Volume 6 Issue 1 (March 2026)
DOI 10.24191/jaeds.v6i1.174
eISSN 2805-5756

Journal of Applied Engineering
Design & Simulation

Sustainability Readiness Assessment of Electric Vehicle Battery Recycling Industry in Indonesia: A Maturity Model Approach

Elisa Kristiani[1,*], Dendi Prajadhiana Ishak[2]
[1]Department of Industrial Engineering, Faculty of Engineering, University of Indonesia, Depok Indonesia.
[*]corresponding author: ekristiani11@yahoo.co.id

ABSTRACT

The rapid growth of electric vehicle (EV) adoption in Indonesia has raised concerns regarding end-of-life battery waste management. Although the government has established a roadmap targeting implementation by 2030, there is no structured instrument to assess the readiness of the EV battery recycling industry. This study proposes a maturity-based assessment instrument, namely the Sustainable EV Battery Recycling Maturity Model, to evaluate the readiness of the EV battery recycling industry in Indonesia. The model measures industry readiness through a set of defined indicators and maturity levels, adapted from existing maturity model concepts (e.g., CMM-based maturity levels) and contextualized to the Indonesian setting. The framework was developed through a systematic literature review and expert consultation, resulting in five dimensions: Technology, Governance, Economy, Social, and Environment, comprising a total of 15 sub-indicators. The indicators and sub-indicators were validated by three experts with relevant experience in the field using the Content Validity Index (CVI), while the weighting process was conducted using the Hesitant Fuzzy Analytic Hierarchy Process (HF-AHP). To demonstrate its practical applicability, the model was implemented in a hazardous waste management company to calculate a maturity index score. The results indicate that the current readiness level is at the "Defined" stage, with governance and regulatory alignment identified as key areas for improvement. Overall, this study provides a structured assessment framework to support the development of sustainable EV battery waste management systems, particularly in emerging economies.

Keywords: EV Battery Recycling; Maturity Model; Readiness Assessment; HF-AHP; Sustainability.

Abbreviations

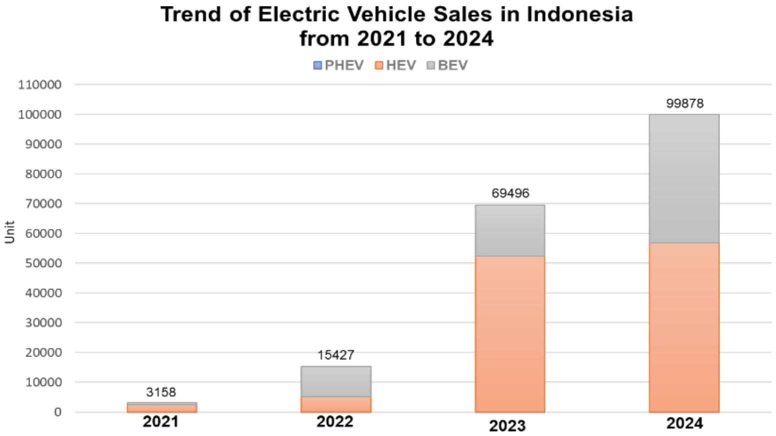
CVI	Content Validity Index
EoL	End-of-Life
EV	Electric Vehicle
HF-AHP	Hesitant Fuzzy Analytic Hierarchy Process

1.0 INTRODUCTION

Transportation is one of the most significant contributors to global greenhouse gas emissions, therefore the transition to electric cars is viewed as an important strategy for reducing emissions and reliance on fossil fuels [1]. In Indonesia, EV adoption has increased rapidly in recent years. Based on the GAIKINDO findings shown in Figure 1, the number of EV sales increased significantly from 3,158 in 2021 to 99,878 in 2024, showing a rapidly expanding market.

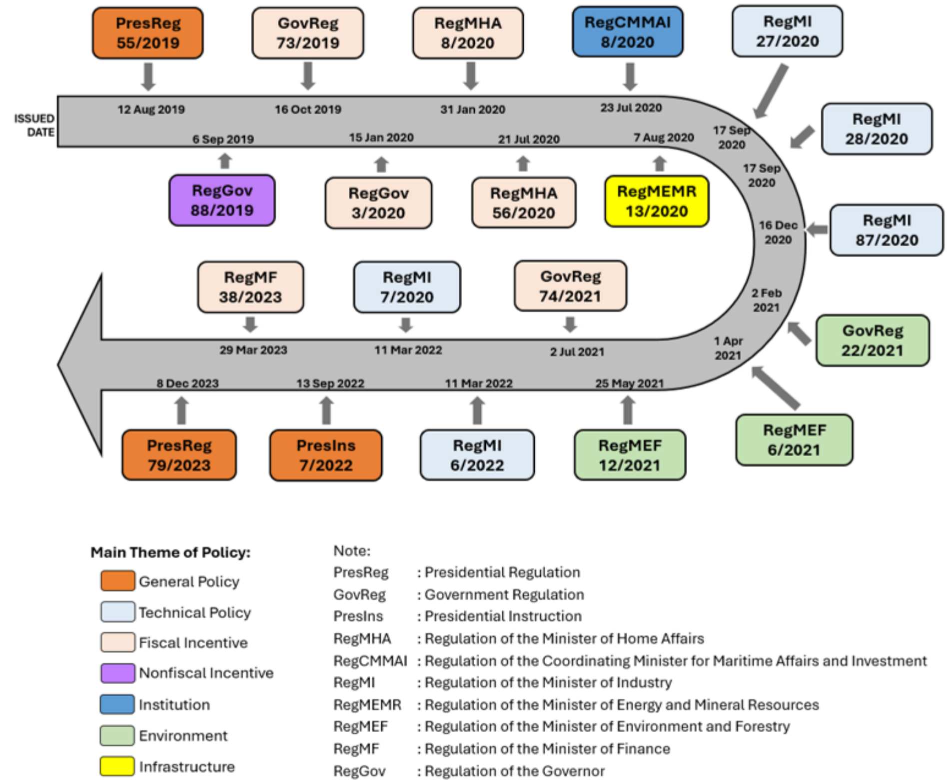
Indonesia already has several regulatory frameworks supporting EV adoption, including Presidential Regulation No. 55/2019, which aims to accelerate the development of the electric vehicle ecosystem. Since its issuance, multiple supporting regulations have been introduced; however, most of these policies primarily focus on promoting EV adoption rather than addressing end-of-life battery management. As illustrated in Figure 2, EV-related regulations in Indonesia span multiple domains and involve various government institutions. Despite the large number of policies, only a limited portion explicitly addresses environmental aspects and EV battery waste management. This indicates that regulatory attention remains concentrated on upstream development, with insufficient focus on downstream processes such as recycling. Although the regulation provides a general basis for battery waste handling and incentives for recycling activities, there are still no detailed implementing regulations specifically governing EV battery recycling. Existing environmental regulations, such as Government Regulation No. 22/2021 and Minister of Environment and Forestry Regulation No. 6/2021, classify EV batteries as hazardous (B3) waste, but they do not specifically address the unique characteristics, lifecycle management, and value recovery potential of EV batteries.

