Evaluation of a critical mineral recycling network: A case study on nickel recycling from production waste in Korean eco-industrial parks

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Abstract

The transformation of industrial paradigms towards global carbon neutrality and the enhancement of national security may initially appear unrelated, yet both necessitate a vital intermediary: critical minerals. Despite global efforts focused on securing critical minerals through supply chains, challenges persist due to geopolitical instability and complex inter-country dynamics. The recycling of embedded resources in products emerges as a crucial and inevitable strategy to build resilient domestic supply chains, especially in countries facing resource shortages. This study introduces a closed-loop system utilizing public and open-source data to recover nickel, a pivotal critical mineral, with South Korea serving as a representative mineral-deficient nation. The methodology targets the manufacturing industry and various industrial complexes, assessing the potential for resource recycling by fostering networks among related companies within each complex. The findings underscore that these networks within industrial complexes encompass 86% of the manufacturing industry, forming a cohesive framework for developing a nickel integration network. Implementation of such networks in concentrated industrial complexes with diverse manufacturing sectors is anticipated to significantly enhance critical mineral self-sufficiency in high-demand countries.

1. Introduction

Global carbon neutrality target and a shift in industrial paradigms are driving up demand for critical minerals to meet the accelerated transformation of mineral-intensive industrial sectors such as electric vehicles and renewable energy **(MOTIE, 2023)**. The international community acknowledges critical minerals as critical raw materials for reaching net-zero goals through a transition to clean technologies, and inextricably tied to national competitiveness **(Dou et al., 2023)**. Furthermore, achieving net-zero goals is believed to be closely connected to the availability of critical minerals **(Wang et al., 2023; Bobba et al., 2020, Carrara et al., 2020, Elshkaki and Shen, 2019; Frenzel et al., 2017; Blagoeva et al., 2016).** According to SNE Research **(SNE, 2023)**, the global electric vehicle market and battery market are expected to grow ten-fold and thirteen-fold, respectively, by 2030 compared to 2021, and a typical electric car requires six times the mineral input of a conventional vehicle, and an onshore wind power plant requires nine times the mineral resources of a natural gas plant **(IEA, 2022; Kirsten et al., 2020)**. Furthermore, the International Energy Agency (IEA) predicts that demand for critical minerals such as lithium (42 times), cobalt (21 times), nickel (19 times), and rare earths (7 times) will increase from 2020 to 2040 as clean energy, including electric vehicles and renewable energy, expands in the process of achieving carbon neutrality **(IEA, 2022)**. According to a World Bank assessment, the output of minerals and metals required for clean energy transition would expand significantly by 2050, with estimates ranging from 108% to 964% **(Hund et al., 2020; Jiskani et al., 2022)**.

However, critical minerals such as lithium, nickel, cobalt, and graphite are concentrated in specific nations, particularly with China controlling the processing supply chain **(IEA, 2022; Ballinger et al., 2019)**. Recent geopolitical crises, such as Russia's invasion of Ukraine, the Israel-Hamas war, and supply restriction policies by key supplier countries such as China and Indonesia, have increased rivalry for critical minerals among major importing nations. As a consequence, a series of policies that restrict the export of critical minerals from supplier countries is causing supply instability and price fluctuations **(Nidhi, S., 2023)**.

In the current global landscape, countries such as China and Indonesia in Asia, alongside nations in Central and South America and Africa, exert control over critical mineral resources through resource nationalization policies, which include export controls **(OECD, 2023; Agusdinata and Liu, 2023**). Demand countries are responding by internalizing their supply chains, promoting Mineral Security Partnerships (MSP), and expanding collaboration with ally-centric initiatives such as the IEA's Critical Minerals Task Force **(Vivoda et al., 2023; MOTIE, 2023)**. Meanwhile, countries such as South Korea, which imports 95% of its minerals, face the key challenge of securing critical minerals to maintain long-term industrial competitiveness. Despite efforts such as long-term supply contracts, overseas resource development, domestic production, recycling, and stockpiling, South Korea is constrained in meeting the increasing demand for critical minerals. The vulnerability of its supply chain is exacerbated by the absence of domestic manufacturing facilities for these critical minerals **(MOTIE, 2023; UNEP, 2013)**.

2. National Critical Mineral Strategy Implications

An analysis of major national strategies on critical minerals, including those of the US, Canada, EU, Australia and South Korea, reveals variations in the lists of critical minerals based on each country’s economic, environmental, and social considerations. However, 16 critical minerals (Aluminum, Antimony, Bismuth, Cobalt, Gallium, Rare Earth Elements, Lithium, Magnesium, Vanadium) are universally designated as critical across these nations, with slight differences Manganese, Graphite, Niobium, Platinum Group Metals, Tantalum, Titanium, Tungsten, and in designation between supply and demand countries. Notably, these 16 minerals are crucial for advancing industries such as semiconductors, batteries, and electric vehicles, as well as for national security sectors like aerospace and defense. Recognizing their importance, nations are expected to intensify efforts to secure these critical minerals to promote advanced industries and bolster domestic security. Furthermore, the strategies for securing these critical minerals show clear similarities. Major countries are pursuing three primary initiatives to enhance mineral security.

First, there is a strong emphasis on domestic resource development. Resource-rich nations such as the US, Canada, and Australia aim to obtain critical minerals by extracting virgin materials, often through partnerships with indigenous communities to foster mutual understanding. This approach is part of broader efforts to address resource nationalism in mineral-rich states amidst escalating demand for critical minerals. Conversely, the EU and South Korea, both substantial importers of critical minerals, are focusing on exploring and developing their domestic resources with an emphasis on safety and environmental considerations. For instance, the EU's Critical Raw Materials Initiative targets extracting 10%

of its demand within the EU, while South Korea plans to map its critical minerals through comprehensive exploration techniques, including geological surveys, drilling, modeling, and mine design, to enhance development potential.

