ESOGÜ Müh. Mim. Fak. Dergisi 2025, 33(2), 1847-1853 J ESOGU Eng. Arch. Fac. 2025, 33(2), 1847-1853

CRITICAL METAL SELECTION FOR LOW CARBON EMISSION USING THE ANALYTIC HIERARCHY PROCESS

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Keywords

Analytical Hierarchy Process
Critical Metals
Low-Carbon Economy
Sustainable Resource Management

Abstract

The transition to low-carbon economies has heightened the demand for critical metals essential in renewable energy technologies, electric vehicles, and energy storage systems. These metals play a fundamental role in enabling the green technologies required to meet global carbon neutrality targets. However, their extraction, processing, and supply chains introduce environmental, economic, and geopolitical challenges. This study employs the Analytical Hierarchy Process (AHP) to systematically evaluate and prioritize critical metals by considering multiple criteria, including environmental impact, economic viability, resource availability, and technical performance. By integrating expert insights and robust data, the AHP framework provides a comprehensive and structured approach to decision-making in sustainable resource management. The results underscore lithium's critical role, driven by its favourable environmental and technical properties, followed by cobalt for its strategic relevance despite ethical concerns, nickel for its high energy density, and neodymium for its role in permanent magnet applications. These findings aim to inform policymakers, industry leaders, and stakeholders in making well-grounded decisions that align with sustainable development objectives and facilitate the transition to a low-carbon future.

ANALİTİK HİYERARŞİ PROSESİ KULLANILARAK DÜŞÜK KARBON EMİSYONU İÇİN KRİTİK METAL SEÇİMİ

Anahtar Kelimeler

Analitik Hiyerarşi Prosesi
Kritik Metaller
Düşük Karbonlu Ekonomi
Sürdürülebilir Kaynak Yönetimi

Öz

Düşük karbonlu ekonomilere geçiş, yenilenebilir enerji teknolojileri, elektrikli araçlar ve enerji depolama sistemlerinde hayati öneme sahip kritik metallere olan talebi artırmıştır. Bu metaller, küresel karbon nötrlüğü hedeflerine ulaşmak için gerekli yeşil teknolojilerin etkinleştirilmesinde temel bir rol oynamaktadır. Ancak, bu metallerin çıkarılması, işlenmesi ve tedarik zincirleri çevresel, ekonomik ve jeopolitik zorluklar ortaya çıkarmaktadır. Bu çalışma, çevresel etki, ekonomik uygulanabilirlik, kaynak mevcudiyeti ve teknik performans gibi birden fazla kriteri dikkate alarak kritik metalleri sistematik bir şekilde değerlendirmek ve önceliklendirmek için Analitik Hiyerarşi Süreci (AHP) yöntemini kullanmaktadır. Uzman görüşlerini ve güvenilir verileri içeren AHP çerçevesi, sürdürülebilir kaynak yönetimi bağlamında kapsamlı ve yapılandırılmış bir karar alma yaklaşımı sunmaktadır. Bulgular, lityumun hem çevresel hem de teknik açıdan avantajlı özellikleri nedeniyle en kritik metal olduğunu, etik kaygılara rağmen stratejik önemi dolayısıyla kobaltın ikinci sırada yer aldığını, ardından enerji yoğunluğu nedeniyle nikelin ve kalıcı mıknatıs uygulamaları açısından neodimyumun geldiğini ortaya koymaktadır. Bu analiz, politika yapıcılara, sanayiye ve paydaşlara sürdürülebilir kalkınma hedefleriyle uyumlu kararlar almalarında rehberlik etmeyi ve düşük karbonlu bir geleceğe geçişi desteklemeyi amaçlamaktadır.

Araştırma Makalesi		Research Article	
Başvuru Tarihi	: 11.02.2025	Submission Date	: 11.02.2025
Kabul Tarihi	: 03.06.2025	Accepted Date	: 03.06.2025

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https://doi.org/10.31796/ogummf.1637660

1. Introduction

The urgency to mitigate climate change and reduce greenhouse gas emissions has led to a global push for transitioning towards low-carbon economies. This transformation is heavily relying on adopting of renewable energy technologies, energy-efficient systems, and sustainable transportation solutions. Critical metals such as lithium, cobalt, nickel, and rare earth elements (REEs) are indispensable for manufacturing batteries, wind turbines, solar panels, and electric vehicles, which are foundational to achieving these objectives. Despite their significance, the procurement and utilization of critical metals are fraught with challenges. The environmental impact of mining and processing, coupled with geopolitical risks and resource scarcity, necessitates a strategic approach to their selection and use. For instance, lithium-ion batteries are pivotal in energy storage but require materials that are often sourced from ecologically sensitive regions. Similarly, cobalt mining has faced scrutiny over ethical concerns, including child labor and unsafe working conditions in certain supply chains.

