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Are we ready yet? Assessing Indonesia's readiness for transformative EV battery end-of-life management

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Abstract: Indonesia has big ambitions to become a major player in the EV ecosystem, including EV batteries, but currently lacks a comprehensive system for managing its end-of-life phase. This research explores how end-of-life management for EV batteries can be effectively implemented in Indonesia by examining the country's regulatory, economic, and social readiness. Using a descriptive qualitative approach, in-depth interviews were conducted and analysed through content analysis based on pre-coded data. The readiness level is assessed by benchmarking Indonesia's EV battery ecosystem development against global best practices. The findings of this research indicate that several regulations need to be adjusted to place greater emphasis on end-of-life management for EV batteries. The secondary market for used EV batteries is also key to maximising their economic value. Additionally, raising public awareness about the importance of energy transition is essential to boosting demand for EV batteries.

Keywords: end-of-life management; electric vehicle battery; circular economy; sustainability; readiness level.

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1 Introduction

Electric vehicles (EVs) are becoming a solution in the transportation and logistics sector to achieving net-zero emissions (Wrålsen et al., 2021). Hence, EV demand has grown exponentially and is expected to continue to grow in the future. In 2021, the total number of EVs (four-wheel vehicles) on roads globally reached 16.5 million, which is three times higher than in just three years. This number is expected to increase to approximately 140 million by 2030 (IEA, 2022). Lithium-ion is the most-used technology for EV batteries due to their high power and energy density, which is suitable for high storage capacity systems such as EVs. So, EV production growth will contribute to EV battery growth.

Indonesia is committed to reducing emissions by 29% below business as usual by 2030, or 41%, with international assistance, which has been taken into Law No. 16 of 2016 (Government of Indonesia, 2016). Then, Indonesia strengthened its commitment after COP26 in Glasgow in 2021 to achieve net-zero emissions by 2060 (BRIN, 2022). Indonesia is also ambitious to become a major player in the EV batteries industry worldwide since nickel reserves account for 52% (72 million tons) of the total global reserves, which is the primary raw material for EV batteries (ESDM, 2020).

However, EV batteries cause other major non-carbon emissions problems, which need to be addressed soon. The negative environmental impact comes from the emission of toxic gases during the mining phase and up to the manufacturing process. In addition, the high demand for water resources required for this activity is alarming (Lakshmi, 2023). The waste problem is also one of the most pressing issues in the EV batteries industry. In 8–10 years of use, EV batteries will be obsolete and have no further use for EVs, even though they retain 75%–80% of their original capacity. It was estimated that more than 12 million tonnes of EV batteries could be wasted during 2021–2030 (Lim, 2021). In addition, hazardous materials contained in EV batteries could lead to significant health hazards if not correctly disposed of. Improper disposal of these batteries can subject millions of individuals to neurotoxic substances such as lead, resulting in health problems (Jordan, 2023).

Commercial use of electric motorcycles in Indonesia has reached 10,546 units in 2021 (Putri, 2024). So, it can be said that EV battery waste in Indonesia will appear at least in the next 1–2 years. Indonesia must start preparing facilities and end-of-life (EOL) road maps for EV batteries. EOL management for EV batteries must become a part of the EV battery ecosystem if Indonesia truly has the ambition to become a major player in this field.

Up to this point, the implementation of EOL management for EV batteries in Indonesia may indeed be limited. There are no specific regulations related to EOL management for EV batteries in Indonesia. In addition, there is limited research and study found that specifically discussed the issue in this topic, which left the empirical study gap on this issue. In this case, there is a need for an acceleration of innovation and research to study the implementation of EOL management for EV batteries, especially in Indonesia. However, the question remains: Is Indonesia ready to implement this innovation system to manage the EV battery ecosystem?

This paper aims to explore the ecosystem of the EV battery EOL management system in Indonesia, including stakeholders that contribute to the system and their roles as well as the required regulations. This paper also assesses the readiness level of implementing

EOL management for EV batteries in Indonesia. Then, this research will provide policy implications to stakeholders for managing the EV battery ecosystem, especially the EOL phase.

A literature review is performed to understand the current research and development of EOL management for EV batteries as well as to learn about the state-of-the-art of EV batteries. The paper uses in-depth interviews to gain information regarding the growth and current condition of the EV battery ecosystem in Indonesia. The information gathered from the interview then be analysed using content analysis and benchmarked with the best practices worldwide to assess Indonesia's readiness level and create policy implications.

The paper is structured as follows: Section 1 presents the introduction and background of the study. Section 2 provides related literature on the topic, such as EOL management for EV batteries and its affecting factors. Section 3 discusses the research methods and study deliverables. Section 4 contains the study's findings. Lastly, Section 5 presents the study's summary, conclusions, and implications.

