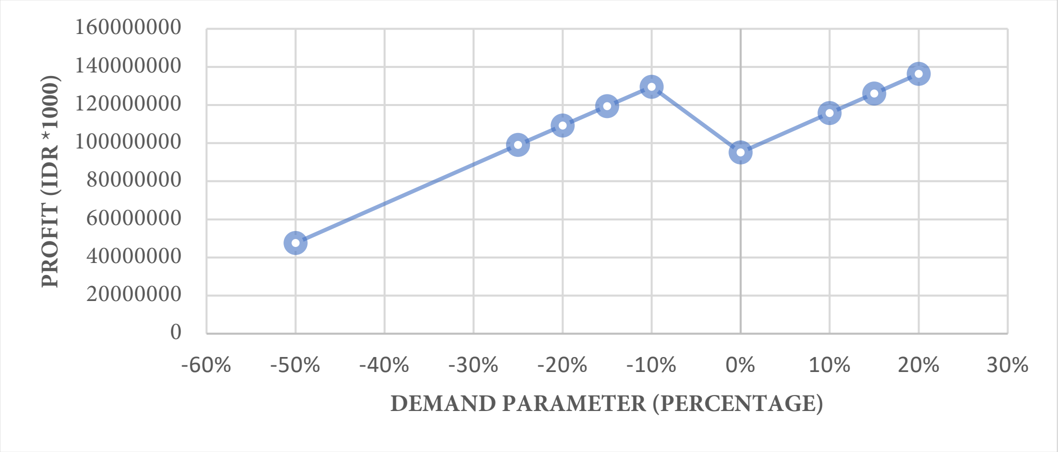


Figure 4. Sensitivity of profit recycle based on demand parameters

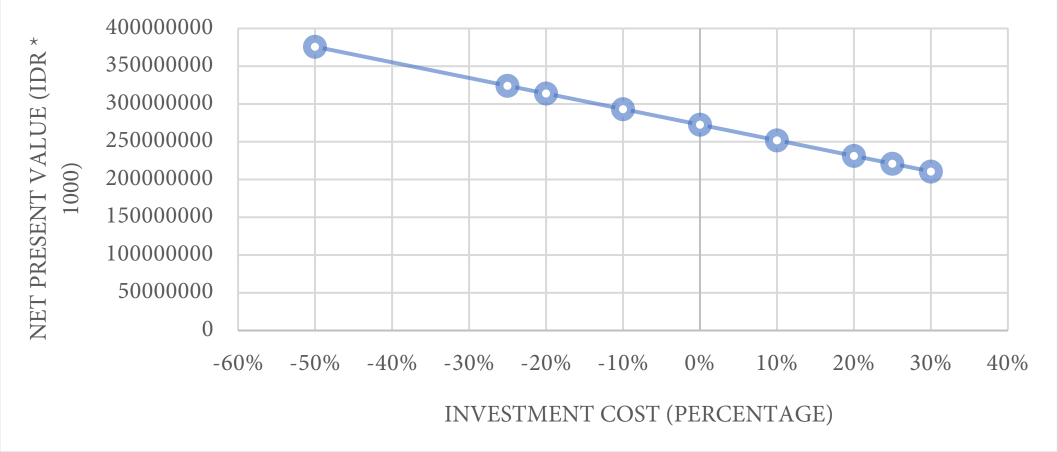


Figure 5. Sensitivity of net present value based on investment cost

number of recycling facilities increases to two. This decline in profitability is attributed to adjustments in operational costs and profit margins associated with establishing new facilities, particularly in Surabaya. Conversely, within the range of a 0% to 20% change in demand, profits increase as the decision to establish two recycling facilities optimizes the production capacity of recycled materials, thereby enhancing profit maximization.

Further insights into the financial implications of investment value changes are provided in Figures 5, 6, and 7. These figures reveal that as investment values rise, the NPV, IRR, and ROI values decrease. For NPV, an increase in investment value leads to higher cash outflows, and if the corresponding cash inflows are insufficient to offset these outflows, the NPV value of the recycling facility project diminishes. Similarly, the sensitivity of the IRR value demonstrates that greater investment requires higher cash inflows to achieve the desired rate of return. This indicates that substantial investment values tend to result in lower IRR if cash flows do not proportionally align with investment costs.

For ROI, the sensitivity analysis shows that increased investment values raise the threshold for achieving an acceptable ROI level. Consequently, as investment costs rise, the ROI decreases, reflecting the greater challenge of maintaining profitability relative to the initial investment. These findings emphasize the importance of balancing investment value and cash flow management to ensure the financial sustainability of recycling facilities.