Literature has extensively documented the role of critical metals in the green transition. Graedel et al. (2015) highlighted the increasing criticality of metals such as lithium and cobalt due to their indispensable applications in battery technologies. Sverdrup and Ragnarsdottir (2014) investigated rare earth elements (REEs), underscoring their importance in wind turbine technologies, while also pointing to geopolitical challenges arising from their geographical concentration in a limited number of countries. Furthermore, Sovacool et al. (2020) discussed the environmental trade-offs and potential harms associated with mining operations, emphasizing the need for balanced policies to ensure sustainable extraction practices. The significance of these metals also has prompted numerous global initiatives aimed at ensuring a stable supply. For example, Schäfer et al. (2020) identify key metals essential for achieving the bloc’s Green Deal goals while also addressing potential supply chain vulnerabilities. Similarly, the U.S. Department of Energy has launched initiatives such as the Critical Materials Institute to develope recycling technologies and reduce reliance on imports. These efforts highlight the growing international acknowledgment of the strategic importance of critical metals in a low-carbon future. Recent studies have explored the integration of decision-making tools to prioritize critical metals. For instance, Babbitt et al. (2021) examined the life cycle from a circular economy perspective to evaluate the environmental impacts of various metals used in electric vehicle applications. Their findings stress the necessity of incorporating recycling and circular economy principles to reduce dependence on raw material extraction. Moreover, advancements in materials science have further highlighted the importance of the strategic selection of metals that meet both performance and sustainability criteria. For instance, research by Koech et al. (2024) on alternative battery chemistries illustrates the potential to reduce reliance on cobalt through the development of manganese-based cathodes. This demonstrates how innovation can help alleviate pressure on critical supply chains. In this context, it is imperative to identify and prioritize critical metals most suitable for supporting low-carbon technologies while minimizing adverse social and environmental impacts. The selection process involves evaluating multiple environmental, economic, and technical criteria to ensure that the selected metals align with sustainability goals and industrial needs. Analytical tools such as the AHP offer a systematic framework for addressing these multifaceted challenges. This study aims to apply the AHP methodology to provide a robust analysis of critical metal selection for low-carbon applications. By considering factors such as environmental impact, cost-effectiveness, resource availability, and technical performance, this research aims to support the development of a more sustainable and resilient supply chain for critical metals. The findings aim to inform decision-makers in government, industry, and academia, and to promote a balanced approach to resource utilization and environmental stewardship.

2. Methodology

This study adopts the AHP, a structured and widely used decision-making framework that facilitates the prioritization of alternatives based on multiple criteria. The methodology involves several systematic steps to derive a comprehensive ranking of critical metals.

2.1. Problem Structuring

The first step involves defining the decision-making problem, which, in the context of this study, pertains to the selection of critical metals for low-carbon technologies. A hierarchical structure has been developed, comprising the main goal (critical metal selection), criteria (such as environmental impact, economic viability, resource availability, and technical performance), and sub-criteria (such as carbon footprint, extraction costs, supply risk, and energy density).

2.2. Construction of Comparison Matrices

Pairwise comparison matrices were employed to evaluate the relative importance of criteria and sub-criteria. These matrices were derived from the opinions of experts in mining and mineral processing engineering.

Saaty's 9-point scale was used to assess the relative importance of the two components (Saaty, 2008). The decision-makers provided input by comparing pairs of criteria on a scale from 1 (equal importance) to 9 (extremely important).

2.3. Consistency of Matrices

The consistency of a matrix is determined by calculating its consistency index (CI).

CI= (λ_max-a)/(a-1)

where λmax is the maximum eigenvalue and a is the dimension of the matrix. The consistency of pairwise comparisons was verified by calculating the Consistency Ratio (CR):

CR=CI/RI

where RI indicates Saaty's random index values for various matrix dimensions. A CR value less than 0.1 indicates an acceptable level of consistency.

2.4. Evaluation of Alternatives

A pairwise decision matrix is constructed to compare alternatives with respect to a given criterion and to assess the extent to which one alternative is preferred over another.

2.5. Sensitivity Analysis

To ensure robustness, sensitivity analysis is conducted by varying the weights of criteria and observing changes in the ranking of metals. This step helps to identify the stability of the results under different scenarios.