Second, there is a strong emphasis on enhancing international cooperation. Both supply and demand countries recognize the challenges of relying solely on domestic sources for stable critical mineral supplies. Supply countries often assert control over supply chains to ensure access to critical minerals, while demand countries prioritize mobilizing international cooperation, especially among nations sharing similar values. The Mineral Security Partnership (MSP), comprising Australia, Canada, Finland, France, Germany, India, Italy, Japan, South Korea, Norway, Sweden, the UK, the US, and the EU, exemplifies a significant alliance for critical mineral cooperation. Participating countries collaborate on projects of mutual interest, establish working groups to assess investment opportunities, and foster closer collaboration. **(MOTIE, 2023)**

Third, there is a strong emphasis on proactive recycling, a concept increasingly prioritized in demand countries like the EU and South Korea compared to resource-supply nations. The EU mandates the incorporation of recycled materials in new battery production under its Battery Regulation, setting targets such as 16% cobalt, 85% lead, 6% lithium, and 6% nickel from recycled sources within eight years of the law's enactment. These percentages are set to increase to 26%, 85%, 12%, and 15%, respectively, thirteen years after implementation **(Regulation (EU), 2023)**. Similarly, South Korea aims to recycle 20% of critical minerals by 2030, establishing a crucial Mineral Recycling Verification Center and creating clusters for centralized procurement and recovery of raw materials. The government plans to actively support recycling programs and related research through financial aid and tax incentives.

The aim of this study is to assess the economic viability of recycling networks, a policy gaining traction among demand countries. Recycling locally generated waste products or unused critical minerals in manufacturing processes is crucial for achieving sustainable long-term growth. In South Korea, recycling is integral to the country's strategy for critical mineral security. With projections indicating a significant increase in waste by around 2040, particularly from permanent magnets and electric vehicle batteries **(SNE, 2023)**, recycling is poised to play a pivotal role in securing future critical minerals. South Korea has committed to enhancing recycling efficiency through the formation of industrial clusters. Rather than continually introducing new policies, it is essential to revisit and identify successful elements from previous initiatives. A reassessment of the Eco-Industrial Parks (EIP) program, which has been successfully implementing eco-friendly recycling technologies and fostering inter-company collaboration since 2005 **(Jung et al., 2013)**, is therefore warranted. By studying cases of recycling technologies in the context of the EIP policy, South Korea's potential to achieve critical mineral security through recycling can be better understood.

3. South Korea’s Policy on Eco-Industrial Parks (EIPs) and Technological Advancements

3.1. EIP Policy Overview and Achievements

While major countries worldwide advocate recycling legislation as a fundamental strategy for securing critical minerals, specific implementation strategies remain underdeveloped. Countries need to thoroughly assess the potential to build upon existing recycling programs before introducing new policies. As a prominent demand country for critical minerals, South Korea needs to actively reuse or recycle waste in production to ensure a stable supply chain. Evaluating the applicability and scalability of technologies developed through previous Eco-Industrial Park (EIP) initiatives can be seen as the initial step towards implementing a sustainable recycling policy. EIP plays a pivotal role in industrial ecology, which aims to mimic natural ecosystems by designing closed-loop systems or circular resource utilization structures to maximize resource efficiency and minimize environmental impact. The concept aims for zero waste discharge through industrial symbiosis, where businesses collaborate to share economic and environmental benefits. Since the late 1990s, various countries including the EU, US, Canada, Japan, China, and South Korea have embraced this approach to transform industrial complexes into eco-friendly hubs known as Eco-Industrial Parks **(Son et al., 2023; Liu et al., 2018; Chertow, 2007)**.

Since 2005, South Korea has implemented an EIP policy aimed at converting industrial complexes into sustainable, eco-friendly environments within a 12-year period, establishing a circular system that reuses waste generated within industrial zones. The policy emphasizes resource and energy efficiency through direct inter-company recycling of waste. Targeting 105 industrial complexes, the initiative has successfully implemented 235 projects with a government investment of 81 billion KRW (approximately 62 million USD). These projects have generated economic profits amounting to 2.4 trillion KRW (around 1.8 billion USD) through cost savings and increased revenue. Environmentally, achievements include reducing waste 6.8 million metric tonnes, saving 1.7 million tonnes of oil equivalent (Mtoe) in energy consumption, and reducing greenhouse gas emissions by 8.5 million metric tonnes of CO_2-equivalent **(MOTIE, 2014)**. Since 2019, the focus has shifted from individual company environmental initiatives towards transforming industrial complexes into smart ecosystems where companies within the same industry and value chain can autonomously collaborate through data connectivity and sharing **(MOTIE, 2019).**