2 Literature review

2.1 The system of EV battery

The system of an EV battery involves multiple stages, starting from raw material extraction to delivering the final product to consumers. EV batteries predominantly use lithium-ion technology, requiring critical minerals like lithium, typically extracted from spodumene or brine deposits and cobalt. These raw materials undergo processing to create battery cells, which are then assembled into battery packs for integration into EV (Muliawati, 2023).

In Indonesia, the EV battery supply chain comprises the upstream sector, which includes mining and metallurgy of materials like nickel, cobalt, and manganese. The midstream sector focuses on processing these materials, with facilities producing intermediates like Mixed Hydroxide Precipitate and nickel pig iron, though some chemical products are still lacking. The downstream sector involves high-tech facilities for manufacturing precursor materials, cathodes, and battery components, with ongoing efforts to establish more comprehensive production capabilities within the country (Muliawati, 2023).

2.2 EOL management for EV battery

EOL management for EV batteries includes all activities to manage waste batteries that have reached their useful life in EV. EOL management is an important strategy to extend the lifespan of EV batteries and re-purify the minerals contained therein. So, EOL management for EV batteries can be useful for reducing the disposal of battery waste in landfills and raw material extraction from mining (Meegoda et al., 2022).

Several strategies could be implemented for EV battery EOL management, among which recycling, repurposing, and remanufacturing are the main types of EOL management for EV batteries (Chirumalla et al., 2022). There are multiple ways to recycle EV batteries, which can be classified into three process categories: pyrometallurgy, hydrometallurgy, and direct recycling (Gaines, 2018). In the repurposing

strategy, the main goal is to lengthen the life cycle by applying the used batteries to other applications, such as energy storage systems (ESS) (Kotak et al., 2021). Lastly, the remanufacturing program aims to identify and replace any defective parts in a battery pack. This is so that the battery management system is met. The battery can be used in EVs at a lower price with lower performance (Hickey, 2022).

2.3 Readiness level analysis

NASA first developed the concept of readiness level in the 1970s to measure the readiness of new technology, called the technology readiness level (TRL). TRL has a matrix for evaluating technology on a scale of 1–9, starting from the concept of new technology to the deployment of the technology (Mankins, 2009). Then, the TRL concept evolves to measure broader readiness levels, such as innovation for business models, because a matrix from a technology perspective alone is not enough to measure readiness at the business model level (Lunner and Worrnann, 2018).

Innovation readiness level (IRL) has been developed based on the TRL concept to manage innovation for business aspects to the commercial stage (Evans and Johnson, 2013). The IRL concept originates from several business model elements that need to be considered, such as customer, funding, team, intellectual property, business, and TRL (KTH, 2024). The following are 9 IRL scales to measure the readiness of innovation to the commercialisation stage adopted by Evans and Johnson (2013):

- 1 general specification of capabilities to execute business model generated
- 2 detailed specification of capability requirements generated
- 3 active development of capability begun
- 4 first general demonstration of capability achieved
- 5 good demonstration of capability achieved
- 6 first demonstration of capability in the market
- 7 first transaction involving full product in final form
- 8 capability successfully used in business
- 9 capability in routine use to support full-scale production.

EOL management for EV batteries is an emerging topic and is considered an innovation in a business model at the implementation stage. Thus, IRL is more appropriate for measuring readiness levels because it covers the aspects needed to implement an innovation. This readiness level analysis is needed to determine where Indonesia is adopting EOL management for EV batteries. The results will become a basis for policymakers and industry players to accelerate the development of EOL management for EV batteries.

2.4 Indicators succeeding the EOL management for EV batteries

Kurdve et al. (2019) mentioned that the system of EV batteries is affected by political/legal, economic, and social factors, which is necessary for successful

implementation. This research will focus on these three indicators to assess the readiness level.

2.4.1 Regulatory aspect

The government's role is also crucial in the EOL management of EV battery activities. The government can exert control to ensure the effectiveness of the EV Battery EOL management system by measuring various indicators such as the reduction of natural resource usage, the number of batteries in landfills, and the availability of reusable used batteries. The EU Battery Directive, with its 2023 update, sets ambitious recycling targets aimed at improving sustainability, increasing recovery rates, and reducing environmental impact (EU Directive, 2006; EU Directive, 2023). This regulation is expected to become a global standard for battery EOL management (Connellan et al., 2023). Similar frameworks are being developed in Asia, particularly in China, Japan, and South Korea, to focus on materials recovery (Yang et al., 2021). These regulations aim to reduce dependence on primary materials and promote sustainability within the EV battery sector by implementing strict recycling targets.