3. Application of the AHP

The AHP is a multi-criteria decision-making tool that enables the ranking of alternatives through pairwise comparisons. The appropriate critical metal selection process involves the following steps:

i. Define the objective: Selection of critical metals for low-carbon emission technologies.

ii. Establish criteria, sub-criteria and alternatives: The main criteria and sub-criteria for selection were summarized in Table 1. These were identified based on established research and expert opinions. Table 2 presents the references along with the corresponding criteria and sub-criteria. The alternatives considered in this study are Lithium (Li), Cobalt (Co), Nickel (Ni), and Neodymium (Nd).

iii. Structure the hierarchy: Objective at the top, criteria in the middle, and alternatives at the bottom (Figure 1).

Table 1. Criteria and Sub-Criteria Used in the AHP Model.

Main criteria	Sub criteria	Description
Environmental Impact	Carbon Footprint	Greenhouse gas emissions during extraction and processing
	Waste Generation	Solid and hazardous waste produced during mining and refining
Economic Viability	Market Price	Current and projected market value of the metal
	Cost of Extraction	Expenses related to mining, refining, and transportation
Resource Availability	Proven Reserves	Geologically verified reserves of the metal
	Recycling Potential	Feasibility and efficiency of recycling processes
Technical Performance	Energy Density	Energy storage capacity in battery and energy systems
	Efficiency	Performance in industrial applications
	Durability	Lifespan and reliability in specific uses

Table 2. The Main Criteria and Sub-Criteria of the Study

Main criteria	Sub criteria	Reference
Environmental Impact (MC_1)	Carbon Footprint (SC_1)	Graedel et al., 2015
	Waste Generation (SC_2)	(Da Silva Lima et al., 2021)
Economic Viability (MC_2)	Market Price (SC_3)	(Ponomareva et al., 2024)
	Cost of Extraction (SC_4)	Sverdrup and Ragnarsdóttir (2014)
Resource Availability (MC_3)	Proven Reserves (SC_5)	Akinyele and Rayudu (2014)
	Recycling Potential (SC_6)	Yang et al. (2020)
Technical Performance (MC_4)	Energy Density (SC_7)	(Jia et al., 2013)
	Efficiency (SC_8)	(Petrova, 2023)
	Durability (SC_9)	(He et al., 2021)

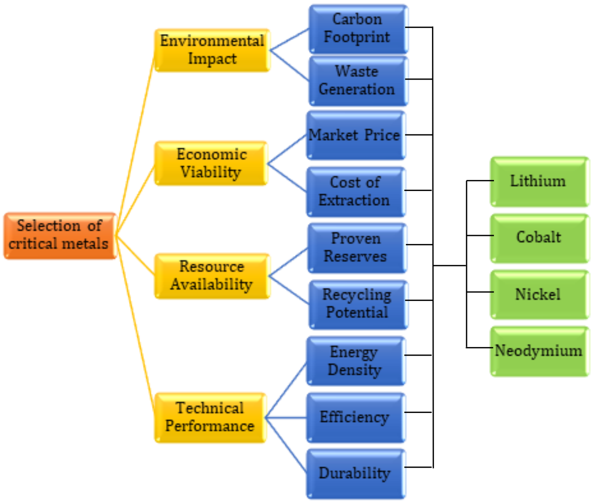


Figure 1. Hierarchical Structure of the Study

iv. Perform pairwise comparisons: Expert judgments were used to assign weights to criteria and rate alternatives. The pair-wise comparison matrices of the study are presented in Tables 3-5. The pair-wise matrices were constructed according to Saaty's 9-point scale. The criteria weights were computed using the ExpertChoice® 2000 application. The experts' opinions were used to construct the pairwise comparison matrices.

Table 3. Pairwise Comparison Matrix for The Main Criteria

Critical Metal Selection	MC_1	MC_2	MC_3	MC_4	Weights
MC_1	1	3	5	7	0.565
MC_2	1/3	1	3	5	0.262
MC_3	1/5	1/3	1	3	0.118
MC_4	1/7	1/5	1/3	1	0.055
CR= 0.04					

Table 4. Evaluation of Sub-Criteria with Respect to Main Criteria

MC_1	SC_1	SC_2	Weights
SC_1	1	3	0.750
SC_2	1/3	1	0.250
CR= 0.00			

MC_2	SC_3	SC_4	Weights
SC_3	1	2	0.667
SC_4	1/2	1	0.333
CR= 0.00			

MC_3	SC_5	SC_6	Weights
SC_5	1	1/3	0.250
SC_6	3	1	0.750
CR= 0.00			

MC_4	SC_7	SC_8	SC_9	Weights
SC_7	1	2	3	0.540
SC_8	1/2	1	2	0.297
SC_9	1/3	1/2	1	0.163
CR= 0.01				

