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Research Article

Evaluation of reverse supply chain strategies for end-of-life EV batteries in Vietnam using AHP–TOPSIS

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Abstract. The booming development of electric vehicle (EV) adoption in Vietnam has worsened the problem of end-of-life EV battery management in a sustainable and economically feasible way. Reverse supply chain management (RSCM) plays a critical role in reducing environmental risks, resource dependency, and circular economy goals. However, the choice of suitable reverse supply chain strategies is impaired by several economic, environmental, technical, and policy-related barriers. This study proposes an integrated AHP-TOPSIS framework for the evaluation and prioritization of reverse supply chain alternatives for EV batteries in the Vietnamese context. Ten key barriers were identified, from an extensive literature review and expert consultation by twelve domain specialists. High collection and transportation costs (weight = 0.244) and high recycling and processing expenses (weight = 0.162) were shown to be the most significant barriers when AHP was applied to determine their relative importance. The four options—Direct Recycling, Second-Life Applications, Centralized Recycling, and Decentralized/Hybrid Recycling—were then ranked using TOPSIS. According to the findings, Decentralized/Hybrid Recycling had the highest closeness coefficient, followed by Second-Life Applications, while Direct Recycling had the lowest. The results show how adaptable and localized reverse supply chain topologies can help solve the issue of cost-related barriers. In order to promote sustainable EV battery management in Vietnam, the suggested framework provides policymakers and industry stakeholders with useful insights.

Keywords: TOPSIS; MCDM; Battery Vehicle; Reverse Supply Chain Management



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1. Introduction

The rapid global transition to electric mobility has resulted in electric vehicles (EVs) becoming a backbone of low-carbon transportation policies, particularly in emerging economies in their struggle to balance economic development and sustainability (Ninh, 2021). At the centre of the EV ecosystem are lithium-ion batteries that account for a huge proportion of the cost, resource intensity and environmental footprint of vehicles (Ngoc & Nishiuchi, 2024). While in the society the deployment of EVs is being used for emission reduction from tailpipes, the sustainability of this transition is more recently being reviewed from a life-cycle perspective, and in particular in relation to end-of-life management of EV batteries (Christensen et al., 2021). Reverse supply chain management (RSCM) including collection, transportation, inspection, reuse, remanufacturing, recycling and safe disposal, therefore emerged as an important enabler of circular economy principles in the EV sector (Karunakaran et al., 2023).

Vietnam is a particularly good case study for investigating EV battery reverse supply chains. As one of the fastest-growing economies in Southeast Asia, there has been a rapid growth of EV adoption in Vietnam, which is helped by urbanization, rising income levels, and government policies to boost the adoption of clean transportation. Domestic manufacturers and international players are investing a lot in the production of EVs and supporting infrastructure, which is expected to result in a large stock of EV spent batteries in the future (Alipanah et al., 2021; Hermsen et al., 2025). However, Vietnam's institutional, regulatory and logistical frameworks for end-of-life EV battery management are still in the early stages of development. Limited recycling infrastructure, fragmentation of the collection systems, technological limitations and unclear policy responsibilities have led to major challenges in setting up efficient and sustainable reverse supply chains (Chu et al., 2025; Xie et al., 2020). These challenges point to the need for structured decision support tools that could help policymakers and industry stakeholders prioritize appropriate reverse supply chain strategies from multiple and often conflicting criteria (Garrido-Hidalgo et al., 2020; Gonzales-Calienes et al., 2022).

In this context, multi-criteria decision-making (MCDM) techniques have taken the limelight as effective techniques for tackling the complex multi-dimensional character of reverse supply chain decisions. Methods such as the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are especially suitable for assessing alternatives containing economic, environmental, technical, and social criteria (Alghassab, 2022). AHP allows for the structured breaking down of complex problems and the identification of relative importance weights using expert judgment, and TOPSIS allows for ranking of alternatives against a list of ideal and negative ideal solutions with a relative closeness measure (Aishwarya et al., 2025; Tahir et al.,

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2024). The AHP-TOPSIS integration has been largely used for sustainable supply chain management, waste management, and energy systems because of its conceptual clarity, computational ease, and practical relevance (Lu et al., 2025; Zhang et al., 2024).