In this study, we analyze the economic potential of key technologies for recovering critical minerals **(Table 1)**, developed over the past 12 years through EIP programs. Our focus is on assessing the economic viability of a nickel recovery network crucial for electric vehicle battery production. Nickel, historically used in stainless steel, is now in high demand for batteries, leading suppliers to redirect resources from stainless steel production. Recent trends indicate constraints in nickel supply, particularly from major reserves in Indonesia, due to export levies and limited new manufacturing facilities, resulting in an unstable supply chain **(Guru, 2023)**. Recovering nickel from waste generated in domestic industrial processes is crucial for evaluating economic performance, especially in countries like South Korea heavily reliant on imported critical minerals. Moreover, amid an unstable nickel supply chain exacerbated by increasing battery demand, such initiatives not only stabilize the supply chain but also foster collaborative networks among firms towards an eco-friendly economy. While the quantitative impact of nickel recovery from process effluents may currently be modest relative to total demand, the potential for nickel recovery from expanding battery production and a growing volume of waste batteries lays the groundwork for a circular economy. Understanding the economic potential of recycling critical minerals and expanding these efforts within regional industrial complexes and across national industries contributes significantly to the economic aspect of a circular economy. This study first addresses the expansion potential of such networks in Korean regional industrial complexes, evaluating economic impact of nickel recovery from process waste. Subsequently, we estimate the theoretically recoverable amount of nickel, extending our analysis to all national enterprises. Furthermore, by demonstrating tangible environmental benefits such as waste reduction and greenhouse gas (GHG) mitigation, it supports the strengthening of government policies.

TABLE 1 The most important technologies for recovering critical minerals **(MOTIE, 2014)**.

EIP Technology	Applications	Industry
Recovery of valuable metals from waste materials	1. Copper recovery from the PCB manufacturing process 2. Gallium and Indium recovery from transparent electrode waste scrap 3. Recovery of silver from silver coating scrap	Semiconductor, Printed Circuit Board (PCB), Photovoltaic industry, display, machinery and metal processing
Recovery of valuable metals from wastewater	Recovery of copper, nickel and indium from wastewater	Semiconductor, Printed Circuit Board (PCB), display, photovoltaic industry, LED industry
Recovery of valuable metals from industrial sludge	1. CeO_2 recovery from slurry 2. Copper extraction from sludge 3. Extraction of aluminum oxide from waste artificial marble	Printed Circuit Board (PCB), the refinery industry, construction and building materials
Recovery of valuable metals from waste oil	Molybdenum recovery from used lubricant	Photovoltaic industry, LCD and materials industries

3.2. Nickel Recovery Technology in the Supply Chain Network

The technology implemented within the EIPs commercially involves recovering high-purity nickel raw materials from nickel electroplating effluents and establishing a resource circulation network. Previously, nickel electroplating effluents were typically outsourced for treatment, incurring expenses and resulting in the loss of valuable nickel metal. However, a resource circulation network was established by selectively removing contaminants from nickel-containing waste through pH adjustments and ion exchange resins. Through electrolytic extraction, 99.8% high-purity electrolytic nickel was successfully recovered and reintegrated into the resource circulation network, returning it to the waste suppliers and demand partners - nickel electroplating enterprises **(KITECH, 2016)**.

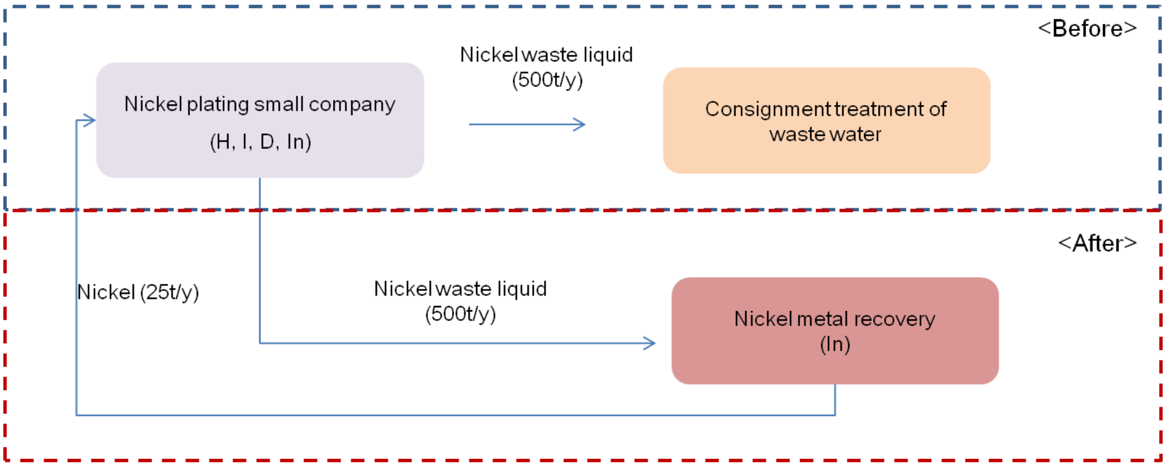

FIGURE 1 Treatment and recycling networks for nickel recovery **(KITECH, 2016)**.

Four nickel plating enterprises (H, I, D, In) participated in the pilot project, validating a total annual economic gain of 450 thousand USD through savings in raw material acquisition costs. Additionally, they achieved an environmental benefit by eliminating the generation of 500 tonnes of wastewater **(Figure 1).**

4. The methodology

To effectively disseminate and utilize commercialized technology for recycling critical minerals, it is essential to develop a mechanism for identifying potential demand companies and assessing the feasibility of commercialization. In this study, a system was established to integrate company information, EIP project details, and target technologies by aggregating data from public and open sources. This approach was used to identify prospective demand companies and evaluate the feasibility of commercialization. Globally, various platforms have been developed to share information on industrial symbiosis, but actual utilization cases are scarce due to insufficient quantity and quality of information needed to develop these networks **(Chen and Liu, 2021)**. Furthermore, encouraging platform user participation is challenging when there are inconsistencies in data formats and quality related to industrial classification, waste, and resources, or when data are lacking.