Received on 26.02.2026
Accepted on 28.04.2026
Published on 30.04.2026



	2021	2022	2023	2024
PHEV	35	10	70	74
HEV	2473	5100	52434	56684
BEV	685	10327	17062	43194
Total	3158	15427	69496	99878

Figure 1. EV Sales in Indonesia (2021–2024)
Source: Adapted from GAIKINDO (GIIAS 2025)



Note:
PresReg : Presidential Regulation
GovReg : Government Regulation
PresIns : Presidential Instruction
RegMHA : Regulation of the Minister of Home Affairs
RegCMMAI : Regulation of the Coordinating Minister for Maritime Affairs and Investment
RegMI : Regulation of the Minister of Industry
RegMEMR : Regulation of the Minister of Energy and Mineral Resources
RegMEF : Regulation of the Minister of Environment and Forestry
RegMF : Regulation of the Minister of Finance
RegGov : Regulation of the Governor

Figure 2. Mapping of Key Policy Themes Related to EVs in Indonesia
Source: Hadinata et al. (2025)

Following the regulatory perspective, it is also important to understand the technical and environmental characteristics of EV batteries and their end-of-life management. In the context of EV battery waste management, understanding the characteristics and end-of-life treatment options of EV batteries becomes essential. The major technology used in EVs is lithium-ion batteries, which include valuable but hazardous substances such as lithium, cobalt, and nickel [2]. If not properly managed, discarded EV batteries may pose significant environmental and health risks. Several end-of-life management strategies can be applied, including reuse (or repurposing), remanufacturing, and recycling [3]. Reuse involves refurbishing batteries through inspection, component replacement, and reassembly to enable second-life applications [4]. Remanufacturing focuses on restoring battery performance so that it can be reused in electric vehicles. Recycling, meanwhile, entails dismantling batteries to recover valuable metals such as cobalt and nickel, thereby reintegrating these materials into the production cycle and supporting a circular economy [5].

Global forecasts show a significant rise in EV battery waste by 2030, emphasizing the significance of organized recycling infrastructure and standard regulations [6]. China could be considered the best practice example of managing EV battery waste since the government has developed particular regulatory laws, such as the laws for Power Battery Industry Management, which are implemented in 2023. The regulations cover the whole recycling process, from collection to disposal, and are supported by national standards and traceability procedures [7]. However, such regulatory frameworks are inherently prescriptive and typically designed for systems that have already reached a high level of industrial and institutional readiness. In contrast, emerging ecosystems such as Indonesia require a different approach—one that focuses on assessing current conditions rather than prescribing end-state regulations. In this context, the proposed maturity model does not aim to replicate the China regulatory framework, but instead builds upon its underlying principles by translating them into measurable dimensions and indicators. This enables a systematic evaluation of readiness levels and supports the identification of gaps across different stages of development.

In comparison, Indonesia has not started EV battery waste management on the industrial level. Institutional coordination across technological, regulatory, economic, and social dimensions is still in its initial stages, and current recycling facilities are still in their early phases of development. The systematic assessment of the recycling industry's readiness has gotten very little attention, despite the fact that regulations have primarily focused on speeding up EV adoption.

Several previous studies have looked at EV battery waste management in Indonesia from different angles, ranging from the need for cross-sector collaboration and stronger regulations to support a sustainable recycling system [8], to technical discussions such as bioleaching and compliance with hazardous waste (B3) rules [9], as well as circular economy strategies using tools like SWOT and IFE–EFE analysis [10]. More recent studies have also highlighted behavioral, technological, and policy aspects: some model consumer behavior around end-of-life battery disposal uses structural equation modeling to show that public participation matters for making circular practices work [11]; others review Indonesia’s lithium battery development, including the use of local materials and different recycling methods assessed by recovery efficiency and environmental impact [12]; and some estimate future EV battery waste volumes while proposing policy directions to support a more sustainable EV ecosystem [13].

While these studies offer valuable insights from technological, behavioral, regulatory, and strategic perspectives, further research is needed to develop a structured framework for assessing industry readiness. Previous research has introduced maturity model approaches in the broader context of sustainable waste management systems in Indonesia, particularly in developing smart and circular waste management frameworks [14]. However, these existing models are generally designed for conventional municipal or industrial waste systems and do not specifically address the unique characteristics, technological risks, and governance complexities associated with EV battery recycling. More importantly, they have not been developed as integrated readiness assessment tools that simultaneously capture technological, governance, economic, environmental, and social dimensions within the Indonesian EV battery recycling context.

To address this gap, this study proposes a Sustainable EV Battery Recycling Maturity Model tailored to the Indonesian context. The proposed model provides a structured and multidimensional assessment framework to evaluate the current level of industry readiness across technological, governance, economic, social, and environmental dimensions.

The study contributes to the existing literature by applying a maturity model approach to the context of EV battery recycling, which remains relatively underexplored, particularly in developing countries such as Indonesia. In addition, the model offers practical value by serving as a reference for policymakers in formulating strategies to enhance industry maturity and accelerate the development of EV battery waste management systems. It also provides a useful tool for hazardous waste management industries to evaluate their current practices and identify areas for continuous improvement.