Existing literature on reverse supply chain management of EV batteries has focused mostly on developed economies such as China, the European Union, and the United States, where regulatory frameworks and recycling technologies are relatively mature. Several studies have assessed recycling technologies, the environmental effects using life cycle assessment, or optimised logistics networks using mathematical programming (Oliveira Silva et al., 2024; Sharmili et al., 2023; Shukla et al., 2024). Other works have used MCDM methods to rank recycling strategies, collection models, or policy options for battery waste management. However, these studies frequently assume well-established institutional structures and may not adequately address the constraints experienced in developing and emerging economies. Moreover, many analyses focus on technological or environmental criteria, with limited attention on economic feasibility, policy readiness, and practicality of operations in real-world situations (Agarwal & Bharti, 2022; Setyadi & Perbawa, 2024). A critical gap in the literature is the limited number of empirical and decision-oriented studies with a focus on EV battery reverse supply chains in Southeast Asian countries and Vietnam, in particular. Despite the increasing size of the EV market in Vietnam and the strategic importance of this country in regional manufacturing networks, there are limited systematic evaluations of reverse supply chain alternatives for the Vietnamese context. Furthermore, current studies that employ MCDM methods to manage EV batteries tend to be based on one method only, and this may fail to adequately account for both the importance of criteria consideration and the firm ranking of alternatives. The combined use of AHP and TOPSIS has so far been under-explored for EV battery reverse supply chain decision-making in emerging economies, particularly when anchored on expert insights of the existing regulatory, infrastructural, and market conditions in local economies.

Against this backdrop, the present study aims to develop a structured and context-specific decision support mechanism for evaluating reverse supply chain management alternatives for EV batteries in Vietnam. By combining AHP and TOPSIS, the aim of the present study is to systematically identify and weight the relevant evaluation criteria based on expert judgment and also to rank alternative reverse supply chain strategies according to their overall sustainability performance. The objectives of this research are threefold: firstly, to identify key economic, environmental, technical, and policy-related criteria affecting EV battery reverse supply chain decisions in Vietnam, secondly determine the relative importance of these criteria using the AHP method, and thirdly prioritise feasible reverse supply chain alternatives using TOPSIS. By using this method, the study hopes to close existing gaps in the literature and provide valuable information for the creation of effective, sustainable, and policy-aligned EV battery reverse supply chains in Vietnam.

2. Materials and methods

This study examines and ranks the reverse supply chain management (RSCM) options for end-of-life electric vehicle (EV) batteries in Vietnam using an integrated Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) framework. In order to address the multifaceted and intricate nature of reverse supply chain decision-making, the suggested technique entails the methodical integration of expert judgment and quantitative analysis. The identification of criteria and alternatives, the calculation of criteria weights using AHP, and the ranking of alternatives using TOPSIS are the three successive steps of the methodical process.

2.1 Identification of Criteria and Alternatives

A combination of expert-driven and literature-based methods were used to identify evaluation criteria and reverse supply chain options. First, a thorough study of peer-reviewed journal publications, policy reports, and technical materials about reverse logistics, the circular economy, EV battery recycling, and sustainable supply chain management was carried out. An initial pool of obstacles affecting the EV battery reverse supply chain's performance was gathered from the literature and categorized under economic, environmental, technological, and policy-related dimensions as stated in expert validation was then conducted to guarantee contextual relevance to Vietnam. Twelve specialists were assembled for the panel, including academics, professionals from the EV industry, battery recyclers, legislators, and sustainability consultants with extensive knowledge of reverse logistics or EV battery management. Structured surveys and follow-up conversations were used to gather data. Ten major obstacles (Table 1) influencing the reverse supply chain management of EV batteries in Vietnam were ultimately identified based on expert consensus.