In this study, to address these challenges, dispersed corporate information from government departments and public institutes has been consolidated into integrated resources encompassing energy and emission data. Moreover, reliability has been bolstered by incorporating successful industrial symbiosis case data from existing business implementations. However, future improvements are necessary, such as introducing indicators like a similarity index, to mitigate challenges related to data updates and variations in applied processes even for similar products.

4.1. Data Set

The manufacturing facility data used in this study are sourced from public and open-access datasets. They include information from 196,640 target companies, encompassing factory registration details (Factory ON) provided by the Korea Industrial Complex Corporation (KICOX), energy usage and greenhouse gas emission data categorized by industrial sectors from the Korea Energy Agency (KEA), waste disposal information from the Allbaro system, water environment information from the WEMS, and waste recycling data from the Ministry of Environment (MOE).

4.2. Network Construction Algorithm

The algorithm used to assess the economic feasibility of recycling generated waste consists of five phases **(Figure 2 and Figure 3)**. Initially, EIP technologies and business models are categorized. The second phase involves classifying the types of waste. Thirdly, industries are categorized by linking them with industry codes. In the subsequent phase, potential resource quantities are estimated based on the ratio of recyclable nickel content. Finally, economic feasibility is analyzed considering processing costs, recovery costs, and transportation expenses at specified discount rates. The nickel metal content in wastewater is determined using market transaction prices and the specified rate for each electroplating company. Recycling costs are calculated based on expenditure differences between companies that have implemented recycling programs and those that have not.

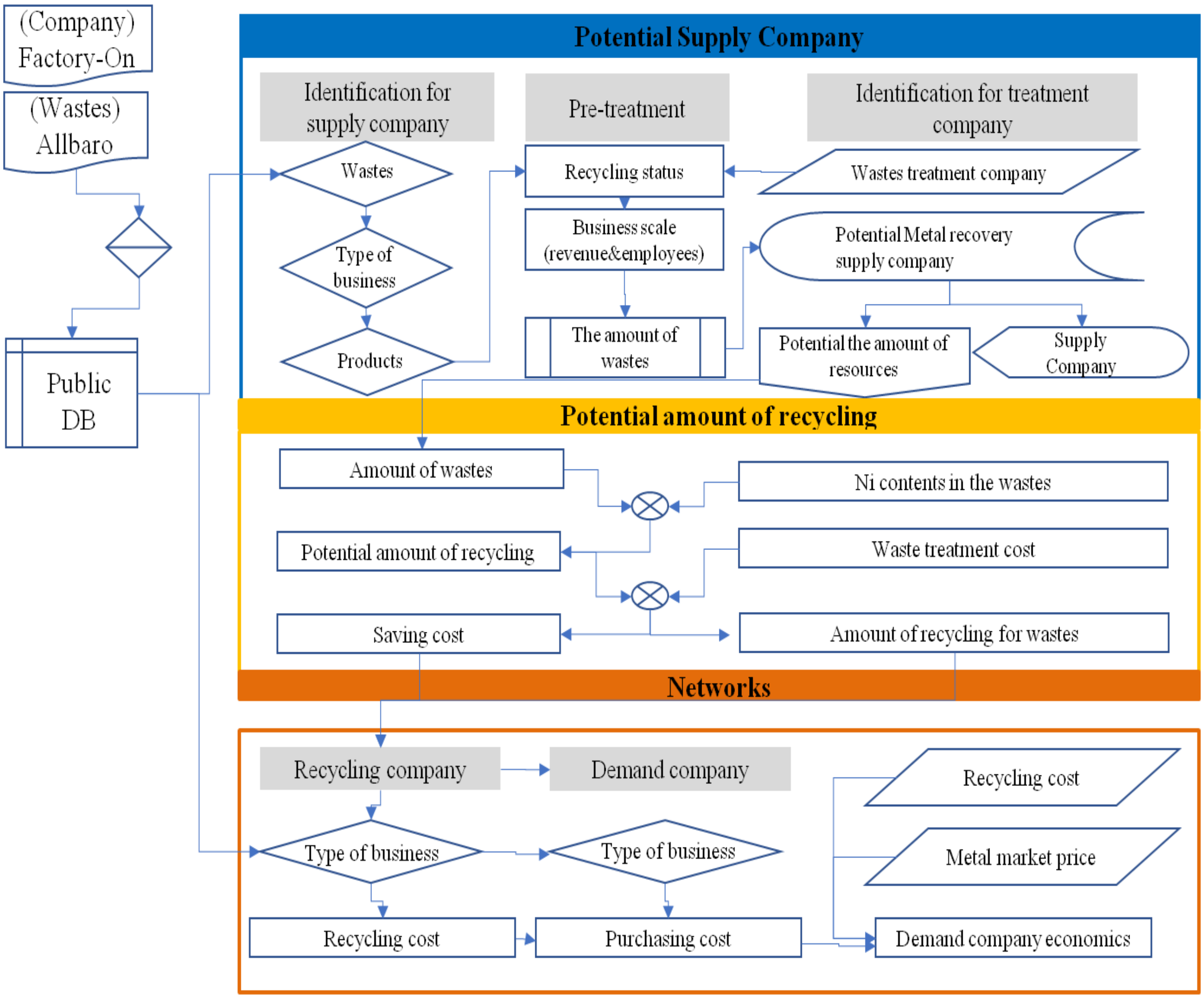

FIGURE 2 Algorithms of the flow of recycled materials.