Table 5. Comparisons of The Alternatives with Respect to Sub-Criteria

SC_1	Li	Co	Ni	Nd	Weights	CR
Li	1	2	3	4	0.467	0.01
Co	1/2	1	2	3	0.277	
Ni	1/3	1/2	1	2	0.160	
Nd	1/4	1/3	1/2	1	0.095	

SC_2	Li	Co	Ni	Nd	Weights	CR
Li	1	3	4	5	0.538	0.04
Co	1/3	1	2	4	0.243	
Ni	1/4	1/2	1	3	0.149	
Nd	1/5	1/4	1/3	1	0.070	

SC_3	Li	Co	Ni	Nd	Weights	CR
Li	1	3	5	7	0.565	0.04
Co	1/3	1	3	5	0.262	
Ni	1/5	1/3	1	3	0.118	
Nd	1/7	1/5	1/3	1	0.055	

SC_4	Li	Co	Ni	Nd	Weights	CR
Li	1	2	4	6	0.499	0.01
Co	1/2	1	3	5	0.313	
Ni	1/4	1/3	1	2	0.120	
Nd	1/6	1/5	1/2	1	0.068	

SC_5	Li	Co	Ni	Nd	Weights	CR
Li	1	4	6	8	0.617	0.06
Co	1/4	1	3	5	0.228	
Ni	1/6	1/3	1	3	0.105	
Nd	1/8	1/5	1/3	1	0.050	

SC_6	Li	Co	Ni	Nd	Weights	CR
Li	1	2	3	5	0.473	0.02
Co	1/2	1	2	4	0.284	
Ni	1/3	1/2	1	3	0.170	
Nd	1/5	1/4	1/3	1	0.073	

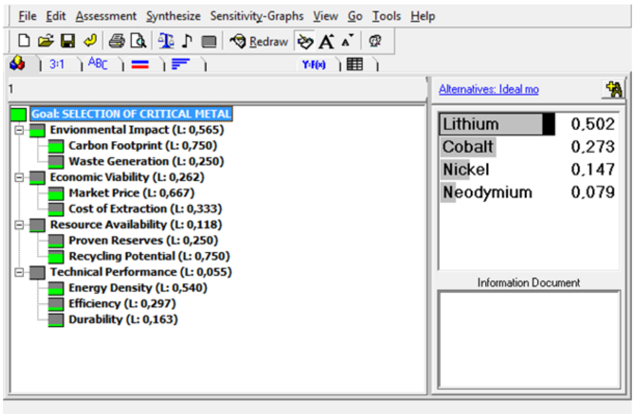
SC_7	Li	Co	Ni	Nd	Weights	CR
Li	1	3	5	7	0.569	0.03
Co	1/3	1	3	5	0.264	
Ni	1/5	1/3	1	2	0.106	
Nd	1/7	1/5	1/2	1	0.061	

SC_8	Li	Co	Ni	Nd	Weights	CR
Li	1	2	3	5	0.473	0.02
Co	1/2	1	2	4	0.284	
Ni	1/3	1/2	1	3	0.170	
Nd	1/5	1/4	1/3	1	0.073	

SC_9	Li	Co	Ni	Nd	Weights	CR
Li	1	2	3	5	0.483	0.01
Co	1/2	1	2	3	0.272	
Ni	1/3	1/2	1	2	0.157	
Nd	1/5	1/3	1/2	1	0.088	

v. Compute consistency ratio: In the study, the CR values of the pairwise comparison matrices range from 0 to 0.10. It can be concluded that all comparisons were consistent.

vi. Rank the alternatives: Figure 2 displays the AHP result. With a score of 0.502, it is clear that lithium is the most preferred material, followed by cobalt, nickel, and neodymium. The percentage significance for lithium, cobalt, nickel, and neodymium are 50.20%, 27.30%, 14.70%, and 7.90%, respectively. The alternatives' rankings with respect to the primary criteria are shown in Figure 3. For instance, lithium is better than cobalt, nickel, and neodymium when the Environmental Impact main criterion is taken into account.