Table 1
Criteria and Barriers for EV Battery Reverse Supply Chain Management in Vietnam

Main Criterion	Barrier Description	Abbreviations
Economic	High cost of collection and transportation of end-of-life EV batteries (Azadnia et al., 2021)	BCO
	High recycling and processing costs due to limited economies of scale (Lander et al., 2021)	BRC
Policy & Regulatory	Lack of policy incentives for battery recycling and second-life use (Joshi et al., 2021)	BPI
	Weak regulatory framework for end-of-life EV battery management (Dababneh et al., 2025)	BRF
	Poor coordination among stakeholders and the responsible authorities (Joshi et al., 2021)	PCO
Environmental	Limited capability for resource recovery and emission reduction (Kang et al., 2023)	LRC
	Environmental risks associated with improper handling and disposal (Joshi et al., 2021)	BER
Technical	Insufficient technical expertise and skilled workforce (Kang et al., 2023)	BSK
	Lack of advanced battery recycling and processing technologies (Rallo et al., 2022)	BTE
	Inadequate infrastructure for safe storage, dismantling, and recycling (Tripathy et al., 2023)	BIN

Table 2
Alternatives

Abbreviation	Full Name	Explanation
DRC	Direct Recycling	EV batteries are collected at the end-of-life stage and sent directly to recycling facilities to recover valuable materials. Focus is on centralized or dedicated recycling processes (Hayagan et al., 2024; Roy et al., 2024).
SLA	Second-Life Applications	Batteries that are no longer efficient for vehicles are repurposed for secondary applications, e.g., stationary energy storage systems, solar energy storage, or backup power (Etxandi-Santolaya et al., 2023; Michelini et al., 2023).
CRY	Centralized Recycling	Batteries from multiple sources are collected and transported to a centralized facility for processing and material recovery, allowing economies of scale and better control of safety and environmental impacts (Ma et al., 2024; Soldan Cattani et al., 2025).
DHR	Decentralized/Hybrid Recycling	Recycling is done at smaller, regional facilities closer to collection points. Sometimes, a hybrid approach combines both local dismantling and centralized processing. It reduces transport costs and can improve flexibility (Alex et al., 2026).

In parallel, viable reverse supply chain alternatives were identified, including direct recycling, second-life battery use, centralized recycling systems, decentralized collection and processing models, and hybrid models. These alternatives (Table 2) were verified by the expert panel as realistic and implementable in the current and near-future EV ecosystem in Vietnam.

2.2 AHP for Criteria Weight Determination

The Analytic Hierarchy Process (AHP) was employed to determine the relative importance of the ten identified barriers. Pairwise comparison matrices were developed based on expert judgments, where each element a_{ij} represents the relative importance of criterion i over criterion j .

The normalized matrix is expressed as (Chang, 1996; Saaty, 1987):

$$n_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad \forall i, j = 1, 2, \dots, n \quad (1)$$

The priority weight w_i for each criterion was calculated as the average of the normalized values:

$$w_i = \frac{\sum_{j=1}^n n_{ij}}{n} \quad (2)$$

The consistency of expert judgments was verified using the Consistency Index (CI) and Consistency Ratio (CR) defined as:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (3)$$

$$CR = \frac{CI}{RI} \quad (4)$$

where λ_{\max} is the maximum eigenvalue of the pairwise comparison matrix, and RI is the random index based on matrix order. A judgment matrix is considered consistent if $CR < 0.1$.