EV batteries contain hazardous materials. Hence, taking care of the batteries in terms of collection and transportation needs special attention (Kurdve et al., 2019). In Indonesia, hazardous materials management has been regulated under Government Regulation No. 74/2001, which was implemented following Law No. 32/2009 on Environmental Protection and Management. It is complicated because multiple ministries are responsible for chemical control, such as the Ministries of Environment, Industry, and Trade, along with other ministries like Health, Manpower, and Transportation. Hence, it is essential to investigate further whether the legislation in Indonesia concerning hazardous materials has also effectively encompassed the management of used EV batteries.

Lastly, the standardised design of EV battery packs also influences the EOL management of EV batteries. This approach can facilitate the automation of battery disassembly, enhance process safety, and improve recovery quality, leading to a higher battery return rate (Malinauskaite et al., 2021). However, the standardised design will limit the innovation in producing battery packs, and experiments are needed to find an optimal balance to acquire a competitive advantage over their competitors (Ahuja et al., 2020). So, it is important to investigate if standardised battery design is necessary for the development of the EV battery ecosystem in Indonesia, given the competition among battery producers compared to the effectiveness of battery recycling.

2.4.2 Economic aspect

Battery price plays a crucial role in the EV battery ecosystem, particularly in its EOL management. It will influence the remanufacturing and repurposing activities in terms of the used battery price to consumers (Olsson et al., 2018). High new battery prices represent significant potential earnings on repurposed and remanufactured batteries, while excessive pricing may restrict the amount of EVs supplied to the customer (Ahuja et al., 2020).

Economically, used EV batteries must be sold at lower prices than the original to attract consumers, while remanufacturers need to innovate to meet OEM standards. Balancing new battery prices is crucial to ensure resale values are neither too high nor too

low, allowing revenues from the secondary market to cover operational costs while maintaining affordable prices for customers.

The battery price itself is influenced by its raw material costs, which cover over 60% of the total battery cost (Sakti et al., 2015). The prices have dropped to \$139/kWh in 2023 and are expected to decrease further, reaching \$113/kWh by 2025 and \$80/kWh by 2030 (BloombergNEF, 2023). Due to price fluctuations, it is recommended that used EV battery prices be represented as a percentage of current battery prices rather than a fixed amount.

Another factor is incentives. Incentives could be in the form of tax, financial investment, and other funding to cover facility construction, technology adoption, or recycling facilities, which are the most expensive (Ahuja et al., 2020; Alamerew and Brissaud, 2020). Song and Chu (2019) formulated an incentivising model for EV Battery manufacturers and retailers. It showed a correlation between the growth of incentive levels and an increase in the overall profit, and greater incentive levels are associated with a higher rate of recycling used EV batteries. The incentives given to end-users also contributed to the demand for used EV batteries. The Indonesian government is implementing a value-added tax (PPN) incentive to boost EV purchases, as outlined in Regulation of Minister of Finance Number 38 of 2023 (Cabinet Secretariat, 2023). The incentive program appears effective, with the domestic wholesale volume of EVs reaching 1,560 units in May 2023 – a 21% increase from April and a 680% rise compared to May 2022 (Ahdiat, 2023).

In the case of EV batteries, the increased sales of EVs mean an increased demand for their batteries, which leads to increased demand for the second market of EV batteries. This will allow a higher rate of used EV batteries in the EOL ecosystem and reduce demand fluctuations.

2.4.3 Social aspect

The incentives program alone is not enough to increase the demand for EVs. The shift in consumer preference towards EVs is pivotal to increasing the demand for EVs, leading to effective EOL management for EV batteries. A societal commitment towards sustainability and SDGs mindset is needed to succeed in this transformation (Quinteros-Condoretty et al., 2021). In addition, increasing stakeholder understanding of sustainable business practices might help to inspire society to be more conscious about environmental issues and result in responsible behaviour (Yamane and Kaneko, 2021).

Lastly, it is essential to certify used EV batteries in order to increase consumer confidence and stimulate demand. Although used EV batteries can still have up to 80% of their original energy storage, making them a valuable resource for second-life applications, customers may question the quality and safety factors since the product is second hand. In this case, certification in the used EV Batteries becomes critical to ensure that only reliable products are distributed and consumers can trust the product, especially certified products from third parties (Darnall et al., 2018).

Kamath et al.'s (2023) simulation study found that the economic value of battery remanufacturing remains low. However, offering warranties and certifications can significantly increase the perceived value of used EV batteries. Consumers are also showing the greatest willingness to buy products that include certifications, particularly those addressing ethical and environmental concerns (Chatterjee et al., 2022).

A summary of all indicators succeeding the system of EOL management for EV batteries can be seen in Table 1.