4.3. Criteria for Evaluation

The economic, environmental, and social evaluations of critical mineral recovery are pivotal for project advancement. Particularly, economic evaluation holds significant importance as the primary driver for eco-industrial parks, despite their intended basis in environmental and social agendas **(Roberts, 2004)**. Therefore, for this initiative to succeed, member organizations within the supply, recycling, and demand sectors must demonstrate economic feasibility compared to traditional processing methods. Figure 3 illustrates the proposed economic evaluation criteria for participating companies categorized as suppliers, facilitators, and demanders. Key economic evaluation indicators for each target to support commercialization are outlined below.

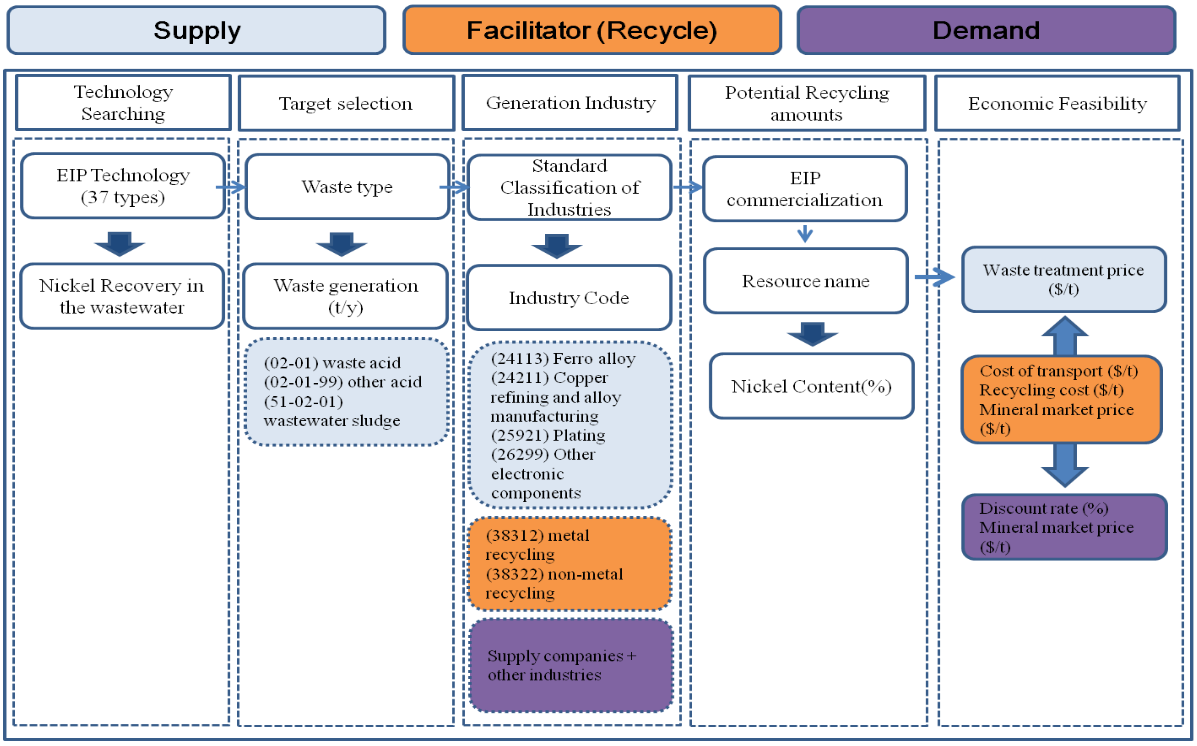

FIGURE 3 Flow sheet of evaluation process.

The pre-feasibility can be expressed as:

$$S_e = \sum_{i=1}^{n} PR_i \times W_c \tag{1}$$

$$R_e = \sum_{i=1}^{n} PR_i \times (S_c - R_c) \tag{2}$$

$$D_e = \sum_{i=1}^{n} PR_i \times M_p \times D_f \tag{3}$$

where i represents the number of companies. S_e denotes the waste disposal cost for supply companies, with PR indicating the potential recycling quantity and W_c representing waste disposal costs. R_e signifies the economic profit for recycling companies, where S_c denotes the sale price and R_c denotes the recycling cost. D_e denotes the purchasing cost for demand companies, with M_p indicating the market price of nickel and D_f representing the discount rate.

5. Results and Discussion

5.1. Economic Implications of Nickel Recovery Networks in Regional Industrial Complexes

Using a standardized algorithm to assess the profitability of nickel recycling within densely concentrated industrial complexes led to the identification of 190 potential supply companies capable of recycling 1,176 tonnes of nickel. The comprehensive examination of the network economy involving supply firms, facilitators, and demand entities revealed an annual economic advantage of 14.8 billion KRW (11.4 million USD) through cost savings and new revenues. This result focuses on supply companies due to their potential roles as facilitators or demand participants within the network, enabling collaboration with other businesses or independent operation. For instance, Company A in the Kumi industrial complex, specializing in electronic component materials, annually discharges approximately 30,352 tonnes of wastewater and 1,689 tonnes of waste sludge containing 0.35% nickel. Utilizing nickel recovery technology on these waste streams could potentially recover 112 tonnes of nickel, saving company A around 35 million KRW (27 thousand USD) in current outsourced waste disposal costs. Considering recycling revenues, the intermediary firm could potentially earn approximately 1.2 billion KRW (898 thousand USD) as a nickel recovery entity. Moreover, demand companies could procure recycled nickel at a lower cost than imported nickel, potentially saving about 210 million KRW (162 thousand USD) in procurement expenses.