2.3 TOPSIS for Alternative Ranking

TOPSIS was applied to rank the reverse supply chain alternatives based on both beneficial and non-beneficial criteria. The decision matrix $D = [x_{ij}]$ was first normalized using vector normalization (Behzadian et al., 2012; Chakraborty, 2022; Chen, 2000):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad \forall i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (5)$$

The weighted normalized matrix was computed as:

$$v_{ij} = w_j \times r_{ij} \quad (6)$$

The positive ideal solution (PIS) and negative ideal solution (NIS) were defined as:

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\}, v_j^+ = \max(v_{ij}) \quad (7)$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\}, v_j^- = \min(v_{ij}) \quad (8)$$

The Euclidean distance of each alternative from the ideal and negative-ideal solutions was calculated as:

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}, S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \tag{9}$$

Finally, the closeness coefficient (CC) was determined as:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{10}$$

Alternatives were ranked in descending order of CC_i , where a higher value indicates greater similarity to the ideal solution and thus higher suitability.

3. Results and discussion

3.1 AHP Analysis

The AHP analysis emphasizes the relative significance of the obstacles influencing the reverse supply chain management of end-of-life EV batteries, as seen in Figure 1. With an AHP weight of 0.244, BCO (High cost of collecting and transportation of end-of-life EV batteries) stood out as the most significant of the ten barriers that were found. This suggests that logistics-related economic factors have a significant impact on supply chain decision-making. The difficulty in attaining cost-effective recycling operations when processing quantities are minimal is reflected in the weight of 0.162 for the second most important barrier, BRC (High recycling and processing costs due to insufficient economies of scale). With BER (Environmental risks associated with incorrect handling and disposal) receiving a weight of 0.133, environmental considerations also play a significant role, highlighting the necessity of safe and legal disposal techniques. At 0.102, LRC (Limited capabilities for resource recovery and emission reduction) is moderately significant, suggesting that present procedures would not fully take advantage of material recovery opportunities or reduce environmental effect. With weights of 0.079 and 0.070, respectively, technical limitations—represented by BTE (lack of sophisticated battery recycling technologies) and BSK (insufficient technical experience and competent workforce)—highlight the need for workforce training and technological advancements. Other obstacles, like PCO (poor stakeholder coordination), BRF (weak regulatory framework), BPI (lack of policy incentives), and BIN (inadequate infrastructure), received lower scores, ranging from 0.039 to 0.061, indicating that although they are significant, they are subordinated to environmental and economic factors. Overall, the results underscore that cost-related and environmental barriers dominate the decision-making landscape, and prioritizing these in policy and operational planning is essential for effective EV battery reverse supply chain management in Vietnam.

The heatmap (Figure 2) depicts the mean decision matrix based derived from 12 experts. It illustrates the performance of four alternatives in the reverse supply chain (DRC, SLA, CRY, and DHR) against 10 identified barriers, based on their respective scores on a five-point scale. Overall, DRC (Direct Recycling) scores the highest values across most barriers, with BCO (4.21) and BRC (4.69) being the most noticeable values, indicating that experts consider direct recycling to be strongly influenced by high costs associated with the collection, transportation, and processing processes. This indicates that although DRC is a major option, it is very sensitive to economic barriers. CRY (Centralized Recycling) shows moderate scores in most criteria, showing balanced performance, especially in economic and environmental barriers like BCO, BRC, and LRC shows consistency with its ability to take advantage of economies of scale. SLA (Second-Life Applications) shows comparatively lower results for cost-related barriers (e.g., BCO and BER) but relatively higher sensitivity to policy- and coordination-related barriers such as BRF and BPI, showing a dependency on supportive regulations and incentives. In contrast, DHR (Decentralized/Hybrid Recycling) has persistently low scores in nearly all barriers, suggesting comparatively lower perceived severity or impact of these barriers, especially in terms of economic and environmental ones. The obvious variation in the intensity of color across the matrix supports the idea that expert judgments are non-uniform and context-sensitive. This decision matrix thus forms a strong and realistic input for the TOPSIS analysis that follows it, which can then provide meaningful discrimination among alternatives, under the multiple conflicting barriers.