Table 1 Indicators succeeding the EOL management for EV batteries

<i>Indicator</i>	<i>Reference</i>	<i>Remarks</i>
Political, legal, and regulations	Connellan et al. (2023)	<i>The regulation specifically built related to the battery is crucial in managing the EOL of EV batteries by addressing the collection process, encompassing recycling rates, efficiency, and the proportion of recycled materials.</i>
	Kurdve et al. (2019)	<i>Collection and transportation laws for hazardous materials are needed since the used EV Battery contains chemical materials that are counted as hazardous materials.</i>
	Malinauskaite et al. (2021) and Ahuja et al. (2020)	<i>Standardised battery design needs to be assessed in the Indonesian context since it can achieve a higher recycling yield but minimise the area of innovation for industry players.</i>
Economical factor	Olsson et al. (2018) and Ahuja et al. (2020)	<i>The price of new EV batteries affects remanufacturing and repurposing activities. High prices present potential earnings on repurposed batteries, while excessive pricing may limit EV supply.</i>
	Al-Alawi et al. (2022)	<i>Prices of raw materials influence the price of new batteries. It is important to manage the raw materials as well</i>
	Ahuja et al. (2020); Alamerew and Brissaud (2020) and Song and Chu (2019)	<i>Incentives to EV battery manufacturers, retailers, and end-users may boost EOL battery demand and sales of EVs, increasing the second market for EV batteries and stabilising demand fluctuations in the EOL ecosystem.</i>
Social factor	Quinteros-Condoretty et al. (2021)	<i>Societal commitment and public awareness of environmental issues may drive the transformation from the use of conventional cars to EVs.</i>
	Yamane and Kaneko (2021)	<i>Government and industry players could play a big role in knowledge sharing related to the importance of being aware of energy transition and the use of EVs.</i>
	Darnall et al. (2018), Kamath et al. (2023) and Chatterjee et al. (2022)	<i>The nature of EV Batteries' second hand products leads to the negative consumers' perceived value; however, it could be addressed by providing <i>certification</i> in terms of safety and quality.</i>

Source: Literature review

3 Research methods

3.1 Data collection methods

This research employs a descriptive qualitative approach using individual depth interviews (IDIs). An IDI is a one-on-one conversation between a resource person and an interviewer, gathering detailed insights from the resource person's experiences (Schindler, 2022). Before each interview, the researcher shares relevant documents to

ensure resource persons understand the context. Following a semi-structured format, pre-prepared questions are supplemented with in-depth follow-up queries. Interviews are conducted online, lasting 50 to 65 minutes and being recorded for thorough analysis. The data collection spans four weeks.

Resource persons are selected based on specific criteria to ensure relevant, high-quality responses. They include professionals from Indonesia Battery Corporation (IBC), policymakers from the Ministry of Investment (BKPM) and Ministry of Industry, and experts from the Lithium Battery Science and Technology Excellence Center (PUI-PT) at Universitas Negeri Sebelas Maret (UNS), representing business, policymaking, and research sectors for comprehensive insights into Indonesia's EV battery ecosystem. There are five resource persons in total.

Table 2 is the profile of the resource person who was interviewed for this research.

Table 2 Resource person's profile

<i>Resource person</i>	<i>Latest education</i>	<i>Institution</i>	<i>Years of experience</i>
RP1	Bachelor's degree in Mechanical Engineering	Ministry of Investment (BKPM) – Expert Staff	>15
RP2	PhD in Chemical Engineering	Associate Professor in Chemical Engineering, Sepuluh Nopember Institute of Technology	>15
RP3	PhD in Environmental Science	Associate Professor at Research Center for Electrical Energy Storage – Sebelas Maret University (UNS)	>15
RP4	Master's degree in Management	Industry Supervisor at Ministry of Industries	>15
RP5	Master's degree in Management	Corporate Strategy SVP at Indonesia Battery Corporation	>10

3.2 Data analysis methods

3.2.1 Content analysis

This study adopts a deductive methodology following Yin's (2014) framework, where a theoretical framework is developed to guide data analysis and align with anticipated outcomes. In this research, we use the theoretical framework from the literature review (Table 1) as a basis for interview questions to get the necessary answers and also as a result of Indonesia's readiness level. It contains the three indicators for succeeding EOL management implementation for EV batteries, followed by its sub-topics on each indicator.

Content analysis is chosen as the method of data analysis due to its suitability for qualitative research (Saunders et al., 2016), focusing on identifying themes and trends within qualitative datasets, particularly interview data in this research. The content analysis method is used to answer the research objective: to explore the EV battery ecosystem in Indonesia. The theme used in this study refers to the elements that shape the

EV battery EOL management system and the categorised topics for the interview questions, which are regulations, legal aspects, and economic and social factors.