2.0 METHODOLOGY

This research adopts a quantitative decision modeling framework to develop a Sustainable EV Battery Recycling Maturity Model, encompassing steps from model conceptualization to practical application. The process is divided into four major phases: scope and design, expert validation, criteria weighting, and case study implementation.

2.1 Scope and design

The proposed maturity model follows a hierarchical structure consisting of three levels: main dimensions, sub-indicators, and maturity levels. The framework was developed through a systematic literature review and expert consultation to identify key indicators relevant to sustainable EV battery waste management.

Five main dimensions were established: technology, governance, economy, social, and environment. These dimensions were further operationalized into 15 measurable sub-indicators representing the industry's operational and strategic capabilities (see Table 1). The model adopts five maturity levels, ranging from Level 1 (None) to Level 5 (Integrated), adapted from the Capability Maturity Model (CMM). The complete definitions of the maturity levels are presented in Table 2.

The proposed framework, named as the Sustainable EV Battery Recycling Maturity Model, sets up as a basis for further weighing and validation procedures that involve evaluation by experts. A detailed description of each dimension and sub-indicator, including the operational definition of maturity levels (Level 1 – Level 5), is provided in the following section to ensure clarity and reproducibility of the assessment.

Table 1: Dimension and Sub-Indicators of the Proposed Maturity Model

Dimension	Sub-Indicator	Description
Technology (C1)	SC1.1	EV battery waste processing capability (e.g., mechanical pre-treatment, pyrometallurgy, hydrometallurgy)
	SC1.2	Automation and integration of waste management systems
	SC1.3	Safety technology and operational risk prevention
Governance (C2)	SC2.1	Regulatory framework and policy for EV battery waste management
	SC2.2	Operational audit and monitoring mechanisms
	SC2.3	Transparency and reporting to regulatory authorities
Economy (C3)	SC3.1	Availability of investment and financing for recycling facilities
	SC3.2	Financial feasibility and return on investment (ROI)
	SC3.3	Cross-sector partnerships and market collaboration
Social (C4)	SC4.1	Workforce capability and competency
	SC4.2	Occupational health and safety (OHS)
	SC4.3	Community awareness and stakeholder engagement
Environment (C5)	SC5.1	Environmental and public health impact
	SC5.2	Waste management value chain integration
	SC5.3	Resource efficiency and material recovery

Table 2: Maturity Levels of the Proposed Model

Maturity Level (Score)	Definition
Level 1 – None (1.00 – 1.80)	No structured processes or formal procedures are in place. Activities are inconsistent and performance remains very low.
Level 2 – Initial (1.81 – 2.60)	Basic efforts exist, but processes are ad hoc and not formally structured. Implementation is inconsistent and largely reactive.
Level 3 – Defined (2.61 – 3.40)	Processes and procedures are documented and more structured. Formal policies are established, but integration across the organization is not yet fully achieved.
Level 4 – Managed (3.41 – 4.20)	Processes are well planned, proactive, and aligned with best practices. Performance is monitored, and continuous improvement mechanisms are implemented.
Level 5 – Integrated (4.21 – 5.00)	Processes are standardized and fully integrated across the organization. Continuous monitoring, evaluation, and systematic improvement are embedded in operations.

2.1.1 Technology Dimension

The technology dimension evaluates an organization's technological capabilities in supporting electric vehicle (EV) battery waste management processes, including processing technologies, system automation and integration, and the implementation of operational safety technologies. Table 3 presents the maturity level descriptions for each technology sub-indicator.

2.1.2 Governance Dimension

The governance dimension focuses on organizational policies, regulatory compliance, and operational oversight mechanisms in EV battery waste management. The assessment covers the existence of formal policies, audit and monitoring practices, and transparency in reporting. Table 4 presents the maturity level descriptions for each governance sub-indicator.

2.1.3 Economy Dimension

The economic dimension evaluates the organization's financial readiness to support the development and operation of EV battery recycling facilities, including investment availability, financial feasibility, and the role of strategic partnerships in ensuring long-term economic sustainability. Table 5 presents the maturity level descriptions for each economic sub-indicator.

2.1.4 Social Dimension

The social dimension assesses human resources and occupational safety aspects involved in EV battery waste management, including workforce competence, the implementation of occupational health and safety (OHS) systems, and stakeholder engagement that support sustainable operations. Table 6 presents the maturity level descriptions for each social sub-indicator.

2.1.5 Environment Dimension

The environmental dimension evaluates the management of environmental impacts arising from EV battery waste processing activities, including impact control measures, waste management value chain integration, and resource efficiency and material recovery in alignment with circular economy principles. Table 7 presents the maturity level descriptions for each environmental sub-indicator.

Table 3: Maturity Level Descriptions for Technology Dimension

Sub-Indicator	Maturity Level				
	1 - None	2 - Initial	3 - Defined	4 - Managed	5 - Integrated
SC1.1 (EV Battery Processing Capability)	No dedicated technology; improper handling; no material recovery	Basic/manual processing; limited recovery	Standardized processes; documented SOPs	Performance monitored (recovery rate, energy, emissions); risk mitigation applied	Advanced, circular economy-based technology; optimized recovery and continuous innovation
SC1.2 (Automation and System Integration)	Fully manual; no integration	Partial automation; no system integration	Automated with internal integration (collection-processing-storage)	Integrated system with real-time monitoring and quality control	End-to-End digital integration
SC1.3 (Safety and Risk Prevention Technology)	No dedicated safety systems	Basic protection tools, inconsistent implementation	Standardized and documented safety systems	Real-time risk monitoring; preventive maintenance	Advanced safety systems and strong safety culture

Table 4: Maturity Level Descriptions for Governance Dimension

Sub-Indicator	Maturity Level				
	1 - None	2 - Initial	3 - Defined	4 - Managed	5 - Integrated
SC2.1 (Regulatory and Policy Framework)	No EV battery-specific policy	Refers to general hazardous waste regulation	Defined and documented EV battery policy	Monitored and regularly evaluated implementation	Adaptive policies aligned with international standards
SC2.2 (Audit and Operational Control)	No formal audit	Irregular audits; weak follow-up	Scheduled audits with documented corrective actions	KPI-based monitoring and data-driven control	Fully integrated into management system for continuous improvement
(SC2.3) Transparency and Reporting	No reporting	Manual, limited, irregular reporting	Regular reporting, documented but underutilized	Systematic, validated, and used for internal evaluation	Digitally integrated reporting with regulators