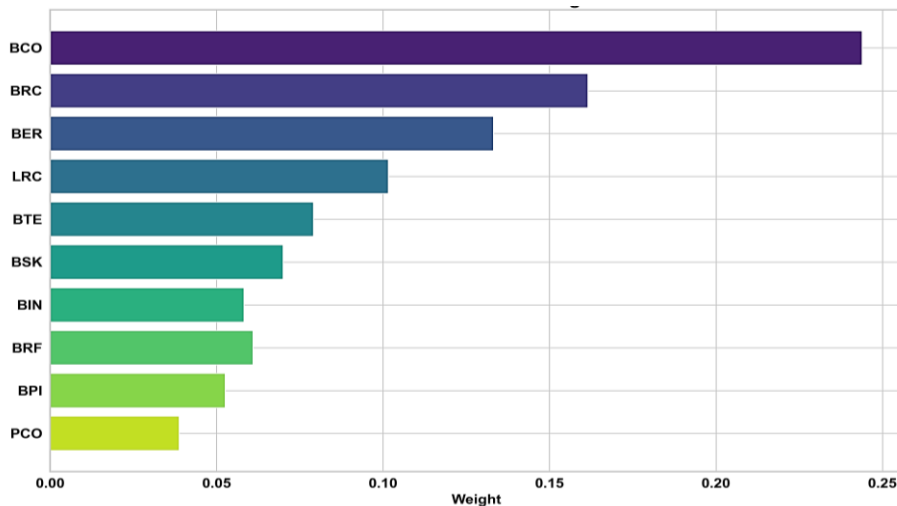


Fig. 1 AHP derived barriers weights

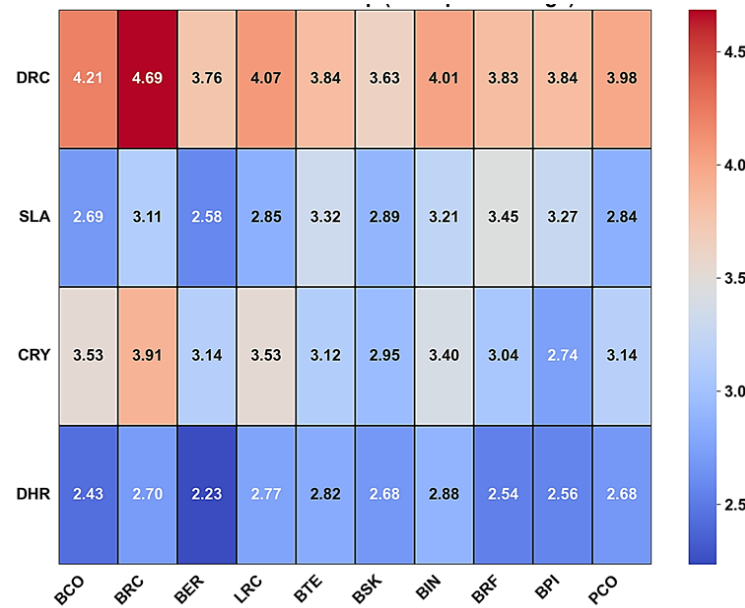


Fig. 2 Decision matrix heatmap

3.2 TOPSIS Analysis

In a continuation of the decision matrix analysis, the TOPSIS results shown in the Figure 3 depicts the final prioritization of the reverse supply chain alternatives for end-of-life EV batteries based on their relative proximity to the ideal solution. The closeness coefficient measures how well each of the alternatives at the same time minimizes the high-impact barriers, but is far from the worst-case scenario. Among the four options, DHR (Decentralized/Hybrid Recycling) has the highest closeness coefficient, close to unity, showing that this alternative is the most balanced and robust in the sense of having a solid and good performance when economic, environmental, technical, and policy-related barriers are taken into account together. The good performance of DHR indicates that the localized or hybrid processing structures may be good solutions to reduce the transportation costs, infrastructure restrictions, and coordination difficulties without losing operational flexibility. SLA (Second-Life Applications) is second up in the ranking with a relatively high closeness coefficient, which is indicative of its potential as a viable strategy, especially if accompanied by positive policy incentives and regulatory frameworks. However, it is dependent on secondary markets, and regulatory clarity slightly limits its overall dominance. CRY (Centralized Recycling) is in the third position with a moderate performance. For the centralized facilities, although they benefit from economies of scale, there is a high sensitivity to the logistics cost and concentration of infrastructure, which makes them less close to the ideal solution. In contrast, DRC (Direct Recycling) has the lowest closeness coefficient, which means that this is the least preferred alternative within the current barrier structure, mainly because it is highly exposed to cost-intensive and environmentally sensitive limitations. Overall, the results obtained from TOPSIS support the findings that decentralized and flexible reverse supply chain configurations are more resilient to multidimensional barriers, providing valuable insights for policymakers and industry players who are seeking sustainable EV battery management solutions for Vietnam.