3.2.2 IRL analysis

IRL analysis is employed qualitatively to assess Indonesia's preparedness to implement EOL management for EV batteries. The 9 IRL scales from Evans and Johnson (2013) are used as the basis for creating IRL scale criteria for EOL management for EV batteries. Then, the literature review was analysed to integrate the information of indicators in EOL management for EV batteries into the 9 IRL scales to have specific criteria needed in this assessment. Table 3 is the IRL scales for implementing EOL management for EV batteries.

Table 3 IRL of EOL management for EV batteries

<i>Scale</i>	<i>Criteria</i>	<i>Criteria in EOL management for EV batteries context</i>
1	General specification of capabilities to execute business model generated	An idea to implement EOL management for EV batteries is generated
2	Detailed specification of capability requirements generated (paper study)	A paper study about EOL management for EV batteries is reported
3	Active development of capability begun	System or technology development is begun
4	First general demonstration of capability achieved	System or technology development is completed
5	A good demonstration of capability achieved	System or technology is tested and simulated in the laboratory in environments that are as close to realistic as possible
6	First demonstration of capability in the market	Test the EOL management system in the market
7	First transaction involving full product in final form	The EOL management for EV batteries has been implemented in a full life cycle
8	Capability successfully used in business	The EOL management for EV batteries implementation is succeed
9	Capability in routine use to support full-scale production	Sustainable implementation in years

Source: Modified from Evans and Johnson (2013)

The IRL analysis is done qualitatively by matching Indonesia's current developments derived from the content analysis to the modified 9 IRL scales. In addition, we compare Indonesia's development with global best practices from secondary sources. The global best practices are assumed to be mature innovations that already have a scale of 8–9 in IRL. The assessment is done for each indicator succeeding EOL management for EV battery implementation. The findings from the IRL analysis will inform policy recommendations for effective EOL management implementation in Indonesia's EV battery ecosystem.

4 Result and discussion

The interview results are categorised into three main themes – regulatory, economic, and social aspects – that influence the successful implementation of EOL management for EV batteries. Each main theme consists of sub-topics, as detailed in Section 2. These themes are used as a basis for interviewing questions related to EOL management for EV batteries in Indonesia. The author identifies existing issues in Indonesia's EV battery management through these factors and uses them to measure the country's readiness for EOL management. A readiness analysis is conducted using the modified IRL framework from Table 3. The current development of Indonesia's EOL management for EV batteries is compared to the worldwide best practices as an assumption of a well-established EV batteries ecosystem.

4.1 Readiness level in regulatory aspect

Based on the results of the interview, it can be found that Indonesia still uses existing regulations to regulate and manage the EV battery ecosystem. For example, RP1 mentioned that in the aspect of investment receipts, Indonesia refers to Government Regulation (PP) Number 5 of 2021 concerning the Implementation of Risk-Based Business Licensing (Government of Indonesia, 2021).

In managing EV battery waste, RP2 mentioned that Indonesia only has regulations governing how to manage hazardous waste in general, so this includes EV battery waste because it contains the chemicals in question. This regulation is referred to as Regulation of the Minister of Environment and Forestry Number 6 of 2021 (KLHK, 2021). Related to this situation, RP3 suggested that there is still a need for how to collect, transport, and then process EV battery waste or even orient it into second-life applications.

In addition, EV battery standardisation has not been established yet. RP3 said that currently, there is no standard for EV batteries, and it may still be under discussion stage at the Indonesian National Standard Agency.

Indonesia already has a basic concept for carrying out EOL management for EV batteries in the form of existing regulations that can be adapted to the implementation of EOL management for EV batteries. However, the specific regulation has not yet been established. Indonesia has also developed a paper study and road map for EV battery recycling.

Compared to other countries that have implemented an ecosystem for EV battery EOL management, specific battery regulations have been established to support the EV battery ecosystem. One of the examples is the EU battery directive. In 2006, when it was first established, the Battery Directive regulated a recycling target of 50% by average weight (EU Directive, 2006). Other than the EU, countries in Asia, including Japan, South Korea, and notably China, have established regulatory frameworks for materials recovery. An example is the Chinese Policy on recycling technology for EV power batteries (Yang et al., 2021).

Seeing this, Indonesia is still far from being prepared to implement EOL management for EV batteries in the regulatory aspect. Currently, there is no specific regulation for the EV battery ecosystem, and the paper study has not yet started, representing IRL Level 1 for battery regulations. A specific system for managing EV battery waste has not yet been developed. However, a basis for creating a new system has been established, representing

IRL Level 2 in this aspect. The standard for EV batteries is partially begun by addressing safety requirements. The other aspects are not yet established. Hence, the IRL is Level 3 for battery standardisation. So, based on Table 3, overall, Indonesia has still reached IRL stage 2 in the regulatory aspect for implementing EOL management for EV batteries, which is ‘paper study about EOL management for EV batteries is reported’.