Furthermore, conducting an economic analysis of an integrated nickel recovery and recycling program within these industrial complexes allows firms to establish closed-loop processes. This approach involves recovering nickel from company waste for reintroduction into the manufacturing cycle. Facilitator companies may collect nickel-containing effluent from neighboring firms engaged in similar activities, thereby promoting onsite recycling. Evaluation of intermediary companies managing waste generated by company A identified approximately 30 facilitator companies in the Kumi national industrial complex involved in recycling and transportation, suggesting potential network alignment to support economically advantageous onsite recycling initiatives. To develop a new business model focused on economic feasibility through the recovery and reuse of critical minerals from discarded materials, waste streams across different regions of Korea were evaluated. Analysis of regional industrial complexes indicated that 207,205 tonnes of nickel-containing waste is generated annually in the Kyunggi region, particularly in the Banwol and Sihwa industrial complexes, which are hubs for electronic and electrical product manufacturing and plating-related industries. From these streams, an estimated 728 tonnes of nickel could be salvaged, adding value amounting to 9.2 billion KRW (7 million USD). Similarly, in the Kyungbuk region, where concentrations of electrical, electronic, and mechanical sectors are found, about 220 tonnes of nickel could be recycled annually at the Kumi national industrial complex, resulting in an annual added value of 2.8 billion KRW (2.2 million USD). (**Figure 4)**

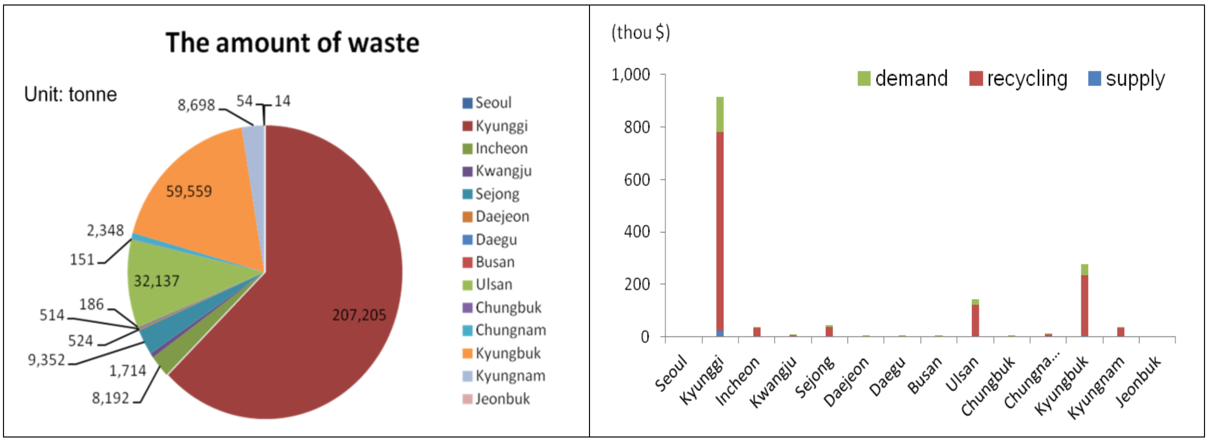

FIGURE 4 Regional industrial complex waste generation in 2022, (left), and regional industrial complex network economic feasibility (right). See Supporting Information S3 for the detailed calculation used for data analysis and comparison.

A distinctive finding from this industrial survey is the substantial waste emissions and extensive resource recycling observed in industrial complexes, particularly those with significant nickel content, highlighting robust economic efficiency. Notably, three companies situated in different industrial complexes contribute 75% to the total economic viability of nickel recycling among the 190 surveyed firms. Therefore, in the initial stages of constructing a nickel recycling network, focusing on those three major waste suppliers offers significant economic advantages (**Table 2**).

Table 2 Economic feasibility of a nickel recycling network among the three major companies. See Supporting Information S3 for the values.

	A (Kyunggi)	B (Ulsan)	C (Kyungbuk)	Total industrial complex
Wastes (t/y)	188,175	32,059	30,352	330,648
Recycling (t/y)	660	112	112	1,176
Supply F/S (1,000 USD)	157	27	27	281
Recycling F/S (1,000 USD)	5,281	898	898	9,415
Demand F/S (1,000 USD)	952	162	162	1,697
Network F/S (1,000 USD)	6,389(56.1%)	1,087(9.5%)	1,086(9.5%)	11,392(100%)

5.2. Potential economic benefit of the nickel recovery network on the manufacturing industry as a whole

After validating the economic viability of recycling waste nickel within industrial complexes, a comprehensive assessment covering all manufacturing enterprises revealed an annual generation of approximately 384,255 tonnes of nickel-containing waste streams (see **Figure 5**, 382,890+1,365 tonnes). An additional recovery potential of about 189 tonnes of nickel was identified, as the difference in recyclable amounts between the country and industrial complex. The total economic potential was estimated at 17 billion KRW (13 million USD), with 2.3 billion KRW (1.8 million USD) contributed by companies outside industrial complexes. This underscores the importance of establishing recycling networks centered around industrial complexes. Notably, 82% of the economic contribution from companies outside industrial parks stemmed from a single enterprise engaged in nickel and zinc refining, which generated 1.9 billion KRW (1.5 million USD). However, due to the absence of surrounding firms, this company can only operate independently as a waste supplier, facilitator, and demander, facing significant economic challenges.