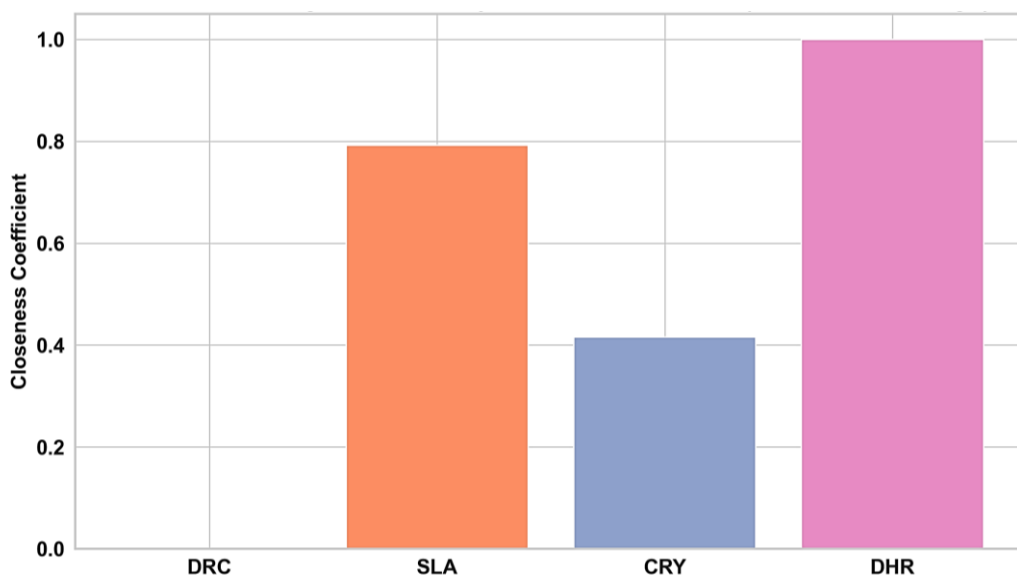


Fig. 3 TOPSIS Ranking of EV RSCM Alternatives

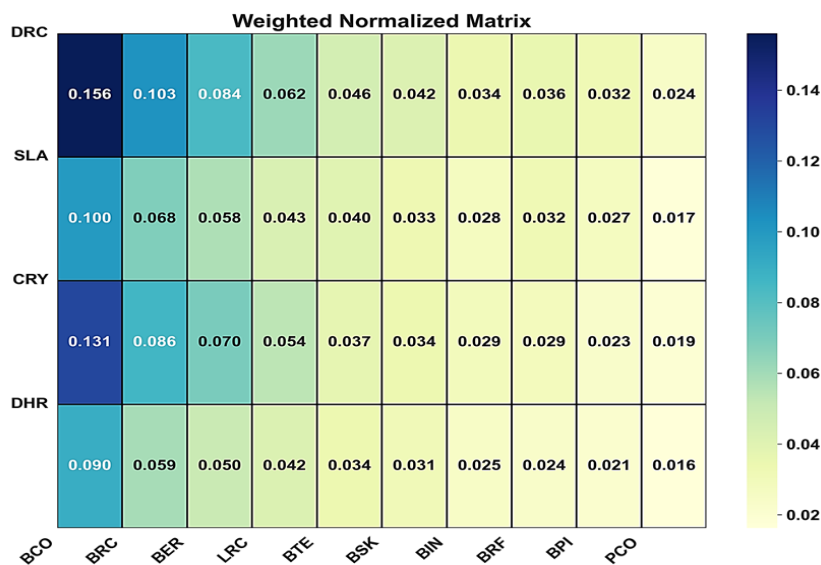


Fig. 4 Weighted Normalized Matrix

In continuation with the TOPSIS-based evaluation, the weighted normalized matrix presented in Figure 4 offers a deeper understanding of the performance of each reverse supply chain alternative after normalization of decision matrix values and multiplication by the AHP-derived barrier weights. This step is used to integrate both the relative importance of the barriers and the performance of each alternative, which can thereby reveal the actual contribution of each barrier to the final ranking of each barrier. As can be seen, BCO (high cost of collection and transportation) has the greatest influence among all alternatives, consistent with its dominating AHP weight and particularly large for DRC, which has the highest weighted value (0.156). This validates the fact that direct recycling is highly sensitive to the cost of logistics. CRY also presents a relatively high weighted score for BCO (0.131), reflecting the fact that it relies on centralised transportation and collection networks. In contrast, DHR and SLA exhibit much lower weighted impacts under BCO, suggesting that decentralized structures and second-life strategies are more effective in offsetting the cost pressures in transportation.

Environmental and capability-related barriers like BER and LRC show medium-weighted values across all alternatives, indicating that environmental risk management and resource recovery efficiency are still relevant but not driving differentiators. Technical and operational barriers, including BTE, BSK, and BIN, exhibit a decreasing level of weighted contributions, suggesting that although there are technological capability and infrastructure limitations, these are overshadowed by economic limitations in their relative significance. Policy- and coordination-related barriers, indicated by BRF, BPI, and PCO, respectively, show the lowest weighted values consistently, suggesting a smaller impact on overall decision-making under current conditions in Vietnam. Overall, the weighted normalized matrix shows that the