Table 4 IRL on regulatory aspect

<i>Topic</i>	<i>Current status</i>	<i>Current best practice</i>	<i>Readiness level</i>
Specific battery regulations	Not yet developed (RP1; RP2; RP3; RP4). Follows existing regulations from multiple ministries (RP1; RP4) Focused on upstream activity (RP1; RP3; RP4)	Regulation for EV Battery in Europe, China, and Japan from raw material extraction until EOL management	1
Collection and transportation laws	Follows existing regulations in hazardous material handling (RP2; RP3; RP4) Same treatment as accu. battery (RP4)		2
Standardised battery design	Focused on safety requirements and two-wheeled vehicles (RP2; RP4)	The standard for battery composition	3
<i>Average innovation readiness level in the regulatory aspect</i>			2

Source: Data analysis

4.2 Readiness level in economic aspect

The status of battery prices in Indonesia is determined by commodity prices and operational costs, which aligns with global best practices, giving it a high readiness level of 9. However, the pricing structure for second-life EV batteries has not yet been established, with best practices recommending a model based on a percentage of the current battery price, resulting in a low readiness level of 1 in this area.

In terms of incentives, Indonesia provides fiscal and non-fiscal incentives to support EV adoption, targeting battery producers, car manufacturers, and end-users, which aligns with international practices. This approach has earned a readiness level of 9. Globally, best practices suggest extending these incentives to include EVB EOL facilities, offering a comprehensive incentive framework.

Regarding the battery life cycle and technology adoption, there have been plans related to EOL management for EV batteries. IBC is committed to building an EV battery ecosystem up to the recycling stage, which has become the company’s strategic plan (IBC, 2024). Informant RP5 also said that IBC has the ambition by 2030 to build an EV battery recycling facility. In government circles, Indonesia has created an EV ecosystem roadmap that includes plans for EV battery recycling (Ministry of Industries, 2022). So, in terms of implementing the EOL system for EV batteries, it is still at level 1.

Gadjah Mada University (UGM) has been conducting research on recycling used lithium batteries since 2013. In 2019, the Research Team succeeded in collecting lithium

from used lithium ferro phosphate (LFP) batteries (UGM, 2019). In this case, the technology development for EV battery recycling is at level 5.

Overall, the topic related to the EOL management plan for EV batteries in Indonesia directly discusses recycling activities, where recycling is the last stage that should be carried out. In practice, several stages can be implemented first, such as repurposing and remanufacturing, before used EV batteries can be recycled (Chirumalla et al., 2022). These stages can be implemented to optimise the economic value of an EV battery.

Informants RP2 and RP3 are agreed with this condition. They explained that EV batteries should be used for other purposes, such as stationary storage systems which do not require high capacity as used in EVs. The batteries can be sorted and graded first at the time of collection to separate their second-life purposes.

Compared to the existing best practice, A joint venture company between Nissan and Sumitomo, 4R Energy, develops technology and infrastructure to remanufacturers, recycle, and resell the batteries derived from Nissan EVs (Nissan, 2021). Nissan graded the battery when it came back to the 4R factory based on their SOH and second-life usefulness.

Implementing second-life EV batteries could benefit stakeholders, especially at the industry level. Following Porter's five forces framework (Porter, 2008), buyers, including end-users, enjoy cost savings from lower-priced, repurposed batteries, further supported by government subsidies and tax incentives. In addition, the selling price of the used EV batteries could be determined based on a percentage of the new battery price and its current capacity (state-of-health). This scheme will lead to providing lower EV prices as well. This scheme enables end-users to derive significant benefits from EOL management for EV batteries. If implemented successfully, it could drive increased demand for EVs and accelerate the transition toward green mobility. Empowered by greater bargaining power, end-users could advocate for more affordable EV prices, compelling the industry to re-evaluate its business models and adopt robust EOL management practices.

Then, the rivalry among manufacturers, remanufacturers, and recyclers drives competition and innovation, reducing costs and resulting in more affordable products for end-users. Suppliers of advanced recycling technologies and raw material extraction processes benefit from increased demand for their services. New players in this ecosystem will also emerge, such as battery recycling and remanufacturers. They will compete to come up with technologies that can improve recycling efficiency or more sustainable practices. Additionally, substitutes in the form of sustainable EOL processes decrease reliance on virgin materials, reducing environmental impact and resource dependency. So, the successful implementation of the practice will automatically create a strong and sustainable ecosystem of EV batteries.

Other economic benefits have also been discovered. Dong et al. (2023) have utilised a range of economic indicators, including payback period, LCOE, and NPV, to examine the economic benefits of employing second-life batteries in a variety of applications. Based on the economic analysis calculations, in the long term, the use of second-life EV batteries is more profitable in terms of faster return on investment and more economical production costs. The emissions produced when using second-life EV batteries are also lower compared to new batteries (Dong et al., 2023). So, implementing EOL management for EV batteries could give economic rewards to different stakeholders while increasing the sustainability of the system.