Moreover, while not classified as an industrial complex, the cooperative association complex for electroplating activities in the Busan region demonstrated economic sustainability due to its concentrated similar electroplating-related firms. Recovering 8 tonnes of nickel from 2,344 tonnes of wastewater is feasible within this cooperative association complex, comprising mainly small and medium-sized enterprises, with an anticipated economic viability of approximately 103 million KRW (79 thousand USD). Given the collective ability of these small and medium-sized businesses to manage wastewater on a smaller scale, the construction of a network with the involvement of intermediary companies facilitating centralized wastewater treatment appears feasible. (**Figure 5**)

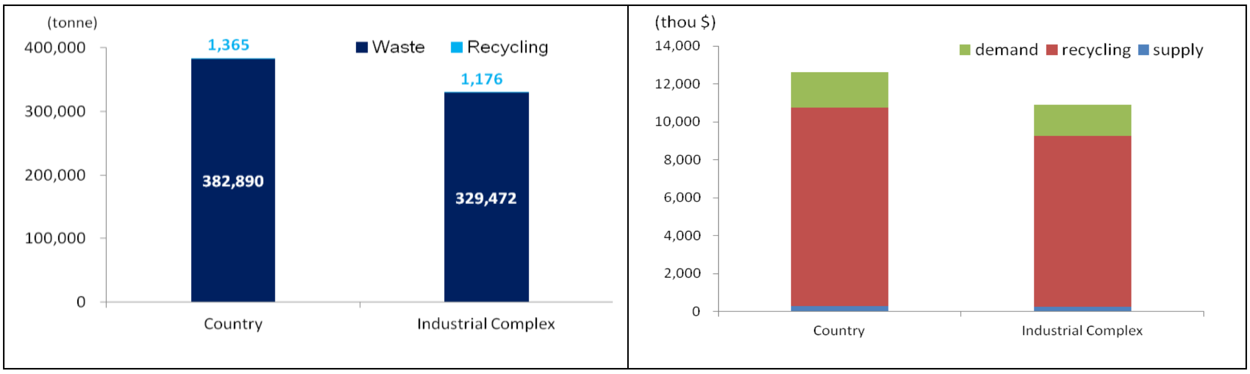

FIGURE 5 Volume of waste streams generated by national and industrial complexes (left), and the economic outcomes achieved by national and industrial complexes (right). See Supporting Information S5 for the detailed calculation used for data analysis and comparison.

5.3. Sensitivity analysis on the impact of the outcomes

In this study, a sensitivity analysis was conducted to examine the key parameters affecting the economic feasibility of recycling networks for nickel. The analysis aimed to identify which parameters within the recycling system exert the greatest influence on economic outcomes. Both internal and external factors were considered: internal factors included recycling costs for technologies, while external factors encompassed waste disposal costs for supply companies and the price of nickel for demand companies.

For the sensitivity analysis, each parameter was individually varied while keeping others constant. The baseline (0%) economic value was set based on a nickel price of 17,250 USD per tonne, using the prevailing rate at the establishment of the nickel recycling network in 2018, alongside waste disposal costs of 403 USD per tonne and recycling costs of 300 USD per tonne. The reference nickel price of 17,250 USD per tonne aligns closely with the six-year average from 2018 to 2023, which was 17,759 USD per tonne. Results indicate that variations in nickel price exert the most significant impact. Economic values of recovered nickel networks fluctuated from 10,565 thousand USD to 11,214 thousand USD. In contrast, variations in waste disposal and recycling costs had a comparatively smaller impact, influencing economic values by approximately 1%. **(Figure 6)**

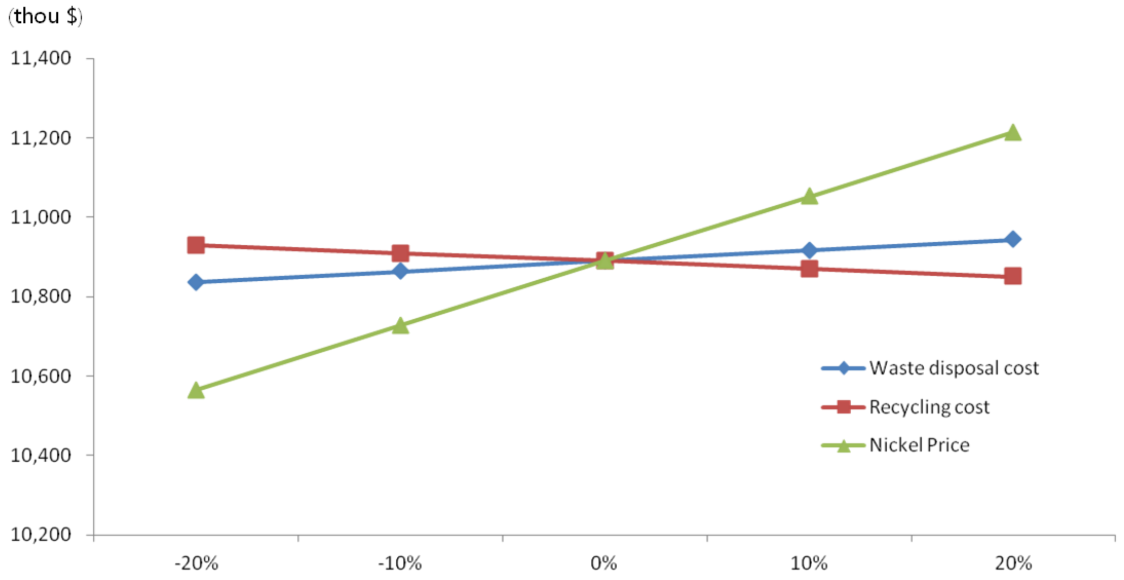

FIGURE 6 Sensitivity analysis on key parameters. See Supporting Information S6 for the detailed calculation used for data analysis and comparison.