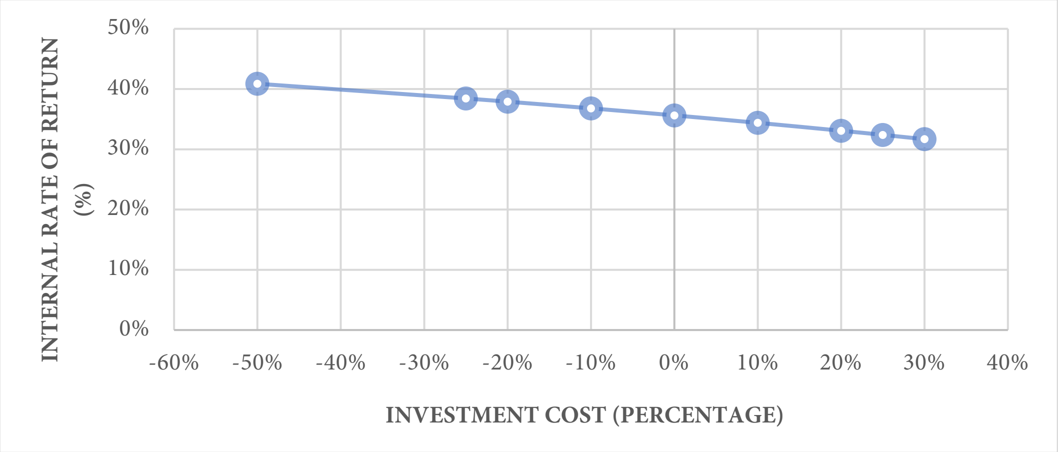


Figure 6. Sensitivity of internal rate of return based on investment cost

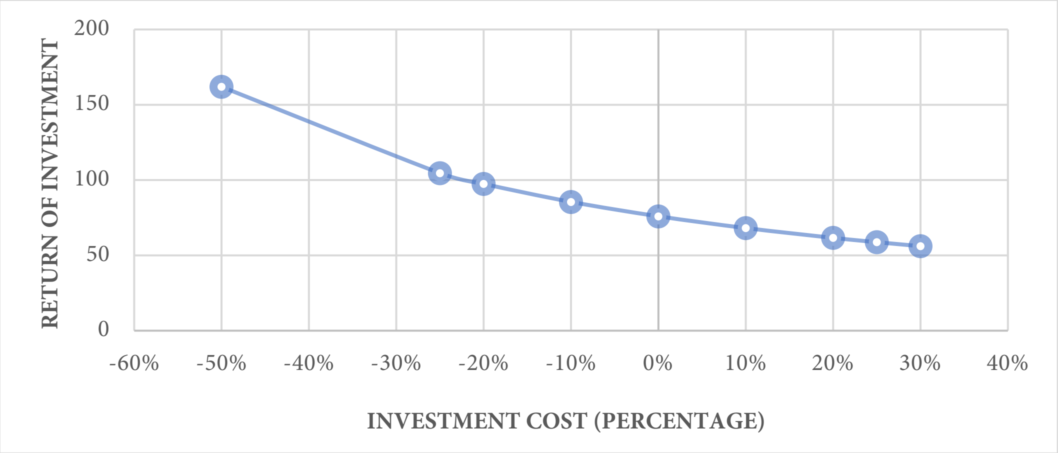


Figure 7. Sensitivity of return of investment based on investment cost

CONCLUSION

This study presents an optimization model for the NMC battery waste recycling network, offering improved cost efficiency, enhanced sustainability, and a significant reduction in waste accumulation by strategically locating recycling facilities and efficiently allocating materials. These findings underscore the potential for a circular economy, where valuable materials like nickel, manganese, and cobalt are recovered and reintegrated into the production cycle, reducing dependency on virgin resources. Achieving this optimization requires effective collaboration among supply chain entities, including the coordination of waste collection, recycling, material delivery to manufacturers, and landfill management, which ensures streamlined operations and financial viability. The investment feasibility analysis, combined with the Mixed Integer Linear Programming (MILP) approach, demonstrates that establishing recycling facilities is both feasible and profitable, supporting the growing demand for sustainable waste management. Beyond economic benefits, the establishment of recycling facilities provides significant social and environmental advantages, such as creating job opportunities, enhancing community awareness of proper waste management, and mitigating the harmful effects of indiscriminate battery disposal, which can release toxic substances into the environment. By reducing the need for raw material mining and alleviating landfill pressures, this recycling approach supports environmental sustainability and aligns with circular economy principles. While this study primarily focuses on land-based supply chain networks within Java Island, future research could expand to other regions or explore diverse transportation modes, addressing Indonesia's unique geographical challenges as an archipelago. Additionally, further studies could develop advanced configurations, such as multi-manufacturer networks, or utilize heuristic methods to solve complex recycling problems involving various electric vehicle battery types. By integrating economic feasibility, operational efficiency, and sustainability, this research offers a valuable decision-making tool for stakeholders and sets the foundation for future advancements in NMC battery recycling supply chains.

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CONFLICT OF INTEREST

The author confirms that there are no conflicts of interest related to the authorship, content, or publication of this research.

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