Table 5: Maturity Level Descriptions for Economy Dimension

Sub-Indicator	Maturity Level				
	1 - None	2 - Initial	3 - Defined	4 - Managed	5 - Integrated
SC3.1 (Investment and Financing Availability)	No dedicated investment	Limited and short-term funding	Formal financial planning and budget allocation	Sustainable and diversified funding sources	Integrated long-term financing strategy
SC3.2 (Financial Feasibility and ROI)	No financial analysis	Basic, non-standard analysis	Formal feasibility and ROI analysis	Periodic financial monitoring and optimization	Integrated with circular economy strategy
SC3.3 (Multi-Sector Partnerships)	No partnerships	Informal/ limited collaboration	Formal partnership with defined roles	Active and coordinated collaboration	Integrated ecosystem partnerships driving innovation

Table 6: Maturity Level Descriptions for Social Dimension

Sub-Indicator	Maturity Level				
	1 - None	2 - Initial	3 - Defined	4 - Managed	5 - Integrated
SC4.1 (Workforce Capability and Competence)	No specific skills	Limited, unstandardized training	Standardized training and certification	Structured competency development programs	National/ international certification and continuous upskilling
SC4.2 (Occupational Health and Safety)	No OHS implementation	Basic rules, inconsistent application	Documented procedures and routine training	Integrated OHS system with audits	Strong safety culture and proactive prevention
SC4.3 (Public Awareness and Engagement)	No engagement	Limited, one-way communication	Regular education programs	Community involvement in environmental programs	Active collaboration with measurable social impact

Table 7: Maturity Level Descriptions for Environment Dimension

Sub-Indicator	Maturity Level				
	1 - None	2 - Initial	3 - Defined	4 - Managed	5 - Integrated
(SC5.1) Environmental and Health Impact Management	No impact management	Limited control measures	Compliance-based management and monitoring	Integrated environmental control system	Preventive and innovative impact minimization
(SC5.2) Waste Management Value Chain	Unstructured value chain	Partially managed but fragmented	Documented and connected processes	Coordinated and monitored value chain	Fully integrated circular value chain
(SC5.3) Resource Efficiency and Material Recovery	No recovery; low efficiency	Limited; unmeasured efforts	Defined and monitored targets	Optimized recovery processes	Maximum recovery through innovation and continuous improvement

2.2 Expert Validation

In the expert validation phase, the beginning step is finding experts to validate the maturity model draft before it is implemented. Experts must have a bachelor's degree and at least five years of experience in the field. To do the validation, the Content Validity Index (CVI) method is used.

This study involved three experts with backgrounds in waste management, the automotive industry, and sustainability consulting. Although the number of experts is limited, their selection was based on the relevance and depth of expertise, which is considered appropriate for content validation using CVI, particularly in specialized domains such as EV battery waste management.

The content validity assessment employed a four-point relevance rating scale, in which experts were asked to evaluate each sub-indicator based on its relevance to the measured construct. The scale ranged from 1 to 4, where 1 = not relevant, 2 = moderately relevant, 3 = highly relevant, and 4 = extremely relevant. The use of a four-point scale eliminates the neutral midpoint, thereby encouraging more decisive judgments and reducing central tendency bias, which can improve the precision of expert evaluations [15].

For the purpose of Content Validity Index (CVI) calculation, ratings of 1 and 2 were recoded as 0 (not relevant), while ratings of 3 and 4 were recoded as 1 (relevant), following the approach proposed by Davis [16]. The Item-Level Content Validity Index (I-CVI) was calculated as shown in Equation (1).

$$I - CVI = \frac{N_c}{n} \qquad (1)$$

where Nc represents the number of expert agreeing on each item (value 3 and 4) and n is the total number of experts.

According to established guidelines, when the number of experts ranges from three to five, an I-CVI value of 1.00 is required to confirm acceptable content validity, indicating full agreement among experts [17]. As presented in Table 8, all sub-indicators yielded an I-CVI of 1.00, indicating complete expert agreement on item relevance and supporting the content validity of the measurement instrument.

Table 8: The Relevance Ratings on Item Scale by Three Experts

Item	Expert 1	Expert 2	Expert 3	Expert in Agreement	I-CVI	UA
Q1	1	1	1	3	1	1
Q2	1	1	1	3	1	1
Q3	1	1	1	3	1	1
Q4	1	1	1	3	1	1
Q5	1	1	1	3	1	1
Q6	1	1	1	3	1	1
Q7	1	1	1	3	1	1
Q8	1	1	1	3	1	1
Q9	1	1	1	3	1	1
Q10	1	1	1	3	1	1
Q11	1	1	1	3	1	1
Q12	1	1	1	3	1	1
Q13	1	1	1	3	1	1
Q14	1	1	1	3	1	1
Q15	1	1	1	3	1	1
				S-CVI/Ave	1	
Proportion relevance	1	1	1	S-CVI/UA		1
Average proportion of items judged as relevance across 3 experts				1		

2.3 Criteria Weighting and Prioritization

The weighting process was conducted to determine the relative importance of each dimension and sub-indicator in calculating the maturity index score. Assigning weights enables a more accurate and representative assessment of industry readiness by reflecting the varying significance of each evaluation criterion.

To address uncertainty and subjectivity in expert judgments, the Hesitant Fuzzy Analytic Hierarchy Process (HF-AHP) was employed. HF-AHP is an extension of the Fuzzy AHP method, designed to handle hesitation and ambiguity in multi-criteria decision making [18]. This approach allows experts to express their preferences using hesitant fuzzy linguistic terms, thereby improving the robustness of the weighting results. In this study, all HF-AHP calculations were carried out using Microsoft Excel, including the construction of pairwise comparison matrices, aggregation of expert judgments, and weight derivation.