Goal: SELECTION OF CRITICAL METAL
- Envionmental Impact (L: 0,565)
  - Carbon Footprint (L: 0,750)
  - Waste Generation (L: 0,250)
- Economic Viability (L: 0,262)
  - Market Price (L: 0,667)
  - Cost of Extraction (L: 0,333)
- Resource Availability (L: 0,118)
  - Proven Reserves (L: 0,250)
  - Recycling Potential (L: 0,750)
- Technical Performance (L: 0,055)
  - Energy Density (L: 0,540)
  - Efficiency (L: 0,297)
  - Durability (L: 0,163)

Lithium	0,502
Cobalt	0,273
Nickel	0,147
Neodymium	0,079

Figure 2. The Result of the Metal Selection

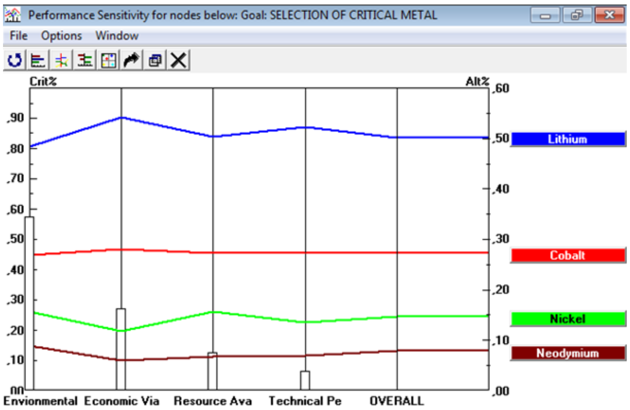


Figure 3. Performance Graph

vii. Apply sensitivity analysis:

Sensitivity analysis is used to examine how flexible the final decision is. By identifying a critical criterion, a decision-maker can make a more informed choice. In other words, variations in a criterion's weight determine how sensitive the alternatives are. Due to the subjective nature of the evaluation, small adjustments in priority may have a significant impact on the final rankings. The consistency of the ranking can be confirmed based on changing criterion weights (Kursunoglu and Onder, 2015; Kursunoglu et al., 2020). The decision-making problem can be subjected to sensitivity analysis using ExpertChoice® 2000 software. Figure 4 displays the dynamic sensitivity of the primary criteria and alternatives. The sensitivity analysis results are presented in Figure 5.

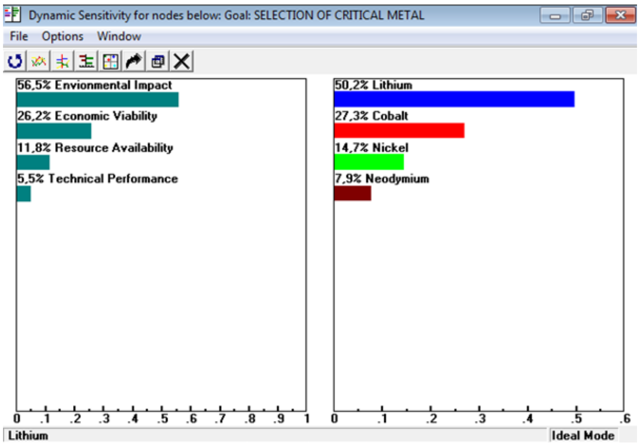


Figure 4. Main Criteria and Dynamic Sensitivity

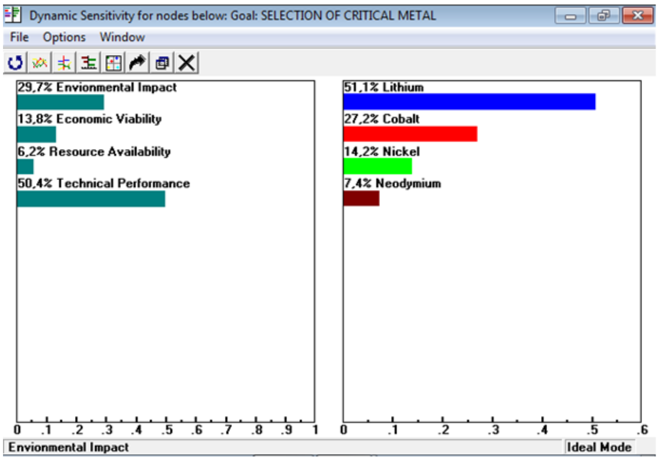


Figure 5. Result of Sensitivity Analysis

As illustrated in Figures 4 and 5, the weight of the Technical Performance criterion increased from 5.5% to 50.40%, while the weight of Environmental Impact decreased from 56.5% to 29.7%, Economic Viability from 26.2% to 13.8%, and Resource Availability from 11.8% to 6.2%. Based on this analysis, it was found that when the Technical Performance criterion holds a weight of 50.40%, lithium emerges as the most favoured element, followed by cobalt, nickel, and neodymium.