Seeing this, Indonesia is still behind global best practices, which have established secondary markets for EV batteries and focus on sorting and grading used batteries before recycling. In this case, Indonesia needs to implement a second-life stage to maximise the economic value of EV batteries before recycling the used ones. However, one of the challenges is that scaling up to this new industry could be a long process and costly to implement. Collaboration and proper strategies are needed among stakeholders.

The current readiness level for technology adoption is 5, but for second-life battery applications, it is only 1, as no system is in place. The average IRL in the economic aspect is 5, indicating that while some progress has been made, significant advancements are still needed, particularly in the second-life battery market.

Table 5 IRL on economic aspect

<i>Topic</i>	<i>Current status</i>	<i>Current best practice</i>	<i>Readiness level</i>
Battery prices	Based on commodity price and operational costs (RP1; RP3)	Based on commodity price and operational costs	9
	The second-life EV battery price is not yet available (RP4)	Percentage of the current battery price	1
Incentives	Fiscal and non-fiscal incentives (RP1; RP2)	Incentives could be given to battery producers, car producers, end users, and EVB EOL facilities	9
	Incentives for car producers, battery producers, and EV users (RP1; RP2; RP3; RP4)		
Battery life cycle	UGM has successfully collected and purified lithium from used batteries	Established a secondary market for EV battery	5
	No evidence for EV battery second life	Sorting and grading the used EV battery for second-life application before recycling	1
<i>Average innovation readiness level in the economic aspect</i>			5

Source: Data analysis

4.3 *Readiness level in social aspect*

The supply of used batteries from EVs is needed to support the secondary market and raw materials for recycling facilities. So, EV users need to be increased so that the implementation of EOL management is optimal. There are some efforts from the Indonesian government to increase the number of EV users, such as incentives.

RP1 mentioned that the Indonesian government has introduced incentives to promote EV use, but these efforts remain insufficient. One of the causes of the ineffective use of EVs is the uneven distribution of information. RP3 mentioned that the information related to incentives and procedures for converting to EVs is still not optimal since many people do not emphasise the benefit of using EVs.

It is also supported by lower environmental awareness from Indonesian citizens. RP5 said that for developing countries like Indonesia, environmental awareness is not crucial to increasing EV demand. They prioritise functionality factors over environmental factors.

Related to public trust, certification for used batteries is necessary to ensure that only quality used batteries are marketed in the secondary market. However, there is no implementation of certification for used batteries in Indonesia, nor is there certification for new batteries, which is normal because the market for used batteries has not yet been formed. Then, the next challenge is for Indonesia to ensure that only certified products are distributed in the secondary market.

In comparison, European countries have a stronger base of EV users, driven not only by incentives but also by heightened environmental awareness and support for clean energy, with 29% of Norwegian EV buyers prioritising the environment (ARF, 2014).

In this case, Indonesia still needs to try to give environmental consciousness to increase EV demand. However, knowledge sharing regarding environmental issues is not completely effective. Informants RP2 and RP5 also added that environmental awareness could be more effective given to segmented and targeted people, such as those with high incomes or a certain range of educational backgrounds. So, it is necessary to carry out demographic segmentation before providing outreach and education to the public regarding the importance of using clean energy and sustainable lifestyles, especially for EV transition.

Table 6 IRL on social aspect

<i>Topic</i>	<i>Current status</i>	<i>Current best practice</i>	<i>Readiness level</i>
Public awareness	Incentives given to increase EV demand and energy transition	Advanced sustainable consciousness to society by utilising knowledge about net-zero emission	6
	Information is distributed unevenly (RP3; RP4)		3
	Environmental awareness is minimum (RP1; RP2; RP4)		3
Public trust	Certification is not yet established (RP3; RP4)	Certification for new and used EV Battery	3
<i>Average innovation readiness level in the social aspect</i>			<i>4</i>

Source: Data analysis

While Indonesia shows moderate public awareness of EVs (readiness level 6), inconsistent information distribution and low environmental awareness limit broader adoption, reflected in a readiness level of 3. There is no established certification procedure for new and used EV batteries. Nevertheless, the development process has commenced, and the readiness level is at level 3. The social aspect's average IRL is 4, which suggests a relatively low to moderate level of maturity in public awareness and trust towards EVs and battery technology. This implies that, despite some progress, substantial efforts are still necessary to improve the public's comprehension, awareness, and trust in these innovations.

5 Conclusions and policy implication

5.1 Conclusions

Indonesia is expected to form a sustainable EV battery ecosystem to strengthen its position as a major player in the EV battery industry. The current EV battery value chain should be transformed into a closed-loop chain to optimise battery value and reduce environmental impact. Hence, Indonesia should strengthen its EOL management for EV batteries.