The HF-AHP procedure in this study consisted of the following main steps: (1) constructing the pairwise comparison matrix based on expert evaluations, (2) converting linguistic assessments into hesitant fuzzy numbers, (3) aggregating expert judgments, (4) checking the consistency of the aggregated pairwise comparison matrix using the consistency ratio (CR), (5) calculating local weights for each dimension and sub-indicator, and (6) deriving global weights within the hierarchical structure. For reproducibility, the number of pairwise comparisons is $n(n-1)/2$ for a matrix with n criteria; therefore, the dimension-level matrix ($n = 5$) required 10 comparisons, and each sub-indicator matrix ($n = 3$) required 3 comparisons (25 comparisons per expert in total).

In the first stage of the HF-AHP procedure, experts conducted pairwise comparisons of criteria and sub-criteria using a predefined linguistic scale. The assessments were based on an eleven-point hesitant fuzzy scale adapted from previous HF-AHP studies [19]. To capture uncertainty and hesitation in expert judgments, experts were allowed to select a range (interval) of linguistic terms rather than a single value. These linguistic evaluations were subsequently transformed into hesitant fuzzy numbers and aggregated to construct collective pairwise comparison matrices at both the dimension and sub-indicator levels. For clarity, only the aggregated pairwise comparison matrix at the dimension level is presented in Table 9, while the same procedure was applied to the sub-indicators.

Table 9: Aggregated Fuzzy Envelopes for Main Criteria

	C1	C2	C3	C4	C5
C1	EE	EHI	Between EHI and WHI	Between WLI and ELI	WHI
C2		EE	EHI; VHI; WHI	Between EHI and WHI	ESHI
C3			EE	WLI	Between ESLI and WLI
C4				EE	Between VLI and ESLI
C5					EE

To ensure the reliability of the comparisons, a consistency check was performed. The consistency ratio (CR) was calculated for both the main dimensions and the sub-indicators. The CR value for the dimension-level matrix was 0.0797, while the CR values for the sub-indicator matrices are presented in Table 10. Since all CR values are below the acceptable threshold of 0.1, the pairwise comparison matrices are considered consistent, indicating that the expert judgments are reliable and suitable for further analysis.

Based on the validated consistency results, local weights for each dimension and sub-indicator were calculated, followed by the derivation of global weights within the hierarchical structure. The global weights were obtained by multiplying the local dimension weight by the corresponding sub-indicator weight. The results are presented in Table 11.

Table 10: Summary of Consistency Ratio Analysis for Sub-Indicator Matrices

No	Dimension	Tested Matrix	λ_{max}	CI	RI	CR	Criteria (CR ≤ 0.1)
1	Technology	C1 Sub-indicator matrix	3.011	0.006	0.58	0.010	Acceptable
2	Governance	C2 Sub-indicator matrix	3.050	0.026	0.58	0.044	Acceptable
3	Economy	C3 Sub-indicator matrix	3.024	0.012	0.58	0.020	Acceptable
4	Social	C4 Sub-indicator matrix	3.001	0.0009	0.58	0.002	Acceptable
5	Environment	C5 Sub-indicator matrix	3.031	0.015	0.58	0.027	Acceptable

Table 11: Local and Global Weights of Dimensions and Sub-Indicators

Dimension	$w_{dimension}$	**Sub-Indicators**	$w_{sub-indikator}$	w_{global}
Technology (C1)	0.178	SC1.1	0.874	0.1556
		SC1.2	0.010	0.0018
		SC1.3	0.116	0.0206
Governance (C2)	0.670	SC2.1	0.962	0.6445
		SC2.2	0.034	0.0228
		SC2.3	0.004	0.0027
Economy (C3)	0.013	SC3.1	0.770	0.0100
		SC3.2	0.015	0.0002
		SC3.3	0.215	0.0028
Social (C4)	0.051	SC4.1	0.679	0.0346
		SC4.2	0.318	0.0162
		SC4.3	0.004	0.0002
Environment (C5)	0.087	SC5.1	0.067	0.0058
		SC5.2	0.828	0.0720
		SC5.3	0.105	0.0091

2.4 Case Study Implementation

The validated and weighted model was applied to a selected hazardous waste management company in Indonesia as a pilot implementation to evaluate its applicability in a real-world context. Due to time limitations, this study was conducted using a single case study of a company engaged in hazardous (B3) waste management.

Nevertheless, the proposed maturity model is designed to be adaptable across different types of facilities within the EV battery waste management ecosystem, such as small-scale collection centers, intermediate processing facilities, and large-scale recycling plants. This adaptability can be achieved by adjusting the scope of assessment and revising indicator weights through context-specific expert judgment, allowing the model to reflect the relative importance of each indicator based on the operational characteristics of the facility being assessed.

To apply the model to the selected case study, a questionnaire was developed based on the defined sub-indicators. Company representatives assessed the organization's current condition using predetermined maturity levels ranging from Level 1 (None) to Level 5 (Integrated). The global weight of each sub-indicator was multiplied by the corresponding maturity level score, and the aggregated weighted scores were used to calculate the overall maturity index. This final index reflects the company's readiness level in managing EV battery waste.

3.0 RESULTS AND DISCUSSION

This section shows the implementation results of the proposed Sustainable EV Battery Recycling Maturity Model in a hazardous waste management company located in Batam, Indonesia. The company was established in 2021 and currently operates in the management of B3 (hazardous and toxic) waste, providing a relevant context for assessing readiness toward future EV battery waste handling.

The assessment yielded a total maturity index score of 2.77. Based on the predefined maturity level criteria, this score falls within Level 3 – Defined (2.61–3.40). This indicates that key enabling processes relevant to EV battery waste management have been formally established and partially documented, leveraging the company's existing B3 waste management practices. However, the score is positioned near the lower bound of Level Defined (0.16 points above 2.61) and remains 0.64 points below the entry threshold of Level 4 – Managed (starting at 3.41). This gap reflects the need for strengthening process standardization, improving monitoring and performance evaluation systems, and enhancing cross-functional coordination. Therefore, targeted improvement strategies and action plans are required to support the transition toward a more controlled and systematically managed level of maturity.

3.1 Maturity Level by Dimension

The overall maturity index score is the result of the maturity levels across the five dimensions. The levels of maturity are represented by a visual graph called a radar chart, which was made to simplify understanding (see Figure 3).