The results of sensitivity analysis indicate that the profitability of recycling networks is significantly influenced by external factors, particularly the market price of nickel. As a result, small and medium-sized enterprises (SMEs) engaged in nickel recycling from waste within industrial parks face challenges in maintaining business sustainability.

Ultimately, it can be concluded that stable and continuous government support, both direct and indirect, is essential until the market stabilizes. Many companies involved in critical mineral resources secure nickel through long-term contracts with resource-rich countries or invest in mining development to support environmentally friendly industries such as electric vehicles, batteries, and solar power. However, this strategy is vulnerable to external factors, particularly the political environment of the resource-rich countries. For resource-poor countries, diversifying supply options becomes imperative.

5.4. Discussion

According to the framework developed in this study, the recoverable nickel from waste generated across all manufacturing industries in South Korea represents approximately 1.6% of total imports. However, companies are hesitant to invest actively, citing concerns over economic feasibility and operational sustainability. To enhance supply chain stability and promote environmentally sustainable industries, government intervention is essential through policies that allocate a portion of strategic stockpiles to recycled materials. Drawing on the successful implementation of the feed-in tariff (FIT) system, initially utilized to bolster the solar industry in various nations, governments can ensure profitability for recycling enterprises and catalyze the emergence of critical mineral extraction ventures across diverse sectors. The FIT system was pivotal in transitioning from fossil fuels to renewable energy sources, supporting renewable energy suppliers by compensating for higher generation costs compared to fossil fuels and thus fostering the sector's early growth. Similarly, for critical minerals, South Korea, rich in manufacturing capabilities but lack in natural resources, holds significant potential to secure these minerals from various waste streams. However, sustained governmental support is crucial during the sector's nascent stages. Establishing robust support mechanisms akin to the FIT system can enable governments to integrate recycled materials into strategic stockpile, creating synergies that stabilize critical mineral supplies and cultivate new market opportunities. In addition, the waste reduction and greenhouse gas (GHG) mitigation effects confirmed through the recycling network could serve as a catalyst for bolstering government support. Although the recoverable amount of nickel in Korea's manufacturing sector represents just 1.6% of total imports, viewed conversely, this figure implies a reduction of 1.6%, equivalent to 1,365 tonnes of waste. Furthermore, recycled nickel can be utilized in new product manufacturing, reducing fresh nickel consumption and concurrently achieving greenhouse gas benefits. The GHG reduction effect identified in this study amounts to 17,745 tCO_2-eq (Global Warming Potential 13 $kgCO_2$-eq/kg Class 1 Ni, **Nickel Institute 2023**). Although the greenhouse gas reduction potential achieved through nickel recycling may not be as significant as large-scale measures like fuel conversion, a global mandate on the use of recycled critical minerals in product manufacturing will address the government’s concerns on secured supply of critical minerals and waste management of waste products.

6. Conclusions

The global shift towards a low-carbon and sustainable economy, coupled with the critical imperative to secure the supply of critical minerals for enhanced national security, is increasingly recognized as urgent and pivotal across industrialized nations. Governments worldwide are pooling resources to ensure the availability of those minerals, highlighted by ambitious commitments such as the installation of 100 million electric vehicles by 2030, underscoring a steadfast commitment to achieving a net-zero carbon economy **(Ballinger et al., 2019)**. Nations acknowledge the crucial role of securing critical minerals in supporting the transition towards achieving the 2050 net-zero targets. However, due to the scarcity of those minerals, consistent procurement efforts require significant investment, especially for countries lack domestic sources.

This study focuses on South Korea as an example, evaluating a network aimed at securing critical minerals present in primary waste streams generated during manufacturing processes. Specifically, this study applied and categorized clean technologies previously developed for EIPs within the manufacturing sector, reflecting regional characteristics. The Kyunggi region, which is prominent in the electronics and equipment sectors, exhibited the greatest potential for nickel recovery. This potential translated into economic benefits amounting to 9.2 billion KRW (7 million USD). Following closely, the Kumi industrial complex in the Kyungbuk region yielded an economic benefit of 2.8 billion KRW (2.2 million USD).

In the South Korean context, industrial complexes have been identified as key hubs harboring 86% of the potential for overall economic benefits, making them viable locations for recovering nickel. The rising significance of critical minerals, notably in secondary batteries for electric vehicles, predicts a significant surge in end-of-life batteries by 2040, prompting current initiatives for their recycling. While immediate economic gains from strategies securing critical minerals in manufacturing processes may be modest, their future value is anticipated to rise. Despite the technology applied in this study yielding only 1,365 tonnes of nickel - equivalent to 1.6% of Korea’s annual nickel metal imports - the current resource strategy targeting a 20% increase in recycling does not encompass the waste analyzed here. Further exploration of various waste materials containing nickel, guided by the developed platform, has the potential to significantly advance Korea's governmental objectives. Over the past 12 years, Korea has introduced 37 eco-friendly technologies through eco-industrial development programs, including seven relevant to critical minerals such as indium, gallium, copper, and molybdenum. The potential for recovering those critical minerals using such technologies warrants deeper investigation. Recycling is poised to become a cornerstone policy ensuring future critical mineral supplies, particularly when integrated with industries generating substantial quantities of waste critical minerals, such as those involved in electric vehicles, secondary batteries, and renewable energy facilities.

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Conflict of Interest Statement

The authors declare no conflict of interest

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section at the end of this article.