alternatives that have lower accumulated weighted impacts across high-priority economic and environmental barriers are closer to the ideal solution. This is the reason that DHR and SLA have higher closeness coefficients in the final TOPSIS ranking, as they can balance the performance among the most influential barriers and limit the exposure to the major cost-related constraints.

4. Conclusion

This study introduced a systematic multi-criteria decision-making method to assess the reverse supply chain alternatives for end-of-life EV batteries in Vietnam using an integrated AHP-TOPSIS methodology. By adding a layer of expert judgment and quantitative analysis, the study identified ten critical barriers across economic, environmental, technical, and policy dimensions. The AHP results showed that economic barriers are most dominating the decision-making process, where high costs of items (0.244) and high costs of recycling and processing (0.162) have the greatest influence. Environmental risks and limitations in resource recovery capability came next, and policy and coordination barriers were found to have relatively less impact. The TOPSIS analysis further showed that Decentralized/Hybrid Recycling remains the most preferred reverse supply chain alternative with its cumulative lower exposure to high-priority cost and infrastructure barriers. Second-Life Applications were also a promising option, especially in applications that were supported by suitable regulatory incentives. In contrast, Direct Recycling scored the lowest in the ranking due to its exposure to logistics-intensive and cost-sensitive constraints.

From a practical standpoint, the results provide insight of great value to policymakers and industry practitioners in formulating cost-effective and environmentally responsible battery management strategies. Future research may further expand this work by including uncertainty modelling using fuzzy or interval-based approaches, by broadening the set of alternatives, or by incorporating life-cycle environmental and economic evaluations to reinforce decision-making on sustainable EV battery management further.

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