Environment aspects scored the highest at 4.07, indicating a high level of resource recovery and environmental compliance, as seen in Figure 3. This relatively high score is plausibly driven by the company's existing B3 operations, where environmental compliance and risk mitigation are tightly linked to licensing requirements, audits, and operational continuity. In practice, this maturity is reflected in the presence of established environmental procedures (e.g., waste segregation and storage protocols, spill prevention/response arrangements, and documentation practices) and the ability to demonstrate compliance-related evidence during internal or external checks.

On the other hand, economy dimension scored the lowest at 1.69, while governance came in second with 2.11. This pattern points to substantial gaps in investment readiness, financial sustainability, and institutional arrangements needed to support EV battery recycling at scale. Governance and economic maturity, however, depend more on organization-wide coordination (e.g., clear process ownership, decision rights, accountability mechanisms) and market certainty (e.g., stable feedstock, contracts, and predictable revenue streams), which remain limited because EV battery waste handling is not yet routinely implemented. The low maturity score in the economic dimension is largely attributable to the high cost structure of EV battery recycling, encompassing both capital expenditure (CAPEX) and operational expenditure (OPEX). Techno-economic studies show that establishing a recycling facility requires substantial upfront investment, often reaching hundreds of millions of USD depending on scale and technology; for example, a recycling plant developed through a joint venture between Neometals and Primobius was estimated to require approximately USD 165 million in capital investment [20]. In addition to high CAPEX, operational costs related to labor, maintenance, and processing remain considerable, with lithium-ion battery processing costs reported to reach around USD 1,560 per ton [21]. Industry evidence from companies such as Li-Cycle further indicates that OPEX may initially exceed or constitute a large proportion of revenues, highlighting the economic challenges faced during early stages of industry development.

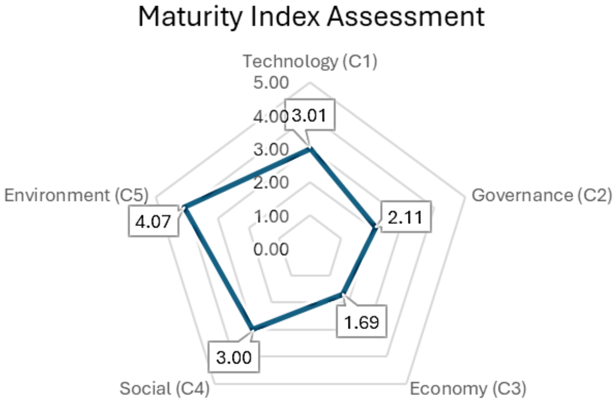


Figure 3. Radar Chart of Maturity Assessment Results

Furthermore, the market for recycled battery materials remains underdeveloped, with demand and price stability still uncertain, which reduces the economic feasibility of recycling operations. In the Indonesian context, these challenges are intensified by limited operational scale, underdeveloped recycling infrastructure, and the absence of targeted financial incentives or subsidy schemes specifically supporting EV battery recycling. As a result, large-scale recycling operations demand long-term financial planning and well-established investment frameworks, both of which remain difficult to implement under the existing level of economic readiness.

The technology dimension achieved a score of 3.01, corresponding to Level 3 – Defined, indicating that relevant technological capabilities and supporting procedures have been formally established. This level of maturity suggests that the company has developed a baseline operational capacity—likely leveraging existing hazardous waste management infrastructure and technical expertise. However, the technological system has not yet been fully optimized or scaled to address the specific requirements of EV battery waste management.

Similarly, the social dimension recorded a score of 3.00, also corresponding to Level 3 – Defined. This indicates that foundational elements related to workforce readiness and stakeholder engagement have been established, although they are not yet consistently implemented across the organization. The result reflects the presence of initial practices such as personnel training, safety and environmental awareness programs, internal communication mechanisms, and early-stage stakeholder engagement relevant to hazardous waste operations.

Overall, the variation in maturity scores across dimensions highlights an imbalance in the company's readiness profile. While environmental practices appear to be well-established due to regulatory compliance requirements, economic and governance dimensions remain underdeveloped, reflecting structural and market-related constraints in the early stage of EV battery waste management development. Meanwhile, the technology and social dimensions demonstrate moderate readiness, indicating that foundational capabilities have been established but require further integration and systematic implementation.

This uneven maturity distribution indicates that future improvement efforts should primarily focus on strengthening the governance and economic dimensions, as these represent the most critical gaps in the current readiness profile. In particular, enhancing governance requires clearer institutional arrangements, defined roles and responsibilities, and improved coordination mechanisms, while improving economic viability involves addressing investment readiness, cost structures, and market development for recycled materials. These priorities can be operationalized through targeted action plans derived from the priority matrix, which identify key sub-indicators requiring immediate intervention. By systematically addressing these areas, the organization can support a more balanced and sustainable progression toward higher maturity levels in EV battery waste management.

3.2 Priority Improvement Analysis

To determine critical areas for improvement, a priority score was calculated by comparing the gap between the expected maturity level (Level 5) and the existing level of each sub-indicator, based on its global weights. The calculation is defined in Equation (2):

$$Need\ to\ Improve = (5 - S_i)\ x\ W_{global,i} \quad (2)$$

Where Si represents the current maturity score and W_{global}, i refers to the global weight of sub-indicator i.

The results are presented in Table 12. The new "Need to Improve" section is based on the weighted performance gap and provides the basis for determining priority in the improvement matrix.

To facilitate strategic consideration, the sub-indicators were further classified into a priority matrix based on their importance and maturity score, as shown in Figure 4. The priority matrix classifies areas for improvement into four categories: (1) primary priority, (2) minor improvement, (3) strengthening, and (4) monitoring.

The results show that the sub-indicators of economy and governance dimensions, represented by SC2.1 (regulatory framework and policy alignment) and SC3.1 (availability of investment and financing), have the highest priority rankings. The sub-indicators low maturity scores and high importance weight suggest key issues with financial and regulatory integration.

Furthermore, SC 1.1 (the ability for handling waste from EV batteries) should receive the significant attention. The primary function that is related to technology processing abilities is highlighted by this sub-indicator.