This begins with extracting raw materials like lithium and cobalt, where sustainable practices are crucial to reducing environmental damage. These materials are then processed into battery cells during production. Once batteries power EVs, their lifespan can be extended through proper usage and maintenance. At the end of their first life, used batteries can be repurposed for secondary applications such as stationary ESS or remanufactured to be used for EVs again. Finally, recycling ensures valuable materials are recovered and reused, reducing the reliance on virgin resources and minimising waste. The decision to remanufacture, repurpose, and recycle depends on the battery SOH, which the industry conducts assessments during collection.

Based on the three main aspects, Indonesia's current readiness to implement EOL management for EV batteries is assessed at level 4 of the IRL. It highlights several areas requiring improvement. Regulatory frameworks, currently centred on general waste management regulations, need enhancement to address EV battery waste specifically. The absence of targeted incentives and promotional efforts aimed at attracting investment in EOL industries is evident, with existing initiatives primarily concentrated on upstream sectors. Strengthening regulatory frameworks and introducing specific incentives could accelerate the development of a robust EV battery ecosystem in Indonesia.

Economically, Indonesia's strategy predominantly focuses on recycling EV batteries at the end of their lifespan. However, there is considerable potential in exploring the second life of EV batteries, which could significantly enhance their economic value and prolong their usability. Establishing a secondary market for used batteries, where batteries unfit for EV use can be repurposed or remanufactured, would not only maximise economic benefits but also mitigate the environmental impact associated with EVs and battery manufacturing.

On the social front, Indonesia faces challenges in increasing EV adoption rates. Despite government incentives, EV uptake has fallen short of targets due to insufficient information dissemination and awareness among potential adopters. Targeted educational campaigns emphasising the environmental advantages of EVs, coupled with tailored incentives for specific demographic groups, could bolster public acceptance and accelerate the transition towards a sustainable transportation ecosystem.

It can be concluded that building an EOL management for EV batteries is very complex, and many stakeholders need to be involved. The government must work together to create appropriate regulations and policies related to the EV batteries ecosystem. This is a challenge in Indonesia because the existing regulations are currently separate and under the control of various ministries. Industry players must also contribute to this system as policy implementers and new market makers for new EV batteries and used EV batteries. Supporting industry players such as waste collectors can also contribute, as recommended by RP3. Finally, the third sector, such as research institutions and not-for-profit organisations, can support government activities ranging

from research aspects to knowledge sharing with the community in an effort to transition to new energy.

Addressing these regulatory, economic, and social dimensions is critical for advancing Indonesia's preparedness to manage EOL effectively and sustainably for EV batteries.

5.2 Limitations

Due to time constraints, this study only focuses on three main aspects of the EV battery ecosystem, namely regulatory, economic, and social, which refer to the general environment of businesses.

This research only covers five experts as resource persons in interviews, which are used as primary data. This may lead to biased results due to a lack of resource persons. Consequently, the study's findings may have been influenced by the researchers' limited knowledge and perspectives, as it did not have access to a sufficient number of experts or professionals in the field of EV battery management who could have provided valuable insights and information.

Moreover, the resource persons come from different institutions with different backgrounds and understanding of the EV battery ecosystem. This may result in inconsistent, conflicting data and broad information relating to the topics. The diverse perspectives of the result make it challenging to integrate the information and may lead to the researcher's level of knowledge to conclude. The researcher uses secondary data from peer-reviewed published articles and reputable online media to mitigate those limitations and strengthen the arguments.

5.3 Policy implication

This study underscores the need for Indonesia's government to refine regulations governing the EV battery ecosystem, particularly focusing on EOL management. Recommendations include adapting existing regulations, such as Ministry of Environment and Forestry Regulation No. 6 of 2021, to address specific aspects of EV battery waste handling and mineral refinement for recycling purposes. Collaborative efforts among key governmental stakeholders – such as the Ministries of Energy and Mineral Resources, Industries, Investment, and Environment – are crucial for effectively drafting and implementing these specialised regulations. Establishing a dedicated institution or unit overseeing the EV battery lifecycle could streamline regulatory efforts and ensure comprehensive management practices.

Meanwhile, businesses within Indonesia's EV battery sector are encouraged to strategise and adapt to capitalise on emerging opportunities in EOL management, including the secondary battery market, recycling facilities, and battery remanufacturing. Ensuring a balanced supply and demand in the secondary market requires accurate data collection and supervision, potentially through innovative models like battery-as-a-service (BaaS), while staying abreast of global EV trends and regulatory developments is essential to align with Indonesia's ambitions as a major player in the EV battery ecosystem and support international sustainability goals.

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