4. Discussion

The prioritization of critical metals derived from the AHP analysis shows strong alignment with existing literature concerning their environmental, economic, and technical attributes. Lithium emerged as the most favorable metal, primarily due to its essential role in energy storage systems—supported by its low carbon footprint and high technical performance. This outcome is consistent with the findings of Babbitt et al. (2021), who highlighted lithium's superior performance in battery technologies and its comparatively lower environmental impact relative to cobalt.

Cobalt, despite scoring highly in terms of energy density and strategic significance, poses notable challenges due to ethical concerns and supply chain vulnerabilities. These issues are extensively documented in studies such as Graedel et al. (2015) and Mancini et al. (2021), which emphasize the need for enhanced governance and alternative sourcing strategies to mitigate associated social and geopolitical risks. Nickel secured a higher ranking due to its strong energy density and efficiency in high-performance battery applications, in alignment with the findings of Manthiram et al. (2016).

However, its environmental impacts particularly those related to waste generation highlight the need for improvements in sustainable extraction methods and recycling technologies, as emphasized by Majeau-Bettez et al. (2011). Neodymium's technical strengths, especially its application in permanent magnets for wind turbines and electric vehicles, are tempered by concerns regarding geopolitical concentration and the environmental consequences of its extraction. Similarly, Sverdrup and Ragnarsdottir (2014) pointed to the vulnerabilities of rare earth elements (REEs) stemming from their uneven global distribution and limited recycling infrastructure.

The evaluation of sub-criteria further illuminated critical trade-offs. For instance, while lithium and cobalt scored highly in terms of carbon footprint reduction, these benefits were counterbalanced by concerns over waste generation highlighting the necessity of balancing environmental and technical priorities. Such trade-offs are also evident in life cycle assessments, such as those conducted by Babbitt et al. (2021), which advocate for circular economy practices to mitigate associated impacts. The findings of this study emphasize the need for integrated strategies that simultaneously address resource criticality and sustainability. These outcomes align closely with the study's recommendation to prioritize targeted investments in recycling and substitution technologies.

Overall, the findings reaffirm the pivotal role of critical metals in enabling the low-carbon transition, while underscoring the need to address their associated environmental and geopolitical challenges. Future research could build on this analysis by integrating dynamic variables such as market trends, technological advancements, and evolving regulatory frameworks to ensure that metal prioritization remains adaptive to global sustainability objectives.

5. Conclusion

The prioritization of critical metals for low-carbon technologies is a multifaceted challenge requiring careful evaluation of environmental, economic, resource, and technical considerations. Using the AHP, this study systematically assessed the relative importance of key criteria and sub-criteria, integrating insights from the latest literature and expert opinions.

The findings highlight the criticality of lithium due to its low carbon footprint, high energy density, and established market dominance in battery technologies. Cobalt, while essential for performance, poses ethical and geopolitical challenges that necessitate innovations in recycling and material substitution. Nickel emerged as a vigorous alternative for energy storage applications, thanks to its favourable balance of cost and efficiency. Neodymium, essential in renewable energy technologies such as wind turbines, highlighted the importance of technical performance and resource availability in strategic metal selection.

This research provides valuable insights for policymakers and industries seeking to align resource strategies with sustainability objectives. The application of AHP in the decision-making process ensures a structured and transparent methodology, enabling the development of well-informed policies that balance environmental and economic trade-offs. Future studies could enhance this framework by incorporating dynamic market conditions, emerging technological innovations, and more extensive stakeholder engagement to further refine the metal selection process. These findings lay the groundwork for developing sustainable supply chains that facilitate the global transition to a low-carbon economy, highlighting the essential balance between resource efficiency and environmental responsibility. Future research should broaden the scope of this study by incorporating additional critical metals and evaluation criteria, including aspects of social sustainability and evolving regulatory frameworks. Moreover, advancements in recycling technologies and alternative chemistries should be continuously assessed to adapt to evolving technological and economic landscapes. By aligning resource utilization strategies with the principles of sustainability and the circular economy, stakeholders can collectively contribute to a greener and more sustainable future.

Acknowledgement

The author thanks the Editors and anonymous reviewers for valuable contributions to the manuscript.

Author Contributions

Investigation, Conceptualization, Methodology, Writing – original draft

Conflict of Interest

No potential conflict of interest was reported by the author.

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