On the other hand, the "strengthen" or "monitor" section has a few sub-indicators of the Environment and Social dimension that perform rather well and consistently. This finding aligns with the radar chart analysis that showed the highest maturity score for the environmental readiness dimension.

Based on the findings given above, future reform actions should prioritize the enhancement of governance frameworks, financial viability procedures, and long-term investment planning. Improvements in the critical areas can help improve the overall maturity level of EV battery recycling management.

Table 12. Maturity Assessment Results and Weighted Priority Analysis

Dimension	**Maturity Index Score**	**Sub-Indicators**	**Assessment Score**	**Global Weight**	**Need to Improve**
Technology (C1)	3.01	SC1.1	3	0.1556	0.6224
		SC1.2	4	0.0018	0.0018
		SC1.3	3	0.0206	0.0412
Governance (C2)	2.11	SC2.1	2	0.6445	1.9335
		SC2.2	5	0.0228	0
		SC2.3	4	0.0027	0.0027
Economy (C3)	1.69	SC3.1	1	0.0100	0.04
		SC3.2	4	0.0002	0.0002
		SC3.3	4	0.0028	0.0028
Social (C4)	3.00	SC4.1	3	0.0346	0.0692
		SC4.2	3	0.0162	0.0324
		SC4.3	2	0.0002	0.0006
Environment (C5)	4.07	SC5.1	5	0.0058	0
		SC5.2	4	0.0720	0.072
		SC5.3	4	0.0091	0.0091

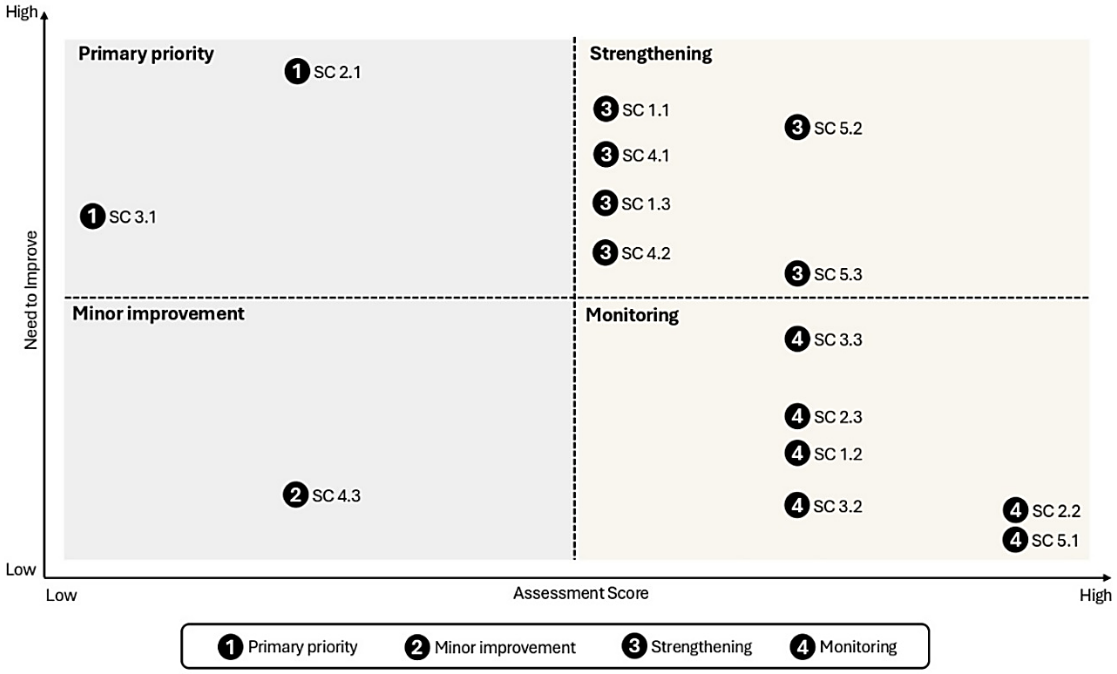


Figure 4. Priority Matrix

4.0 CONCLUSION

This study developed a Sustainable EV Battery Recycling Maturity Model to evaluate the readiness of Indonesia's EV battery recycling sector. The framework has five main dimensions: technology, governance, economy, social, and environment. This dimension and sub-indicator were validated by experts and weighted using the Hesitant Fuzzy Analytic Hierarchy Process (HF-AHP).

The case study implementation provided a total maturity index score of 2.77 (defined level), suggesting that organized processes exist but have not been completely integrated. Although the environment aspect had the highest maturity level, governance and economy aspects were identified as high priority areas for improvement. The priority analysis results show that system readiness can potentially be enhanced by handling concerns such as regulatory compliance, economic viability, and technological capability.

This research contributes methodologically and practically by developing a multidimensional maturity assessment tool tailored to the EV battery waste management industry. Practically, the tool can support the government in formulating strategies to strengthen and accelerate Indonesia's EV battery waste management system.

The model was demonstrated through a case study in a hazardous waste company. However, this study did not conduct a formal post-application evaluation of the tool (e.g., assessing the relevance and distinctiveness of indicators, the clarity of maturity-level descriptions, and ease of understanding/use through a Likert-scale evaluation questionnaire). Therefore, further refinement may be needed based on practitioner feedback. In addition, the model was tested in only one company; future studies should apply and evaluate the model across multiple companies to increase generalizability and provide more targeted improvement recommendations.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the experts who participated in the validation and weighting process of this study. The authors also thank the hazardous waste management company in Batam for providing access and data for the case study implementation. Special appreciation is extended to academic supervisor for their valuable guidance and constructive feedback throughout this research.

AUTHORS CONTRIBUTION

Conceptualization and methodology development were carried out by Elisa Kristiani. Data collection, analysis, and manuscript drafting were conducted by Elisa Kristiani. Supervision, validation, and manuscript review were provided by Ir. Dendi P. Ishak, MSIE., Ph.D. All authors have read and approved the final manuscript.

DECLARATION OF COMPETING OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] A. Awan, M. Alnour, A. Jahanger, and J. C. Onwe, “Do technological innovation and urbanization mitigate carbon dioxide emissions from the transport sector?”, Technology in Society, vol. 71, Nov. 2022, Art. no. 102128, doi: 10.1016/j.techsoc.2022.102128.

[2] Y. Yao, M. Zhu, Z. Zhao, B. Tong, Y. Fan, and Z. Hua, “Hydrometallurgical processes for recycling spent lithium-ion batteries: A critical review”, ACS Sustainable Chemistry & Engineering, vol. 6, no. 11, pp. 13611–13627, 2018, doi: 10.1021/acssuschemeng.8b03545.

[3] M. Graner, F. Heieck, A. Fill, P. Birke, W. Hammami, and K. Litty, “Requirements for a process to remanufacture EV battery packs down to cell level and necessary design modifications”, in Lecture Notes in Mechanical Engineering, Springer, 2023, doi: 10.1007/978-3-031-27933-1_35.

[4] M. Hamed, H. Turan, and S. Elsawah, “Balancing supply diversification and environmental impacts: A system dynamics approach to de-risk rare earths supply chain”, Resources Policy, 2024.

[5] A. Neri, M. A. Butturi, and R. Gamberini, “Sustainable management of electric vehicle battery remanufacturing: A systematic literature review and future directions”, Journal of Manufacturing Systems, vol. 77, pp. 859–874, 2024, doi: 10.1016/j.jmsy.2024.10.006.

[6] E. Woollacott, “Electric cars: What will happen to all the dead batteries?”, BBC News, Apr. 27, 2021. [Online]. Available: https://www.bbc.com

[7] A. Ali, M. A. Bahrani, S. Ahmed, M. T. Islam, S. A. Qadir, and M. Shahid, “Sustainable recycling of end-of-life electric vehicle batteries: EV battery recycling frameworks in China and the USA”, Recycling, vol. 10, no. 2, p. 68, 2025, doi: 10.3390/recycling10020068.

[8] M. M. Nauri, M. S. Aziz, M. Y. Pratama, U. Kamal, and M. A. Fikri, “Strategi penanganan limbah baterai kendaraan listrik demi masa depan Indonesia yang lebih bersih”, Kultura: Jurnal Ilmu Hukum, Sosial, dan Humaniora, pp. 177–194, 2024.

[9] L. P. R. M. Putri, A. Pradana, A. Rachmaddi, and R. R. O. Susue, “Analisis penanganan limbah baterai mobil listrik untuk mendukung pengembangan kendaraan listrik di Indonesia”, Prosiding Forum Studi Transportasi antar Perguruan Tinggi, vol. 10, no. 1, pp. 379–385, 2023.

[10] M. Habiburrahman, A. T. Setyoko, R. Nurcahyo, H. Daulay, and K. Natsuda, “Circular economy strategy for waste management companies of electric vehicle batteries in Indonesia”, International Journal of Productivity and Performance Management, vol. 74, no. 11, pp. 21–45, 2025, doi: 10.1108/IJPPM-01-2024-0015.

[11] F. N. Cahyo and R. Ardi, “End-of-Life Battery Disposal Behavior Electric Vehicles in Indonesian Using Structural Equation Model Approach”, Asian Journal of Engineering, Social and Health, vol. 5, no. 3, Mar. 2026, doi: 10.46799/ajesh.v5i3.758. [Online]. Available: https://ajesh.ph/index.php/gp/article/view/758

[12] C. Latif, M. F. I. Yogianto, I. Hafidz, and A. F. Adziimaa, “Sustainable Lithium Battery Development in Indonesia: The Role of Natural Materials and Recycling Processes in Future Challenges”, Journal of Energy, Material, and Instrumentation Technology, vol. 6, no. 3, pp. 154–165, Aug. 2025, doi: 10.23960/jemit.347. [Online]. Available: https://jemit.fmipa.unila.ac.id/index.php/jurnal/article/view/347

[13] J. Hadinata, A. Sodri, and R. H. S. Koestoer, “Electric Car Battery Waste in Indonesia: Projections and Management Policies”, Aceh International Journal of Science and Technology, vol. 14, no. 1, pp. 1–12, Apr. 2025, doi: 10.13170/aijst.14.1.43071. [Online]. Available: https://jurnal.usk.ac.id/AIJST/article/download/43071/23871

[14] Y. A. Fatimah, K. Govindan, R. Murniningsih, and A. Setiawan, “Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia”, Journal of Cleaner Production, vol. 269, Art. no. 122263, 2020, doi: 10.1016/j.jclepro.2020.122263.

[15] V. Zamanzadeh, A. Ghahramanian, M. Rassouli, A. Abbaszadeh, H. Alavi-Majd, and A. R. Nikanfar, “Design and implementation content validity study: Development of an instrument for measuring patient-centered communication”, Journal of Caring Sciences, vol. 4, no. 2, pp. 165–178, 2015.

[16] L. L. Davis, “Instrument review: Getting the most from a panel of experts”, Applied Nursing Research, vol. 5, no. 4, pp. 194–197, 1992, doi: 10.1016/S0897-1897(05)80008-4.

[17] D. F. Polit, C. T. Beck, and S. V. Owen, “Is the CVI an acceptable indicator of content validity? Appraisal and recommendations”, Research in Nursing & Health, vol. 30, no. 4, pp. 459–467, 2007, doi: 10.1002/nur.20199

[18] D. Yildiz, G. T. Temur, A. Beskese, and T. Bozbura, “Evaluation of positive employee experience using hesitant fuzzy analytic hierarchy process”, Journal of Intelligent & Fuzzy Systems, vol. 36, no. 5, pp. 4921–4937, 2019, doi: 10.3233/JIFS-179467

[19] D. Yildiz, G. T. Temur, A. Beşkese, and F. T. Bozbura, "Evaluation of positive employee experience using hesitant fuzzy analytic hierarchy process", Journal of Intelligent & Fuzzy Systems, vol. 38, pp. 1043–1058, 2019

[20] Argonne National Laboratory, “EverBatt: A closed-loop battery recycling”, Apr. 2019. [Online]. Available: https://publications.anl.gov/anlpubs/2019/07/153050.pdf. [Accessed: Aug. 13, 2021].

[21] Fractal Energy Storage Consultants, “Lithium-ion and lead acid battery recycling report”, Austin, TX, USA, 2020.